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# Deployment of Autonomous Trains in Rail Transportation: Current Trends and Existing Challenges

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**ABSTRACT** Automation is expected to effectively address the growing demand for passenger and freight transportation, safety issues, human errors, and increasing congestion. The growth of autonomous vehicles using the state-of-the-art connected vehicle technologies has paved the way for the development of passenger and freight autonomous trains (ATs), also known as driverless trains. ATs are fully automated trains that are centrally controlled using advanced communication and internet technologies, such as high-speed internet (5G) technology, Internet of Things, dedicated short range communications, digital video detection cameras, and artificial intelligence-based methods. The current study focuses on a detailed up-to-date review of the existing trends, technologies, advancements, and challenges in the deployment of ATs with a full automation level in rail transportation. The basic AT features along with the key technologies that are instrumental for the AT deployment and operations are discussed in detail. Furthermore, a comprehensive evaluation of the state-of-the-art research efforts is performed as well with a specific emphasis on the issues associated with the AT deployment, user perception and outlook for ATs, innovative concepts and models that could be used for the AT design, and the AT operations at highway-rail grade crossings. Based on the conducted review, this study determines the main advantages and challenges from the AT deployment. The identified challenges have to be collaboratively addressed by the relevant stakeholders, including railroad companies, researchers, and government representatives, to facilitate the AT development and deployment considering the perspectives of future users and without affecting the safety level.

**INDEX TERMS** Autonomous trains, driverless trains, connected vehicles, autonomous vehicles, automation trends, automation challenges.

## I. INTRODUCTION

Despite the marginal impacts of COVID-19 on rail freight and passenger volume globally, the share of rail traffic is expected to grow [1]. The implementation of new technologies and better infrastructure will provide much needed impetus to the rail transportation sector. The statistics shows that the rail network has seen a tremendous growth globally in the last two decades. The total length of rail miles increased from 1,099,685 km in 2004 to 1,142,890 km in 2018 (see **Fig. 1**), which is approximately a 4% increase [2]. The growth has been observed in terms of the number of passengers traveling and in terms of freight movements as well (see **Fig. 2**). More specifically, the rail passenger traffic around the world increased from 2,440,732 million passenger-km in 2004 to 4,068,548 million passenger-km in 2018. On the other hand, the rail freight traffic around the world increased from 8,443,020 million ton-km in 2004 to 11,190,112 million ton-km in 2018.

**TABLE 1** shows the distribution of rail passenger and freight traffic as well as the distribution of rail lines globally by major geographical regions [2]. The data show that Asia and Oceania (excluding Russia and Turkey) has the largest rail passenger traffic accounting for 76.1% of the total rail

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**FIGURE 1.** **Changes in the total length of rail miles between 2004 and 2018.**

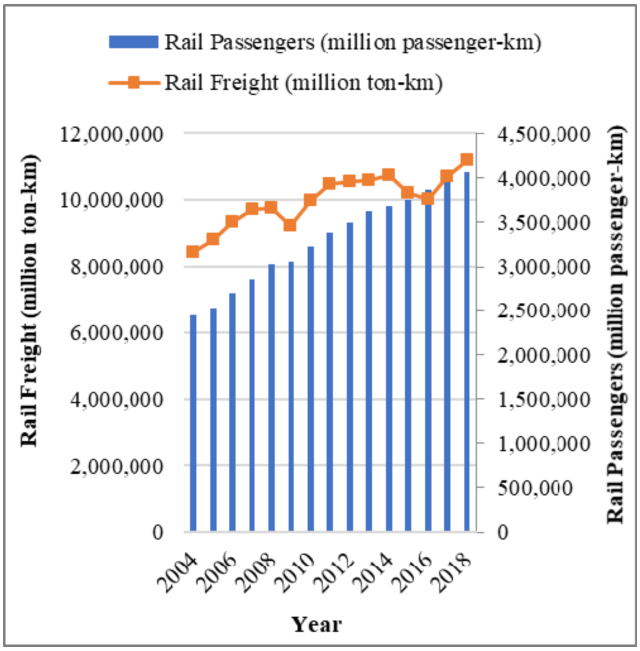


**FIGURE 2.** **Changes in the rail freight and passenger traffic between 2004 and 2018.**

passenger traffic. Europe (including Turkey), Russia, and Africa account for 15.7%, 4.4%, and 2.0% of the total rail passenger traffic, respectively. The lowest rail passenger traffic is observed in America (only 1.8% of the total rail passenger traffic). As for the rail freight traffic, Asia and Oceania, America, and Russia accumulate the largest amount of rail freight traffic accounting for 38.0%, 31.8%, and 21.5% of the total rail freight traffic, respectively. Furthermore, America has the largest rail network (accounting for 34.1% of the total rail miles), followed by Asia and Oceania, Europe, Russia, and Africa.

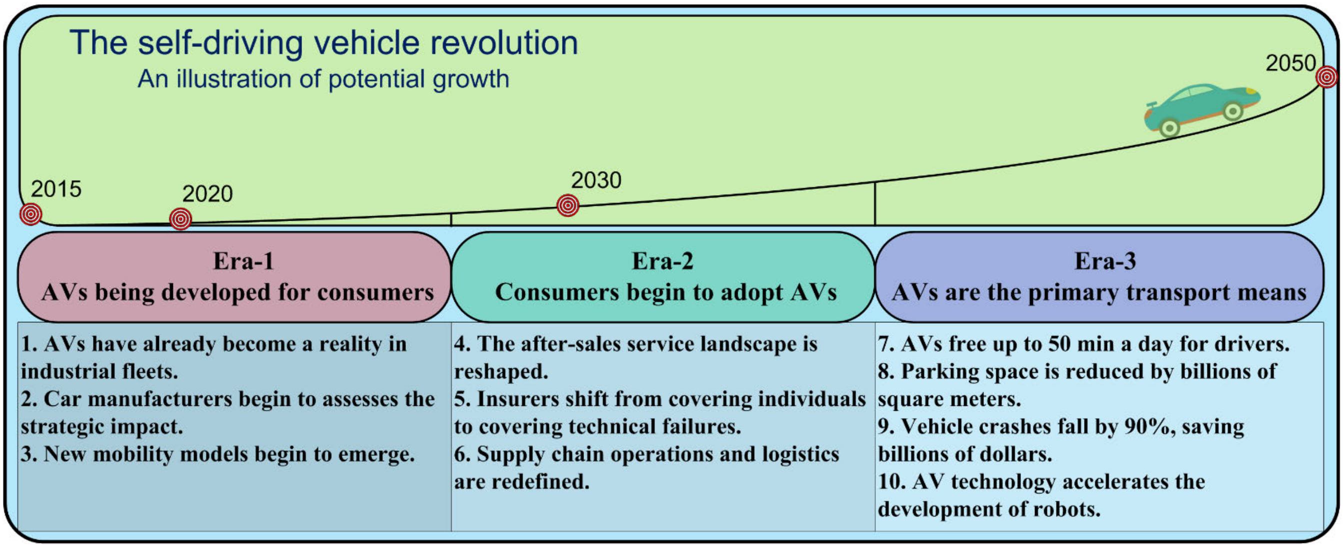
The rail freight transportation market is expected to achieve a cumulative average growth rate of around 2% globally during the projected period of 2020 to 2025 [1]. Despite the fact that North America is recognized as a global leader in rail freight market, it is anticipated that Asia-Pacific is likely to overtake North America in the following years. Although the growth of containerized cargo has been boosted by the development of intermodal transportation [3]–[5], non-containerized and liquid-bulk freight still governs rail freight transport [1]. Furthermore, the development of various cross-country and inter-continental rail networks, such as Chongqing-Xinjiang-Europe international railway, and other initiatives, such as "One Belt One Road" by China, is expected not only to provide a projected growth for rail freight and passenger traffic but to open new economic corridors as well. In particular, the "One Belt One Road" initiative opens a variety of economic corridors, including the following [6]: (1) China-Mongolia-Russia economic corridor; (2) China-Pakistan economic corridor; (3) Bangladesh-China-India-Myanmar economic corridor; (4) China-Indochina Peninsula economic corridor; (5) China-Central Asia-West Asia economic corridor; and (6) New Eurasia Land Bridge economic corridor.

The growth in rail passenger and freight traffic along with a continuous rail network expansion requires railroad companies making improvements in the existing operations to maintain profitability and effectively tackle the demand for rail transportation. Similar to rail transportation, road transportation is facing challenges associated with the growing demand. The introduction of the connected and autonomous vehicle (CAV) technology for road transportation is expected to effectively address the growing demand, safety issues, additional costs, environmental problems, human errors, and increasing roadway congestion. Some of the major benefits of having the autonomous vehicle (AV) technology in transportation include better accessibility, mobility, and improvement in land use. A simultaneous use of the AV technology with electric vehicles can significantly reduce the emissions and protect the environment. Moreover, the deployment of AVs is expected to reduce the vehicle ownership pattern. **Fig. 3** shows the projected growth of driverless vehicles and illustrates the following three eras [7]: (a) "Era 1" – AVs are being developed for consumers; (b) "Era 2" – consumers begin adopting AVs; and (c) "Era 3" – AVs become the primary means of transport. The AVs are generally classified into six levels of automation [8]. Levels "0", "1", and "2" require inputs from a driver, while levels "3", "4", and "5" are mostly based on the auto pilot (the driver input is required only by level "3" upon request – see **Fig. 4**).

Many countries within the European Union (EU) have made a substantial progress to support the development of cooperative, connected, and fully automated mobility. The EU established a framework for Cooperative-Intelligent Transportation Systems (C-ITS) that has the following main objectives [9]: (1) develop a common vision for the EU countries to combine the CAV development and deployment efforts of different stakeholders; (2) launch a C-Roads platform to coordinate the CAV deployment across the EU; (3) address the legal issues associated with the

**TABLE 1.** Percentage of rail passengers, freight, and rail lines globally by geographical location (2004–2018).

| Geographical Location | Rail Passengers (million passenger-km) | Rail Passengers (%) | Rail Freight (million ton-km) | Freight (%) | Length of Rail Lines (km) | Length of Rail Lines (%) |
|---|---|---|---|---|---|---|
| Africa | 982,361 | 2.0 | 2,315,417 | 1.5 | 1,141,683 | 6.8 |
| America | 906,175 | 1.8 | 47,590,186 | 31.8 | 5,701,525 | 34.1 |
| Asia and Oceania (Russia and Turkey excluded) | 37,788,381 | 76.1 | 56,872,292 | 38.0 | 4,492,658 | 26.9 |
| Russia | 2,205,089 | 4.4 | 32,280,372 | 21.5 | 1,278,660 | 7.7 |
| Europe (including Turkey) | 7,794,595 | 15.7 | 10,769,925 | 7.2 | 4,096,830 | 24.5 |



1. AVs have already become a reality in industrial fleets.
2. Car manufacturers begin to assesses the strategic impact.
3. New mobility models begin to emerge.
4. The after-sales service landscape is reshaped.
5. Insurers shift from covering individuals to covering technical failures.
6. Supply chain operations and logistics are redefined.
7. AVs free up to 50 min a day for drivers.
8. Parking space is reduced by billions of square meters.
9. Vehicle crashes fall by 90%, saving billions of dollars.
10. AV technology accelerates the development of robots.

**FIGURE 3.** Projected AV growth and benefits.

CAV deployment; (4) address the cybersecurity issues associated with the CAV deployment; and (5) address the data privacy issues associated with the CAV deployment. The C-Roads program has been successfully implemented in the Netherlands, Austria, Belgium, France, Germany, United Kingdom, Nordic countries (i.e., Denmark, Finland, Norway, and Sweden), and other EU countries as well. The C-ITS framework supports the development of CAVs with advanced features and technologies, such as hazardous location notification, emergency vehicle approaching notification, weather condition services, collision risk warning, in-vehicle speed limits, green light optimal speed advisory, and vulnerable road user protection [9]. Many of the aforementioned CAV development tendencies and technologies can be observed not only in the EU but also in other countries as well (e.g., the United States, Australia, Middle East, and Far East).

The benefits of automation can be extended not only to road transportation, but to rail transportation as well. Many large companies, such as Alstom S.A., Bombardier Transportation, CRRC Transportation, General Electric, Hitachi Ltd., Kawasaki Heavy Industries, Mitsubishi Heavy Industries, and Siemens AG., invested substantial funds into the development and deployment of the autonomous train (AT) technology. In particular, the AT technology market was valued at $5.88 billion in 2018 and is anticipated to reach $15.57 billion by 2026 [10]. The deployment of ATs is expected to offer the following advantages to railroad companies [10]: (1) reduction in accidents and safety improvements; (2) decrease in operational costs; (3) ATs with a full automation level will completely eliminate potential risks due to human errors; (4) reduction in emissions produced; (5) increased capacity for passenger and freight transport; (6) improved reliability of rail services; (7) effective communication with connected vehicles (CVs) and AVs; and others. Along with advantages, there are some challenges that are associated with the AT deployment and reaching the full automation level (e.g., substantial capital costs of automation, required infrastructure improvements, potential cyber-attacks that may disturb the AT operations, legal issues, and many others that will be further discussed in this study).

Although a significant number of survey studies have been conducted to date aiming to investigate various aspects and challenges associated with the deployment of CVs and AVs [11]–[15], very limited survey efforts have been geared towards a comprehensive understanding of advantages and challenges from the AT deployment [16]–[18]. Therefore, this study aims to conduct a detailed up-to-date review of the state-of-the-practice and the state-of-the-art, aiming to identify the existing trends, technologies, advancements, and challenges in the development and deployment of ATs in

|  | *What does the human in the driver's seat have to do?* |  | *What do these features do?* | *Example features* |  |
|---|---|---|---|---|---|
| LEVEL 0 | **You are driving** whenever these driver support features are engaged - even if your feet are off the pedals and you are not steering | **You must constantly supervise** these support features; you must steer, break or accelerate as needed to maintain safety | These features are limited to providing warnings and momentary assistance | • automatic emergency braking<br>• blind spot warning<br>• lane departure | These are driver support features |
| LEVEL 1 |  |  | These features provide steering **OR** brake/acceleration support to the driver | • lane centering<br>**OR**<br>• adaptive cruise control |  |
| LEVEL 2 |  |  | These features provide steering **AND** brake/acceleration support to the driver | • lane centering<br>**AND**<br>• adaptive cruise control |  |
| LEVEL 3 | **Your are not driving** when these automated driving features are engaged - even if you are seated in the driver's seat | When the feature requests<br>**Your must drive** | These features can drive the vehicle under limited conditions and will operate unless all required conditions are met. | • traffic jam chauffeur | These are automated driving features |
| LEVEL 4 |  | These automated driving features will not require you to take over driving |  | • local driverless taxi<br>• pedal/steering wheel may or may not be installed |  |
| LEVEL 5 |  |  | This feature can drive the vehicle under all conditions | • same as level 4, but the feature can drive everywhere in all conditions. |  |

**FIGURE 4.** Automation levels for AVs.

rail transportation. Based on the conducted review, this study identifies the main advantages that can be achieved from the AT deployment. Moreover, the main challenges from the AT deployment that have to be addressed in the nearest future are determined as well. The remainder of this manuscript is organized as follows. In the second section, the current trends in the railroad industry with respect to the AT applications are discussed. The review of state-of-the-art efforts related to ATs is described in detail in the third section. The state-of-the-art summary, identified benefits from the AT deployment, and the associated challenges are presented in the fourth section. The study conclusions and necessary future research works are described in the fifth section. A full list of abbreviations that will be used in this manuscript is presented in **Appendix**.

## II. REVIEW OF THE CURRENT TRENDS IN AUTONOMOUS TRAIN APPLICATIONS

Advancements in rail technology are quickly taking it to the next level from partial or no automation to a full automation level. Highly sophisticated cutting-edge technologies are being used or planned to be used to achieve the full automation level in trains. A few of these technologies that are used in combination are high-speed internet (5G) technology, infrared cameras, ultrasonic cameras, dedicated short-range communications, accelerometers, tachometers, sensors, among others. Based on the International Association of Public Transport framework, there are four grades of automation (GoAs) for trains that include the following (see **TABLE 2**) [19]:

- GoA1: All the major train operations, such as starting, stopping, door operations, addressing emergency situations, and sudden diversions, are manual and involve an onboard driver;
- GoA2: Some of the train operations, such as starting train, stopping, changing the rail tracks, are automated but an onboard driver is still needed;
- GoA3: This level provides autonomous train operations, but in case of an emergency an onboard attendant takes control of the train; and
- GoA4: At this level, the train runs fully autonomous with no onboard driver/attendant (see **Fig. 5**).

**TABLE 2.** Grades of automation for trains.

| Grade of Automation (GoA) | Type of Train Operation | Driver/Attendant Presence Required | Starting Train Motion | Stopping Train Motion | Door Opening and Closure | Emergency Situations |
|---|---|---|---|---|---|---|
| GoA1 | ATP with Driver | Yes | Driver | Driver | Driver | Driver |
| GoA2 | ATP and ATO with Driver | Yes | Automatic | Automatic | Driver | Driver |
| GoA3 | DTO | Yes | Automatic | Automatic | Attendant | Attendant |
| GoA4 | UTO | No | Automatic | Automatic | Automatic | Automatic |

Notes: ATP – automatic train protection; ATO – automatic train operation; DTO – driverless train operation; UTO – unattended train operation.

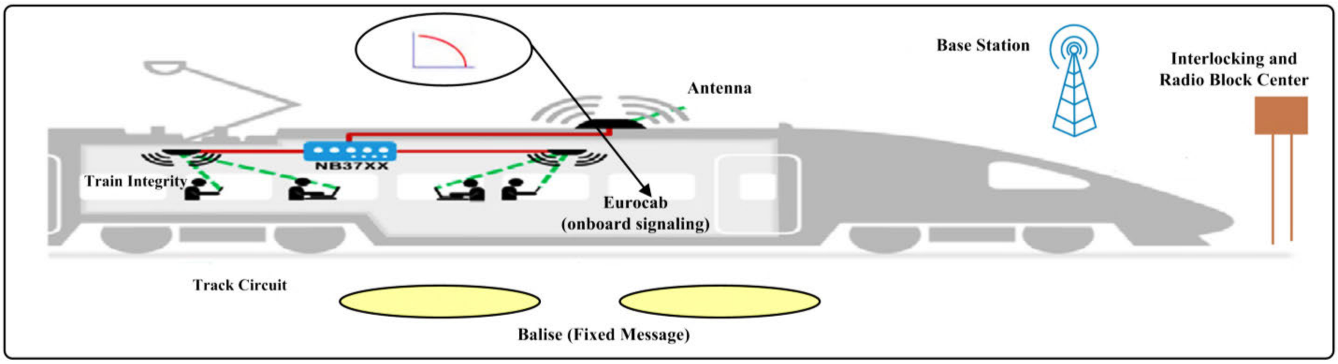


**FIGURE 5.** An example of a fully autonomous passenger train.

Although electric vehicles and AVs are constantly receiving attention and substantial investments, a significant progress has been done towards the deployment of ATs with the full automation level. For example, in the Pilbara region of Western Australia, mining corporation "Rio Tinto" has moved to driverless fully autonomous operations for its entire rail system (heavy haul) in June 2019 [20], while the first autonomous rail journey occurred in October 2017. The Rio Tinto's rail network is recognized as the world's first fully autonomous rail network. It is expected that reaching the level of full automation for ATs will be more difficult for North America, where multiple passenger and freight operators have to share the same rail tracks, trains have various weights and types, and there are numerous yards and junctions.

Similarly, there are multiple challenges in Europe as well. However, the Société Nationale des Chemins de Fer Français (SNCF), the French National Railway, successfully finished the first test using a locomotive-hauled AT that was remotely controlled in July 2019. This test was a part of a larger project aiming to develop prototypes of autonomous freight and passenger trains by 2022 [20]. New automatic metro lines are being introduced in Barcelona (Spain), and the Barcelona Metropolitan Transport authority plans to convert its busiest conventional metro lines into fully autonomous lines in the nearest future. The process is going slower than expected mainly due to complexity of administering such an extensive project [20]. Similar projects are undertaken towards fully automated metros in other countries as well (e.g., Brazil, Canada, Denmark, Germany, Italy, and United Kingdom). The International Association of Public Transport forecasts a major acceleration in the development of fully automated metros in the following years. In particular, the length of fully automatic metro lines is expected to triple between 2019 and 2023 [20]. Even nowadays, over 40 cities around the globe have fully operational automated rail lines (e.g., Paris, Sydney, Vancouver, São Paulo, and Copenhagen). Furthermore, there are more than 60 fully automated rail lines in the world, most of which are located in Asia (e.g., Hong Kong, Singapore, Japan, and South Korea).

This section of the manuscript provides a detailed review of the existing trends, technologies, and advancements associated with the deployment of ATs in the railroad industry, including the following: (1) overview of basic AT features; (2) Internet of Things; (3) artificial intelligence; (4) dedicated short-range communications; and (5) positive train control.

### A. OVERVIEW OF BASIC AUTONOMOUS TRAIN FEATURES

The Railway Technical Research Institute (RTRI, Japan) addressed the sustainable development goals by introducing various research activities as a part of the initiative "RESEARCH 2025" and emphasized on the goals of innovation, industry, and infrastructure for railroads [21]. The main RTRI objective is to develop solutions to different challenges facing the railroad industry (e.g., global environmental problems, social burden associated with aging populations, regional disparity of the economy) in cooperation with the railroad practitioners, research institutions, academic institutions, and other relevant stakeholders. The deployment of ATs with the full automation level is one of the strategies to achieve sustainable development goals. **Fig. 6** and **Fig. 7** show a variety of innovative technologies that are generally used for operations, movement, and maintenance of ATs [21].

Different technologies are deployed in ATs to provide the information to moving trains regarding the passengers at nearby stations, route control and braking patterns, obstacle detection on the tracks or in the vicinity of tracks, entire

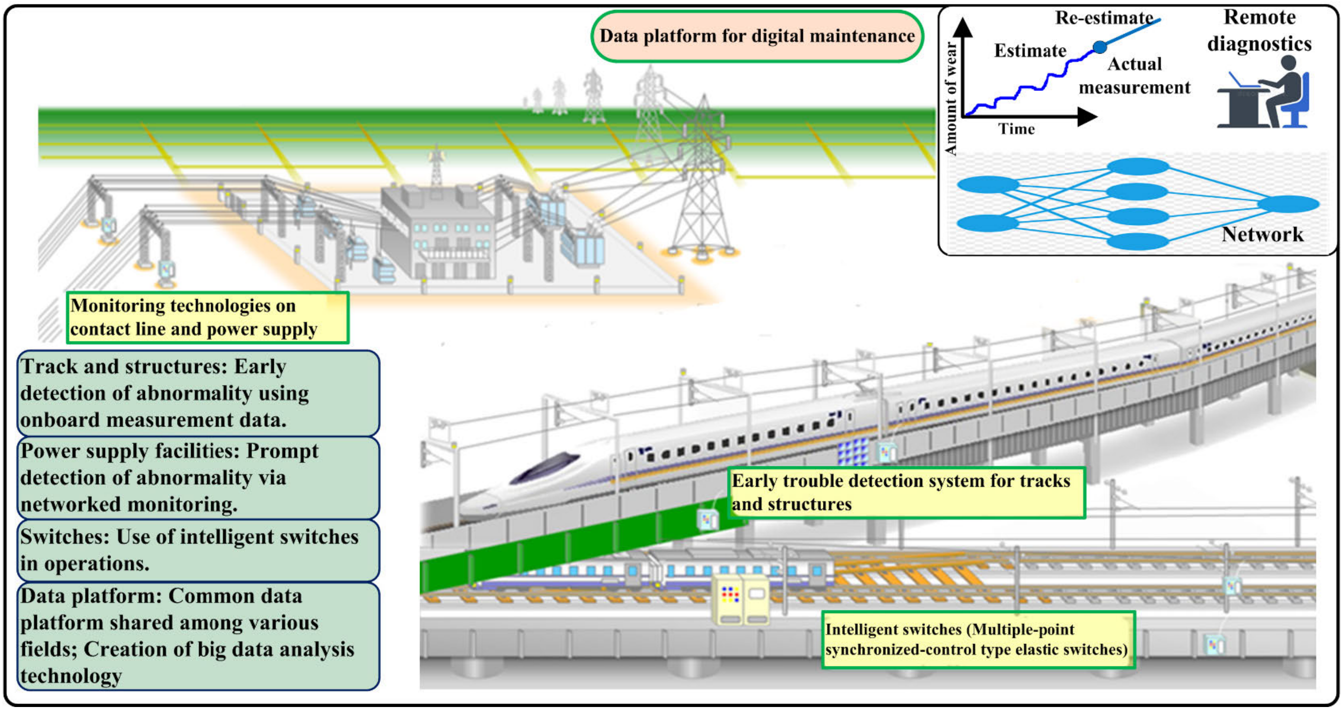


**FIGURE 6.** Basic AT operations.

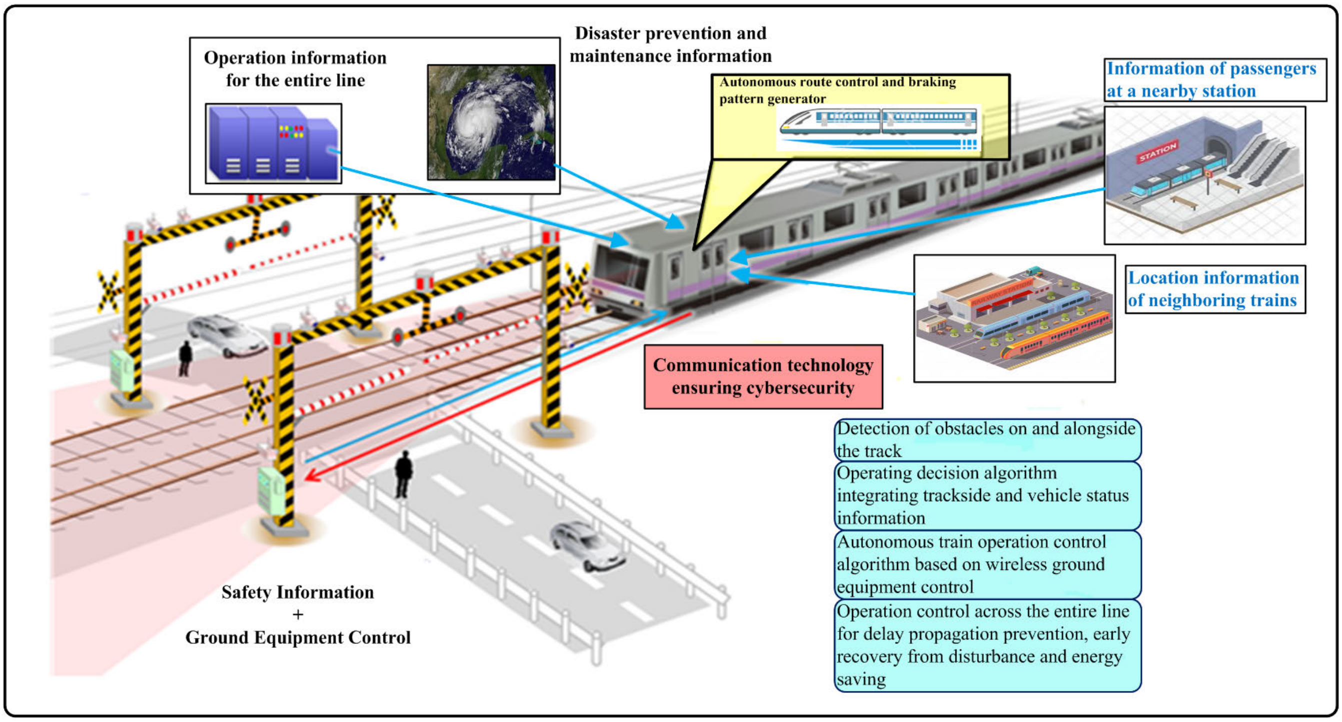


**FIGURE 7.** Digitalized maintenance for ATs.

line operations, disaster prevention and maintenance information, safety and ground equipment control, and the information regarding the location of neighboring trains. ATs also use onboard data measurement devices, which help in early detection of any abnormalities on tracks and structures. Multiple-point synchronized-control type elastic switches, also known as intelligent switches, are deployed on tracks for detection and collecting some operational data. Various types of data collected assist with the development of big data analysis models for improving the effectiveness of AT operations.

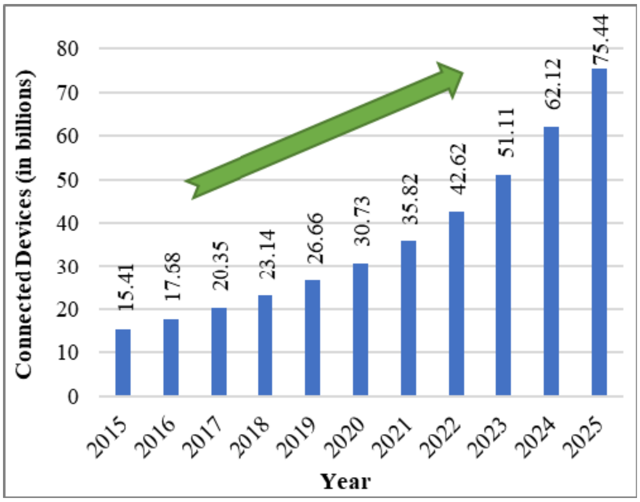


**FIGURE 8.** **The number of IoT connected devices globally between 2015 and 2025.**

The development of new advanced communication and detection technologies is expected to facilitate the deployment of ATs and meet the main sustainable development goals.

### B. INTERNET OF THINGS

The Internet of Things (IoT) technology uses high-speed internet and wireless technology to provide seamless connectivity to various devices, applications, and systems deployed by ATs. The IoT functionality and performance directly depend on advanced computing applications, big data available, machine learning techniques adopted, and artificial intelligence methods that are used for the analysis of critical data collected from surrounding CVs, AVs, and other areas and objects. The data collected and evaluated by means of IoT allow enhancing the efficiency and safety of the overall system, where ATs serve as an integral part. The IoT technology can be effectively used with the Global Positioning System (GPS) to determine the appropriate routing choices for ATs and communicate the changing train location to a central command center and various infrastructure units.

Such communication is critical, especially at the locations where ATs can have potential conflicts with pedestrians or vehicles (e.g., highway-rail grade crossings, where a highway segment intersects with a railroad segment at the same elevation and creates a conflicting point between the arriving trains and vehicles). The number of IoT connected devices is expected to rapidly increase in the following years (see **Fig. 8**), which will provide an opportunity to the railroad industry and other industries to benefit from the IoT advantages [22]–[24]. It is expected that the IoT technology in the railroad industry will become a $30 billion market in the next 15 years.

### C. ARTIFICIAL INTELLIGENCE

The artificial intelligence (AI) component of ATs consists of various interlinked technologies, including the following [22], [25]: (1) natural language processing technologies; (2) robotics; (3) machine learning technologies; (4) vision technologies; (5) speech technologies; (6) planning technologies; and (7) expert systems. The AI technologies are used for the simulation of human intelligence and machine learning. The AI can be applied to solve a specific decision problem and has huge processing power. The AI-based technologies rely on mathematical models, software, and algorithms that can potentially enhance the performance of a given system. Advanced AI techniques (e.g. neural networks, genetic algorithms, tabu search, variable neighborhood search, simulated annealing) can be applied for optimizing various AT operations (e.g., travel time optimization, timetable synchronization, AT routing, intelligent scheduling, AT maintenance procedures, intelligent inspection).

For example, the SNCF railway has been using a variety of AI-based techniques for many years (such as prediction algorithms, real-time data processing, and sequential machine learning) along with different types of supporting equipment (i.e., remote sensors for detecting pressure, vibration, and temperature; devices for automatic alerts, field and onboard equipment), which allowed substantially improving the railroad operations. In particular, the SNCF railway increased its ridership by approximately 50% in the last 10 years and is capable of successfully running 15,000 trains per day [22].

### D. DEDICATED SHORT-RANGE COMMUNICATION

Dedicated short-range communications (DSRC) can be viewed as a short-range communication system with a reliable two-way high-speed radio service that can be effectively deployed for vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication [26]. The DSRC is able to operate continuously in a broadcast-and-receive mode, which provides situational information regarding surrounding vehicles. The CVs equipped with the DSRC technology are able to exchange information at a 5.9 GHz spectrum without having any cellular infrastructure. The information is exchanged by means of a basic safety message (BSM) that contains vehicle size, heading, position, speed, brake status, and steering angle. The BSM can be frequently broadcast between CVs (e.g., every 100 milliseconds). Unlike many other communication technologies that are based on one-to-one communications, the DSRC enables one-to-many communications. The DSRC technology has been developed to effectively work in the fast moving environments, where a sender is moving away from a receiver at speeds that exceed 100 mph. The DSRC is viewed as one of the most effective alternatives for V2V communications due to its unique combination of attributes (i.e., message broadcasting without a network connection, high broadcast frequency, trusted and anonymous communication, and effective functionality in the fast moving environments).

**Fig. 9** shows two different types of communication systems. The first communication system deploys the DSRC technology for road-side unit (RSU), V2V, V2I, and V2X (which is a combination of V2V and V2I) communications. One the other hand, the second communication system

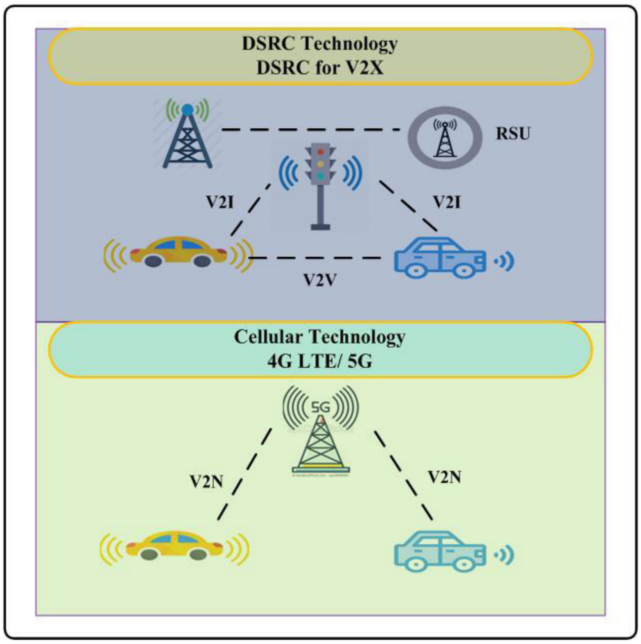


**FIGURE 9.** Vehicle communication systems.

allows interactions between vehicles by means of vehicle-to-network (V2N) communication. It can be observed that the DSRC enables more effective interactions between vehicles and surrounding objects when comparing to basic cellular technology-based communications [27]. In case of the AT deployment, the DSRC will use an onboard unit, which will be installed in the locomotive and will interact with the radio communication-based RSUs that are installed in the proximity of rail tracks. The DSRC can provide necessary warning at highway-rail grade crossings to the surrounding vehicles regarding an approaching AT in a similar way that is used to provide warning to AVs on restricted stretches of highways.

### *E. POSITIVE TRAIN CONTROL*

The positive train control (PTC) technology has been developed as a railroad safety system that automatically slows down a train as soon as it crosses a specified travel speed or skips a signal [28]. Such a system is mainly designed to reduce the impacts of potential human errors and decrease the severity of potential accidents at highway-rail grade crossings as well as train-to-train accidents. Wi-Fi, GPS, and high-band radio transmission are used by the PTC system to identify the location, direction, and speed of the approaching trains. The train crew can be provided a notification if there are any potential issues on rail tracks. Furthermore, the approaching train can be controlled remotely in case there is no timely response from the train crew. The PTC system has been primarily deployed at freight railroads but has the potential for passenger railroad applications with some adjustments in terms of equipment and software. **Fig. 10** shows different components that are directly used by the PTC system. The Advanced Civil Speed Enforcement System (ACSES) is one of the main PTC components and represents the locomotive cab signaling system. Advanced signaling and communication capabilities provided by the PTC system are expected to improve safety of roadway users and train crew at the railroad networks with conventional trains and ATs as well.

## III. REVIEW OF THE RELEVANT STATE-OF-THE-ART EFFORTS

Many state-of-the-art research efforts have been conducted to date to investigate various aspects of ATs, such as current trends, stages of development, use of technologies, safety and reliability issues, level of automation, challenges in the deployment, and others. A detailed up-to-date review of the relevant literature was conducted as a part of this study following the content analysis method, which is considered as a well-established method for systematic reviews of the literature [29]. A thorough literature search was performed via the databases supported by the top scientific publishers (e.g., Elsevier, IEEE, Springer, SAGE, Emerald, etc.) to identify the studies that are the most relevant to the theme of the present survey using the following keywords and phrases: ‘‘autonomous trains’’, ‘‘freight train automation’’, ‘‘passenger train automation’’, ‘‘autonomous train technologies’’, ‘‘rail automation advantages’’, ‘‘rail automation challenges’’, ‘‘autonomous train safety’’, ‘‘autonomous train reliability’’, and ‘‘rail automation perception’’.

The search engines of the considered publishers identified many thousands of articles. However, only a small portion of those articles were dedicated to autonomous rail transportation, while the majority of the articles strictly concentrated on autonomous road transportation (i.e., focusing on CVs and AVs without providing any connection to ATs). The collected studies on the AT deployment were classified into the following categories: (1) CAV technologies and their applications for ATs; (2) general issues associated with ATs; (3) user perception and outlook for ATs; (4) design and technologies for ATs; and (5) ATs and highway-rail grade crossings. The following sections of the manuscript present a description of the collected studies.

### *A. CONNECTED AND AUTONOMOUS VEHICLE TECHNOLOGIES AND THEIR APPLICATIONS FOR AUTONOMOUS TRAINS*

As a result of the conducted literature search, many studies dealing with the CAV technologies were identified, and only some of them discussed how these technologies could potentially influence the AT deployment and operations. For example, Bagloee *et al.* [30] analyzed various issues and opportunities regarding the transportation policies and regulations associated with the CAV technologies. The study highlighted that the deployment of CAV technology is expected to reduce the cost of transportation and increase the accessibility. An essential part of the CAV technology was found to be its ability to communicate with moving vehicles and infrastructure, as well as the possibility of an efficient optimized intelligent routing system. This technology would

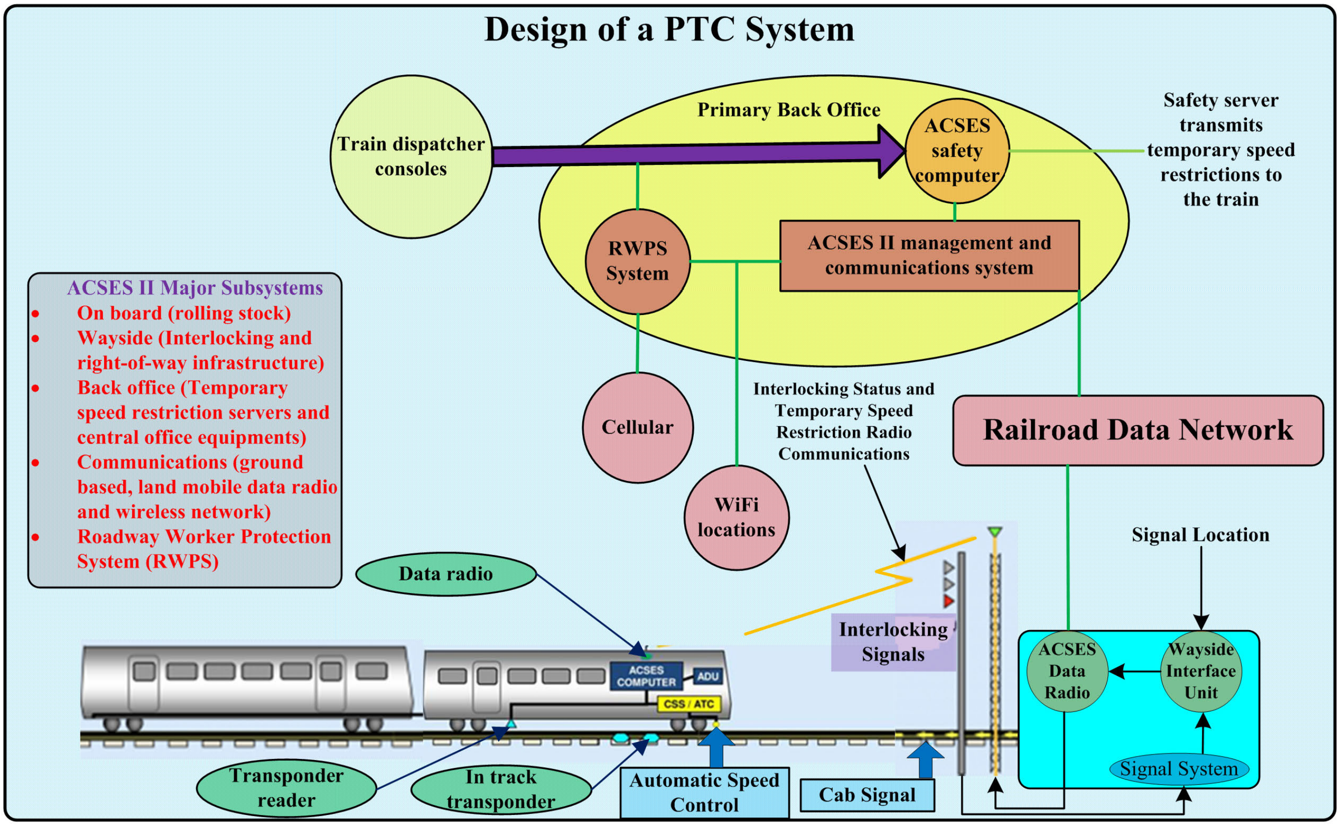


**FIGURE 10.** Design of a PTC system.

be important for the vehicles passing through highway-rail grade crossings and interacting with crossing infrastructure as well as the trains approaching the crossings.

Krasniqi and Hajirizi [31] investigated the current CAV market and technology trends from the preliminary stage to fully driverless vehicles. The IoT technology was found to have a potential to completely alter the automobile market, which could provide a major thrust to IoT in the autonomous technology market. The study listed the major challenges of the autonomous industry, various advantages and disadvantages, and issues related to its deployment. The major focus area of the study was related to the industry thrust of the CAV technology rather than the academic research. The following major CAV-related issues were identified: (1) lack of software that are fail-proof; (2) lack of dynamic maps that can update quickly and provide detailed information regarding street views; and (3) sensors that can detect unanticipated conditions. The study concluded that the DSRC and 5G technologies would be the most suited for improving safety and vehicle communication with trains and surrounding infrastructure.

Crains [32] presented a perspective on the future of autonomous technology in all modes of transportation (not only AVs but ATs, autonomous aircrafts, autonomous vessels, etc.). The study highlighted the Copenhagen metro and Rio Tinto in Western Australia as some of the successful examples of using autonomous passenger locomotives and heavy haul freight locomotives, respectively. It is predicted that the train technologies, such as hyperloop, may advance to a fully autonomous mode, especially for passenger transportation. A number of challenges with the AT deployment were pointed out (e.g., introduction of the PTC system in the United States (U.S.) for freight railroads only; disagreement of railroad unions to adaptation of one-person train crews), which can slow down rail automation if not addressed properly. The study also discussed some technologies that are used in AVs for different purposes, which are comparable to similar technologies that are used in ATs (see **TABLE 3**). Bucsky [33] studied the existing condition of freight traffic and CAV applications in freight transportation. It was highlighted that the level of automation would vary from one mode of freight transportation to another. The highway vehicles are expected to achieve the full automation level with the development of new adaptive digital technologies. The deployment of autonomous trucks could create substantial social costs, as truck drivers would lose their jobs. The study highlighted that the railroad industry would have more developments towards the full automation level. However, such developments would require significant investments. It was indicated that automation would make the road transport more preferential as compared to the other modes, which might lead to some environmental problems.

**TABLE 3.** Comparison of autonomous technologies used in AVs and ATs.

| a/a | Autonomous Vehicles | Autonomous Trains | Utility of Technology |
|---|---|---|---|
| 1 | Cameras | Infrared Cameras | Read signage, traffic control devices, lane markings, surrounding environment, etc. |
| 2 | Laser Illuminating Detection and Ranging (LIDAR) | Laser Illuminating Detection and Ranging (LIDAR) | Create 3D maps and help detecting potential hazards. Can determine the distance and object profile by bouncing the laser beam off the object surface. |
| 3 | Radar | Radar | Accurately measures the speed of nearby vehicles and trains in real time that cannot be adequately achieved by using LIDAR. |
| 4 | Sensors | Ultrasonic Sensors | Sensors perform the role of a self-monitoring device to ensure that a vehicle/train is not speeding and monitor the overall vehicle/train functionality. Also, they perform the role of object detection. |
| 5 | Dedicated Short-Range Communications (DSRC) | Dedicated Short-Range Communications (DSRC) | The DSRC is a short-range communication system with a reliable two-way high-speed radio service that can be effectively deployed for V2V and V2I communication. It can provide warning at highway-rail grade crossings regarding an approaching AT. |
| 6 | Stereo Video | Stereo Video | The stereo video uses two cameras to capture a 3D-environemnt that forms the basis for various assistance systems in the vehicle/train. It helps in measuring the depth accurately. |
| 7 | Human-Machine Interface (HMI) | N/A | It is a combination of systems inside the vehicle, which includes panels and controls for the interaction between the vehicle and its occupants. |
| 8 | Domain Controller | Domain Controller | This is the main "brain" of the autonomous driving system that controls the signals and information from LIDAR, sensors, cameras, etc. and determines necessary actions accordingly. |
| 9 | Motion Control Systems, Actuators, Mechatronic Units | Motion Control Systems, Actuators, Mechatronic Units | They work in combination with other technologies for execution of different actions that were received from the domain controller. |
| 10 | N/A | Positive Train Control (PTC) | It is a GPS-based technology that is used to stop the train, avoid collision, and any unwarranted train movements. |

The Governors Highway Safety Association (GHSA) [34] highlighted that the deployment of autonomous driving systems might create new and unanticipated safety issues (e.g., compliance with traffic laws, compliance with local practices, decisions during emergency situations, recognition, reaction, operations after detection of certain system failures, system security, and others). These issues could occur despite recent technical advancements, such as forward collision warning, obstacle detection, curve speed warning, and high speed alerts [35]. It was recommended that partially automated driving systems should be controlled by a licensed human operator, who can take control of a vehicle (or a train) when needed.

Elliot *et al.* [36] conducted a detailed review study, primarily focusing on recent advancements in CAV technologies. The study highlighted the importance of the DSRC and 5G technologies for effective communication between CAVs, which can be also used for communication between CAVs and trains. It was indicated that the integration of various components into one platform without causing any potential issues for security, reliability, and conflicts in operations would be an important next step in the CAV deployment. Another challenge might be associated with the integration of pedestrian and collision avoidance system into the intersection navigation control.

The Congressional Research Service (CRS) [27] discussed the issues related to the deployment and testing of CAVs. Some of the major issues concerning the deployment of CAVs were found to be data security and protection against any intrusion in the onboard computer system. With the use of CAV technology, many functions currently being performed by the driver will be performed automatically. The interaction of CAVs with the existing infrastructure, ATs, and non-CAVs will generate a huge amount of data related to vehicle location, train location, stability, movements, and others. Any unauthorized access may lead to safety issues not only for the vehicle and for the train but for others as well. **Fig. 11** shows various vulnerable points in a CAV that could be potentially targeted by hackers [27]. Disabled DSRC systems due to the intrusion of hackers would lead to the loss of communication with the approaching ATs that might further create some safety issues. In order to prevent the intrusion of hackers, remote software updates are required for CAVs and ATs on a regular basis. The manufacturers of CAVs and ATs are also mandated to comply with a set of cybersecurity principles and report any cybersecurity threats, incidents, and violations after their occurrence. The data collected from CAVs and ATs could be of interest to other entities as well (e.g., law enforcement agencies, insurance companies, urban planners, first responders in case of an accident occurrence, etc.).

### B. GENERAL ISSUES ASSOCIATED WITH AUTONOMOUS TRAINS

Several studies concentrated on various issues due to the AT deployment. For example, Gebauer and Pree [37] discussed some of the conceptual, technical, and legal challenges of driverless trains on the existing railroads. The concept of "trainlets" was proposed to improve the attractiveness of ATs and make them a more competitive transportation mode. In particular, the entire AT could be divided into many smaller "trainlets", which have the size of a standard automobile. Passengers having the same destination could be placed in the same "trainlet" and travel directly there with a limited number of stops, which could reduce the total delay due

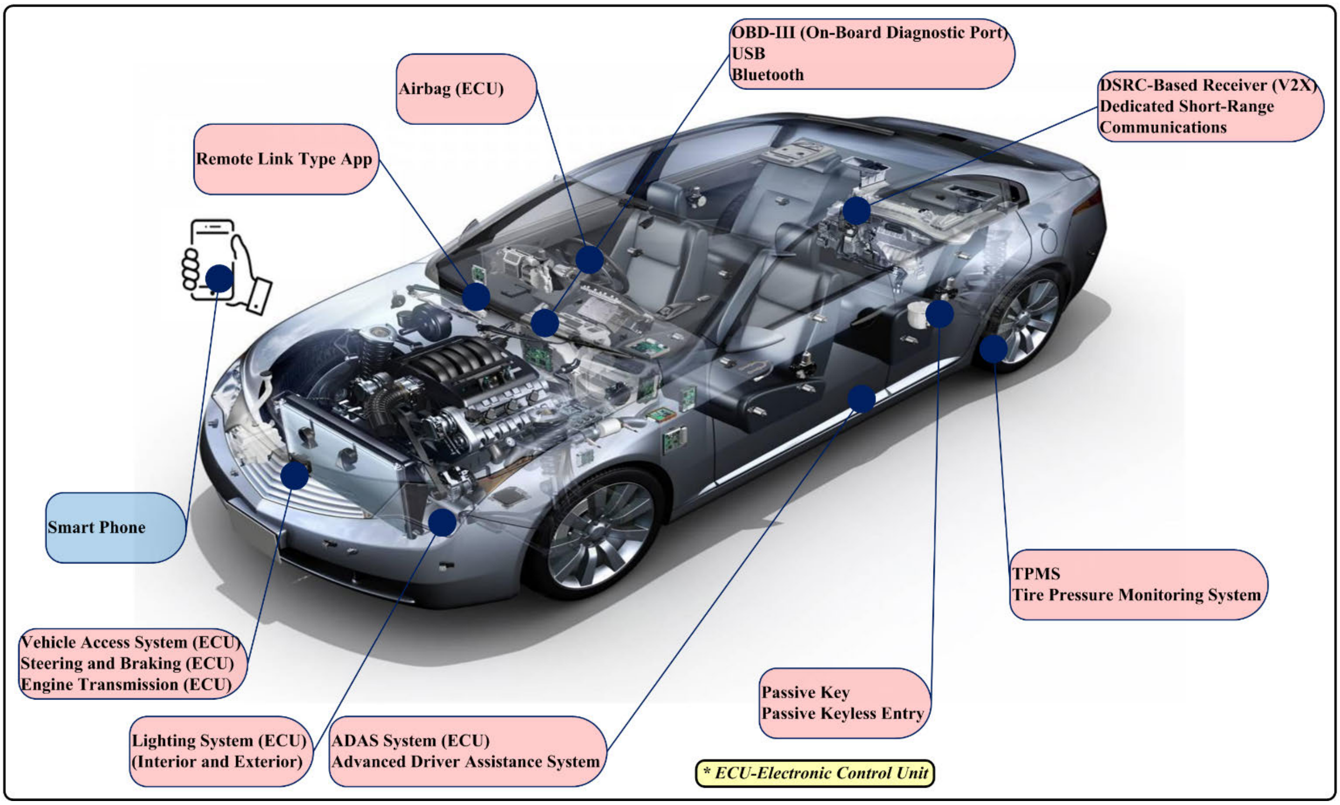


**FIGURE 11.** Vulnerable CAV points that can be subject to an unauthorized access.

to unnecessary stops. The study discussed the autoBAHN project that was launched to validate the technical feasibility of fully autonomous "trainlets", determine economically promising scenarios, demonstrate some applications of "trainlets", and address some of the associated legal issues. A set of simulation experiments were conducted for a short track with a length of 13 km, 13 stops, and an average of 400,000 passengers per year. It was found that "trainlets" were more effective than regular trains, which operate on their given schedules, even with a fairly low occupancy of "trainlets" (i.e., approximately 1.3 passengers per "trainlet"). The developed simulation model could be used to justify the economic feasibility of deploying "trainlets".

Gebauer *et al.* [38] and Gebauer *et al.* [39] also discussed various aspects of the autoBAHN project (i.e., technical, conceptual, and legal). It was mentioned that ATs would have less legal issues that are associated with accidents, when comparing to roadway vehicles, as the access to rail tracks is generally more restricted and managed by the train control systems. Moreover, the economic viability of ATs would depend on how the automation concept would be implemented. In particular, the use of the existing railroad infrastructure with the minimum required alterations would be favorable for the development and deployment of ATs. A new railroad system with ATs should be at least as safe as the existing railroad system in order to meet the regulatory requirements. The autoBAHN project is expected to facilitate the AT deployment on railroads in Europe. Modern technological features (e.g., obstacle recognition system, GPS-based train control system, audio and video communication features) are anticipated to improve the operations of "trainlets". Given the existing interest of manufacturers, railroad companies, and other relevant stakeholders, the autoBAHN project might be implemented in the near future along the major rail lines. Nevertheless, some political and legal requirements must be satisfied before wide implementation of ATs (e.g., the need for railroad security and safety standards with respect to the AT testing processes).

Dordal and Avila [40] presented an intelligent approach, which was based on software agents, to coordinate trains along a single railroad track. The main objective was to improve the utilization of a railroad track and reduce the associated environmental impacts. The behavior of agents was based on certain operational attributes (e.g., specialized rules of conduction, train position, direction, target time to the final destination, etc.). The results showed that the proposed software agent-based system could reduce the total journey time by 22.5%, when comparing to the traditional method of conduction. Furthermore, the fuel consumption was reduced by more than 25%, which could further improve the environmental sustainability of rail transportation and decrease the emissions produced. Hazan *et al.* [41] studied the impacts of

AV deployment on rail transportation. The study pointed out that the introduction of AVs to the market would have many advantages for passengers (e.g., reduced road congestion, increased safety, and more productive travel time). As a result of conducted survey, it was found that about 50% of respondents (out of 5,500 consumers from ten different countries) would consider buying AVs. More importantly, at least 40% of the current train passengers would shift to using AVs. The introduction of ATs with innovative technological features might be able to keep rail transportation competitive and offset the AV benefits.

Powell *et al.* [42] aimed to assess potential benefits and challenges of the AT deployment for the Tyne and Wear Metro (United Kingdom – U.K.) by means of simulation. The results from the conducted simulation analysis demonstrated that a substantial capacity increase could be achieved from the AT deployment when implemented with signaling upgrades. However, low adhesion conditions were found to be one of the obstacles. Moreover, additional infrastructure upgrades would be necessary to transition towards full automation. The most significant obstacle was found to be the presence of shared operations at the existing rail lines. Wang *et al.* [16] conducted a survey of driverless train operations in urban transit rail systems. Along with potential advantages (e.g., lower operational costs, increased capacity, increased flexibility, improved reliability, energy efficiency), a wide range of AT deployment challenges were outlined as well, including safety issues, train control technology issues, communication issues, issues associated with platform screen doors and guideway intrusions, terminal design challenges, as well as detection and management of emergency situations. The study pointed out that a systematic safety assessment framework is needed to standardize the AT operations, reduce potential risks, and enhance the overall reliability.

Trentesaux *et al.* [43] pointed out the growth of ATs, since they have become an important component of competitiveness for many fleet operators. Some of the major benefits of ATs were highlighted, including the following: (1) efficient utilization of the existing infrastructure; (2) effective energy consumption; (3) enhanced quality of service (e.g., better management of arrivals and departures of trains during unpredicted peak traffic demand); (4) improved capabilities in terms of perception; (5) better control than human drivers; and (6) accurate detection of hazardous situations. **Fig. 12** shows an example framework for nominal AT functioning under planned and unplanned operational conditions [43]. It can be observed that the original operational plan could be adjusted by ATs as needed depending on the external circumstances. Apart from various benefits that ATs might be able to provide, various risks and issues that are associated with the AT deployment were pointed out as well: (1) design and operational risks in ATs; (2) issues regarding decision, information, and learning process; (3) safety, ethics, and norms-related issues; (4) fleet interoperability and coordination related issues; (5) human skills, acceptance, and interaction-related issues; and (6) design methodology, deployment, and process related issues. The study concluded that the deployment of ATs would significantly change the railroads. However, the success of ATs will depend on the participation of various stakeholders, such as manufacturers, fleet operators, infrastructure developers, etc.

Wardrop [44] discussed the rationale of developing ATs as well as the challenges that were associated with the deployment of heavy haul freight trains in remote areas. Mining in remote areas is generally expensive, as it is quite difficult to find the required resources. Therefore, the automation of mining process and rail transportation gained popularity among mining companies. Some major issues of deploying trains in remote areas were underlined, including the following: (1) wild animals could appear on railroad tracks, since the tracks are unfenced; (2) highway-rail grade crossings are generally equipped with passive protection devices, which may not lead to an adequate safety level in some instances; (3) detection and mitigation of accidents when trains collide, derail, or break down; and (4) timely response to different incidents that may occur on railroad tracks and stop the AT movement. The study concluded that the combination of onboard driving control systems and remote train dispatching should improve the control of train flows, timekeeping of individual freight trains, and enhance the utilization of rail lines. It was also indicated that the practices that were used for remote heavy haul freight ATs could be implemented to suburban passenger ATs as well.

Antolini [45] focused on the project conducted by the French National Railways (SNCF) company, aiming to develop the prototypes of ATs with partial and full automation levels. The first test for a remotely controlled locomotive-hauled AT was completed by the SNCF in July 2019. The overall goal of the project is to design ATs with a full degree of automation for freight and passenger transport by 2022. The study highlighted that the main challenge of the AT deployment in Europe would be the introduction of ATs on the railroad system, where multiple passenger and freight operators share the same railroad tracks. Furthermore, the trains might have different physical characteristics (i.e., train types and train weights), which could also impose additional operational challenges. French railroad networks have numerous yards and junctions that could potentially impose difficulties for the AT deployment. Despite these challenges, the SNCF remains optimistic and aims to effectively achieve the project objectives. The project with the expected overall cost of 57 million EURO is anticipated to improve punctuality of operations, provide larger capacity, and decrease the environmental impacts.

Kemmeter [46] underlined some of the potential challenges associated with the AT deployment. Certain CAV technologies may not be applicable for ATs (e.g., LIDAR cannot be used to measure the distance to the next train, as the distance between consecutive trains is significant when they operate at a full or close to the full speed). Furthermore, train detection requires installation of cables along the rail tracks as well as a lot of online equipment. Such

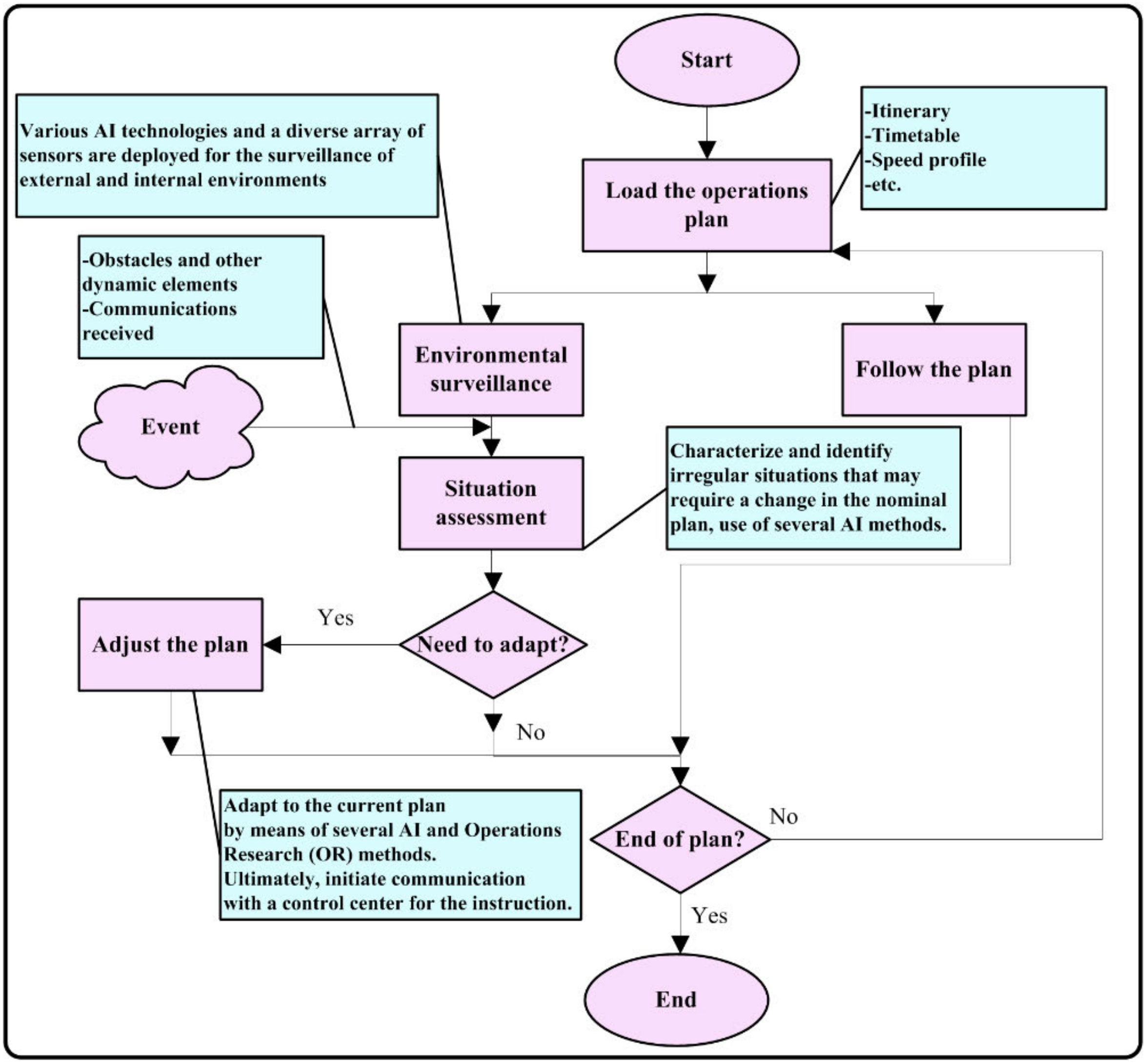


**FIGURE 12.** Nominal functioning of an AT.

train detection equipment is generally costly and requires regular maintenance. Muller [47] evaluated the organizational hindrances from the deployment of freight ATs. The study evaluated four conceptual impacts on innovation activities within advanced markets, including the following: (1) nested architecture and hierarchy of networks; (2) dependency on the path in technological prototypes; (3) dynamics of organization; and (4) technological standoff. It was pointed out that the aforementioned impacts could directly influence the innovation activities. The conducted analysis demonstrated that the economical processes could impose substantial limitations on the innovation activities for the general rail transport operations and freight AT operations. The study concluded that the strategic innovation policies should address the challenges that are associated with the AT deployment.

Pattinson *et al.* [48] highlighted that the future AVs will have to co-exist with the vehicles that are driven by humans. It would be critical to develop the appropriate solutions to determine legal responsibilities for vehicles and drivers in case of accidents. The AV users should understand all the risks involved when deciding to drive such vehicles. Similar legal issues have to be addressed when deploying ATs and human-driven trains on the existing rail lines. Wang *et al.* [49] focused on the safety issues associated with CAVs. Drivers often take control of AVs when they think it is necessary, which creates a "disagreement". Based on the reported data, the rate of such disagreements can be fairly high with up to 3 disagreements per mile for different manufacturers. Such disagreements may further lead to accidents. The study also showed that the majority of accidents are caused by other roadway users – not CAVs. Similar studies should be administered for automated rail systems (especially, for the rail lines that have trains with the grades of automation GoA2 and GoA3, where there may be a potential disagreement between the partially automated train and the driver or the attendant).

Othman [50] indicated that the COVID-19 pandemic made substantial impacts on public transit services around the world, including rail transportation. The ridership on the U.S. rail and bus systems reduced by 79% in Washington, D.C., 83% in Boston, and 74% in New York. Similarly, the transit ridership decreased by more than 80% in Montreal and Toronto (Canada). The future rail transit systems, including autonomous rail transit systems, should have additional protective measures against the spread of airborne diseases (e.g., advanced air circulation, ultraviolet light disinfection). Such measures will help preventing the impacts of airborne diseases on rail transit systems and improve safety of passengers.

The AT deployment is expected to reduce the train crew size, as the ATs with a full automation level will not require any onboard personnel. A number of studies discussed the issues associated with the train crew size reduction. Karvonen *et al.* [51] underlined the importance of train drivers in the metro operations and potential difficulties in transitioning towards fully automated metro lines. Based on the data collected from the Helsinki Metro (Finland), it was found that train drivers actually play a critical role (i.e., anticipation, observation, interpretation, and reaction to events), which may not seem apparent in some instances. Moreover, train drivers are viewed as a link between different actors involved in different metro operations. It was concluded that a lack of understanding of the train driver roles may lead to safety and quality of service issues throughout the AT deployment. Cohen *et al.* [52] used semi-structured interviews and questionnaires, distributed among the automated metro line operators, to determine how automation influenced staffing, costs, reliability, and service capacity. The results, which were collected from 23 metro lines, indicated that the AT deployment could decrease the train crew size by 30-70% (which can be negatively viewed by the public). Moreover, the survey indicated that the capital costs of the automated metro lines were fairly high, but the internal rates of return were promising in some cases. The findings showed that the AT deployment could improve the metro efficiency and productivity. However, additional data would be needed to draw more accurate outcomes.

Cassauwers [53] discussed the employment issues due to the AT deployment. It was highlighted that the introduction of automated systems in passenger and freight rail transportation could lead to the train crew size reduction, which might cause a large number of strikes by railroad unions. Many experts and professionals still have concerns regarding the AT technology performance in emergency situations. The study pointed out that the re-orientation of employees (e.g., transition to customer service or to non-automated rail lines) would be a promising solution rather than layoffs or salary cuts.

### C. USER PERCEPTION AND OUTLOOK FOR AUTONOMOUS TRAINS

Only a few studies investigated the user perception and outlook for ATs. Fraszczyk *et al.* [54] indicated an increasing trend for the AT deployment and underlined the lack of studies focusing on public perception of substantial changes in rail transport associated with ATs. The study specifically concentrated on public perception for the automated metro systems with unattended train operations. A survey was conducted as a part of the study, which involved a total of 50 individuals from 10 different countries. Approximately 75% of the respondents were below 30 years of age. Based on the gender distribution, 72% of the respondents were male and 28% were female. The results of the study showed that 72% of male participants and 93% of female participants approved having a ''fake'' driver room on ATs. The majority of survey participants indicated no concerns associated with the AT maintenance issues and the train design itself. However, staff communication and technical failures were the main two issues that were raised by some of the survey participants. Moreover, most of the survey participants did not raise any employment concerns due to the AT implementation (i.e., train drivers will not be needed for ATs).

Fraszczyk and Mulley [55] studied the user perception and attitude towards ATs in Sydney (Australia). It was pointed out that the AT deployment project in Sydney Metro was technically sound and well-planned, despite the fact that it was introduced late in the planning phase. A survey among 300 participants was performed to meet the study objectives. An almost even distribution of female and male participants was achieved. The study results indicated that many train users and non-users rated the presence of a train driver as important. Moreover, the majority of survey participants were concerned with the safety aspects of the AT operations. The users identified ''reduced ticket price'' and ''increased train frequency'' as the main benefits from the AT deployment. On the other hand, ''energy recovery and sustainability'' were defined at the least important benefits. Based on the survey results, approximately 50% of the existing users indicated that they would use the fully automated metro in the future, and about 35% of the existing users were not sure. In the meantime, approximately 40% of non-users indicated that they would not be willing to use the fully automated metro in Sydney.

Pakusch and Bossauer [56] highlighted that autonomous public transportation has a lot of benefits and can enable sustainable mobility. The study focused on the user acceptance with respect to the technological innovations and developments in autonomous public transportation. A survey among 201 participants was conducted to achieve the study goals. The survey was advertised via different online platforms and social networks in Germany. The age of survey participants varied from 18 to 81 years, with an average age of 26.2 years. A total of 49.3% of the survey participants were female. Most of the survey participants were students due to a number of reasons (e.g., reduced cost of tickets for students, well-developed urban transport in large metropolitan areas). The study results indicated that many users were already familiar with autonomous driving and were willing to use autonomous public transportation in the following years. It was highlighted that the existing policies should be modified to allow the users accessing autonomous public transportation even during the test phases, so they could become more familiar with new technologies and have positive experience in the future. The accessibility to autonomous public transportation would further lead to sustainable mobility behavior of users.

Henne *et al.* [57] discussed the challenges that are associated with the perception of AI-based applications for autonomous systems. It was underlined that the user perception could substantially affect the deployment of autonomous systems. In particular, AVs and ATs should drive safely in various environments and complex situations in order to have a positive user perception. One of the main AI advantages consists in the fact that the AI techniques are capable of abstracting from distinct learned scenarios to effectively solve the present tasks. The study identified a set of approaches that could be potentially used to model the uncertainty in AI-based perception (e.g., uncertainty in model parameters, uncertainty in data). The following approaches were discussed: (1) calibration of the model outputs; (2) detection of out-of-distribution inputs; (3) application of Bayesian Neural Networks; and (4) application of deep ensembles. A combination of methods for assessing the perception uncertainty and dynamic dependability management was found to be a promising solution to effectively address the challenge of unreliable perception of the AI-based applications for autonomous systems.

### D. DESIGN AND TECHNOLOGIES FOR AUTONOMOUS TRAINS

A number of studies proposed innovative concepts and models that could be used for the future AT design. Bock and Bikker [58] presented a new operational concept for rail services, which is inspired by driving on demand. The proposed concept assumed that the train wagons were no longer physically coupled to each other. Furthermore, each wagon had its own computer system along with propulsion. Therefore, each wagon would become an intelligent unit, which can be considered as an AT module prototype. Electronic data transition would allow controlling these trains, so they could drive close to each other with the minimal distance. Each train module was able to join the formation of modules at rail junctions or leave the formation (depending on the final destination). The proposed operational concept was expected to make rail transportation more competitive as compared to road transportation. Haxthausen and Peleska [59] introduced the notion of a controlled distributed system for railroads and presented the specification and authentication of the main algorithm for safe distributed control. The required safety levels were derived based on the abstract vision that could be easily verified with respect to their completeness and soundness. The overall complexity was decreased by dividing the system model into two sub-models, including a controller model and a domain model. It was highlighted that the proposed concept could be used for an automatic train control without the presence of a train driver (i.e., AT applications in rail transportation).

Matsumoto *et al.* [60] discussed the level of reliability, safety, and capacity that is needed for the train control system at busy railroad sections. The study proposed a decentralized autonomous train control (D-ATC) system that can fulfill the existing needs. The proposed D-ATC system had the following main features: (1) train detection on rail tracks; (2) dissemination of the stop point information; (3) detection of a train position; and (4) control of braking. One of the highlighted challenges was to configure the available technologies in a way that would allow the current train control system to co-exist with the newly introduced system. **Fig. 13** shows a comprehensive framework that could be used for introducing a new train control system into the existing one [60]. Such a framework ensures the co-existence of new and conventional train control systems and, more importantly, enables continuous train operations without disruptions. The study pointed out that it would not be feasible to remove the existing automated train control (ATC) devices at the considered railroad sections and install new D-ATC devices in a one train interval (e.g., the last train → the first train). The latter can be justified by the fact that such a procedure would be very expensive, and the replacement time may be insufficient at certain railroad sections. The proposed technology was deployed for the Yamanote and Keihin Tohoku lines (Japan).

Matsumoto [61] discussed various train control systems that were deployed in Japan. The original ATC systems were applied at the rail lines to ensure safe and fast rail transportation. However, the conventional ATC systems were not effective at busy rail lines. Busy rail lines were generally equipped with the D-ATC systems. The study pointed out that the newly designed information technologies allow trains detecting their own positions and transmitting this information to other trains in the vicinity. The train control system, which directly relies on the newly designed information technologies, had been deployed at the Senseki line of the Tohoku District (Japan). The results of pilot tests confirmed the effectiveness of the new train control system. Castells *et al.* [62] discussed different advantages from the AT deployment at metro lines, including increased capacity, flexibility, viable service during off-peak hours, greater efficiency and safety, and cost-effectiveness. It was highlighted that the AT signaling and control systems allow shorter headways between consecutive trains, which increases the rail network utilization. The AT deployment allows better management of the supply and demand (e.g., unused ATs could be easily removed from the network during off-peak hours). ATs also have the ''anti-bunching'' feature that prevents them from getting stuck between consecutive metro stations. Different examples of automated metro systems were presented (i.e., Vancouver, São Paulo, Paris, and Copenhagen).

Marrone *et al.* [63] pointed out the importance of verification process of different AT applications in automated metro systems. The study indicated that the Combined Model-Based Analysis and Testing of Embedded

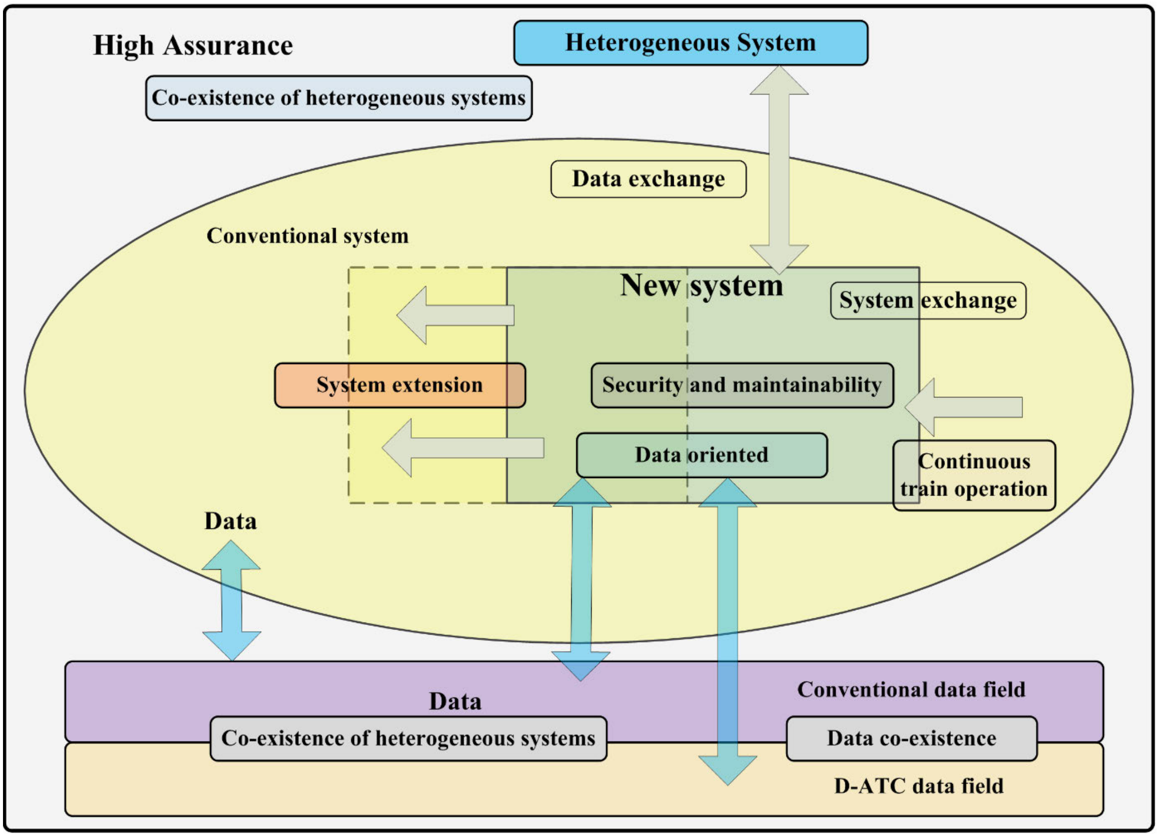


**FIGURE 13.** A framework for co-existence of train control systems.

Systems (MBAT) project conducted in the European Union would help improving the verification process. The procedures adopted for the verification process in automated metro systems could be extended to other complex systems as well. Mohammed *et al.* [64] developed a microcontroller-based prototype for ATs. The proposed AT prototype was able to perform a set of basic operations, including the following: (1) travel via a pre-defined path between a set of stations; (2) sensing the station arrival; (3) proper stopping at stations; and (4) display of synchronized messages regarding the train arrival at a given station. Furthermore, the AT prototype was designed to produce alarm signals to prevent potential safety issues. The study concluded that the proposed microcontroller-based AT prototype could serve as a foundation for more sophisticated control systems.

Balasubramanian [65] discussed various IoT processors that could be utilized to deploy ATs for a long-distance travel. A major emphasis was given to the following aspects: (1) safe and uninterrupted communication between different components of the train during movements; (2) the auto record of errors: (3) use of emerging technology (i.e., IoT); (4) steady implementation of various solutions; and (5) availability of backup options to avoid the dependency on a single component. **Fig. 14** shows an example of communication paths for ATs throughout their long-distance travel. It can be observed that the AT communication paths involve many different components, including manned level crossings (MLCs), track change points (TCPs), control center, signaling cabins, satellite systems, and others [65]. A successful implementation of the IoT technologies is heavily dependent on the availability of high-speed internet. The proposed concept of long-distance ATs is expected to have a variety of advantages, including the following: (1) improved safety level for the AT itself and surrounding trains as well; (2) improved safety performance at highway-rail grade crossings and bridges; (3) provide more effective service to the existing train users; and (4) provide more flexibility to railroad authorities in terms of system improvement projects.

Fraga-Lamas *et al.* [17] highlighted that the railroad industry could benefit from exploiting various opportunities that are offered by the Industrial Internet of Things (IIoT), which is an important component of the paradigm called ''Internet of Trains''. The study presented a comprehensive review with regards to the evolution of rail communication technologies, showing how the rail technology specifications, requirements, and recommendations had been evolving over the past years. The advantages of deploying the latest broadband communication technologies (e.g., 5G technologies, Long-Term Evolution [LTE] technologies) were explained in detail. Moreover, the conducted study presented a set of

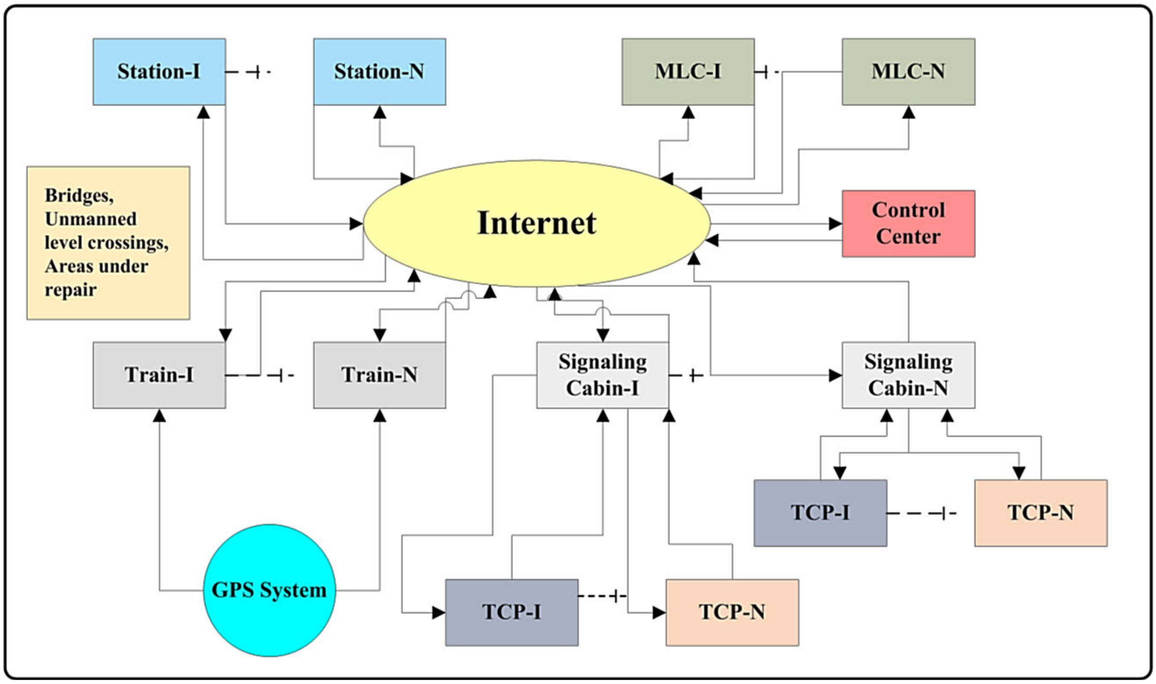


**FIGURE 14.** Communication paths for ATs.

scenarios and architectures for the railroad industry, where it could attain better commercial IIoT capabilities. The latest advancements in smart infrastructure, asset monitoring, predictive maintenance, video surveillance, safety assurance systems, train control systems, signal systems, energy efficiency, and cybersecurity systems were discussed as well. It was concluded that the IIoT and Internet of Trains still face a large variety of issues (e.g., interoperability, standardization, scalability, and cybersecurity) that have to be effectively addressed by researchers and practitioners in the following years. New types of technology should be tuned for specific railroad environments to ensure their adequate implementation.

**Fig. 15** shows a large variety of IIoT-enabled services that are specifically related to rail transportation. It can be observed that the rail IIoT-enabled services cover a wide range of different areas, including the following [17]: (1) information (passenger information systems and freight information systems); (2) train control systems; (3) predictive maintenance; (4) smart infrastructure; and (5) energy efficiency. Furthermore, based on their functionality, the IIoT-enabled technologies for rail applications can be categorized in different groups that include, but are not limited to, the following [17]: image processing and computer vision, algorithms and methods, sensors, modeling and simulation, communication systems, computing, big data and data analytics, and artificial intelligence (see **Fig. 16**). The deployment of the IIoT-enabled technologies is expected to enhance rail operations and maintenance. Furthermore, these technologies will improve the quality of rail services for both passenger and freight components. Researchers and practitioners anticipate that the IIoT will revolutionize the train operations and make rail transportation a more competitive mode.

Romano *et al.* [66] indicated that several AT metro systems had been introduced over the past years in certain countries. However, the demand for rail transportation is constantly changing, and it is instrumental to design flexible and efficient ATs, which could support the existing requirements without affecting the overall performance and safety. It was highlighted that the new generation ATs should have the appropriate types of technology that could achieve operational cost optimization, energy reduction targets, minimization of risks associated with human errors, and high system performance. The modern ATs should have a variety of features that would allow meeting rigorous customer requirements. Bharathi *et al.* [67] presented a technology for automatic train control and operations that could be used for metro train movements. The train was assumed to have a controller enabling the train automatically move from one metro station to another (i.e., an AT prototype). Upon arrival at a metro station, the train could stop automatically by applying the appropriate sensors. The proposed train system was also capable of counting the number of passengers walking in and out of the train doors, which could be further used for estimating the train capacity utilization. The train was equipped with a buzzer to alert the surrounding passengers regarding the closing doors. Such an automatic train system could be effective as it eliminates potential human errors.

Lagay and Abdell [68] discussed various features of the project conducted by the SNCF railroad company, aiming to deploy ATs with a full automation level on French

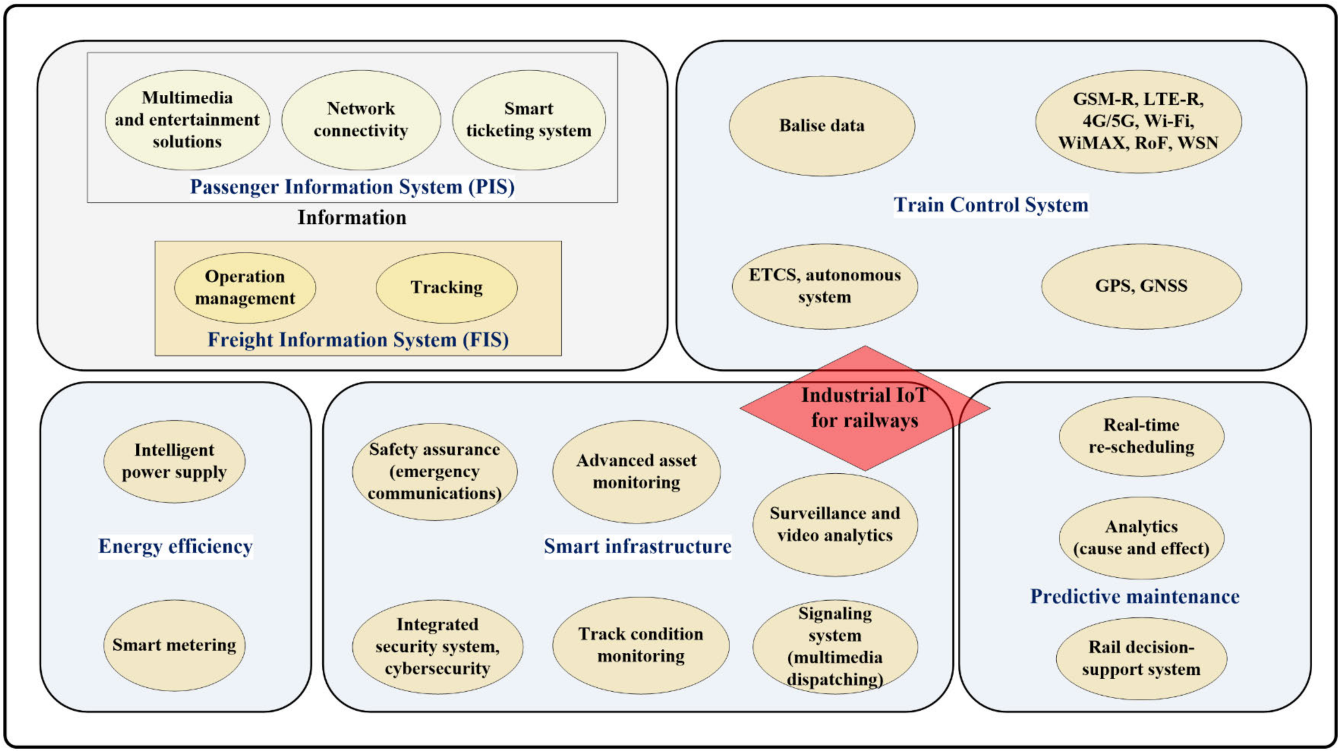


**FIGURE 15.** IIoT-enabled railroad specific services.

railroads. The AT control system was assumed to have three layers, including the AT protection layer, AT operation layer, and AT supervisor layer. A variety of AT technologies and systems were described (e.g., wireless communication, cybersecurity subsystem, train positioning, sensor fusion and data processing, AI, obstacle detection, signaling recognition, and monitoring subsystems). In order to effectively deploy ATs, the SNCF planned to work with different industrial and service sectors, as well as low-cost solutions and high-performance solutions. Arup [69] provided a detailed review of new trends in rail transportation that would further define its development in the following years. The study presented the examples of ATs deployed for passenger and freight transportation. It was highlighted that the AT technologies allow optimizing the running time, increasing the average speed, and operations in a close proximity to other trains. The Dubai Metro was described as an example of the largest driverless metro network in the world (with approximately 75 rail km). The AT deployment also allows effectively addressing the growing demand for rail transportation (e.g., São Paulo's Metro Line 4 is the only driverless metro line that handles 700K passengers per day on a 8-km stretch).

Kimiagar [22] discussed the emerging trends in the technology used for rail transit, such as AI, train control systems, dynamic route optimization, predictive maintenance, and simulation modeling. Various AI braches that could be applied in rail transit were described (e.g., machine learning, image and obstacle recognition, robotics, and planning). The IoT applications in rail transportation are projected to exponentially increase in the following years. The study presented different train control systems that are responsible for various functions, including the train arrival time estimation, timetable development, ride comfort, safety aspects, interlocking, train position determination, and safe braking. The steps required for the transition from conventional trains to ATs were pointed out as well. Pickering *et al.* [70] underlined the need for innovative solutions that could be used to effectively address the increasing demand for rail transport in the U.K. The study presented a simulation model that emulated the rail service between Coventry and Birmingham, which are both located in the U.K. The results from the conducted simulation analysis demonstrated that the AT deployment could substantially increase the rail network capacity, as consecutive trains could be operated at a smaller distance (taking into consideration the "safe" separation distance between consecutive trains). The study highlighted that a smaller distance between consecutive ATs could be achieved via the implementation of advanced technologies (i.e., accurate train positioning, V2V communication, predictive braking, fast and reliable switches).

A few studies concentrated their efforts on railroad signaling system modeling and improvements. Kunifuji *et al.* [71] indicated that the efficiency of the existing railroad signaling system was quite low (e.g., the time allocated to certain activities along rail tracks was not sufficient due to low flexibility of the existing signaling system). The study proposed an

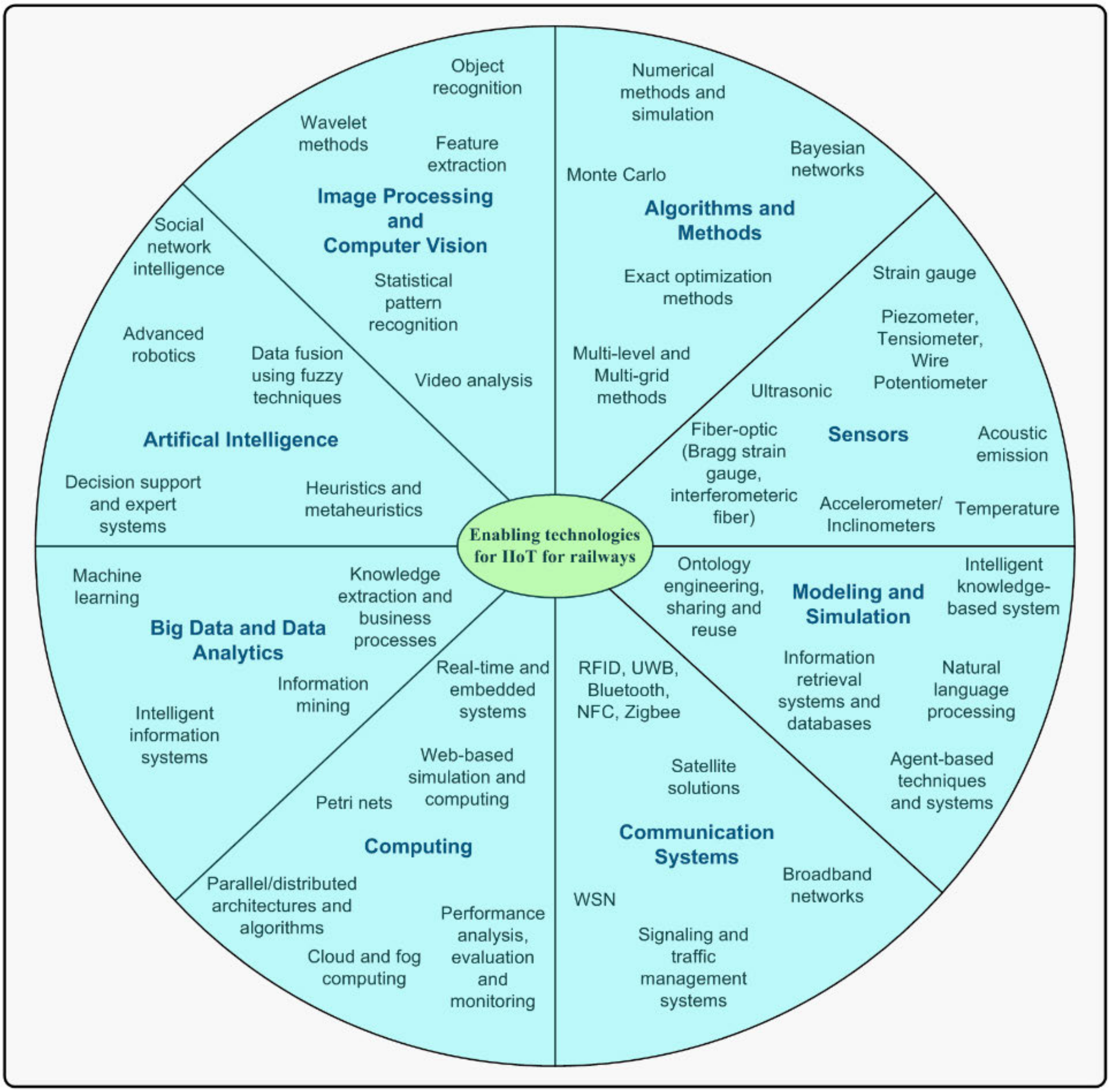


**FIGURE 16.** IIoT-enabled technologies for rail transportation.

alternative railroad signaling system that was based on the network and autonomous decentralized technology. It was highlighted that the developed system would improve not only the flexibility of signaling but the overall safety and reliability as well. The main challenge with the deployment of new railroad signaling system consisted in the fact that re-modeling of the control logics might be required for different types of signal devices. Harb *et al.* [72] introduced the FRSign dataset, which can be viewed as a large-scale dataset for vision-based railroad traffic light recognition and detection. The study highlighted a lack of open source data for the AT deployment. The recordings for the FRSign dataset were made on selected operational trains in France. An illustrative dataset with more than 100,000 images, which covered a total of six types of French railroad traffic lights and their possible combinations, was released as an open source. The developed dataset can be used for automatic classification of railroad signaling panels by state and by type. Furthermore, the developed dataset could assist to facilitate the AT deployment.

Some of the previous studies focused on optimizing the energy efficiency in rail transportation and evaluation of the alternative energy sources that would be critical for the AT development. For example, Brenna *et al.* [73] indicated that many European countries pursue the environmental sustainability and energy efficiency goals. One of the alternatives to improve the environmental sustainability of rail transportation is the AT deployment. The study developed a genetic algorithm to optimize the energy consumption for autonomous subway trains. Along with the energy consumption, the fitness function of the algorithm minimized the total delay. The energy optimization was achieved through the control of train movements (e.g., setting the train speed, determination of stop positions). The proposed methodology was applied for a real-life subway line in Milan (Italy) and demonstrated substantial energy savings.

Mandara *et al.* [74] presented a prototype of the fully automated metro train with improved safety features. The improved safety level was achieved by introducing a monitoring unit that could detect potential safety hazards on rail tracks in front of the train. The Li-Fi technology was suggested for communication purposes. The roof of the proposed train system was assumed to have a set of solar panels, so the renewable energy source could be partially used instead of solely relying on the electric power. The proposed train system also deployed a set of sensors to estimate the weight of passengers inside the train and ensure that the train capacity is not violated. It was highlighted that the proposed driverless train system could effectively prevent potential issues caused by human errors. Richert [75] described the new generation trains that would have the hydrogen fuel cells and storage batteries as power sources. The East Japan Railway Company, Toyota Motor Corporation, and Hitachi, Ltd. entered into collaboration to develop the prototypes of such trains. The main objective of the project is to improve the environmental sustainability of rail transportation and its competitiveness as compared to other modes.

As indicated earlier, innovative AI-based techniques are critical for the future development and deployment of ATs. A number of the collected studies deployed the AI-based methods for addressing some of the issues that are associated with the train design and operations. Gschwandtner *et al.* [76] highlighted some of the main operational differences that could affect object detection on highway streets and rail tracks. The study proposed a method of using lane detection techniques for ATs in order to effectively detect the surrounding obstacles on rail tracks. The developed algorithm combined various techniques used in lane detection and strong geometric constraints that are specifically applicable for rail tracks. The imposed geometric constraints decreased the processing cost and produced robust outputs. However, the accuracy of the proposed method could be influenced by custom rail properties. Weichselbaum *et al.* [77] proposed a 3-D vision-based obstacle detection system that could be used by ATs in open terrain environments. A number of modifications were applied in the system to improve its performance on a high-speed stereo engine. Stereo matching and slanted correlation masks were able to substantially improve the obstacle detection rate (i.e., from 89.4% to 95.75%). The false positive detection rate comprised 0.25% only. The developed system was evaluated using the real-world test data and proved its effectiveness.

Xie *et al.* [78] highlighted that the adoption of the European Rail Traffic Management System (ERTMS) and the AT deployment could be considered as two main solutions to enhance the safety of rail operations and effectively increase the existing capacity to ensure that the demand is met. The study proposed a methodology allowing the application of discrete event controllers for the AT control system in rail transportation. The modeling was performed using the Colored Petri Nets along with its extensions, considering some important aspects (e.g., rail operational requirements, collision-free systems). It was found that the proposed methodology could be efficient in emulating AT control systems and similar complex systems. Talvitie *et al.* [79] addressed the positioning of high-speed trains within 5G new radio networks by means of new radio synchronization signals. The proposed positioning method took into consideration the time of arrival along with the angle of departure, which were both computed using new radio synchronization signals. The Extended Kalman Filter was used to track the train position based on the assumed train movement model and given measurements. It was found that the time of arrival measurements were able to provide better accuracy, when comparing to the angle of departure measurements. Moreover, the best accuracy was accomplished when both measurements were taken into account. The proposed train positioning method could be useful in a variety of rail applications, including the AT operations.

Yin *et al.* [18] presented a state-of-the-art review on the AI applications in high-speed rail transportation. The study outlined a variety of areas where the AI-based techniques could be used to improve rail transportation, including timetable synchronization and optimization, knowledge-based customer service, speed control and trajectory control, intelligent equipment, and intelligent maintenance. Many of the aforementioned AI applications would be critical for the AT development as well. Furthermore, a comprehensive framework was developed for the AI applications in high-speed rail transportation, considering operational efficiency and customer comfort criteria. Along with the aforementioned efforts, many other studies applied various AI-based methods, optimization, simulation, and other operations research techniques to address different decision problems and issues that are related to train operations, including energy and power sources [80]–[96], train speed control and trajectory control [97–[106], timetable synchronization and optimization [107]–[117], as well as intelligent maintenance and prognostics [118]–[127].

### E. AUTONOMOUS TRAINS AND HIGHWAY-RAIL GRADE CROSSINGS

A highway-rail grade crossing (HRGC), also known as ''a level crossing'', represents the location, where a highway segment intersects with a railroad segment at the same elevation. Each HRGC creates a conflicting point between the arriving trains and vehicles. A significant number of accidents involving trains and vehicles at HRGCs are reported every year in many countries [128]–[131]. A number of studies have been conducted to enhance safety at HRGCs, which would be critical for the development and deployment of the future

ATs. Hsu and Jones [132] analyzed the CV transmission range requirements at HRGCs, aiming to improve the overall safety of approaching vehicles and passing trains. The study assumed that the approaching trains had the onboard communication units that transmitted the information regarding the train speed and location to the CVs. The time-to-collision and stopping distance were used in the reliability-based risk analysis. A set of Monte Carlo simulations were executed to determine the risk probabilities that a CV would not stop before the train arrival time or within the transmission range. The results from the conducted analysis demonstrated that the CV collision risk with a 600-meter transmission range would be lower, when comparing to the non-CVs, for the HRGCs with passive protection and 300-meter sight distance to the train. Moreover, the CV collision risk was found to be lower for the HRGCs with active protection and a 300-meter transmission range. It was concluded that a provision of 600-meter transmission range would be a feasible alternative to enhance the safety levels at passive and active HRGCs.

Zaouk and Ozdemir [133] underlined that the accidents between vehicles and trains at HRGCs cause a significant number of fatalities and injuries. The study mainly concentrated on the following aspects in order to improve safety at HRGCs: (1) interaction of drivers with crossings and traffic patterns; (2) systematic collection of accident data and its evaluation; (3) enforcement and regulations; (4) public perception and education; (5) institutional issues; and (6) technological development and its modernization. It was highlighted that the DSRC technology could be effectively integrated with HRGC systems to prevent potential safety issues and improve traffic flows via HRGCs. In particular, the status of an HRGC may be directly broadcast to approaching CVs, so they could take the appropriate actions (e.g., slow down or completely stop because of an approaching train). One of the major challenges with the development of CV and AV technologies was found to be its limited testing in various environments (e.g., HRGCs with passing ATs and conventional trains) under various operational scenarios. Effective testing of the new technologies at HRGCs is critical to make sure that the approaching vehicles and passing trains would be able to safely interact with each other.

Voege *et al.* [134] indicated that a high level of safety is viewed as one of the main operational goals of rail transportation. The study highlighted that automation is expected to eliminate human errors, which is critical to ensure safety at HRGCs (as collisions between approaching vehicles and passing trains often occur as a result of human errors). It was underlined that the ATs with a full automation level would be able to control the appropriate speed levels at different segments of the rail line. New generation AVs would also have the speed control features to make sure the appropriate speed would be selected when approaching HRGCs. Moreover, the introduction of new maintenance concepts (e.g., predictive maintenance) would allow reducing the probability of accidents due to deteriorating conditions of certain railroad assets. U.S. DOT [135] listed the main principles of automation, including the following: (1) safety prioritization; (2) adaptation of technologically neutral policies; (3) elimination of outdated regulations; (4) consistent regulatory and operational environment; (5) proactive preparation for automation; and (6) protect the freedom for citizens to drive (e.g., some users may be still willing to have manually-driven vehicles). The study highlighted the importance of effective interactions between AVs and passing trains at HRGCs. A variety of stakeholders are involved to design a safe system for AV-train interactions.

U.S. DOT [136] aimed to determine a set of primary requirements for AVs to safely pass through HRGCs. The study pointed out that the development of new generation technologies is constrained by the uncertainties and differences in perspectives between the relevant stakeholders and industries (e.g., automated driver assistance systems, Federal Highway Administration, and railroad authorities). It was recommended that the representative group of stakeholders should reach a consensus on a sufficiently broad set of requirements for AVs to safely pass through HRGCs. The CAV technology could serve as an effective alternative for improving safety of users at crossings. Bertini and Wang [137] and the U.S. Government Accountability Office (GAO) [138] also pointed out that the CAV technology could improve interactions between approaching vehicles and passing trains at HRGCs. Neumeister *et al.* [139] discussed the Rail Crossing Violation Warning (RCVW) system, which was introduced to improve safety at HRGCs. Based on the RCVW concept, the road-side units communicate to the CVs regarding the approaching train. The RCVW systems rely on different components, including computing platforms, DSRC, GPS, and driver-vehicle interface. The study highlighted that the initial RCVW prototype would be steadily improved to meet the performance standards through an extensive field testing.

Virtanen *et al.* [140] studied the issues associated with the AVs passing through HRGCs with and without any protection. The use of AV perception sensors, vehicle-to-everything messaging, and train-tracking solutions could provide the required information for the AVs to safely pass through HRGCs. It was underlined that the protected HRGCs can be detected with the AV perception sensors. Furthermore, the messages could be sent to a vehicle using road-side units in the vicinity of protected HRGCs (see **Fig. 17**). On the other hand, the AV perception sensors alone may not be sufficient to detect an approaching train at unprotected HRGCs, especially under inclement weather conditions. The study presented a train-tracking solution that could detect train arrivals and produce safety messages for AVs. Wang *et al.* [141] proposed a new active warning system that is based on the readily available CV technologies to improve safety at HRGCs. The system relied on a wireless communication via the DSRC between the onboard equipment and road-side units to activate the warning messages due to approaching trains. In case the highway users are at greater risk, the system would send visual and auditory alerts along with displaying the expected

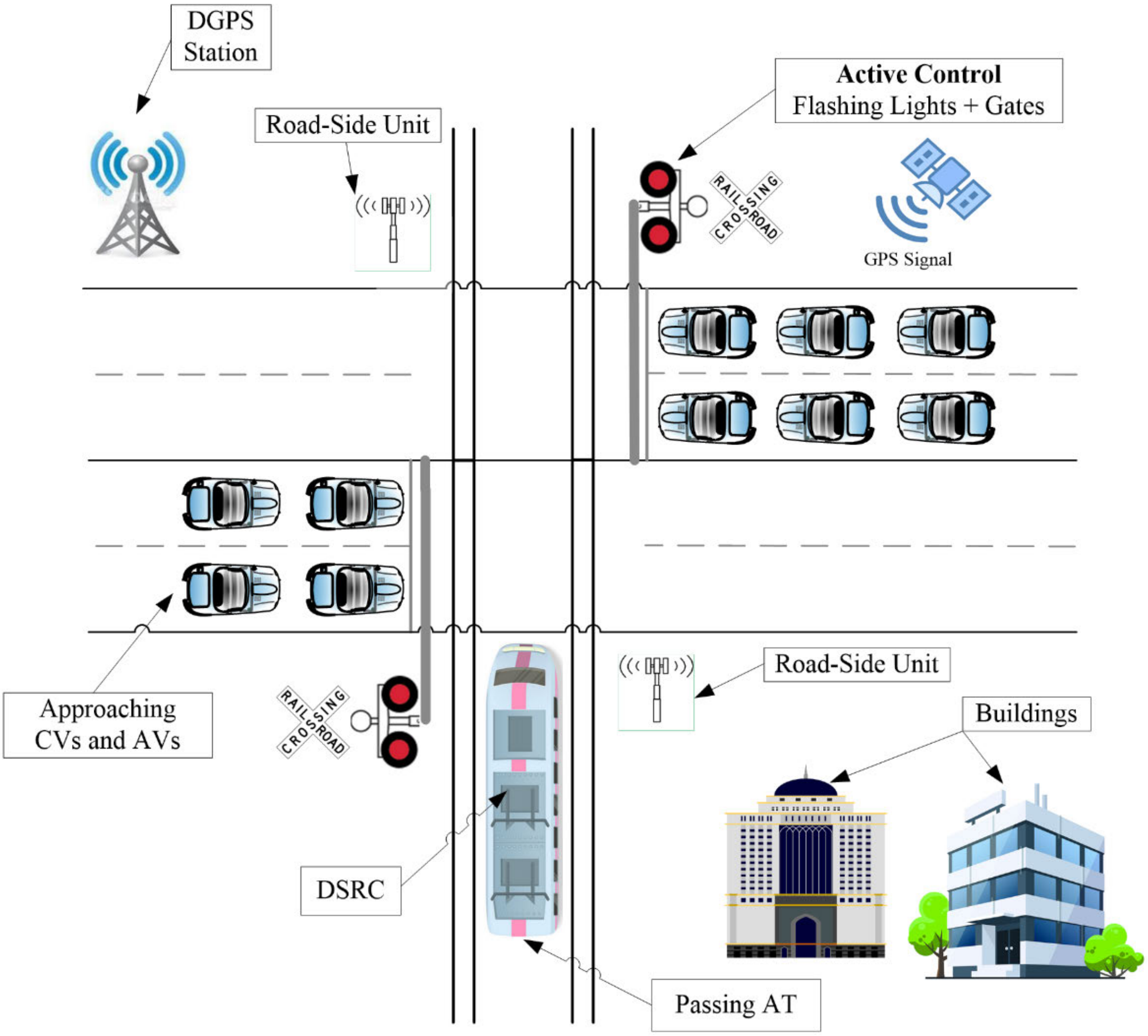


**FIGURE 17.** Approaching vehicles and passing AT at an HRGC.

waiting time. The suggested warning system was evaluated using a simulation model and field applications. The results from the conducted experiments indicated that the proposed active warning system could effectively decrease potential collisions between approaching vehicles and passing trains.

Knapp *et al.* [142] highlighted that it is critical for CAVs to effectively sense the surrounding environment. Therefore, there should be consistent standards for designing the roadway and rail infrastructure (e.g., pavement markings should have the appropriate contrast and width, so they can be easily detected by CAVs when approaching HRGCs). The Manual on Uniform Traffic Control Devices (MUTCD) provides a comprehensive guidance on the use of different traffic control device types in the U.S. Furthermore, the MUTCD provides details regarding the requirements for pavement markings and signage at HRGCs. In some countries (e.g., Canada), there are other types of manuals that are specific to HRGCs. Li and Liu [143] developed a comprehensive intersection management strategy for effective V2V and V2I communication. It was assumed that AVs could check the status of an intersection and identify traffic congestion by means of V2I communication. A static conflict matrix was used to determine the priority of passing a given intersection. Without loss of generality, the proposed methodology could be extended for V2I communication in the vicinity of HRGCs, so the approaching AVs would have the information regarding the status of a given HRGC.

Rosyidi *et al.* [144] presented a radar-based sensor system, which could be used to improve safety at HRGCs and prevent potential collisions between trains and vehicles. The radar-based sensor was deployed to identify the approaching train and send the information to the micro-controller, which could initiate gate closing and opening operations at a given HRGC. In case of the approaching train, the proposed HRGC crossing system also activates warning lights to alert the pedestrians.

U.S. DOT [145] examined the best ways of how various engineering firms, transportation agencies, researchers, and other infrastructure stakeholders could effectively collaborate and prepare the existing passenger and freight rail infrastructure for the CV and AV deployment. The following aspects were explored: (1) information requirements for the vehicles approaching HRGCs; (2) the existing barriers for the data collection and exchange between different entities (e.g., public highway agencies, private freight railroad operators, public transit/commuter railroad agencies); (3) CV and AV implementation approaches that could potentially benefit highway and rail systems; and (4) additional research efforts needed to address the CV and AV architecture issues and challenges. The study pointed out that the existing PTC system would not be able to effectively provide the train location information to the vehicles approaching HRGCs in the U.S., as the PTC system had been installed only on less than 50% of the national rail miles. It was indicated that the train automation and train crew size reduction could facilitate the deployment of CV and AV technologies in the vicinity of HRGCs.

U.S. DOT [146] underlined that more than $8 million were invested in the U.S. into the automated transit research, including the first fully automated bus rapid transit system. Furthermore, around $60 million were allocated for the deployment of automated driving systems across the country. It was also indicated that more efforts have been made towards modernizing the regulatory environment of automated driving systems. The main goals of automation were categorized into three groups: (1) protect users and communities; (2) promote effective markets; and (3) facilitate coordinated efforts. The proposed comprehensive plan focused not only on CAVs but also on the modal interface points (e.g., HRGCs, marine ports).

## IV. REVIEW SUMMARY

**TABLE 4** summarizes the findings that were revealed from the reviewed studies, including the following information: (1) author(s) and year; (2) study objective; and (3) notes, important considerations, and study outcomes. Furthermore, the main advantages and challenges from the AT deployment, which were identified as a result of the conducted state-of-the-practice and state-of-the-art review, are presented in the following sections.

### A. ADVANTAGES FROM THE DEPLOYMENT OF AUTONOMOUS TRAINS

As a result of the conducted state-of-the-practice and state-of-the-art review, the following main advantages from the AT deployment have been identified:

- ATs are expected to ***improve the overall safety*** throughout the transportation process [16], [62]. Human errors are viewed as one of the main causes of accidents in rail transportation networks. The ATs with a full automation level will not require any onboard personnel, which will practically eliminate any possibilities of human errors and associated accidents. Fully automated systems and computer-based programs are expected to control the AT movements more precisely as compared to human operators. New generation sensors, platform supervision technologies, detection systems, and intrusion prevention systems will guarantee an acceptable safety level.
- The AT deployment will allow ***increasing the existing capacity and utilization of rail lines*** [42], [45], [52], [70], 78]. The capacity increase can be achieved by reducing the headway between consecutive ATs. Unlike conventional trains, ATs rely on different technologies that would allow substantially decreasing the headway without affecting the safety level. Shorter headways are expected to increase the service frequency of metro stations, reduce the waiting time of passengers at metro stations, and facilitate the alighting and boarding process. Some experts underline that the capacity increase is one of the main reasons for rail automation, as many conventional rail lines operate near their capacity limits [62].
- Although automation requires substantial initial investments, ATs have ***lower operational costs*** as compared to conventional trains [16], 62]. Operational cost savings stem for the train crew size reduction (i.e., ATs with a full automation level will not require any onboard staff) and the associated management, training, and labor costs. For example, some of the automated metro lines in Paris (France) were able to reduce the operational costs by approximately 30% due to the AT deployment [147]. The operational costs savings due to the AT deployment will depend on physical and operational characteristics of a rail line.
- The AT deployment is expected to ***improve the overall service reliability*** [16], [52], [71], which is considered as an important aspect for passenger and freight rail transportation. An increase in the level of automation allows reducing potential disruptions in train operations due to human errors. The future ATs are anticipated to detect disruptions in the planned operations and respond promptly to ensure the comfort and safety of passengers. Furthermore, the ability to adjust the AT running times and more precise dwell times at metro stations or freight terminals would make ATs more reliable as compared to conventional trains. The service reliability is also enhanced by ***increasing the service availability***, as metro stations can be visited more frequently due to reduced train headways.
- Automation will allow ***improving service flexibility and fleet management*** [16], [62]. More ATs can be deployed during peak hours to make sure that the demand is effectively met and reduce the waiting time of passengers at metro stations. On the other hand, unused ATs could be easily removed from the network during off-peak hours. The AT fleet management and removal of unused ATs from rail lines can be effectively performed, as ATs are not human-driven. An effective fleet management will

**TABLE 4.** Summary of the reviewed studies.

| a/a | Author(s) and Year | Study Objective | Notes, Important Considerations, and Study Outcomes |
|---|---|---|---|
| *Connected and Autonomous Vehicle Technologies and Their Applications for Autonomous Trains* | | | |
| 1 | Bagloee et al. (2016) [30] | Analyze various issues and opportunities regarding the transportation policies and regulations associated with the CAV technologies. | An essential part of the CAV technology was found to be its ability to communicate with moving vehicles and infrastructure. This technology would be important for the vehicles passing through highway-rail grade crossings and interacting with the trains approaching the crossings. |
| 2 | Krasniqi and Hajirizi (2016) [31] | Investigate the current CAV market and technology trends from the preliminary stage to fully driverless vehicles. | The IoT technology was found to have a potential to completely alter the automobile market, which could provide a major thrust to IoT in the autonomous technology market. The study concluded that the DSRC and 5G technologies would be the most suited for improving safety and vehicle communication with trains and surrounding infrastructure. |
| 3 | Crains (2017) [32] | Present a perspective on the future of autonomous technology in all modes of transportation. | A number of challenges with the AT deployment were pointed out (e.g., introduction of the PTC system in the U.S. for freight railways only; disagreement of railroad unions to adaptation of one-person train crews), which can slow down rail automation if not addressed properly. |
| 4 | Bucsky (2018) [33] | Study the existing condition of freight traffic and CAV applications in freight transportation. | The study highlighted that the railroad industry would have more developments towards the full automation level. However, such developments would require significant investments. It was indicated that the automation would make the road transport more preferential as compared to the other modes, which might lead to some environmental problems. |
| 5 | GHSA (2018) [34] | Determine potential issues from the deployment of autonomous driving systems. | The following safety issues were identified: compliance with traffic laws, decisions during emergency situations, recognition, reaction, operations after detection of certain system failures, system security, and others. It was recommended that partially automated driving systems should be controlled by a licensed human operator. |
| 6 | Elliot et al. (2019) [36] | Detailed review of recent advancements in CAV technologies. | The study highlighted the importance of the DSRC and 5G technologies for effective communication between CAVs and trains. Addressing security issues, reliability issues, and conflicts in operations would be an important next step in the CAV deployment. |
| 7 | CRS (2020) [27] | Investigate the issues related to the deployment and testing of CAVs. | The interaction of CAVs with the existing infrastructure, ATs, and non-CAVs will generate a huge amount of data (e.g., vehicle location and train location). Any unauthorized access may lead to safety issues not only for the vehicle and for the train but for others as well. |
| *General Issues Associated with Autonomous Trains* | | | |
| 8 | Gebauer and Pree (2008) [37] | Determine the conceptual, technical, and legal challenges associated with the AT deployment. | The concept of “trainlets” was proposed to improve the attractiveness of ATs. The entire AT could be divided into many smaller “trainlets”, which have the size of a standard automobile. The studies discussed the autoBAHN project that was launched to validate the technical feasibility of fully autonomous “trainlets”. It was highlighted that the economic viability of ATs would depend on how the automation concept would be implemented. In particular, the use of the existing railroad infrastructure with the minimum required alterations would be favorable for the development and deployment of ATs. Given the existing interest of the relevant stakeholders, the autoBAHN project might be implemented in the near future. |
| 9 | Gebauer et al. (2012a) [38] | | |
| 10 | Gebauer et al. (2012b) [39] | | |
| 11 | Dordal and Avila (2016) [40] | Develop a software agent-based system to coordinate trains. | The results of the study showed that the proposed software agent-based system could reduce the total journey time by 22.5%. The fuel consumption was reduced by more than 25%, which could further improve the environmental sustainability. |
| 12 | Hazan et al. (2016) [41] | Study the impacts of AV deployment on rail transportation. | As a result of conducted survey, it was found that about 50% of respondents (out of 5,500 consumers from ten different countries) would consider buying AVs. More importantly, at least 40% of the current train passengers would shift to using AVs. |
| 13 | Powell et al. (2016) [42] | Assess benefits and challenges of the AT deployment for the Tyne and Wear Metro (U.K.). | Low adhesion conditions and the presence of shared operations at the existing rail lines were found to be the main obstacles. Moreover, additional infrastructure upgrades would be necessary to transition towards full automation. |
| 14 | Wang et al. (2016) [16] | Review the driverless train operations in urban transit rail systems. | Along with potential advantages, different AT deployment challenges were outlined. A systematic safety assessment framework is needed to standardize the AT operations, reduce potential risks, and enhance the overall reliability. |
| 15 | Trentesaux et al. (2018) [43] | Investigate advantages and disadvantages from the AT deployment. | The deployment of ATs would significantly change the railroads. However, the success of ATs will depend on the participation of various stakeholders, such as manufacturers, fleet operators, infrastructure developers, etc. |
| 16 | Wardrop (2019) [44] | Identify the challenges associated with the freight train deployment in remote areas. | Mining in remote areas is generally expensive, as it is quite difficult to find the required resources. Therefore, the automation of mining process and rail transportation gained popularity among mining companies. |
| 17 | Antolini (2020) [45] | Determine potential challenges of the AT deployment by the SNCF railroad company. | The main challenge of the AT deployment in Europe would be the introduction of ATs on the railroad system, where multiple passenger and freight operators share the same railroad tracks. The trains might have different physical characteristics. |
| 18 | Kemmeter (2020) [46] | Investigate the AT deployment challenges. | Certain CAV technologies may not be applicable for ATs. Train detection requires installation of cables along the rail tracks as well as a lot of online equipment. Such train detection equipment is generally costly and requires regular maintenance. |

**TABLE 4.** ***(Continued.)*** **Summary of the reviewed studies.**

| a/a | Author(s) and Year | Study Objective | Notes, Important Considerations, and Study Outcomes |
|---|---|---|---|
| 19 | Muller (2020) [47] | Evaluate the organizational hindrances from the deployment of freight ATs. | The study evaluated four conceptual impacts on innovation activities within advanced markets. It was concluded that the strategic innovation policies should address the challenges that are associated with the AT deployment. |
| 20 | Pattinson et al. (2020) [48] | Discuss and analyze the legal issues associated with AVs. | It is critical to develop the appropriate solutions to determine legal responsibilities for vehicles and drivers in case of accidents. Similar legal issues have to be addressed when deploying ATs and human-driven trains on the existing rail lines. |
| 21 | Wang et al. (2020) [49] | Study the CAV safety issues. | Drivers often take control of AVs when they think it is necessary, which creates a "disagreement". Such disagreements may further lead to accidents, which can occur at the rail lines with the grades of automation GoA2 and GoA3 as well. |
| 22 | Othman (2021) [50] | Conduct a comprehensive review of the AV public acceptance and perception. | The COVID-19 pandemic made substantial impacts on public transit services around the world. The future rail transit systems, including autonomous rail transit systems, should have additional protective measures against the spread of diseases. |
| 23 | Karvonen et al. (2011) [51] | Investigate challenges from the AT deployment in metro systems. | Train drivers are viewed as a link between different actors involved in different metro operations. It was concluded that a lack of understanding of the train driver roles may lead to safety and quality of service issues throughout the AT deployment. |
| 24 | Cohen et al. (2015) [52] | Determine the effects of automation on metro line operations. | The results indicated that the AT deployment could decrease the train crew size by 30-70% (which can be negatively viewed by the public). The findings showed that the AT deployment could improve the metro efficiency and productivity. |
| 25 | Cassauwers (2020) [53] | Study the employment issues due to the AT deployment. | The study pointed out that the re-orientation of employees (e.g., transition to customer service or to non-automated rail lines) would be a promising solution rather than layoffs or salary cuts. |
| | | *User Perception and Outlook for Autonomous Trains* | |
| 26 | Fraszczyk et al. (2015) [54] | Study public perception of substantial changes in rail transport associated with ATs. | The survey involved 50 individuals from 10 different countries. The majority of survey participants indicated no concerns associated with the AT maintenance issues and the train design itself. However, staff communication and technical failures were the main two issues that were raised. |
| 27 | Fraszczyk and Mulley (2017) [55] | Investigate the user perception and attitude towards ATs in Sydney (Australia). | The survey involved 300 individuals from Sydney (Australia). The study results indicated that many train users and non-users rated the presence of a train driver as important. The majority of survey participants were concerned with the safety aspects of the AT operations. |
| 28 | Pakusch and Bossauer (2017) [56] | Study the user acceptance to technological innovations in autonomous public transportation. | The survey involved 201 individuals from Germany. Many users were already familiar with autonomous driving and were willing to use autonomous public transportation in the following years. The existing policies should be modified to allow the users accessing autonomous public transportation during test phases. |
| 29 | Henne et al. (2019) [57] | Address the user perception challenges towards AI-based applications for autonomous systems. | A combination of methods for assessing the perception uncertainty and dynamic dependability management was found to be a promising solution to effectively address the challenge of unreliable perception of the AI-based applications for autonomous systems. |
| | | *Design and Technologies for Autonomous Trains* | |
| 30 | Bock and Bikker (2000) [58] | Develop a new operational concept for rail services. | The proposed concept assumed that the train wagons were no longer physically coupled to each other. Each wagon had its own computer system along with propulsion, which can be considered as an AT module prototype. |
| 31 | Haxthausen and Peleska (2000) [59] | Propose a controlled distributed system for railroads. | The proposed concept could be used for an automatic train control without the presence of a train driver (i.e., AT applications in rail transportation). |
| 32 | Matsumoto et al. (2001) [60] | Design a decentralized autonomous train control (D-ATC) system. | The proposed D-ATC system had the following main features: (1) train detection on rail tracks; (2) dissemination of the stop point information; (3) detection of a train position; and (4) control of braking. |
| 33 | Matsumoto (2005) [61] | Review various train control systems that were deployed in Japan. | The newly designed information technologies allow trains detecting their own positions and transmitting this information to other trains in the vicinity. |
| 34 | Castells et al. (2011) [62] | Study the operational AT features at metro lines. | The AT signaling and control systems allow shorter headways between consecutive trains, which increases the rail network utilization. The AT deployment allows better management of the supply and demand. |
| 35 | Marrone et al. (2012) [63] | Study the verification process of different AT applications. | The study indicated that the Combined Model-Based Analysis and Testing of Embedded Systems (MBAT) project conducted in the European Union would help improving the verification process. |
| 36 | Mohammed et al. (2014) [64] | Develop a microcontroller-based prototype for ATs. | The proposed AT prototype was able to perform a set of basic operations (e.g., travel via a pre-defined path between a set of stations, proper stopping at stations). The proposed AT prototype could serve as a foundation for more sophisticated control systems. |
| 37 | Balasubramanian (2016) [65] | Investigate various IoT processors that could be utilized to deploy ATs for a long-distance travel. | A successful implementation of the IoT technologies is heavily dependent on the availability of high-speed internet. The proposed concept of long-distance ATs is expected to have a variety of advantages. |

**TABLE 4.** ***(Continued.)*** **Summary of the reviewed studies.**

| a/a | Author(s) and Year | Study Objective | Notes, Important Considerations, and Study Outcomes |
|---|---|---|---|
| 38 | Fraga-Lamas et al. (2017) [17] | Review the evolution of railroad communication technologies. | The IIoT and Internet of Trains still face a large variety of issues (e.g., interoperability, standardization, scalability, and cybersecurity) that have to be effectively addressed by researchers and practitioners in the following years. New types of technology should be tuned for specific railroad environments to ensure their adequate implementation. |
| 39 | Romano et al. (2017) [66] | Study the existing AT metro systems and changing demand. | The new generation ATs should have the appropriate types of technology that could achieve operational cost optimization, energy reduction targets, minimization of risks associated with human errors, and high system performance. |
| 40 | Bharathi et al. (2018) [67] | Design a technology for automatic train control and operations. | The train was assumed to have a controller enabling the train automatically move from one metro station to another (i.e., an AT prototype). Upon arrival at a metro station, the train could stop automatically by applying the appropriate sensors. Such an automatic train system could be effective as it eliminates potential human errors. |
| 41 | Lagay and Abdell et al. (2018) [68] | Discuss various features of the AT deployment project in France. | A variety of AT technologies and systems were described. In order to effectively deploy ATs, the SNCF railroad company planned to work with different industrial and service sectors, as well as low-cost solutions and high-performance solutions. |
| 42 | Arup (2019) [69] | Review new trends in rail transportation. | The AT technologies allow optimizing the running time, increasing the average speed, and operations in a close proximity to other trains. The AT deployment also allows effectively addressing the growing demand for rail transportation. |
| 43 | Kimiagar (2019) [22] | Review the emerging trends in the technology used for rail transit. | The study presented different train control systems that are responsible for various functions (e.g., train timetable development, ride comfort, safety aspects, and interlocking). The steps required for the transition from conventional trains to ATs were pointed out as well. |
| 44 | Pickering et al. (2020) [70] | Design a simulation model to investigate the AT deployment. | The results from the conducted simulation analysis demonstrated that the AT deployment could substantially increase the rail network capacity, as consecutive trains could be operated at a smaller distance. |
| 45 | Kunifuji et al. (2009) [71] | Design an alternative railroad signaling system. | A new railroad signaling system was based on the network and autonomous decentralized technology. The developed system would improve not only the flexibility of signaling but the overall safety and reliability as well. |
| 46 | Harb et al. (2020) [72] | Develop a dataset for railroad traffic light recognition and detection. | The developed dataset can be used for automatic classification of railroad signaling panels by state and by type. Furthermore, the developed dataset could assist to facilitate the AT deployment. |
| 47 | Brenna et al. (2016) [73] | Optimize the energy consumption for autonomous subway trains. | The study developed a genetic algorithm to optimize the energy consumption for autonomous subway trains. The energy optimization was achieved through the control of train movements (e.g., setting the train speed, determination of stop positions). |
| 48 | Mandara et al. (2019) [74] | Suggest a prototype of the fully automated metro train with improved safety features. | The improved safety level was achieved by introducing a monitoring unit that could detect potential safety hazards on rail tracks in front of the train. The roof of the proposed train system was assumed to have a set of solar panels. |
| 49 | Richert (2020) [75] | Present new generation trains with alternative power sources. | The new generation trains would have the hydrogen fuel cells and storage batteries as power sources, which is expected to improve the environmental sustainability of rail transportation and its competitiveness as compared to other modes. |
| 50 | Gschwandtner et al. (2010) [76] | Develop a method of using lane detection techniques for ATs. | The developed algorithm combined various techniques used in lane detection and strong geometric constraints that are specifically applicable for rail tracks. The accuracy of the proposed method could be influenced by custom rail properties. |
| 51 | Weichselbaum et al. (2013) [77] | Propose a 3-D vision-based obstacle detection system for ATs. | Stereo matching and slanted correlation masks were able to substantially improve the obstacle detection rate (i.e., from 89.4% to 95.75%). The false positive detection rate comprised 0.25% only. |
| 52 | Xie et al. (2017) [78] | Develop discrete event controllers for the AT control system. | The modeling was performed using the Colored Petri Nets along with its extensions, considering some important aspects (e.g., rail operational requirements, collision-free systems). |
| 53 | Talvitie et al. (2018) [79] | Propose a train positioning method. | It was found that the time of arrival measurements were able to provide better accuracy, when comparing to the angle of departure measurements. Moreover, the best accuracy was accomplished when both measurements were taken into account. |
| 54 | Yin et al. (2020) [18] | Review the AI applications in high-speed rail transportation. | The study outlined a variety of areas where the AI-based techniques could be used to improve rail transportation. A comprehensive framework was developed for the AI applications in high-speed rail transportation, considering different criteria. |
| *Autonomous Trains and Highway-Rail Grade Crossings* | | | |
| 55 | Hsu and Jones (2017) [132] | Analyze the CV transmission range requirements at HRGCs. | It was concluded that a provision of 600-meter transmission range would be a feasible alternative to enhance the safety levels at passive and active HRGCs. |
| 56 | Zaouk and Ozdemir (2017) [133] | Investigate various CAV-based alternatives to improve safety at HRGCs. | One of the major challenges with the development of CV and AV technologies was found to be its limited testing in various environments (e.g., HRGCs with passing ATs and conventional trains) under various operational scenarios. |
| 57 | Voege et al. (2017) [134] | Investigate different aspects and effects of automation. | Automation is expected to eliminate human errors, which is critical to ensure safety at HRGCs (as collisions between approaching vehicles and passing trains often occur as a result of human errors). |

**TABLE 4.** *(Continued.)* **Summary of the reviewed studies.**

| a/a | Author(s) and Year | Study Objective | Notes, Important Considerations, and Study Outcomes |
|---|---|---|---|
| 58 | U.S. DOT (2018a) [135] | Discuss various features of automation and how to prepare for the future. | The study highlighted the importance of effective interactions between AVs and passing trains at HRGCs. A variety of stakeholders are involved to design a safe system for AV-train interactions. |
| 59 | U.S. DOT (2018b) [136] | Determine a set of primary requirements for AVs to safely pass through HRGCs. | The development of new generation technologies is constrained by the uncertainties and differences in perspectives between the relevant stakeholders and industries (e.g., automated driver assistance systems, Federal Highway Administration, and railroad authorities). |
| 60 | Bertini and Wang (2016) [137] | Prepare a roadmap for the CAV applications in Oregon (U.S.). | The CAV technology could improve interactions between approaching vehicles and passing trains at HRGCs. |
| 61 | GAO (2018) [138] | Analyze the safety challenges at HRGCs. | The CAV technology could improve interactions between approaching vehicles and passing trains at HRGCs. |
| 62 | Neumeister et al. (2019) [139] | Design a Rail Crossing Violation Warning (RCVW) system. | Based on the RCVW concept, the road-side units communicate to the CVs regarding the approaching train. The RCVW systems rely on different components, including computing platforms, DSRC, GPS, and driver-vehicle interface. |
| 63 | Virtanen et al. (2019) [140] | Study potential issues associated with the AVs passing through HRGCs. | Protected HRGCs can be detected with the AV perception sensors. The AV perception sensors alone may not be sufficient to detect an approaching train at unprotected HRGCs, especially under inclement weather conditions. |
| 64 | Wang et al. (2019) [141] | Proposed a new active CV-based warning system. | The system relied on a wireless communication via the DSRC between the onboard equipment and road-side units to activate the warning messages due to approaching trains. The system can send visual and auditory alerts along with displaying the expected waiting time. |
| 65 | Knapp et al. (2020) [142] | Review the codes and standards for the future AV deployment. | The MUTCD provides a comprehensive guidance on the use of different traffic control device types in the U.S. Furthermore, the MUTCD provides details regarding the requirements for pavement markings and signage at HRGCs. |
| 66 | Li and Liu (2020) [143] | Propose a strategy for the intersection management, considering the presence of AVs. | It was assumed that AVs could check the status of an intersection and identify traffic congestion by means of V2I communication. The proposed methodology could be extended for V2I communication in the vicinity of HRGCs |
| 67 | Rosyidi et al. (2020) [144] | Improve safety at HRGCs. | Presented a radar-based sensor system, which could be used to prevent potential collisions between trains and vehicles. The radar-based sensor was deployed to identify the approaching train and send the information to the micro-controller. |
| 68 | U.S. DOT (2020a) [145] | Investigate the best way to prepare for the CV and AV deployment. | The existing PTC system would not be able to effectively provide the train location information to the vehicles approaching HRGCs in the U.S., as the PTC system had been installed only on less than 50% of the national rail miles. |
| 69 | U.S. DOT (2021) [146] | Develop a comprehensive plan for the AV deployment. | More than $8 million were invested in the U.S. into the automated transit research. The proposed comprehensive plan focused not only on CAVs but also on the modal interface points (e.g., HRGCs, marine ports). |

also facilitate timely maintenance (e.g., unused ATs can undergo scheduled maintenance procedures).

➢ The introduction of ATs in the existing rail networks will ***improve the energy efficiency*** [17], [43], [73]. ATs are expected to consume less energy as compared to conventional trains, since acceleration, traction, and braking procedures will be optimized for ATs by means of computer-based and AI technologies. Similarly, the energy consumption by the AT air-conditioning system can be optimized as well by introducing the appropriate sensors that can control the amount of needed fresh air [148]. Furthermore, the LED lighting systems may be introduced within ATs to reduce the energy consumption for lighting [149]. The new generation ATs will also rely on renewable energy sources, which will allow reducing the electric energy consumption [16], [74]. Since ATs can visit metro stations more frequently due to shorter headways, the actual AT length can be decreased. The deployment of shorter ATs can also decrease the energy consumption.

### *B. CHALLENGES FROM THE DEPLOYMENT OF AUTONOMOUS TRAINS*

As a result of the conducted state-of-the-practice and state-of-the-art review, many different challenges from the AT deployment have been identified and classified into the following categories: (1) design challenges; (2) operational challenges; (3) technology-related challenges; and (4) human aspect-related challenges. The identified challenges are discussed in the following sections.

#### 1) DESIGN CHALLENGES

➢ Achieving a full automation level for the existing passenger and freight rail lines will require ***substantial initial investments*** [16], [45], [46], [52]. ATs rely on modern technologies, many of which are quite expensive to obtain. The cost of installing the PTC and DSRC technologies for effective communication is also fairly high. The approximate cost of the PTC technology can go up to $35K per locomotive, while the approximate cost of the DSRC road-side unit can go up to $40K [150]. Some experts indicate that the cost of automation might be one of the main barriers for the future AT development and deployment [33].

➢ Although the automation of rail transportation is viewed as less complicated to implement as compared to road transportation, ***the AT risk management issues*** do exist. In particular, the AT operations in emergency situations have to be investigated more in depth. The AT braking distance due to emergency situations has to be optimized (i.e., generally larger weight of trains requires longer stopping distance) to prevent a high impact due to collisions and unforeseeable activities on tracks, such as intrusion by animals or trespassing [43], [53]. Adequate design improvements have to be made to ensure a proper response of ATs in emergency situations.

- Along with the automation of trains, the relevant stakeholders should ***increase the level of automation for maintenance procedures***. Some of the critical maintenance procedures that could be fully automated include ballast replacement, ballast tamping, as well as track relaying [17]. Fully automated maintenance procedures are expected to ensure the adequate operational conditions of the rail infrastructure and avoid potential delays of ATs along the rail lines.
- One of the advantages from the AT deployment is an increase in the capacity and rail line utilization due to shorter headways between consecutive ATs. Due to shorter headways, ***the rail terminal designs have to be upgraded*** to ensure that the train turnaround requirements are met [16]. The future AT terminals should have specific areas designated for train storage (when they are not being deployed), coupling and decoupling of train units, and maintenance procedures.
- The appropriate stakeholders should focus on the development of ***consistent codes and standards*** for designing the roadway and rail infrastructure (e.g., pavement markings should have the appropriate contrast and width, so they can be easily detected by CAVs when approaching HRGCs) [142]. An improved design of the roadway and rail infrastructure would allow CAVs and ATs to effectively sense the surrounding environment.
- Another significant challenge that substantially slows down the AT development and deployment is associated with ***legal issues*** [37]–[39]. The existing laws and regulations put a lot of emphasis on safety and security and require extensive testing of the AT technologies before they could be implemented in practice. Railroad companies, researchers, government representatives, and other relevant stakeholders should collaboratively develop more effective policies that could facilitate the AT development and deployment considering the perspectives of future users and without affecting the safety level.

### 2) OPERATIONAL CHALLENGES

- ATs are being continuously developed and upgraded in many countries. However, it will not be possible to fully automate all passenger and freight rail lines at the same time (i.e., manually-driven trains will have to share rail lines with ATs, which may create some operational challenges) [42], [45]. New policies and operational strategies should be developed to improve ***coordination of trains at shared rail lines***, so that manually-driven trains can co-exist with ATs.
- ATs rely on a wide range of different systems, and ***the interoperability between these systems*** should be steadily enhanced. Otherwise, the future ATs will not be able to reach their full potential in the operational effectiveness. One of the approaches the can be used to improve the interoperability of AT systems is the implementation of semantic data models [17]. The semantic data models allow an effective integration of the data generated by various systems.
- The future research should investigate different ***coordination mechanisms between various autonomous systems*** (e.g., how to minimize the total waiting time of autonomous buses that expect the arrival of certain passengers that are travelling on an AT). Without effective coordination mechanisms the users of autonomous systems may not be able to experience all the benefits of automation. Furthermore, a lack of effective coordination mechanisms may lead to certain operational deficiencies (e.g., excessive idle time of autonomous buses, ATs, and AVs).
- Operations scheduling problems generally have high computational complexity, and efficient solution algorithms are required to solve these problems [17], [151]–[153]. To ensure a successful AT deployment, many different ***planning and scheduling problems*** have to be solved, including train line balancing, timetable development and optimization, real-time train rescheduling, train reordering, and track maintenance [154]–[159]. The future studies should concentrate on the development of efficient solution algorithms for these decision problems.
- ***The share of freight rail transport is fairly modest***, when comparing to other transportation modes [17]. Automation may not be able to fully address this issue, and additional actions will be required from the relevant stakeholders. One alternative that can be considered is to improve the service quality and ensure timely deliveries to the end customers. Moreover, the introduction of cost-competitive services and interoperability improvements are also viewed as viable options.

### 3) TECHNOLOGY-RELATED CHALLENGES

- There is a continuous evolution process in rail signaling systems, where ***communication-based train control systems*** (e.g., radio technology, microwave technology) ***are being used instead of track-circuit signaling*** [16]. Additional steps and procedures have to be undertaken by the relevant stakeholders to ensure a smooth transition from one rail signaling system to another.
- Despite the fact that the existing ATs rely on a variety of AI-based technologies [18], [22], [25], more research still has to be done in order to ***improve the informational, decisional, and learning processes***. These processes have to be performed considering a variety of physical and operational attributes, including the train speed and location, speed and location of other trains

on a given rail line, presence of objects on tracks, status of railroad signals, and others. Effective informational, decisional, and learning processes will improve the reliability of AT operations.

- ➢ More efforts should be geared towards improving ***cybersecurity*** of ATs. Cyber-attacks may substantially disrupt the AT operations [17], as ATs heavily rely on the computer-based AI technologies. Such disruptions may negatively affect the comfort of passengers or even lead to safety issues. Therefore, robust cybersecurity measures should be developed in the future to prevent unauthorized access in the AT computer systems. Moreover, the future ATs should be programmed accordingly; so the required software updates are regularly performed, and the AT computers remain resilient to the new and already-known cyber-threats.
- ➢ The future research should focus more on ***enhancing the existing wireless sensor networks***, especially in the railroad environments. There exist several issues associated with wireless sensor networks that have to be addressed, including communication reliability, fast transmission rates, measurement of vibrations, management of high-volume data, energy harvesting, energy efficiency, and data fusion [17].
- ➢ Throughout the AT operations, there is always ***a risk of intrusion of people or objects*** on rail tracks [16]. The existing communication and surveillance technologies have to be enhanced to make sure that unexpected objects on rail tracks will be detected in a timely manner, so ATs could respond properly (e.g., make an emergency stop due to trespassing). This will also help improving safety and security of passengers.
- ➢ The COVID-19 pandemic made substantial impacts on public transit services around the world and caused a significant reduction in ridership [50]. The future rail transit systems, including autonomous rail transit systems, should have additional ***protective measures against the spread of airborne diseases*** (e.g., advanced air circulation, ultraviolet light disinfection). Such measures will help preventing the impacts of airborne diseases on rail transit system operations and improve safety of passengers.

#### 4) HUMAN ASPECT-RELATED CHALLENGES

- ➢ Train drivers perform many different functions (i.e., anticipation, observation, interpretation, and reaction to events). Moreover, train drivers are viewed as a link between different actors involved in various rail operations [51]. There still exists a major challenge in ***understanding all the roles performed by train drivers and how these roles can be performed by ATs***. The safety level and quality of service may drastically decline if ATs are not able to perform the main train driver roles.
- ➢ ***User perception*** remains one of the AT deployment barriers. Based on the conducted review, many users still have concerns regarding the AT performance in emergency situations without the onboard staff [54], [55]. Additional educational programs should be developed and administered, so the future users will be aware of how ATs operate not only under normal but also under disruptive conditions and emergency situations as well. Furthermore, the existing policies should be modified to allow the users accessing autonomous public transportation systems even during the test phases, so they could become more familiar with new technologies and have positive experience in the future [56].
- ➢ The existing communication systems within ATs must be improved. ***The ATs used on metro rail lines should*** not only ***be able to communicate*** with the surrounding infrastructure and other ATs but ***with the onboard passengers*** as well. Generally, train drivers inform passengers in case of changes in the planned schedule or emergency situations [16]. Since ATs won't have any onboard staff, the pertinent information should be transmitted by the operational center directly into ATs in the form of the voice messages and/or text messages and/or videos, so the passengers will have the pertinent information throughout their journey.
- ➢ One of the main concerns with the AT deployment in many countries is associated with ***the employment issues***. Based on the existing projections, the AT deployment can reduce the train crew size by 30-70% [52] and result in layoffs [32], [53]. Layoffs may further cause a large number of strikes by railroad unions. The employment issues due to the AT deployment have to be addressed by the appropriate stakeholders in the nearest future, as they may substantially slow down the AT development and deployment. The re-orientation of employees (e.g., transition to customer service or to non-automated rail lines) would be a promising solution rather than layoffs or salary cuts [53].

## V. CONCLUDING REMARKS AND FUTURE RESEARCH NEEDS

The statistics shows that the rail network has seen a tremendous growth globally in the last two decades. The growth has been observed in terms of the number of passengers traveling and in terms of freight movements as well. The total length of rail miles increased from 1,099,685 km in 2004 to 1,142,890 km in 2018. The growth in rail passenger and freight traffic along with a continuous rail network expansion requires railroad companies making improvements in the existing operations to maintain profitability and effectively tackle the demand for rail transportation. Automation is expected to effectively address the growing demand for passenger and freight transportation, safety issues, additional costs, environmental problems, human errors, and increasing congestion. The growth of autonomous vehicles using the state-of-the-art connected vehicle technologies has paved the way for the development of passenger and freight autonomous trains (ATs), also known as driverless trains. The current study focused on a detailed up-to-date review of the existing trends, technologies, advancements, and challenges in the deployment of ATs with a full automation level in rail transportation.

The basic AT features along with the key technologies that are instrumental for the AT deployment and operations were discussed in detail, including the Internet of Things, artificial intelligence-based methods, dedicated short-range communications, and positive train control. Furthermore, a comprehensive evaluation of the state-of-the-art research efforts was performed as well with a specific emphasis on the issues associated with the AT deployment, user perception and outlook for ATs, innovative concepts and models that could be used for the AT design, and the AT operations at highway-rail grade crossings. A variety of advantages from the AT deployment have been identified, including the following: (1) improvement in the overall safety by eliminating any possibilities of human errors; (2) increasing the existing capacity and utilization of rail lines; (3) lower operational costs as compared to conventional trains; (4) improvement in the overall service reliability; (5) improvement in the service flexibility and fleet management; and (6) improvement in the energy efficiency. Based on the conducted state-of-the-practice and state-of-the-art review, many different challenges from the AT deployment have been identified as well, such as the design challenges, operational challenges, technology-related challenges, and human aspect-related challenges. The identified challenges have to be collaboratively addressed by the relevant stakeholders, including railroad companies, researchers, and government representatives, to facilitate the AT development and deployment considering the perspectives of future users and without affecting the safety level.

In order to determine effective solutions for the existing challenges from the AT deployment, this study can be expanded in several dimensions, including the following:

- Develop a comprehensive cost-benefit model that can be used to capture the initial investment and operational costs that are associated with the AT deployment along with the benefits that could be achieved from the AT deployment. Such a model would assist the relevant stakeholders with the investment decisions and justification of the AT deployment projects for passenger and freight transportation.
- Identify the required steps and procedures that have to be undertaken by rail terminal operators to automate the maintenance process of rail lines and ATs. Fully automated maintenance procedures are expected to ensure the adequate operational conditions of the rail infrastructure and avoid potential delays of ATs along the rail lines.
- Determine potential alternatives for the new rail terminal designs that would be able to provide adequate turnaround conditions for ATs, taking into consideration shorter headways between consecutive ATs for better rail line utilization and capacity increase.
- Conduct a comprehensive survey among different stakeholders (e.g., railroad companies, researchers, government representatives) to identify the main legal issues associated with the AT development and deployment in different countries and provide constructive recommendations based on the lessons learned.
- Perform a set of interviews with a diverse group of train drivers (e.g., train drivers of different gender, age, nationality, etc.) to better understand all the driver roles and functions that are required for effective and safe train operations. The outcomes from the conducted interviews could be used in the design of the future ATs to make sure that they would be able to perform all the key roles and functions.
- Conduct a comprehensive survey among a diverse group of potential AT users (e.g., users of different gender, age, nationality, etc.) to determine their perception with regards to the future AT deployment. Different aspects will be considered (i.e., not only the safety perspective but also the aspects associated with the cost of using ATs, service availability, service frequency, human error risks, energy sustainability, and energy efficiency).

## APPENDIX

### ABBREVIATIONS USED

4G – the Fourth Generation Technology
5G – the Fifth Generation Technology
ACSES – Advanced Civil Speed Enforcement System
ADAS – Advanced Driver Assistance System
AI – Artificial Intelligence
AT – Autonomous Train
ATC – Autonomous Train Control
ATO – Automatic Train Operation
ATP – Automatic Train Protection
AV – Autonomous Vehicle
BSM – Basic Safety Message
CAV – Connected and Autonomous Vehicle Technology
C-ITS – Cooperative-Intelligent Transportation Systems
CRS – Congressional Research Service
CV – Connected Vehicle
D-ATC – Decentralized Autonomous Train Control
DGPS – Differential Global Positioning System
DSRC – Dedicated Short-Range Communications
DTO – Driverless Train Operation
ECU – Electronic Control Unit
ERTMS – European Rail Traffic Management System
ETCS – European Train Control System
EU – European Union
FIS – Freight Information System
GHSA – Governors Highway Safety Association
GNSS – Global Navigation Satellite System
GoA – Grade of Automation
GPS – Global Positioning System
GSM – Global System for Mobile Communication
GSM-R – Global System for Mobile Communication – Railway

| | |
|---|---|
| HMI | – Human-Machine Interface |
| HRGC | – Highway-Rail Grade Crossing |
| IIoT | – Industrial Internet of Things |
| IoT | – Internet of Things |
| LIDAR | – Laser Illuminating Detection and Ranging |
| Li-Fi | – Light Fidelity |
| LTE | – Long-Term Evolution |
| LTE-R | – Long-Term Evolution – Railway |
| MBAT | – Model-Based Analysis and Testing of Embedded Systems |
| MLC | – Manned Level Crossing |
| MUTCD | – Manual on Uniform Traffic Control Devices |
| NFC | – Near-Field Communication |
| OR | – Operations Research |
| PIS | – Passenger Information System |
| PTC | – Positive Train Control |
| RCVW | – Rail Crossing Violation Warning |
| RFID | – Radio-Frequency Identification |
| ROF | – Radio over Fiber |
| RSU | – Road-Side Unit |
| RTRI | – Railway Technical Research Institute |
| RWPS | – Roadway Worker Protection System |
| SNCF | – Société Nationale des Chemins de Fer Français |
| TCP | – Track Change Point |
| TPMS | – Tire Pressure Monitoring System |
| U.K. | – United Kingdom |
| U.S. | – United States |
| U.S. DOT | – United States Department of Transportation |
| UTO | – Unattended Train Operation |
| UWB | – Ultra-Wideband Technology |
| V2I | – Vehicle-to-Infrastructure |
| V2N | – Vehicle-to-Network |
| V2V | – Vehicle-to-Vehicle |
| V2X | – Combination of V2V and V2I |
| Wi-Fi | – Wireless Fidelity |
| WiMAX | – Worldwide Interoperability for Microwave Access |
| WSN | – Wireless Sensor Network |

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