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Review

An Overview of Current Challenges and Emerging Technologies to Facilitate Increased Energy Efficiency, Safety, and Sustainability of Railway Transport

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Abstract: This article presents a review of cutting-edge technologies poised to shape the future of railway transportation systems, focusing on enhancing their intelligence, safety, and environmental sustainability. It illustrates key aspects of the energy-transport-information/communication system nexus as a framework for future railway systems development. Initially, we provide a review of the existing challenges within the realm of railway transportation. Subsequently, we delve into the realm of emerging propulsion technologies, which are pivotal for ensuring the sustainability of transportation. These include innovative solutions such as alternative fuel-based systems, hydrogen fuel cells, and energy storage technologies geared towards harnessing kinetic energy and facilitating power transfer. In the following section, we turn our attention to emerging information and telecommunication systems, including Long-Term Evolution (LTE) and fifth generation New Radio (5G NR) networks tailored for railway applications. Additionally, we delve into the integral role played by the Industrial Internet of Things (Industrial IoT) in this evolving landscape. Concluding our analysis, we examine the integration of information and communication technologies and remote sensor networks within the context of Industry 4.0. This leveraging of information pertaining to transportation infrastructure promises to bolster energy efficiency, safety, and resilience in the transportation ecosystem. Furthermore, we examine the significance of the smart grid in the realm of railway transport, along with the indispensable resources required to bring forth the vision of energy-smart railways.

Keywords: railway transportation challenges; emerging technologies; sustainable transport; remote sensor networks; weather conditions; transportation safety; smart grid

Citation: Kljaić, Z.; Pavković, D.; Cipek, M.; Trstenjak, M.; Mlinarić, T.J.; Nikšić, M. An Overview of Current Challenges and Emerging Technologies to Facilitate Increased Energy Efficiency, Safety, and Sustainability of Railway Transport. *Future Internet* **2023**, *15*, 347. https://doi.org/10.3390/fi15110347

Academic Editor: Om P. Malik

Received: 3 September 2023
Revised: 21 October 2023
Accepted: 23 October 2023
Published: 25 October 2023

1. Introduction

The European Union's long-term goals are based on green energy transition. Thus, the European Commission has adopted a package of measures aimed at energy efficiency improvements, along with legally binding guidelines for meeting the objectives of the Paris Climate Agreement [1]. According to those guidelines, at least 32% of energy consumption in the European Union (EU) by 2030 must be from renewable sources. Member states, including the Republic of Croatia, need to ensure that at least 14% of fuel (energy) in the transport sector is secured from renewable sources, and the overall energy efficiency would need to be increased by 32.5% by 2030 [2]. Obviously, the strategy for the decarbonisation of the energy sector also causes significant changes in the transportation sector in terms of usable energy sources, which, in turn, is reflected upon the propulsion technologies currently in use, particularly in railway transport [3]. Specifically, 20% of the global consumption of fossil fuels is currently attributed to the transportation sector [4], which, in turn, makes it the second largest carbon dioxide (CO_2) emission source [5] contributing significantly to the alarming increase in atmospheric CO_2 concentrations [6] and associated greenhouse effects [7]. The contribution of railway transportation to the overall emissions of greenhouse gases (GHGs) varies depending on the country, with 4% of the overall GHG emissions share having been reported in [8]. The EU Strategic Program for Transport Research and Innovation developed the first long-term strategic approach to prepare for the envisaged transportation system transition in terms of research and innovation that combines innovative low-carbon technologies with connected and automated transport services and smart mobility [9], wherein a multitude of options is currently available for railway sector decarbonisation [10].

The need for a transition to more autonomous and connected transport has been identified as a necessary condition for achieving higher levels of efficiency and the decarbonisation of the transportation sector. According to the European Commission (EC), the goal is that by 2030, high-speed rail traffic will double across Europe, and this is planned both for urban and intercity collective travel [9,11]. For journeys of less than 500 km, carbon-neutral automated mobility for smaller groups of people or goods should be available [11]. Also, the EC document [12], "... Digitalisation and robotisation in the field of the mobility of people and the transport of goods provide society with several potential benefits such as better accessibility and convenience for passengers, efficiency and productivity for logistics, improved traffic safety and reduced emissions. At the same time, there are concerns relating to safety, security, privacy, labour and the environment ...", recommend that intensive research and development (R&D) of suitable solutions for intelligent transportation systems (ITSs) needs to be carried out. This need for additional R&D is especially emphasised in the fields of communication systems and sensor networks to minimise the risks of deploying these new technologies [13]. In particular, demands for the accelerated digitalisation of the transportation sector result in extremely large amounts of data, which mandate the utilisation of cloud computing. On the other hand, the implementation of long-term evolution (LTE) or fourth and fifth generation (4G/5G) mobile communication networks [14] and different remote (networked) sensor nodes [15], as well as robotics [16] and artificial intelligence (AI) in logistics [17], are seen as key factors for further advances in digitalised and automated railway transportation [18], including autonomous rail vehicles [19].

Steady progress in the development of sensor networks is visible in all domains, especially in the field of transport. Therefore, the effectiveness of communication equipment is particularly important due to requirements on transport volume and speed [20]. To this end, the Internet of Things (IoT) paradigm [21] or, more precisely, the advanced system of machine-to-machine communication (M2M) [22], together with different front-end intelligent sensors [23], allows for the transparent integration of large numbers of heterogeneous external systems [24]. Thus, it can facilitate the development of new digital services and novel possibilities for their application, especially when transport safety and security are concerned [25]. Also, the development of communication systems according to 5G functionalities opens new possibilities in the field of ITS and communications between traffic entities and their environments, and such internet of vehicles (IoV) paradigm [22] is especially important in the field of autonomous and cooperative vehicle management [26]. Reference [27] provides an overview of the possible technologies, protocols, and architectures of intelligent systems based on the concept of vehicle communication systems, with an emphasis on a wide variety of communication types such as vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I) and vice versa (I2V), vehicle-to-pedestrian (V2P) communication, and, generally speaking, any communication between a vehicle and a heterogenous communication node (V2X) [26]. Furthermore, future transport systems based on non-fossil vehicle propulsion technologies are also closely related to smart grid systems and 5G software-defined vehicle networks that have important roles in that field of research [28]. In particular, 5G communication networks offer distinct advantages in terms of connection speed and data transfer reliability (up to 20 times faster data rates for the same transmission quality) compared to the standard Global System for Mobile Communications-Railway

(GSM-R) systems [29], and this low latency of 5G networks enables the implementation of various security functions over multiple heterogenous domains [30]. Thus, 5G communications have been suggested for the digitalisation of urban railways [31] and the telemetric monitoring and automation of railroad networks [32], along with sophisticated applications in the accurate positioning of railway traffic entities in real time [33]. The latter is significant in the context of railway traffic safety, especially when atmospheric and weather conditions at micro-locations are taken into account [34]. This primarily concerns railway traffic incidents related to weather conditions [35], but it may also refer to the feasibility of the scheduled transportation by rail under adverse weather conditions [36]. The application of smart remote sensor networks facilitating timely and structured information about atmospheric conditions may offer an additional advantage in the planning of railway transportation, as indicated in [36], which is of particular importance when considering increased weather condition volatility due to climate change [37].

Having the above issues in mind, this paper presents a review of state-of-the art and emerging technologies needed for the future development of smarter, safer, greener, and more sustainable railway transportation, while also outlining its inherent challenges. In that respect, Section 2 deals with energy efficiency and advanced propulsion technologies, such as the hybridisation of locomotive diesel-electric powertrains, and other measures of on-board locomotive electrification, including purely battery-based propulsion and the utilisation of hydrogen fuel cells. Section 2 also discusses the hydrogen economy and logistics in the context of railway transportation, as well as the utilisation of alternative fuels such as biofuels, and the production of synthetic fuels for transport using renewable energy sources. Section 3 deals with advanced information and telecommunication (ITC) systems based on long-term evolution (LTE) 4G/5G radio networks (RNs) suitable for railway applications and compares them with the current GSM-R communication standard. The use of remote sensor networks for the collection and processing of structured data aimed at improving the transportation energy efficiency and safety under varying weather conditions is also discussed in Section 3, along with some practical examples of remote sensor use for improving railway transport safety and energy efficiency. Section 4 discusses the recent advances in creating a new IoT-based paradigm within the Industry 4.0 concept for railway transport, with applications such as predictive maintenance, multimodal transport, and railway system resilience improvement measures. The roles and benefits of smart grids in future railway transport are also assessed. For each of these categories, practical examples are used to illustrate the benefits of emerging technologies. The concluding remarks are summarised in Section 5, which also gives guidelines for future research directions.

2. Measures for Improving Railway Transport Energy Efficiency and Sustainability

This section presents an overview of the means and measures for railway transport energy efficiency improvement, such as those based on hybrid electric powertrain architectures equipped with different energy storage technologies, along with advanced fully electric propulsion technologies based on hydrogen fuel cells and high-performance batteries.

2.1. Hybridisation of Conventional Diesel Engine-Based Locomotive Powertrain

The needs of industry and society for cheap energy continue to be largely covered by fossil fuel sources, and this is becoming an increasingly complex task in the face of highly fluctuating prices for oil and its derivatives. These arguments are key motivations for the massive electrification of the transport sector, which is mostly pronounced in road transport through the introduction of hybrid electric and fully electric vehicles [4]. Such advanced propulsion technologies, having enabled the penetration of electrified vehicles in the transport sector, have also been recognised as key factors for the development of intelligent transport systems [38] and their integration within the smart grid [39], especially when considering the increased participation of renewable sources in the overall energy balance of modern society [40].

The fully electrified railway traction system is based on the distribution of DC or AC electrical power through the overhead conductor (or third rail in some cases), thus supplying low voltage (up to 800 V) or medium voltage (up to 25 kV) to the fully electric locomotive [41], whose main advantage over their diesel-electric counterparts is in a higher power-to-mass (power-to-weight) ratio [40]. According to reference [42], a notable portion of existing railway tracks characterised by lower traffic density and rather lengthy routes have not yet been electrified due to the rather high investment costs of electrification [43]. Therefore, a significant number of diesel locomotives is still retained in the fleets of national and private railway companies [44]. However, the use of diesel-electric locomotives requires significant allocations for diesel fuel. Therefore, there is a trend in the R&D of hybridised diesel-electric propulsion [45] with a special emphasis on the introduction of energy storage systems based on advanced large-capacity electrochemical batteries. In that respect, special attention should be given to the safety aspects of battery application, where high-temperature sodium-nickel chloride (ZEBRA) batteries [46] and lithium batteries such as those using lithium iron phosphate ($LiFePO_4$) and lithium-titanate (LTO) chemistry stand out from the safety point of view [47]. According to the simulation study in reference [48], such advanced batteries were successfully applied in the hybridisation of a diesel powerplant in an isolated production plant micro-grid, indicating significant potentials for diesel fuel savings and a reduction in greenhouse gas emissions, amounting to over 12% compared to the non-hybridised microgrid case. Consequently, it is realistic to expect that the hybridisation of diesel locomotive propulsion (i.e., by installing a battery storage system of sufficient capacity and power ratings) could reach similar levels of fuel efficiency. In that respect, reference [49] reports up to 20% of fuel savings for certain operating modes, with similar reductions in greenhouse gas emissions and other pollutants [50], and a real possibility of reducing the acoustic noise emissions of the locomotive due to the use of stored electricity within the battery with a lower power output from the diesel engine [51].

Optimising energy consumption in rail transport is a multidimensional nonlinear problem subject to technological traffic constraints, especially when an increased degree of autonomy is considered, such as in the case of autonomous vehicles. Namely, their operation is characterised by additional safety constraints in terms of near objects' proximity warnings and automatic collision avoidance, which mandate driving mission altering in real time. Current trends in railway energy saving research have focused on driving strategy, propulsion, and energy storage systems [52], whereas reference [53] provides a preliminary solution for predictive monitoring and control system adaptation to optimise the energy consumption of an autonomous railway vehicle. The approach presented in [54] has shown that over a 16% reduction in fuel consumption can be achieved by using a relatively simple rule-based control strategy within the battery-hybrid diesel-electric locomotive for a wide range of freight loads. The simulation study presented in [54] included a point mass model of a freight train and a realistic mountainous railway route characterised by realistic track slopes and velocity limitations, along with a simulation model of a hybridised locomotive powertrain comprising a quasi-static model of a suitably sized battery energy storage system (Figure 1a). The overall quasi-steady-state model of the battery hybrid locomotive from [54] is shown in Figure 1b, wherein the locomotive powertrain sub-models were modelled by means of static characteristics (maps), which were also originally developed in [54]. In this model, the train driver (modelled as a proportional gain velocity controller) tries to maintain the train velocity near its target value, thus commanding appropriate accelerator (Notch) and braking (Brk) commands to the diesel-electric power plant and the battery energy storage system, wherein the braking command may also be used to recuperate kinetic energy and store it into the battery. The battery system is also equipped with a suitable state-of-charge (SoC) controller, which prevents battery overcharging and deep discharging regimes (lower portion of Figure 1b). The results presented in [54] show that the return of investment period of such diesel-electric locomotive hybridisation effort would be approximately one-fourth of the battery system's calendar life, so that the perceived fuel savings would be compensated by threefold within the expected lifetime of modern lithium-ion batteries aimed for this application.

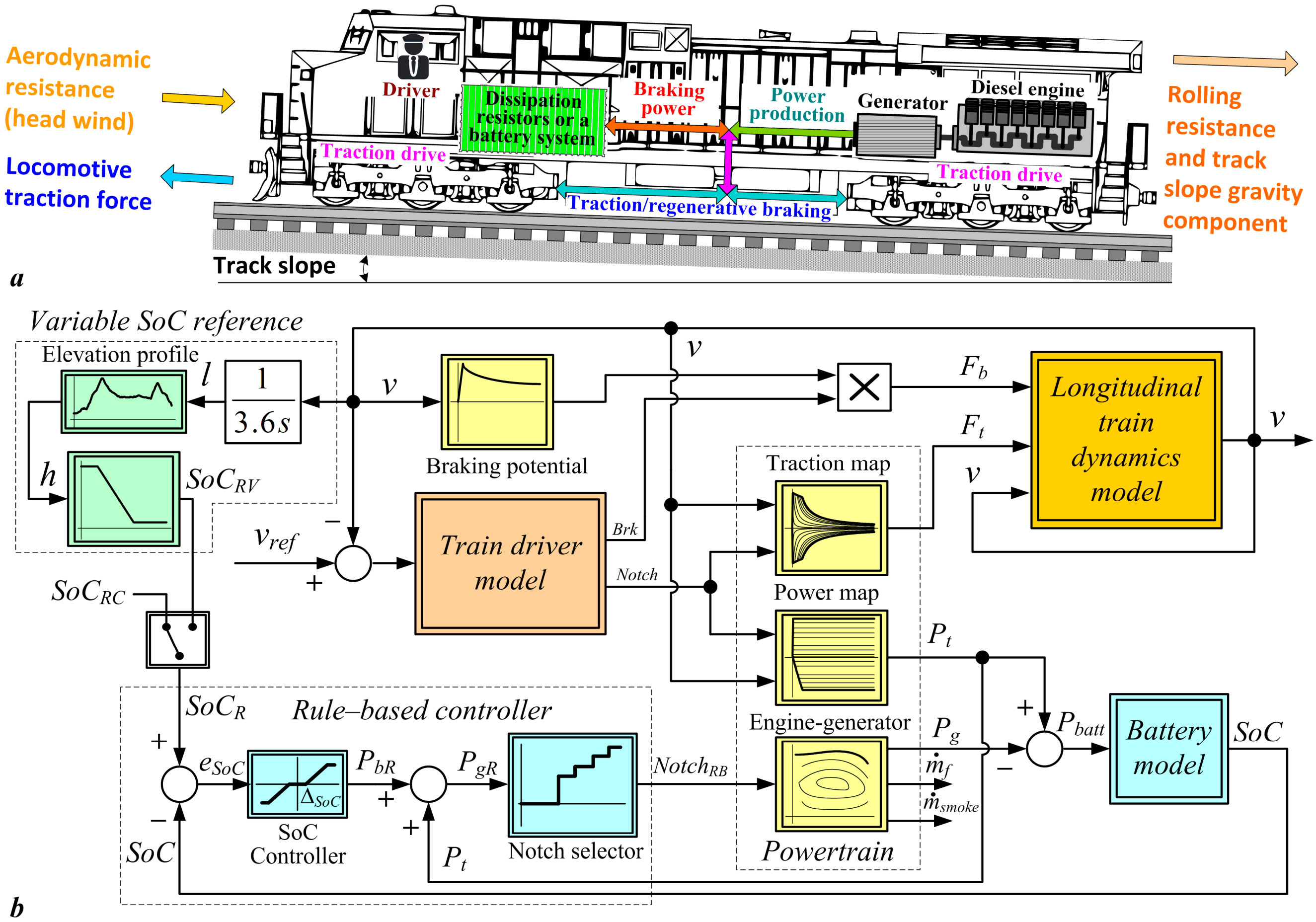

Figure 1. Principal representation of battery-hybrid diesel-electric locomotive (**a**) and quasi-static model of proposed battery hybrid locomotive from [54] (**b**).

Based on the above discussion, great care needs to be devoted to the proper choice of battery technology and the overall hybrid powertrain design, which is to be used in future railway propulsion systems. To assess the economic viability, trade-offs, and challenges of diesel locomotive powertrain hybridisation, several aspects thereof need to be considered:

1. Battery costs in terms of the investment cost, replacement costs, and running (operational) costs, wherein battery durability plays a particularly important role [54]. Typically, the latest generation of lithium-based batteries, such as those based on $LiFePO_4$ and LTO technologies, are more durable and less susceptible to aging compared to the more commonly used lithium-ion batteries. However, their initial costs are typically also greater, and their energy density is typically 30–50% lower compared to other currently available lithium batteries [47].
2. Battery safety, in terms of a wide temperature operating range and the ability to withstand large charge-discharge rates, wherein advanced $LiFePO_4$ and LTO technologies again provide the safest operational margins, especially when thermal runaway is considered [47].

3. The costs and complexity of retrofitting the diesel electric powertrain with additional battery energy storage, primarily in terms of available space and mass constraints, interfacing with the internal power distribution system (power bus) and the appropriate energy management control strategy [54]. Special attention should also be given to the primary mover (diesel engine) refurbishment or possible replacement of older engines with more efficient modern designs, which is also indicated in [54].
4. The choice of adequate hybrid powertrain topology, wherein there are many possible solutions with varying degrees of complexity for the same achieved powertrain performance, which should not be inferior to the performance of the conventional powertrain with similar traction characteristics. In that respect, the requirement of minimal modifications to the overall powertrain would also be desirable from the standpoint of production and overall powertrain assembly [54].
5. The utilisation of advanced software tools and communication technologies should also be considered for the purpose of driving mission energy efficiency optimisation and operational safety improvement, especially when considering variable driving conditions along the track [36].

2.2. Utilisation of Battery-Based Locomotive Propulsion

Although the research on battery-electric locomotives and their commercial applications is definitely on the rise, this topic has been researched rather modestly to date [55]. Advanced batteries, such as those based on sodium-metal halide and lithium-ion chemistries, were suggested in [56] as possible alternatives to diesel engine-based propulsion, especially when light duty hauling (power ratings less than 400 kW) is considered, with the possibility of periodic kinetic energy recuperation cycles, such as in mining operations [56]. This claim is further corroborated by the authors of [57], who propose the utilisation of a high discharge power and high-energy-density lithium polymer batteries for a battery-electric shunting locomotive.

In fact, viable prototypes of purely battery-electric locomotives were recently introduced for rail yard switching operations and light to medium cargo hauling in industrial railway sidings and logistics terminals [58]. The authors of [59] showed that retrofitting the locomotive propulsion to a fully battery-based energy source may even be accomplished by using new developments of "mature" battery technologies, such as lead-acid batteries with activated carbon-based negative electrodes. These so-called ultra-batteries [60] supersede conventional lead-acid batteries in terms of pulsed power capabilities and service life while retaining their favourable temperature stability and ease of maintenance, and they have already been proposed for stationary energy storage use [61]. A lithium-titanate battery system was recently used to demonstrate the viability of battery-based propulsion for passenger multiple units in [62]. On the other hand, the authors of [63] investigated the possible use of battery-based propulsion for the so-called "last mile" regime for a freight locomotive as an alternative to the so-called "electro-diesel" configuration (with a diesel generator as a secondary energy source), which is suitable for rail transportation over electrified and non-electrified railway routes. The authors of [63] also considered the possibility of using battery recharging waystations, whose benefits and optimal placement along the railway route were recently investigated in detail in [64]. A techno-economic study of freight railway electrification by means of an overhead line, hydrogen fuel cells, and batteries for the railway lines in Norway and the USA [65] has shown that hydrogen fuel cells and batteries can be competitive technologies provided that renewable energy sources are available for charging and hydrogen production. Moreover, a comparative analysis of a 3 kV direct current (DC) electrification system and trains with on-board battery-ultracapacitor energy storage was carried out as a part of the preliminary techno-economic study in [66]. The study showed that more favourable economic indices would be obtained with energy storage-equipped passenger trains rather than investing in the electrification of lengthy railway routes with infrequent traffic.

Owing to their exceptionally long cycle life of over 10^6 charge-discharge cycles characterised by deep discharges and large discharge rates [67], ultracapacitors have shown great potential in terms of supplementing batteries and hydrogen fuel cells for high-power/short-duration (pulsed) loading regimes [68]. This has been illustrated for both stationary energy storage systems in microgrids [69] and those with potential use in transportation applications [70], wherein $LiFePO_4$ batteries are considered as good candidates in terms of energy density and operational safety [48]. Moreover, it seems that the energy densities of the next generation of commercial ultracapacitors are approaching the energy densities of electrochemical batteries, thus allowing for prolonged loading compared to ultracapacitors from just a decade ago [67]. In this sense, the battery energy storage system within a locomotive would need to be augmented with a relatively low-capacity ultracapacitor module, thus forming a hybrid energy storage system using an appropriate power converter topology (see, e.g., the discussion in [71]). The key benefits of such an approach to battery energy storage hybridisation are related to reduced battery heat stresses and prolonged service and calendar life [72]. As indicated in [73,74], ultracapacitors and battery cells both require precise voltage balancing and temperature monitoring for correct operation over a wide range of operating regimes.

The commercial viability of battery-based locomotive propulsion has even been recognised through patents, such as the one presented in [75], which describes in detail a future battery-powered all-electric locomotive powertrain, along with different feasible configurations of batteries and the possibilities for augmenting conventional diesel-electric propulsion. In that sense, the authors of [76] investigated the utilisation of battery-electric locomotive use within a heavy-haul freight train, with different combinations of diesel-electric and battery-electric locomotives having been subjected to a thorough performance assessment over a realistic mountainous railway route. To be able to meet the predefined range requirements, a battery-electric locomotive was used in a tandem operation with conventional diesel-electric locomotives (see Figure 2), thereby providing hauling assistance for very heavy loads over the demanding terrain configuration considered in [76]. The results showed that (i) a single battery-electric locomotive represents the most energy-efficient solution when relatively light loads are considered (up to 300 t) and when used in conjunction with mid-journey battery charging; (ii) when a battery locomotive is used in tandem with diesel-electric locomotives, it can result in notable fuel savings (of up to 30%) and a related reduction in greenhouse gases emissions; and (iii) with the declining trend of battery costs, it is likely that such solutions may yield notable financial savings over the lifetime of the battery energy storage system. This clearly indicates that battery-based railway propulsion has the potential to both aid the transition from the conventional diesel-based freight haul and to inaugurate the future fully electric railway mobility. It is also worthwhile to investigate the utilisation of batteries for local railway sub-station microgrids equipped with renewable energy sources, which ought to further improve the energy efficiency indices and sustainability in terms of reducing the subscribed power and associated electricity costs [77].

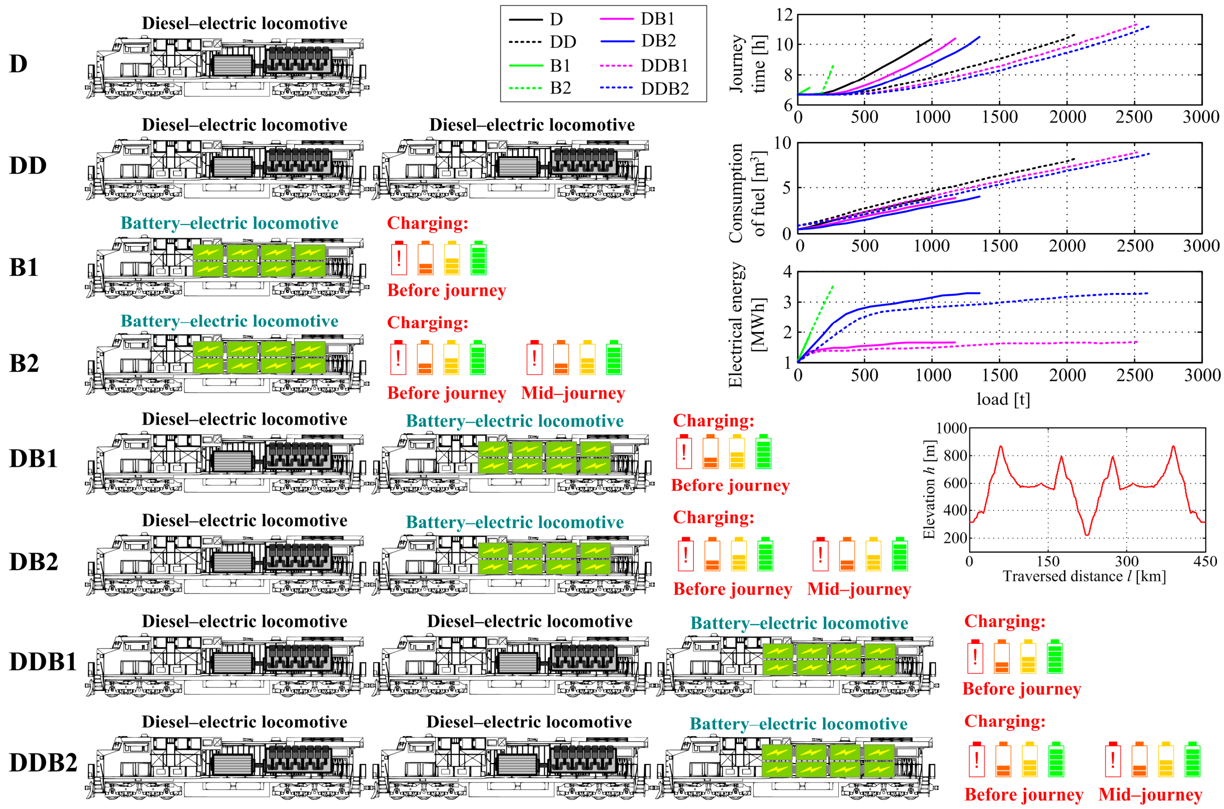

Figure 2. Diesel-electric and battery-electric 1.6 MW locomotive combinations investigated in reference [76] and main results in terms of journey time, fuel consumption, and electric energy expenditure for a mountainous railway route with respect to freight train load.

2.3. Electric Powertrain Featuring Hydrogen and Other Types of Fuel Cells

As mentioned above, the techno-economic study in [65] showed that hydrogen fuel cells and batteries can be competitive technologies in rail freight hauling when used in synergetic relation with renewable energy sources, while at the same time achieving zero net emissions of greenhouse gases. On a smaller scale, this kind of fuel cell plus battery hybrid power source was investigated for the case of a hypothetical 200 kW hydrogen fuel cell stack coupled with a nickel-metal hydride (NiMH) battery for tramway propulsion in [78], which also provided a component sizing and parameterisation methodology based on a realistic driving cycle on a metropolitan tramway line.

For larger-scale, high-power applications, i.e., those suitable for freight haul and passenger transport over greater distances, reference [79] demonstrated that solid oxide methane-fed fuel cells in combination with a gas turbine, steam, and ammonia-organic Rankine cycles can be used to produce power in excess of 2900 kW, with waste heat recovery used for additional power production and the heating of the passenger compartments. Moreover, the key advantage of solid oxide fuel cells is that, apart from methane, they can utilise other gaseous fuels for electricity generation such as ammonia and hydrogen, which is beneficial from the standpoint of their practical use [79]. Polymer electrolyte membrane fuel cells were proposed in combination with a suitable energy storage system to power an existing railcar as an eco-friendly solution for short- to medium-length non-electrified railway lines characterised by an altitude difference between the embarkation and arrival points [80]. The possibility of using fuel cells for sustained high-power output has motivated the design of a prototype fuel cell shunting locomotive to avoid diesel engine-related emissions of particulates and nitrogen oxides and acoustic noise emissions [81]. On the other hand, the authors of [82] investigated the possibility of retrofitting the conventional passenger train with hydrogen fuel cells as a power source to be used over a non-electrified railway route, with the main advantages being reduced energy consumption and the elimination of greenhouse gas emissions, while at the same time modernising the current rolling stock and increasing the overall passenger comfort. A similar study carried out in [83] indicated that fuel cells may provide a viable low-emission solution for a demanding railway route characterised by steep slopes if they are used with a suitably sized electrical energy storage system.

A comparison of three characteristic fuel cell-powered railway vehicles presented in [84] indicated that such solutions are indeed technically feasible, with the main concerns being their relatively low payloads and the availability of hydrogen fuelling infrastructure. Even though hydrogen fuel cell trains are still emerging technologies, which are yet to appear in commercial transportation roles, the costs of hydrogen generation are showing clear trends towards becoming cost-competitive to conventional fuels [85]. For example, the results of a study presented in [86] indicated that switching from diesel-based train propulsion to that based on hydrogen fuel cells would result in an annual saving of 9.5 million litres of diesel fuel, as it would be substituted with 2198 tonnes of hydrogen annually. This study also indicated that the cost of hydrogen production by means of electrolysis from renewable energy sources would amount to approximately EUR 6.40/kg of hydrogen, which makes this a competitive alternative to conventional fuels.

Finally, efficient hydrogen production and distribution infrastructures play crucial roles in the penetration of fuel cell technologies in future 100% renewable transportation systems [87]. The key components of the hydrogen supply chain need to be carefully analysed so that the distribution system can be operated with high efficiency, even when subject to hydrogen supply uncertainties, as suggested in reference [88]. One important aspect of hydrogen production is the so-called power-to-x concept, wherein electrical power is used for the production of hydrogen and relatively simple synthetic fuels that can be used instead of conventional (fossil-based) ones [89]. To meet the demand for hydrogen in railway applications, a novel optimisation-based concept for the planning of hydrogen-based railway train refilling was proposed in [90], whereas the authors of [91] investigated the performance of an on-site hydrogen production facility in supplying heavy-haul freight trains. The latter analysis showed that a return-of-investment rate of nearly 19% per year can be reached, so that such hydrogen production facility may indeed be able to support heavy-duty rail transport in a sustainable manner [92].

2.4. Alternative Fuels Utilisation

As indicated in [87], alternative fuels may play vital roles in the future 100% renewable transportation systems. Adopting the tenets of a circular economy and the utilisation of alternative fuels for heavy machinery in railways was identified in [92] as one of the potential means to mitigate environmental impacts. Biofuels, such as bioethanol, may be used alone or within gasoline blends, thus contributing to the reduced utilisation of petroleum-based fossil fuels [93]. Waste oil from the food industry has already been recognised as a source of raw material for the manufacturing of diesel fuel substitutes [94] that can easily be adopted for use in diesel-based railway traction [95]. Naturally, bioethanol and bio-diesel production would result in an increased use of arable land, especially when considering the production of corn (maize) and soy as precursors for ethanol and bio-diesel production [96]. However, the life cycle assessment (LCA) study carried out in [97] indicated that biofuels in general may have the lowest cumulative environmental effect compared to other conventional propulsion technologies.

Another promising technology for cleaner transportation is that based on bio-methane and biogas, which can be used to power both light and heavy-duty transport [98]. Reference [99] has already shown that such an approach utilising gas engines instead of diesel-based ones in combination with battery energy storage may lead to significant fuel savings and a consequent reduction in carbon emissions. In that respect, the utilisation of dual-fuel locomotives may benefit from the existing distribution infrastructure for liquefied natural gas (LNG) [100], with one of the key benefits being that the utilisation of gas engines results in significantly fewer particulate matter emissions [101]. However, one of the disadvantages of LNG (and other liquefied gases) use is the need for large-scale cryogenic gas storage [102].

On the other hand, the authors of [103] assert that massive transportation electrification is essential to utilise renewable energy sources to their maximum potentials. According to [103], the inevitable excess power production from renewables that cannot be immediately absorbed by the energy and transportation sector should be utilised for hydrogen and synthetic fuel production (the power-to-x concept mentioned earlier). With dimethyl ether (DME) having been recognised in [103] as a likely substitute for diesel fuel, its production and subsequent utilisation within conventional railway traction based on internal combustion engine technologies may lead to a significant reduction in railway systems' carbon footprint. The power-to-gas concept and the logistical aspects of synthetic gas distribution pathways were extensively investigated in [104], whereas reference [105] presented a novel process chain for the sustainable production of synthetic fuels based on renewables, as illustrated in Figure 3. It is based on the use of renewables for the generation of electric power, which is subsequently used for water electrolysis and hydrogen production. This hydrogen can then be stored within hydrogen fuel cells or used for synthetic hydrocarbon production by combining it with carbon dioxide reclaimed from the atmosphere using catalytic processes. Reference [105] also points out that railways may likely be able to achieve the necessary economies of scale, especially when hydrogen infrastructure is considered, while according to [106], the cost and complexity of alternative fuel infrastructure for railways could be much lower than that for road vehicles, particularly due to a priori known schedules (timetables) and traffic volumes.

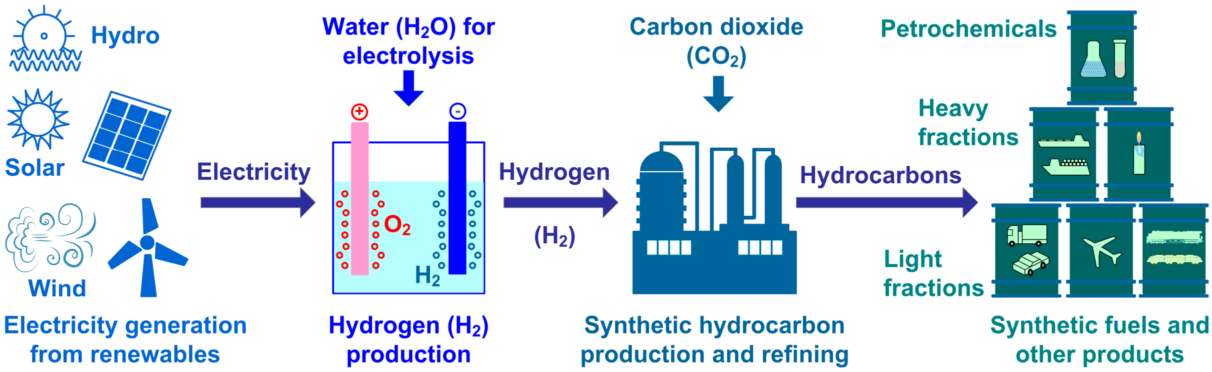

Figure 3. Renewables-based synthetic hydrocarbon production chain according to [105].

A detailed comparative analysis of different alternative fuels and their production paths was also carried out in [103], and their advantages and disadvantages in terms of economic and infrastructural barriers are presented in Tables 1 and 2. Currently, biofuels and synthetic fuels do not require additional (new) infrastructure and supply chains, i.e., the existing infrastructure for fossil fuels can be used practically without adaptation, whereas hydrogen use in transport would require extensive new infrastructure to account for the particularities of hydrogen as fuel (such as aforementioned cryogenic storage facilities). The production costs of both hydrogen and synthetic fuels are still rather high, but they could make viable alternatives when excess power production from renewables such as photovoltaics (PVs) cannot be stored in electrical energy storage systems. In this sense, hydrogen and synthetic fuels may be considered as long-term energy storage, which could be used to support the energy and transportation sector when power production from renewables is low. Finally, the production of biofuels, although relatively inexpensive, highly efficient, and readily available in terms of technology, has one distinct disadvantage in terms of arable land use for energy production, thus affecting food prices. A good overview of the recent advances in low-carbon and sustainable energy technologies can be found, for example, in reference [107].

Table 1. Economic barriers for alternative fuels and hydrogen use in transport [103].

	New Infrastructure	Production Costs	Production Efficiency	Food Price
Hydrogen	Yes *	High	Low **	Not affected
Biofuels	Not needed	Low	High	Affected
Synthetic fuels	Not needed	High	Low	Not affected
PV for synthetic fuels	Not needed	Low	High	Not affected

* When distributed PV-based hydrogen production is considered, the existing power grid could be used for necessary power allocation. ** Low efficiency of the complete production cycle (well-to-wheel).

Table 2. Infrastructure barriers for alternative fuels and hydrogen use in transport [103].

	Fuelling Infrastructure	Supply Chain	Land Demand	Intermittency Friendly
Hydrogen	New	New	No concern	Yes **
Biofuels	Existing	Existing	Yes (arable land)	No
Synthetic fuels	Existing	Existing	No concern	Yes **
PV for synthetic fuels	Existing	Existing	No concern *	Yes

* If photovoltaic systems are located on non-arable land and buildings. ** In case of excess electricity production from renewables used for hydrogen and synthetic fuel production.

3. Communication Technologies for Improved Energy Efficiency and Safety in Railways

This section presents a cross section of communication systems for railway transport energy efficiency and traffic safety improvement, focusing on low-cost narrow-band communication technologies suitable for pervasive sensing, supervision, and control.

3.1. State of the Art in Communication Systems in Railways

According to [108], future railways and related industries are going to be increasingly reliant on the ITS paradigm, ushering innovative integrated security services, along with improved fleet management and Industry 4.0 concepts such as the predictive maintenance of railway vehicles and infrastructure to reduce their operational costs and augment the traffic capacity. These measures are expected to improve the performance of key management systems, such as those related to traffic scheduling and transportation system capacity planning, along with railway transportation safety and energy efficiency, interoperability, and support to multimodal transportation [108]. For that to happen, communication systems supporting the smart railway paradigm should be characterised by high availability, data throughput and reliability, along with integrated software support needed to optimise the utilisation of existing fleets and energy resources within the railway network [108]. Hence, future smart railways are likely to incorporate many emerging wireless communication technologies that are capable of offering the desired level of decision-making flexibility and integrated security features needed to operate the critical infrastructure.

GSM-R networks currently represent the standard paradigm in the field of railway communication systems, which are used for both voice communication and data transfer [108]. Over time, other communication technologies have been considered for this task, with the current focus being on the development of long-term evolution radio networks for railways (LTE-R), which can be broadly considered as counterparts of 4G/5G cellular communications. These communications are good candidates for the future implementation of the Industrial Internet of Things (Industrial IoT, or shortly IIoT) concept in railway transportation, where massive data communications between heterogenous nodes, such as in the case of V2I, V2V, and infrastructure-to-infrastructure (I2I) communications will be key for the effective operation of smart railway networks, as illustrated in Figure 4. The key comparative features of GSM-R and LTE-R radio communication technologies according to [108] are summarised in Table 3. These point to the unsurpassed performance of LTE-R based communication networks in terms of throughput and communication channel availability. Other communication standards (both proprietary and open ones) have also been considered for wireless communication in railways, and their comparative features in terms of their compliance with railway communication systems are listed in Table 4. Obviously, there does not appear to be a single wireless communication standard that can fulfil all of these strict requirements, which has further strengthened the case for LTE (4G/5G)-based communications as a backbone for future smart railways and railway related the IoT paradigm of smart trains. It should also be noted that even though LTE-R can provide improved railway communication services compared to the currently used GSM-R, it cannot support certain emerging railway features such as autonomous driving and massive IoT applications. A possible solution for these issues may be through the introduction of railway-adapted 5G communication systems (5G-R), which are expected to offer highly competitive performance in terms reliability and even higher data transfer rates [109].

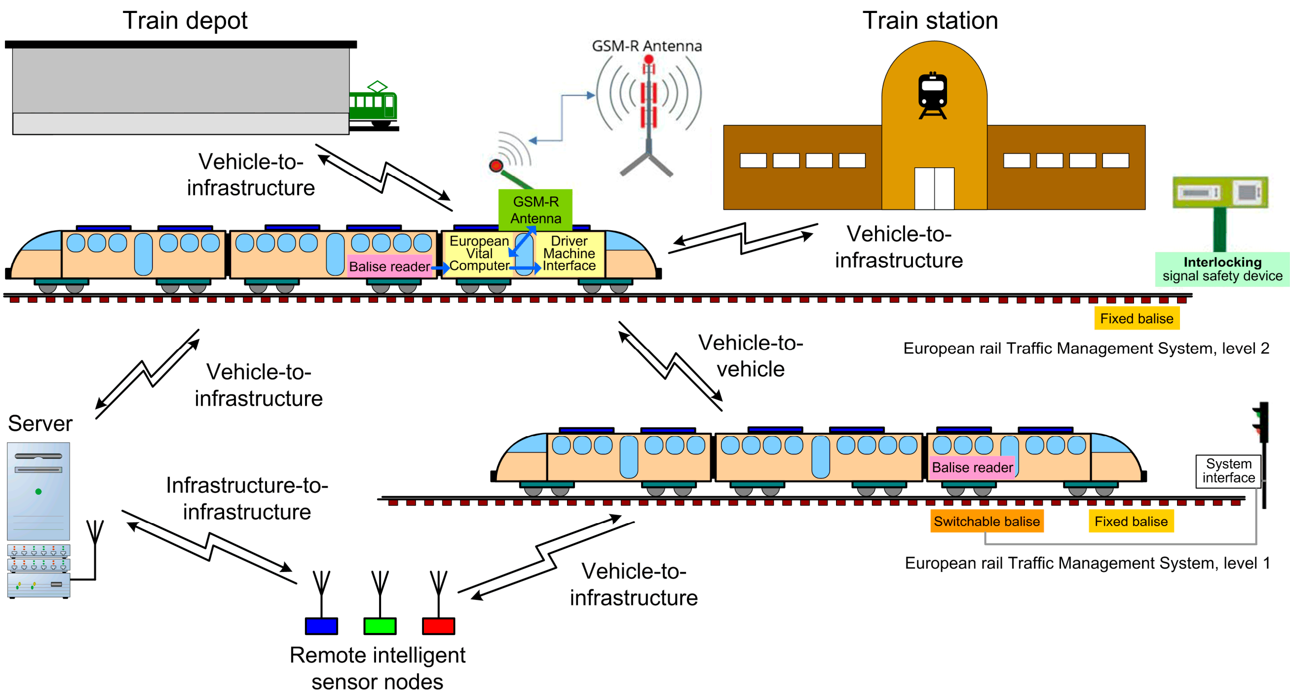

Figure 4. Some uses of wireless communications in future smart railways, as indicated in [26,108].

Table 3. Comparison of GSM-R and LTE-R radio communication technologies in railways [108] in terms of performance and maturity.

Parameter	Frequency	Channel Bandwidth	Peak Data Rate	Maturity	Market Support
GSM-R	921–925 MHz download 876–880 MHz upload	200 kHz	172 kbps	Mature	Until 2030
LTE-R	450 MHz, 800 MHz, 1.4 GHz and 2.1 GHz	From 1.4 to 100 MHz	50 Mbps download 10 Mbps upload	Emerging	Building standards

Table 4. Comparison of different wireless sensor networks technologies in terms of compliance with railway communication requirements [108].

Technology	Robustness	Real-Time Performance	Range	Throughput	Network Scalability	Power-Saving Awareness
IEEE 802.11	Not compliant	Not compliant	Full	Full	Partial	Not compliant
IEEE 802.15.4	Partial	Not compliant	Partial	Not compliant	Partial	Full
Zigbee	Partial	Partial	Partial	Not compliant	Full	Full
Zigbee Pro	Partial	Partial	Full	Not compliant	Full	Partial
IEEE 802.15.1	Partial	Full	Not compliant	Partial	Not compliant	Partial
Bluetooth	Partial	Full	Not compliant	Partial	Not compliant	Partial
Wireless HART	Full	Full	Partial	Not compliant	Partial	Full
ISA 100.11a	Full	Full	Partial	Not compliant	Partial	Full
WISA	Full	Full	Not compliant	Partial	Partial	Full

These communication systems can be integrated with the railway traffic control system. For example, the European Rail Traffic Management System (ERTMS) is a system of standards for the management and interoperation of signalling for railways by the European Union. The ERTMS system is based on the technical specification for interoperability for "traffic-control and signal-safety" subsystems, which was designed by the European Union Railways Agency (ERA). The ERTMS system can be installed at several levels, depending on the equipment installed on the track and the way information is transmitted to the train. Figure 4 shows two levels of implementation of such systems:

(a) Level 1, which includes constant monitoring of the train movement and occasional communication between the train and the track (using so-called Eurobalise). Trackside signals are required at this level.
(b) Level 2, which includes constant monitoring of the train movement and constant communication between the train and the track using the GSM-R system. At this level, signalling equipment is not required along the track.

Fifth generation communications offer some distinct innovations and possible advantages, such as the introduction of Filter Bank Multi-Carrier (FBMC) modulation instead of the Orthogonal Frequency-Division Multiplexing (OFDM) [108]. In particular, FBMC can facilitate a higher bandwidth utilisation efficiency, and consequently, better utilisation of the existing spectrum and synchronisation for simultaneous communication between both stationary and mobile communication nodes (both V2V and V2I communications) [108]. In fact, FBMC can provide increased robustness to timing and frequency variations compared to the OFDM method with lower error probability rates [110], while also being able to provide better spectral containment of signals, thus offering increased robustness even for high-volume data rates [111]. These features may become highly attractive in future high-speed railways, which should feature increased transportation safety levels. For that to happen, augmented communication capabilities are needed [112] due to inherent problems with high-velocity train localisation (positioning) using the existing railway communication networks [15]. Radio channel modelling was proposed in [112] to facilitate the design of a novel communication system that is suitable for high-speed railways and to assess its performance under realistic operating conditions. Some recent advances in wireless communication technologies that could be applicable in future smart railways include (i) intelligent self-powered sensor nodes [113] and related communication systems for the condition monitoring of freight wagons [114], (ii) stochastic modelling [115] and the application of radio-over-optical fibre communications [116] aimed at improving wideband communications in high-speed railways, (iii) energy-efficient communication protocols [117] and wide-area networks (WANs) in intelligent transportation [118] including the IoT paradigm [119], and (iv) the development of effective high-throughput wireless networks for railways using 5G communication technologies [120].

V2V communications have not yet been deployed in railways, but there is a clear research trend in exploring the possibilities of the future incorporation of direct and indirect (V2I-based) V2V communication systems into smart railway systems. V2I communications can be viewed as keys for rail transport management, such as by using virtual coupling between autonomous trains running in platoons and communicating over a centralised radio link [121]. According to [121], this concept can also be used for the dynamic coupling and decoupling of individual freight wagons and should notably improve the railway system capacity and throughput under varying freight transport demand. A comparative analysis of direct and indirect V2V communication between trains using fifth generation radio networks for railways (5G-R) for the purpose of platooning was presented in [122], wherein direct communication, although faster, requires additional means of synchronisation due to the absence of a central clock on the fixed communications node (repeater). The results in [122] also indicate that using advanced communications characterised by low latency can facilitate the high-precision synchronisation of train speeds and mutual distance within a platooning configuration. The introduction of nonlinear train dynamics and motion resistances due to track gradient and curvature, as well as the locomotive power limitations and safety constraints at junctions into the rail traffic model based on high-bandwidth communication for the precise position and speed of the trains, may lead to significant reductions in headways, thus improving the railway system's capacity and throughput [123].

Most of the above efforts are either aimed at developing intra-vehicle communications over the limited-range wireless sensor networks of on-board trains [113,114,117] or massive V2V or V2I communication networks [115,116,118,120], which utilise a substantial portion of the communication bandwidth to carry a wide range of both service-related and user data. However, from a practical standpoint, it is particularly worthwhile to investigate the possibility of narrow-band (NB) communications within the IoT paradigm for railways, wherein limited amounts of highly structured service data could be exchanged during low-volume V2I communications. These structured data could then be used to improve the transportation safety and energy efficiency while also preserving the communication system bandwidth for other tasks [34].

Since autonomous (or driverless) trains are driven remotely with the aid of a central computer control system augmented with advanced wireless communication technologies (such as 5G and IoT), advanced sensor suites (e.g., cameras, LIDAR), and artificial intelligence-based algorithms [124], the main goal is to obtain at least the same level of transportation safety as in the case when a human driver is present in the driver's cabin [125]. In that respect, human-machine cooperative action based on expert know-how and information sharing [126] has been identified as one of the key aspects of automated railway transportation safety and reliability [127], which are also necessary for the wider acceptance of autonomous trains [128]. Recent research in expert systems and artificial intelligence for railways, including applications for maintenance, traffic planning and management, safety, and security, and autonomous driving was extensively reviewed in reference [129]. In the above examples of the utilisations of Industry 4.0 technologies in automated traffic and autonomous transport, equally important operational aspects for safe operation are the reliability and cybersecurity of the wireless communication systems in railways [130] due to their inherent vulnerabilities compared to fixed lines (such as signal loss and interference) [131]. This applies both to V2X communications [30] and the utilisation of wireless sensor networks to enhance traffic safety and facilitate automated and autonomous transport [23]. Different solutions can be used to ensure secure data exchange, such as the implementation of secure data link architecture, and decentralised and pairwise secure key exchange between communication nodes [23]. Suitable metrics are developed to establish the maturity of different cybersecurity models [132] and gauge their resilience to cyber-attacks [133], wherein risk management techniques play important roles in cyber-attack mitigation and communication link recovery [131]. Naturally, these advanced transportation features are subject to strict regulatory oversight, wherein balance between traffic safety and the need for innovative solutions needs to be maintained [25].

3.2. Narrow-Band Internet of Things for Distributed Supervision and Control

As mentioned earlier, 5G New Radio (NR) networks have already superseded the bandwidth and data throughput of GSM-R networks, thus becoming instrumental for the introduction of novel technologies in future railway Information and Communication Technologies (ICT). These may include Industrial IoT and other "cross-industry" solutions for traffic system integration with other industrial or public systems [108]. These can be broadly classified as wide-bandwidth (i.e., high data rate) services such as real-time video data feeds, and narrow-bandwidth (low data rate) IoT services such as those related to metering (low refresh rate sensors) [134].

About two-thirds of total IoT applications are characterised by low data transmission rates [134], thus making NB-IoT a pervasive technology and emphasising the need for highly reliable NB communications in the future Industrial IoT framework. Some of the key characteristics of NB-IoT systems include [134] (i) a low power consumption, which makes them highly autonomous as they use battery power alone (with battery lives extending well over 10 years); (ii) enhanced coverage and low latency sensitivity; and (iii) compatibility with LTE cellular networks. These features make the NB-IoT devices that are already present within existing mobile networks good choices for a multitude of services in areas with poor signal coverage [135]. Moreover, there is a possibility to use these systems for a wide variety of purposes, such as security and safety, logistics and transport, agriculture, manufacturing, health care, as well as smart city, smart home, retail, utilities, and energy applications [136], as shown in Figure 5. In railways, user data can be weather-related (precipitations, wind speed and direction, relative humidity, temperature, and similar), as well as security information-related (e.g., occupancy and motion detection). To make the NB-IoT technology even more pervasive, new access methods for multiple devices are currently being investigated [137], along with data transmission error correction solutions [138] and intelligent queuing and data traffic prioritisation algorithms [139].

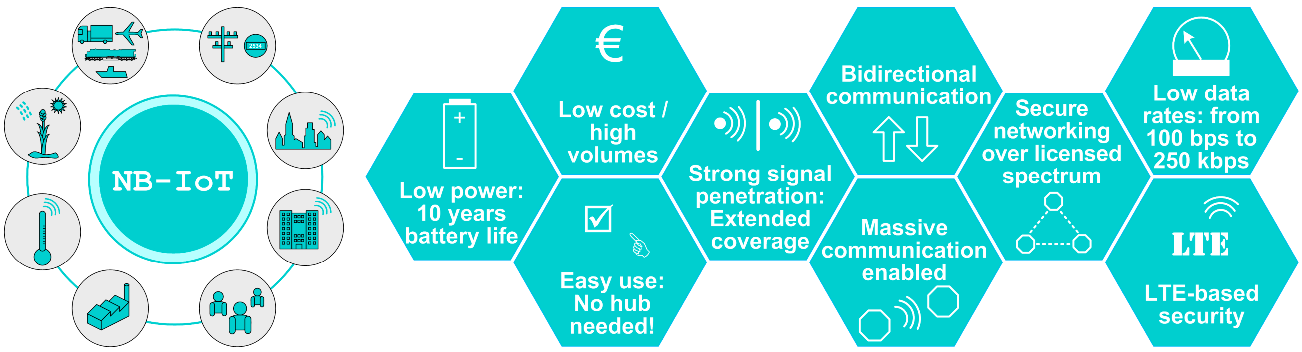

Figure 5. Key features of narrow-band IoT technology based on cellular LTE networks [131].

Since a railway system's safety integrity level (SIL) primarily depends on the closed and limited safety functions of a product or a system that is used within it, the utilisation of extended-reliability components would favourably affect the final SIL level. Since NB-IoT devices are frequently designed with a long service life, autonomous operation, and high reliability already in mind, their utilisation may contribute to the SIL level improvement. This may be achieved by using a transmission code and safety code [140] along with different cryptographic techniques [141] to ensure the correctness of data transfer, which can be easily programmed within the NB-IoT node embedded microcontroller system. It is also critical that the latter possesses a fault-tolerant architecture [142], wherein using tried and tested hardware would also increase the microcontroller system reliability [143]. By using all of these measures, it would be possible to achieve a high SIL 4 level of the NB-IoT remote sensor node, which would be characterised by less than 10^{-9} faults per hour (see discussions in [142,144]), which would be required to reliably monitor the integrity and safety required by the monitored systems [145]. Naturally, a safety analysis should be performed at all operational stages of the equipment lifecycle [146].

A principal schematic depicting the structure of an NB-IoT sensor node and its communication with the host (server) is shown in Figure 6 for the case of collecting the atmospheric data along the track (i.e., temperature, relative humidity, and wind speed and direction) presented in [36]. There, the remote sensor node provides unstructured data for processing to obtain useful information about the track conditions. These data are prepared for transmission by means of quadrature amplitude modulation (QAM) of the radio band carrier signal (see, e.g., [147]) used in LTE communication networks. The conversion of the parallel QAM data output into signals that aresuitable for transmission is based on inverse fast Fourier transform (IFFT). At the receiver side, the inverse process is performed on the received radio signal, i.e., fast Fourier transform, or FFT is used in conjunction with the QAM demodulator for data extraction, which is subsequently forwarded to the target database, and it is accessible to selected subscribers.

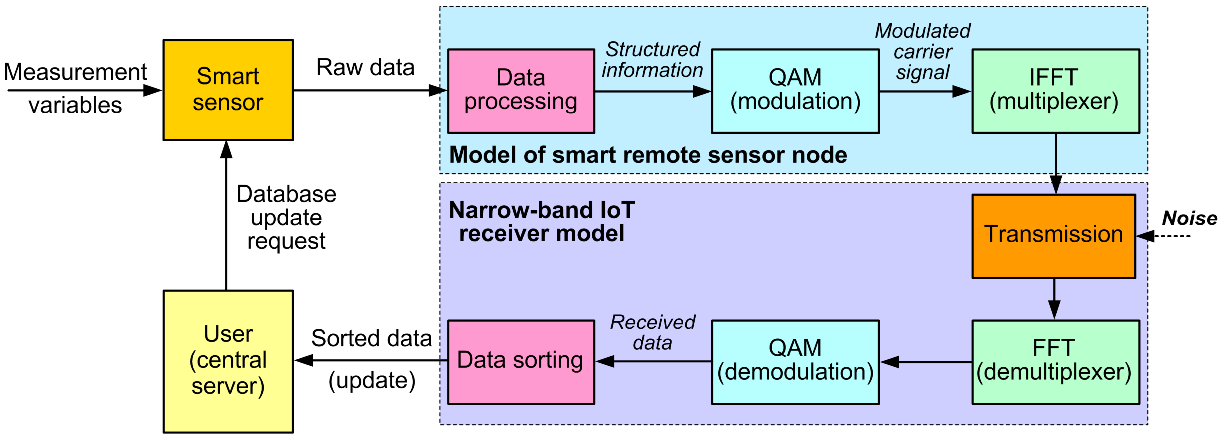

Figure 6. Principle of operation of LTE NB-IoT remote sensor node [36].

3.3. Some Examples of Remote Sensor Use for Improving Transport Energy Efficiency and Safety

Railway transportation energy efficiency, safety, and security may be significantly improved through the implementation of ITS [148]. Within the ITS concept, distributed NB sensor networks may play crucial roles because they can be used for remote data collection and the interactive signalling of trains with high decision autonomy [34].

In one such example, presented in [149], the problems of adhesion coefficient and head wind velocity affecting the energy expenditure and transportation safety were analysed. It was postulated that these influential factors, which can be estimated from measured atmospheric variables (temperature, humidity, wind speed, and wind direction) can be subsequently used for the prediction of worsened conditions on the railway track and for the predictive scheduling of trains depending on the estimation of the journey time duration using a suitable mathematical model [36]. Thus, the deployment of NB remote sensor networks could significantly increase the transportation safety and security indices. Figure 7 illustrates the concept developed in [149], wherein head wind and track adhesion (estimated based on atmospheric variable measurements) have been used to estimate the feasibility of the driving (freight hauling) mission over a demanding mountainous railway route (see also [36]). A suitable knowledge base utilising these structured information sets from the remote sensors, and the simplified model of the freight train are used to determine whether the driving mission is feasible or not under the existing weather conditions. It was indicated in [149] that this kind of approach may be useful for dispatching services to amend the freight train timetables in real time. Moreover, track conditions can be used to optimise the energy (fuel) expenditures based on a suitable computer model supplied with the real-time track condition information, thus supporting the transportation sector's "greening" and sustainability [36].

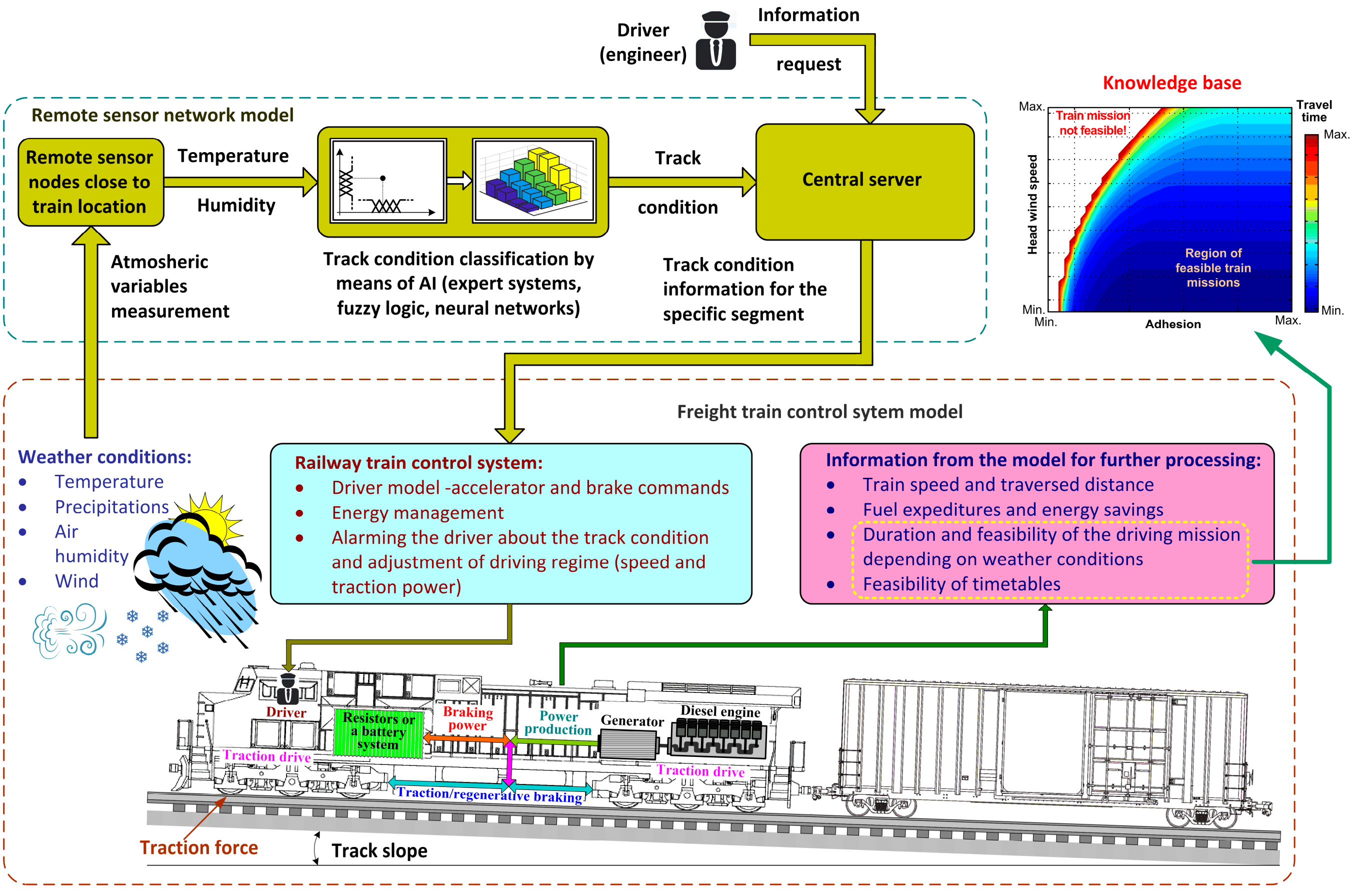

Figure 7. Principal representation of train supervision system with information flow [149].

Another example of possible NB-IoT sensor use in conjunction with AI for increased traffic safety was presented in [150]. A traffic entity management algorithm based on fuzzy logic was designed to reduce traffic congestion in the case of a partial restriction of one of the two routes of the transport corridor, which is a typical problem in railways (Figure 8). Under the assumptions of available traffic entity (vehicle) queue lengths (e.g., by using NB-IoT remote sensor nodes for vehicle registration and tracking) the proposed fuzzy logic-based traffic entity scheduling algorithm was compared with conventional traffic scheduling, and it demonstrated the ability to effectively minimise vehicle queue lengths under stochastic conditions of incoming traffic flows [150].

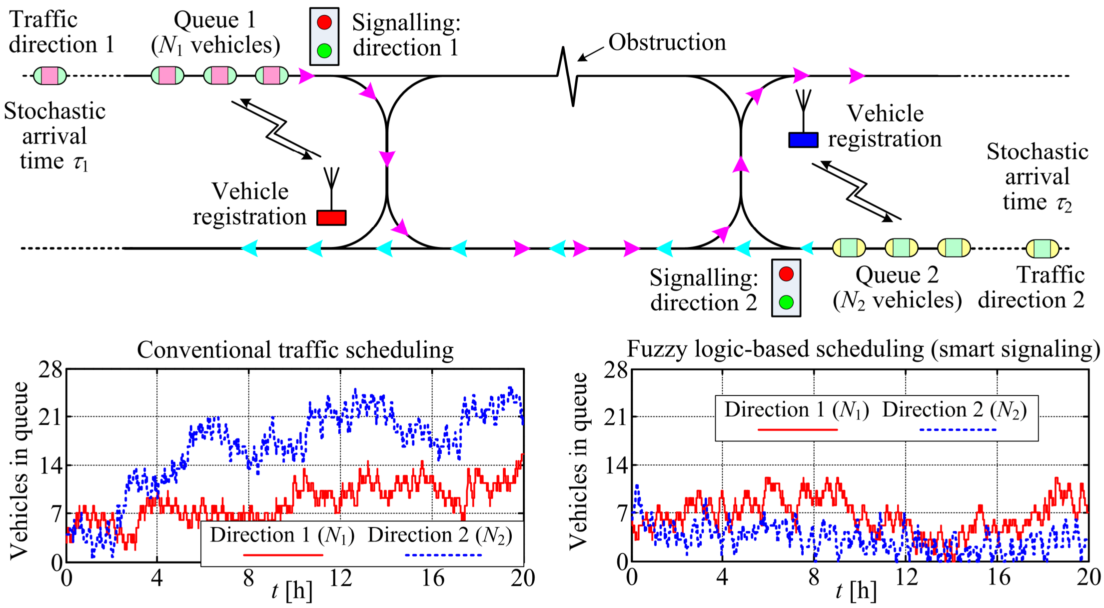

Figure 8. Bidirectional railway traffic network segment under obstruction with signalling system and comparison of conventional and smart scheduling approach from [150].

4. Industry 4.0 Concept in Railway Transportation

Industry 4.0 is a concept applied to many different industries and enterprises to make them more intelligent, dynamic, and flexible to meet the challenges of the highly dynamic global market [151]. This is carried out by integrating information technology (IT) systems with different physical systems (such as existing conventional industries) to create the so-called interconnected fully digitalised cyber-physical system [151], whose implementation also introduces inherent new challenges [152]. The above cyber-physical system paradigm has ushered a new way of thinking about technical systems, processes, business models, products, and services, and naturally, the potential new customer pools opening due to the digitalised approach inherent to Industry 4.0 [153]. Industry 4.0 can be regarded as the industry's development stage after previous industry revolutions. Figure 9 illustrates this on the example of logistics and transportation systems development. Advances in the transportation and logistics sectors have been closely linked to advances in other industries [154] and thus may also serve to increase both the competitiveness and sustainability levels of related enterprises [155].

A railway transportation system consists of many subsystems such as a railway track and related groundworks, signalling and safety systems, telecommunications, electric power stations as part of the electrification infrastructure including the overhead power lines, signalling and safety devices to secure road and pedestrian crossings, and other auxiliary systems. It is evident that the railway infrastructure is a complex and demanding system with high operational and maintenance costs. The Industry 4.0 concept and the related digital transformation can benefit many of these subsystems, especially with the improvement in energy efficiency, transportation safety, and security. These subsystems may include (i) autonomous and automated transportation, (ii) multimodal and intermodal transport systems, (iii) the application of big data analytics and artificial intelligence for predictive maintenance, (iv) the supervision of critical infrastructure and resilience improvement measures, and (v) smart grid connection, as outlined below.

It should also be noted that the technologies presented in this work represent the front end of the more complex and comprehensive railway governing and organisation system, which includes non-technical systems such as economic and business models, executive decision making, and an overall transportation and energy policy. However, these aspects of the transportation system are beyond the scope of this work.

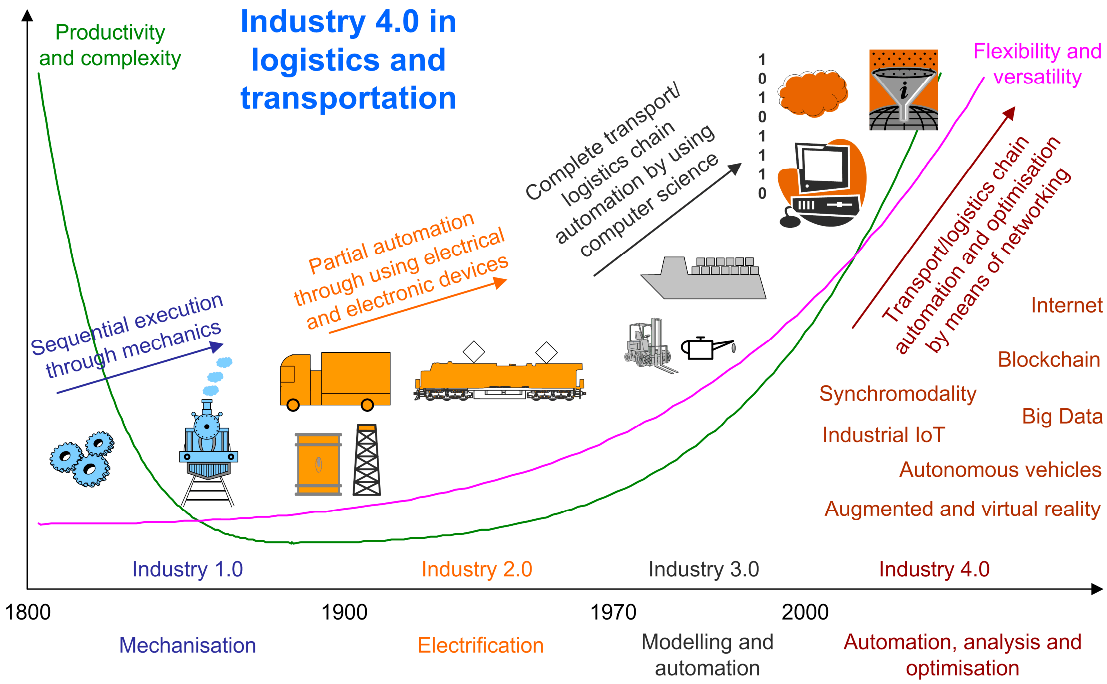

Figure 9. Industrial revolutions and their consequences to transportation and logistics [151].

4.1. Autonomous Trains and Automated Railway Traffic

Due to the demand to reduce automobile traffic in highly urbanised areas, new innovative transportation technologies are introduced that can facilitate high levels of urban mobility with less traffic congestion and improved energy efficiency. The Autonomous Rail Rapid Transit (ARRT) vehicles that were proposed recently have the advantages of rapid implementation, adaptation of the driving mission en route, autonomous management, and possible integration, coexistence, and cooperation with other urban modes of transport (so-called intermodality). Some examples of such hybrid transportation systems include an autonomous personal transit (shuttle) system for public transport [156], shown in Figure 10, and a tram-like shuttle vehicle using virtual corridors defined for roadways [157], wherein these vehicles use built-in sensors to drive along the virtual route, with the additional benefit of being able to modify their driving missions in real time. These vehicles can undergo real-time route adaptation according to current traffic conditions, so the flexibility of road vehicles can be combined with the simultaneous regulation of such traffic in accordance with the rules of conventional railway traffic. These advantages make ARRT systems good candidates for future transportation in medium-sized cities [158].

Figure 10. Example of autonomous vehicle using the concept of virtual tracks and equipped with 5G remote sensing and communication platform [150].

Innovative autonomous transport systems can also be made compatible with the current metro railway infrastructure with the possibility of having significantly lower implementation costs if they are integrated into the existing traffic infrastructure [159]. With the introduction of IoT, artificial intelligence and Big Data analytics, and next generation 5G communications, the autonomous vehicle supervision and control combines sensors, communication, and control and navigation software [160]. Spatial and temporal information about traffic entities is crucial for the effective management of vehicles with increased autonomy, such as when multiple independent autonomous high-speed trains are driven on the same railway track with hard mutual distance constraints [161]. Alternative very close formations may be used for the purpose of implementing advanced train dynamics control features, such as the concept of seamless inter-changeability (trains coupling and uncoupling on the move), as presented in [162]. A Global Navigation Satellite System (GNSS) is typically used for geospatial positioning and vehicle speed estimation, such as for the predictive control of autonomous transportation systems [163]. Due to the GNSS limitations of positioning precision and signal availability, high-speed trains also require alternative positioning methods, such as the use of independent inertial measurement unit (IMU) sensor suites [164] or signals from 5G communication networks. The latter can indeed provide very accurate location information with much higher availability that GNSS [15], which can be used for the cooperative control of multiple trains, further augmented by train-to-train communications [165].

The Industry 4.0 concept can facilitate a more systematic utilisation of information flows, including Industrial IoT technologies for better interconnectedness of different traffic entities and big data analytics for the purpose of transportation optimisation. Thus, it represents a key enabling technology to facilitate automated rail traffic control and energy use optimisation and their integration in a straightforward fashion. This has been illustrated by previous examples in references [149,150], wherein the advanced information and communication technologies, data from remote sensor networks, and artificial intelligence have been successfully used to improve railway transportation safety and energy efficiency. Similarly, the utilisation of sensor suites on-board traffic entities coupled with massive data throughput inherent to 5G radio networks was identified in [156] as enabling technologies to increase the safety of autonomous transport. To that end, the authors of [154] discuss the concept of a "digital railroad" aimed to improve transportation safety by means of digital railway signalling systems, whereas the authors of [155] put forward arguments for the increased usage of emerging technologies, such as drones, smart sensors, robotics, blockchain, and artificial intelligence within the framework of Industry 4.0 for transport and logistics to improve their safety and energy efficiency. These aspects of Industry 4.0 in railway transport will also be discussed in the following subsections.

4.2. Multimodal Transportation

Railway transport can be divided into passenger transport and freight transport. There is a strong pressure on technological development and the integration of rail freight transport into the single European railway system (according to EU Directive 2012/34/EU). Also, with the process of globalisation and environmental requirements, the costs of transport services are a major factor in the overall business process, so they need to be optimised. Rail freight transport optimisation is primarily focused on energy efficiency and deeper integration with other transport and logistics sectors [166]. Due to these requirements, intermodal freight transport and multimodal transportation in general are developing rapidly [167]. Intermodal freight transport is the movement of goods stored within the same loading unit (i.e., a transport container) via successive modes of transport without handling the goods themselves when changing the mode of transport [168]. By integrating and coordinating the use of different modes of transport that are available in intermodal transport networks, intermodal freight transport provides an opportunity for the optimal use of physical infrastructure to ensure cost-effective and energy-efficient transport services [168]. Figure 11 illustrates the difference between single-modal and multimodal transport chains. The number of necessary cargo-handling operations, connecting transport, and information exchange becomes increasingly complex in the case when multimodal transport is employed for the cargo to be moved from its origin to its destination [169]. We can conclude that an information and communication infrastructure with a suitable database that supports the management of this type of transport is needed for efficient multimodal transport.

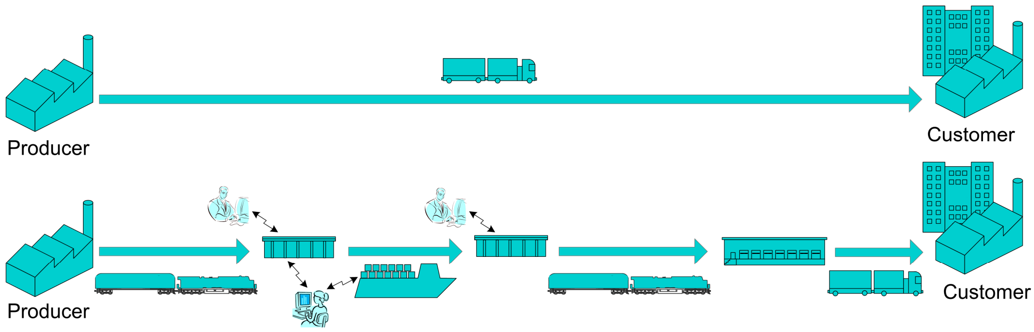

Figure 11. Comparison of single-modal and multimodal transport chains [159].

With the aid of information providers, so-called synchronous transport can be achieved by choosing modalities according to the latest logistical information, such as the transport requirements of goods and current traffic information [170]. It is therefore evident that the railway infrastructure needs to accelerate its digitalisation as a key pre-requirement for the subsequent improvement of rail transport cost-effectiveness [171] and energy efficiency [172] to increase its sustainability. There is a clear trend towards improving the energy, economic, and ecological (EEE) indicators in railway transport [173], as well as other transportation domains such as maritime ports [174], which are keys when considering the intermodal transport of large volumes of goods and the sustainability of the overall transport sector [175]. Cutting-edge technical solutions, such as innovative containers and loading/unloading systems, may further help to achieve higher levels of technical interoperability, as well as to lower the overall transportation costs, such as when multimodal transport is considered compared to the case of railway transport alone [176]. This is also true when hazardous materials need to be transported [177], where risk assessment also plays a major role in transport planning and its subsequent implementation.

Optimising energy consumption and transportation time and cost in rail transport represents a multidimensional nonlinear problem with several technological traffic constraints, especially when increased degrees of autonomy are concerned, where a number of additional safety constraints also appear [19]. It was shown in [178] that a high level of synergy between facilities and equipment, management, business operations, and information systems is a key requirement for highly effective logistics and transportation processes, which may be sought by using optimisation tools. Consequently, these kinds of optimisation problems usually involve multiple objectives that need to be minimised, so optimisation methods that are suitable for multi-criteria optimisation problems need to be employed [179]. Dynamic programming (DP) was used in [167] to obtain an optimal combination of transport modes for a cargo container multimodal transport problem using rail, road, and waterborne transport and was subject to overall transport cost and duration. Since cargo transport routing is subject to optimisation in these kinds of applications, integer-valued states for routing description and mixed-integer linear programming (MILP) optimisation algorithms can also be used for that purpose [180].Geographic information system (GIS) software programs or stochastic programming [171] can be used to optimise the efficiency of multimodal transport, especially when considering passenger transport and ticket costs [181]. The optimisation of autonomous vehicles' traffic for multimodal transport is a relatively recent field of research [182], so experts from other areas such as mechatronics are often required [152] to carry out the analysis with sufficient levels of accuracy (see, e.g., [36]).

4.3. Predictive Maintenance

Big data is the most important term in today's digitalisation trend, and it denotes massive data sets [183] characterised by large volumes and different and complex structures, together with the requirement of complex analysis tools for the purpose of visualisation and the subsequent processing of data as input parameters for other systems. M2M data exchange, associated with smart sensors and IoT devices, and characterised by large data volumes, may be of particular interest when railway transport safety is concerned because of its utility in predictive maintenance in conjunction with proper classification and pattern recognition algorithms [184]. Predictive maintenance or condition-based maintenance recommends appropriate actions using a large set of collected data subjected to the processing and extraction of key features that are subsequently used for classification (normal operation, emerging fault, developed fault, and imminent failure) [185]. The classification result is subsequently used for timely maintenance decision making (Figure 12), thus reducing maintenance time and costs and avoiding unscheduled overhauls [185]. Sources of analysis data in railways can be wide and varied, such as (i) intelligent sensor networks on-board freight trains [114], (ii) optical sensors such as LIDAR (light detection and ranging) devices on-board trains, which are used for accident prevention [186], and (iii) cameras and other sensors aboard unmanned aerial vehicles (UAVs) used for infrastructure monitoring [187], just to name a few.

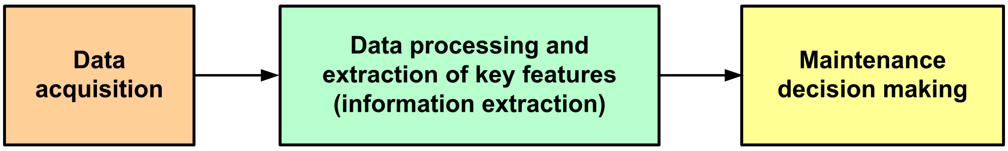

Figure 12. Principal representation of condition-based maintenance process [185].

Intelligent sensor networks on-board freight trains can be arranged depending on the type of transmission medium (wire, optics, or wireless) and type of data transmission, i.e., single-hop and multi-hop networks [114] (Figure 13). Naturally, wireless communication between sensor nodes and the data hub offers some distinct advantages over wire- or optics-based data links, particularly with respect to the lack of maintenance. In that respect, an electrical power supply for individual sensor nodes also plays a significant role, especially with freight wagons, which are typically unpowered, except for braking system pneumatics and the terminal signal light. Hence, such sensor nodes should either be equipped with a long-life battery or an energy harvesting system for on-board power supply [114]. One such case of autonomous sensors used for the online monitoring of the braking system pressure and mechanical vibrations by means of accelerometers, with a vibration energy harvesting system based on an inertial pendulum mounted on bogey suspension, was presented in [113]. The main conclusion in reference [113] was that the developed energy harvesting and ultracapacitor energy storage systems may need further miniaturisation and protection from environmental conditions before being deployable en masse. Other types of sensors that may be used for the online condition monitoring of railway vehicles include on-board inertial measurement units [188] and smart sensors within tunnels to facilitate an advanced risk assessment analysis [189]. Note that there are already commercially available on-board sensor systems that satisfy stringent requirements in terms of power autonomy (e.g., powered by means of solar panels) and high levels of robustness and ingress protection (IP class), thus allowing them to operate over a wide range of environmental conditions [190,191] that are characteristic for rail freight transport.

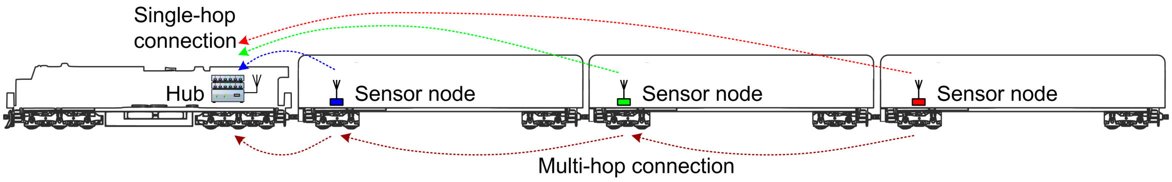

Figure 13. Example topologies of wireless sensor networks on-board a freight train [114].

Research in intelligent maintenance techniques in railways typically involves the utilisation of artificial intelligence, such as fuzzy logic and artificial neural networks (ANNs), and machine learning (ML) models in the form of support vector machines (SVMs) and support vector regression (SVR) models [184]. In that sense, the authors of [192] investigated a fuzzy logic-based thermography system for predictive maintenance in electric railway traction. Thermal cameras are used to collect thermal imaging data about rails and the catenary-pantograph system, and a fuzzy logic system utilising complex membership functions is used for image processing and related condition monitoring. Similar work related to track condition monitoring was carried out in [193], wherein the support vector machine (SVM) approach was used to model track geometry deterioration with a prediction accuracy over 70% reported in the paper. On the other hand, the authors of [194] utilised measurements from a ground-penetrating radar and compared the conventional frequency analysis (FFT) approach with the AI approach using long short-term memory (LSTM) neural networks and convolution neural networks (CNNs) for the prediction of hazardous conditions such as railway track fouling and deformation, with both AI methods performing remarkably well. Another example of CNN utilisation for predictive maintenance would be the analysis of features of vibration signals for the purpose of early fault detection, as shown in [185]. Figure 14 illustrates the ability of the CNN used in [185] to extract and classify key features of different types of early mechanical faults of rotational equipment with respect to normal operating conditions. The distribution of test samples extracted from input signals and the output layer for the CNN are obtained by means of an appropriate visualisation software tool, which represents the results in a two-dimensional space of non-dimensional variables [185]. The results show good potential for predictive maintenance in railways when vibration measurements are readily available using on-board accelerometers, whose deployment was presented in [113].

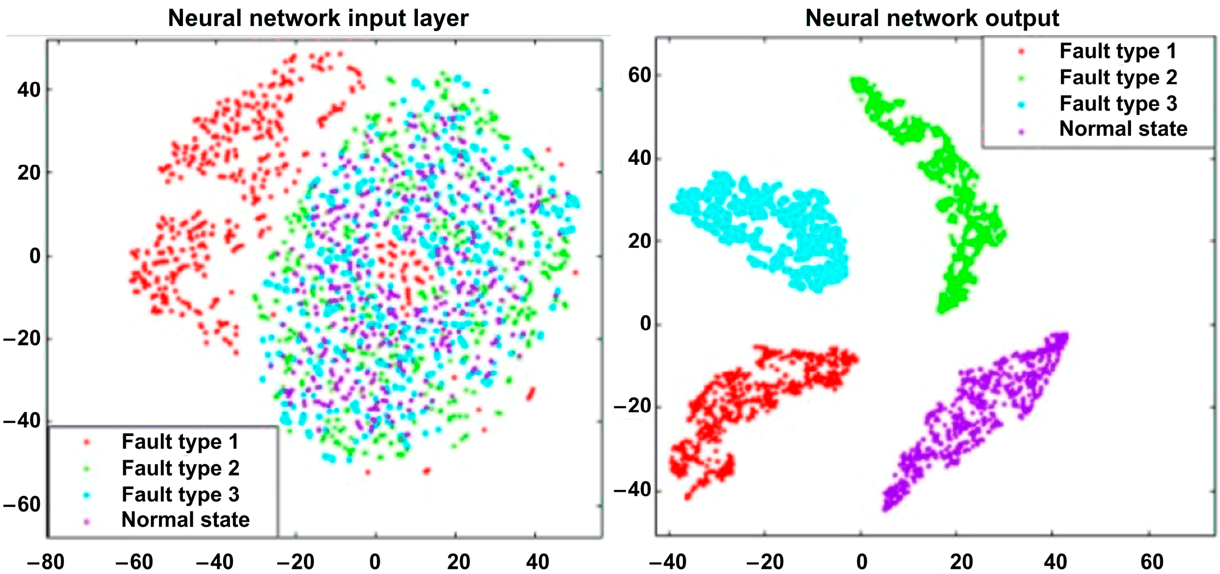

Figure 14. An example of early fault detection results obtained by means of CNN [185].

With the introduction of battery-based and hybrid propulsion in railway vehicles, specific aspects of battery energy storage system maintenance also need to be considered, which can be carried out within a multi-criteria optimisation framework [195]. Moreover, the three-dimensional (3D) reference architecture model from Industry 4.0 can be adapted to describe intelligent high-speed railways in terms of their (i) intelligent features, (ii) system levels, and (iii) life cycles, wherein intelligent features encompass different aspects of the railway vehicle and infrastructure maintenance [196].

4.4. Resilience Improvement Measures and Inspection of Critical Infrastructure

Railways, along with other transport networks, water and gas distribution networks, and electrical power grids fall into the category of critical infrastructure networks that are essential for the functioning of society and the economy [197]. The increased transport demand and the related increase in the railway network congestion results in an increased complexity in their operation. Increased transport demand and increased complexity of transport services cause disruptions within the controlled set of transport services. With climate change-related events affecting the railway infrastructure, such as damaging the tracks due to heat-related buckling, or flash floods and other extreme weather events affecting the infrastructure (Figure 15; see also [35]), there is a clear need for measures aimed at increasing railway systems' resilience to external events [198], including both anticipated and unforeseen ones [199].

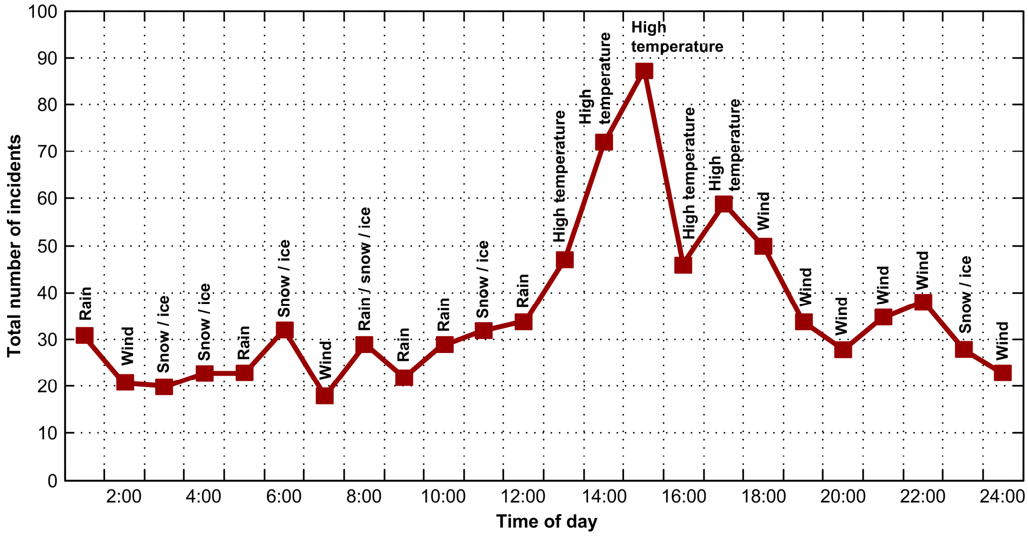

Figure 15. Total number of hourly railway incidents during a single day by most common types of causal events per hour of day (1995–2005); USA data obtained from [35].

According to [197], there are four characteristic approaches to estimate railway systems' resilience from the available literature:

1. Topological approaches that use network and graph theory to perform assessments by removing links from the network in a stochastic manner (thus emulating stochastic disturbances) or according to a predefined strategy (thus emulating deterministic disturbances) using a well-defined mathematical theory;
2. Simulation approaches, which model traffic flows within the system using software tools and can overcome the main disadvantage of the topological approach, i.e., the exponential growth of the problem with the number of combinations;
3. Optimisation approaches, which can handle combinatorically complex scenarios in a systematic manner without the need to analyse every possible combination of events (which would be needed if the topological or simulation approach is used);
4. Data-driven approaches, which do not require explicit traffic network modelling and can provide good a posteriori insights about network resilience using historical data.

Research on railway traffic network resilience focuses on different aspects of railway network operation and a wide variety of research methodologies, as indicated above.

For example, the topological approach used in [200] to model the railway transportation system in Paris, France was able to identify which railway system components have a major effect on the overall system's functioning, which may be crucial for emergency planning and train routing. Obviously, this kind of approach may also be used to model and analyse other kinds of traffic networks, with the concept of friability (loss of resilience) introduced in [201] to evaluate the effect of removing traffic hubs from the network due to traffic interruption. Object-enhanced time Petri net models were used in [202,203] to model and analyse the behaviours of railway transportation networks subject to traffic disturbances. As such, this approach offers a good basis for the development of future software tools at the strategic and operational levels of traffic management and control and for resilience assessment [202] practically throughout all the phases of railway traffic system conception [203]. Machine learning methods [204] and Bayesian network models [205] have also been used in traffic network resilience and vulnerability assessment studies. On the low-end side, resilience improvement measures may include advanced strategies for train platooning and dynamic interval optimisation to minimise departure delay times and, consequently, to dynamically adapt the train departure timetables [206]. The timetable design is obviously a trade-off between the opposing requirements of stability and feasibility, and robustness and resilience, wherein the former requirements are typically met by using deterministic traffic models, whereas the latter require a stochastic-oriented modelling approach [207]. Other methodologies that are typically used in the resilience assessment of low-level and small-scale problems may include the use of dedicated traffic simulation suites, such as the Simulation of Urban Mobility (SUMO) [208] and the hardware-in-the-loop (HIL) approach, to validate the simulation results [209].

Naturally, special attention needs to be paid to cybersecurity challenges associated with the utilisation of IoT-based technologies and the overall cyber-physical system complexity, cloud services and interconnected infrastructure, and remote access security measures to prevent or alleviate the hazard of cyber threats and to ensure the availability and continuity of railway services [210]. A possible example is radio unavailability in tunnels and logistics facilities, and the presence of local radio interference or intentional jamming that prevents wireless communication between moving or stationary traffic subjects. The latter problem may be solved by using spread-spectrum (channel hopping) communications, wherein channel selection may be based on the game theory approach [211]. These aspects may be of particular importance when high-speed railway signalling equipment is concerned [212], as well as in the case of the transport of hazardous materials, whose routing needs to be carefully planned and executed to minimise the transportation risks [213].

Another crucial aspect of railway transportation system resilience is the comprehensive inspection, surveillance, and supervision of critical railway infrastructure, such as tracks [192,194]; overhead power supply lines [192]; power stations, communication, and signalling equipment [214]; and tunnels [179], bridges, and viaducts [215]. To that end, reference [196] illustrates how the use of numerous inexpensive narrow-band remote sensors can improve railway transportation safety in the presence of varying tractions due to the variability of atmospheric conditions (cf. also Figure 7). To automate the surveillance and inspection processes, novel image acquisition methods using LIDAR-based photogrammetry are commonly used [187,216] along with high-definition (HD) video cameras [215] and thermal imaging using forward-looking infrared (FLIR) cameras (Figure 16a). These are increasingly being mounted on UAV-based platforms to scan the terrain, buildings, and other parts of railway infrastructure [217], as illustrated in Figure 16b.

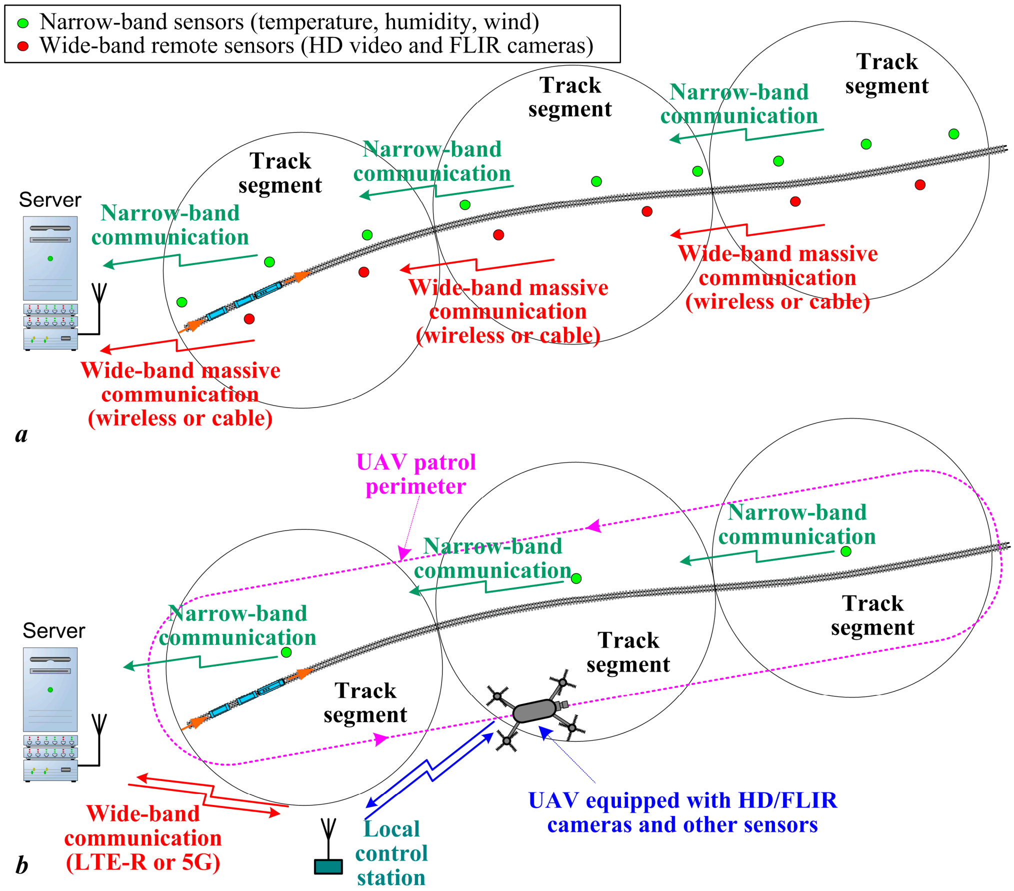

Figure 16. Illustration of narrow-band and wide-bandwidth remote sensor networks for railway infrastructure surveillance (**a**) and possibilities of reducing the number of sensors when using UAV-based surveillance platforms (**b**) based on discussion presented in [218].

The main advantage of UAVs compared to conventional means of surveillance is that one UAV can carry high-performance sensors and cover a very geographically large area using mobile data connection for data transmission, while a conventional surveillance system requires much more expensive information, communication, and energy infrastructure, a larger number of sensors to cover the entire area that should be monitored [218] (cf. Figure 16a,b), and possible different transmission systems for high and low data rate sensors. However, when UAVs are used for surveillance, especially during long missions, there is a certain risk of collision with the surrounding terrain or other aircraft, as indicated in [219]. Reference [219] analyses different collision risk sources and possible outcomes and recommends the utilisation of an emergency parachute for a UAV in order to mitigate the risk of propulsion failure and the loss of UAV control. To extend the aerial coverage of the railway infrastructure, hybrid propulsion technologies may be considered for the surveillance UAVs, such as the internal combustion engine-generator set coupled with the auxiliary battery energy storage system. It was shown in [220] that such a propulsion system has at least double the energy density (and therefore endurance) of a conventional battery-based UAV propulsion while still retaining high control of the flexibility that is inherent to electric propulsion. Such hybrid propulsion-based UAVs for long-duration flight missions are already available commercially [221–223], so their more widespread use in critical infrastructure inspection and surveillance can be expected in the future.

Deep learning methods are frequently used in machine vision applications for critical infrastructure resilience analysis and protection, with ANNs typically being used for that purpose [224]. Among different neural network types, CNNs are normally used for feature extraction in object detection, e.g., to recognise patterns such as edges, shapes, colours, and textures in UAV-recorded HD pictures [225]. In the case of LIDAR use, the classification of features of the so-called "point cloud" has been performed by using the so-called random forest algorithm, which appears to be well suited for the problem of the classification of large 3D data point clouds [226]. Other methodologies used for feature detection during an HD picture analysis may include the Hypercomplex Fourier Transform (HPT) model [218] and a particular type of CNNs, the so-called Region-based Convolution Neural Networks (R-CNNs) [227].

4.5. Smart Grid Paradigm in Railway Transport

The concept of a smart grid (SG) does not have a single unambiguous definition. According to [228], "it combines a set of technologies and end-user solutions and addresses a wide range of policy drivers" in order to integrate the actions of all users connected into the electricity network (electrical grid), from electrical power sources to consumers, and the entities that can perform both tasks (so-called "prosumers"), so that continuous, efficient, economic, and sustainable energy balance can be maintained within the grid [229]. The smart grid paradigm encompasses a wide range of hardware, software, and communication system solutions (Figure 17), thus enabling the following advanced functionalities within the electricity grid [228]:

1. Demand response and demand-side management, which is accomplished through the utilisation of smart metering and smart consumers, local or distributed generation (DG), electrical energy storage (ESS), and, generally, any distributed energy resources (DERs) coupled with providing timely information about energy prices [230];
2. Renewable energy sources (RES), along with distributed generation, residential micro-generation, and energy storage (the so-called microgrid concept), which have the potential to improve the energy sector's environmental impact [231], and are thus accommodated within the SG paradigm, which also provides means of resource aggregation [232];
3. Improved reliability and security of the power supply through an improved resilience to deterministic and stochastic disturbances such as adverse weather conditions and cyber threats [233], and through measures such as predictive maintenance, fault isolation techniques, and an enhancement of the power transfer capabilities [228];
4. The optimisation and efficient operation of assets and opening access to markets by means of intelligent distribution system nodes [230], wherein efficient asset management is carried out based on the timely response to highly dynamic demand using enhanced power transmission paths and an aggregated power supply [228];
5. Maintaining the power quality, which is key for the correct operation of sensitive equipment [228].

To be able to provide the above functionalities within the SG paradigm, the following technologies need to be massively deployed within the electrical grid [228]:

- Information and communication technologies, which enable two-way communication to ensure the interoperability of automation and control and to ensure connectivity between heterogeneous communication nodes connected to different energy sources and loads [234], with the possibility of using the existing electrical network for narrow-band and broad-band communications (operating network, business network, and consumer network) (appropriate hardware and software for secure communications are needed for energy trading and demand-side response [235] and for the seamless integration of intermittent renewable energy sources into the electricity grid [231]);
- Sensing, control, and automation technologies, such as intelligent electronic devices for protective relaying, smart metering, fault recording, and any other sensing, control, automation and ICT systems for rapid diagnosis and event management [235], and advanced power flow control [232];
- Power electronics and energy storage technologies at different scales (power and energy ratings), including high-voltage direct current (HVDC), flexible alternating current transmission systems (FACTSs), and various back-to-back power converter

topologies, which can facilitate the straightforward integration of renewable energy sources and electrical energy storage systems into the electricity grid [236].

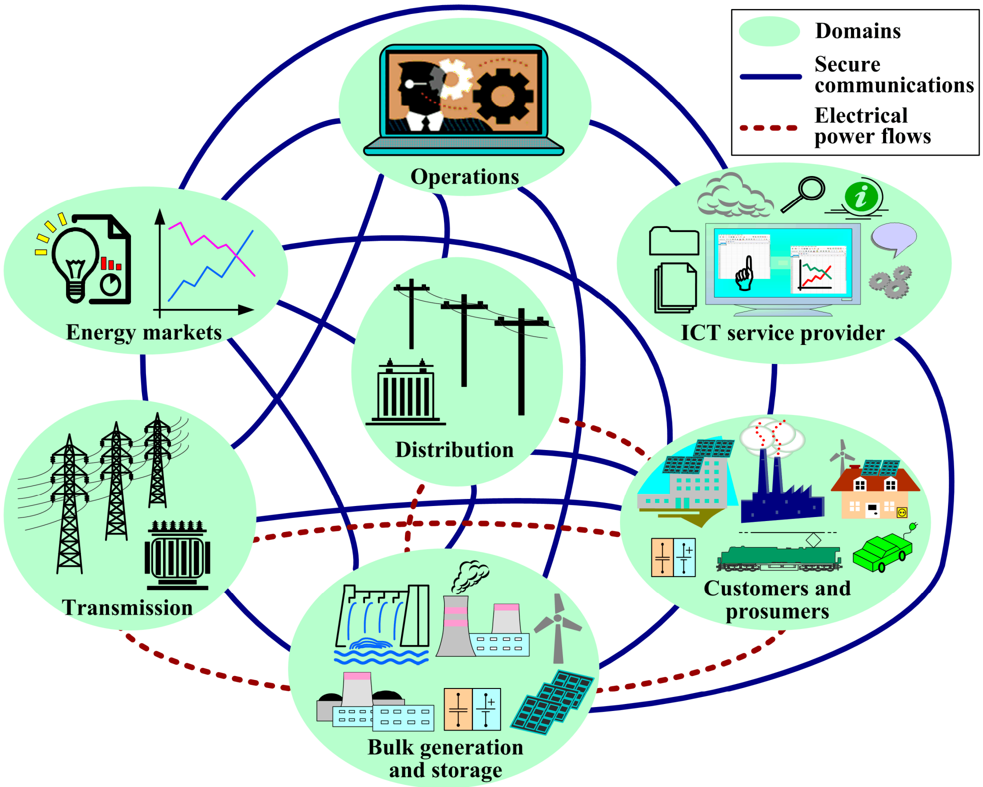

Figure 17. Conceptual model of smart grid [230].

A smart grid architecture model (SGAM) [237] is used to describe the complex interplay between the individual parts of a smart grid system [230] and can be divided into five individual layers (business, function, information, communication, and component), as shown in Figure 18. Naturally, the information flow within the model depends on reliable ICT resources to timely coordinate the interactions between the aforementioned layers. According to the standard presented in [237], these layers are further divided into different domains and zones, wherein domains cover the complete energy conversion sequence, whereas zones are divided to facilitate different hierarchical levels of the energy management system (see Figure 18). As discussed in [238], the SGAM concept is also applicable to the development of advanced energy management control systems in smart railways. A novel Internet of Energy (IoE) concept is proposed as a way of integrating different energy technologies into smart power systems using advanced ICT-based tools that were already developed within the Industrial IoT concept [239].

Although smart grid technologies are market mature and have proven their benefits through successful implementation and use, such as increased reliability, energy availability, and energy efficiency using advanced ICT systems [240], there is currently relatively little effort in the research and development of smart grids for railway projects. The specific issues of railway transportation safety, security, and availability make the influx of such new technologies much more challenging. In that respect, a particular emphasis needs to be paid to reliable and secure broad-band communications to facilitate the integration of distributed power sources, energy storage systems, and smart energy management systems into the railway power system [241]. As illustrated in Figure 19, electrified railway power systems are connected to the main power grid, which provides the bulk power supply for the railway traction, wherein the electrical system operators (ESO) are tasked with balancing the power generation and demand, and the electricity market operators (EMOs) manage energy trading, either via contractual agreements or on energy markets [241]. The railway system operator (RSO) is tasked with controlling the railway traffic to ensure safe and reliable traffic flow, and it is also responsible for controlling the railway power system. In a smart grid for railways scenario, the RSO would also operate the distributed energy resources within the railway power system, that is, the energy storages and distributed generation assets, as shown in Figure 19.

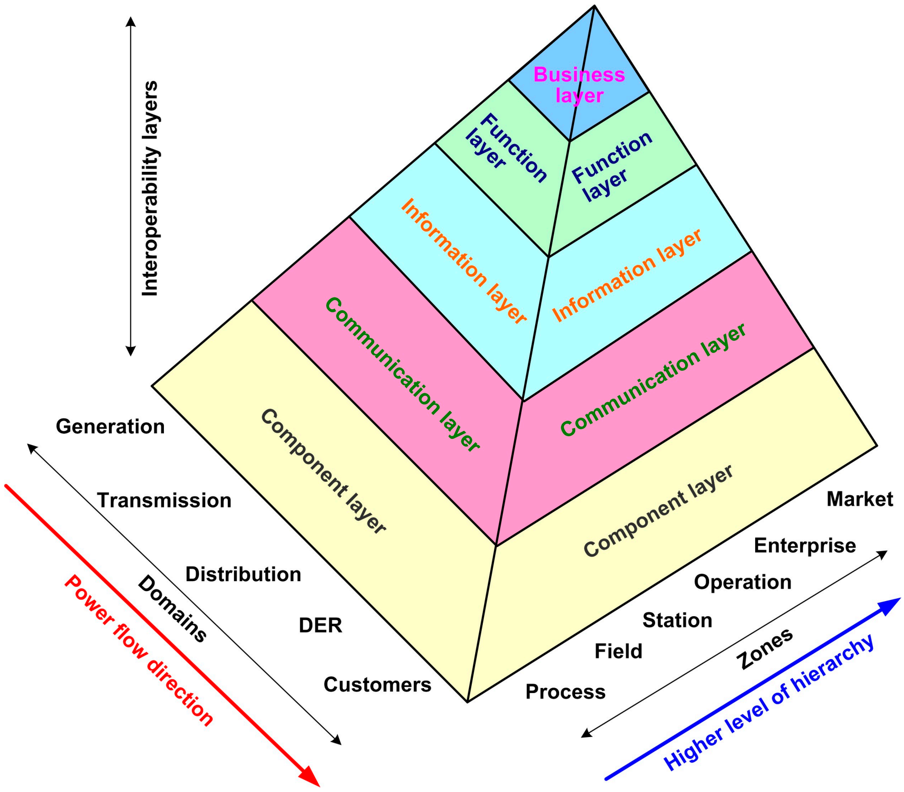

Figure 18. Conceptual representation of smart grid architecture model (SGAM) [237].

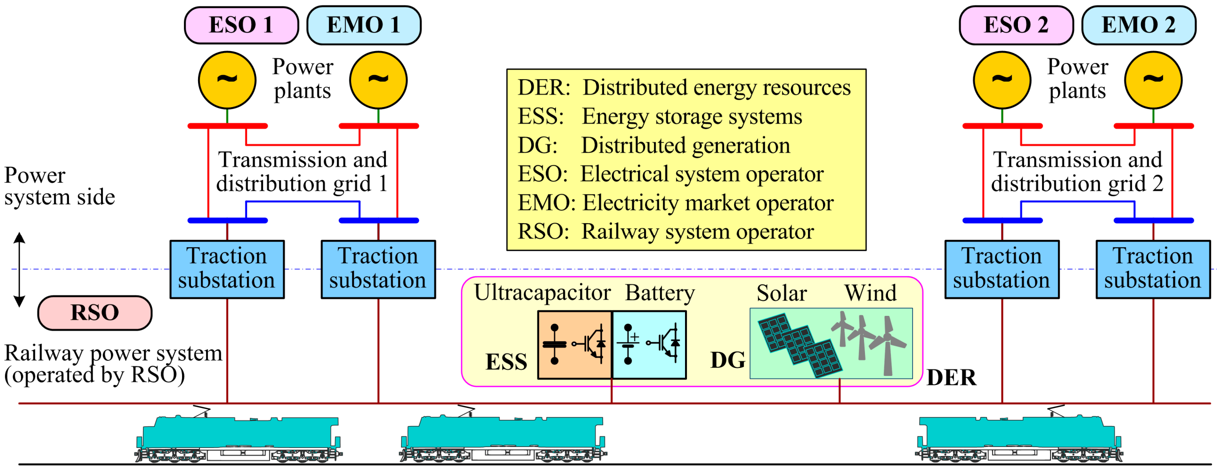

Figure 19. Railway power system interconnection with power distribution, transmission grid, and local distributed energy resources [241].

To facilitate the. effective control of a railway smart grid, the railway power system obviously needs to incorporate many advanced electrical power subsystems alongside DERs and ESS for local power balancing [241]. The effective power flow control between the railway power grid and the main power grid requires the non-reversible sub-stations (SSTs) to be augmented by power subsystems that are capable of real-time energy balancing, such as reversible sub-stations (RSSTs) and intelligent sub-stations (ISST), as shown in Figure 20. Such resources, along with the local ESS, can effectively handle reverse power flows from electric trains equipped with dynamic on-board energy management (DOEM) systems used for kinetic energy recuperation [238]. Since such a railway energy management system (REM-S) interacts with the main power grid and energy markets, its operation needs to be optimised [238] on a daily basis (day-ahead optimisation), which can take into account the daily train schedules, and on a short time scale (with schedules that are 15 min ahead being typical), which needs to fulfil the day-ahead power profile while taking into account the excesses and restrictions of local power production by coordinating between sub-stations and DERs. Real-time operators subsequently fulfil the commanded 15 min power profiles while also taking into consideration the real-time information and power flows from the local power network [238].

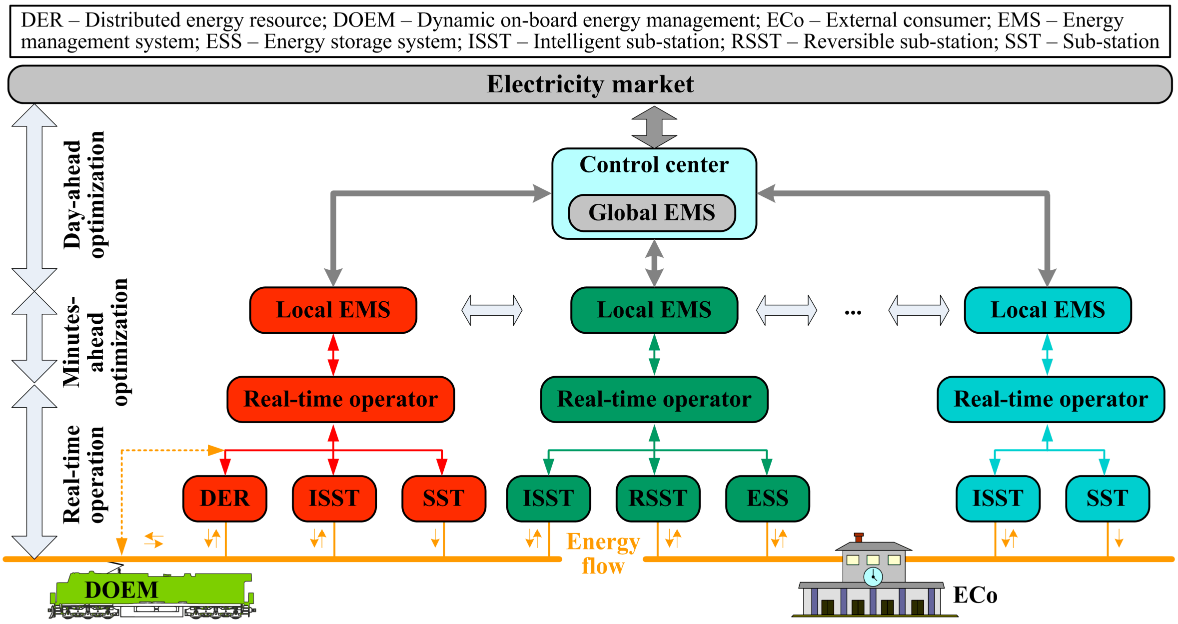

Figure 20. Concept of smart grid-based railway energy management system [238].

Obviously, the type of distributed energy resources (DG and ESS) and the means of their control would play crucial roles both in the day-ahead optimisation and local power flow control based on short time scale schedules. To this end, reference [242] considers a railway-to-grid smart energy management system based on advanced power converter topologies with electrical energy storages for a DC railway network, which can effectively re-route the energy between the power grid and the railway electrical network and increase their flexibility. Different power converter topologies for the integration of PV energy sources into the railway power grid are assessed in [243], whereas the authors of [244] discuss the use of energy storage systems on-board railway trains and propose a two-level hierarchical energy management system using AI in the form of a fuzzy logic system. It reports between 22.3% and 28.7% of improvement in energy efficiency with on-board ESS. The integration of a regenerative braking energy recuperation system with energy storage and PV systems into the railway power grid was analysed in [245]. Power flow optimisation has been performed by means of MILP and has shown the potential to reduce the cost of operation by about 30% compared to the conventional railway grid scenario.

The expected evolution of the information integration of the modern railway traffic management system and energy management towards the future smart railway, which is characterised by a wide use of wireless communication networks, independent power sources, and wide data processing capabilities of individual transport entities and infrastructure, opens up space for new research and areas that are not covered by this work.

Examples of those are traffic regulations, technological problems of timetable management, the issues of maintaining new technological systems that are not directly included in the railway system, and technological systems that have direct consequences on the safety of railway traffic.

5. Conclusions

This paper presents a detailed overview of the most modern technologies proven through research projects for the future development of smarter, safer, and greener rail transport systems. Firstly, this paper focused on emerging propulsion technologies that are crucial for sustainable transportation, such as those based on battery energy storage technologies, hydrogen fuel cells, and alternative fuels. The literature review showed that battery-assisted propulsion, either through the hybridisation of diesel-electric locomotives or in combination with conventional diesel-electric propulsion, can result in notable fuel savings and greenhouse gas emission reductions, and it can apparently achieve profitability using state-of-the-art lithium batteries. Hydrogen fuel cells have become attractive alternatives to conventional propulsion, especially for smaller-scale railway vehicles. However, hydrogen's increased penetration is predicated by the deployment of novel hydrogen refuelling infrastructure, which, according to the literature, may become profitable in railway applications through achieving an economy of scale. In that respect, the utilisation of optimisation tools to plan hydrogen-based railway train refilling and using on-site hydrogen production facilities to supply heavy-haul freight trains may also play an important role in the future uptake of hydrogen-based railway propulsion systems. Synthetic fuels and biofuels may also be considered as low-carbon-footprint alternatives for railway transportation, but their penetrations are much less certain due to the low efficiency of the synthesis process in the former case and the effect on arable land use and food production in the latter case. Railway transport energy efficiency measure improvements are likely to encompass all of the above alternative propulsion systems and energy sources in the near future, with the end result currently being uncertain due to many technologies currently being researched, developed, and increasingly deployed and investigated in realistic operating conditions. The process of selecting optimal propulsion systems for railway traction roles will likely take years before the field tests ultimately point to solutions that are the most competitive in terms of investment and running costs while simultaneously satisfying the ever more stringent environmental regulations.

Secondly, this paper presented the emerging information and telecommunications systems based on long-term evolution and fifth generation new radio (5G NR) networks, with an emphasis on communication systems that are suitable for railway applications. According to the methodology of the integration of experiences from various research projects and different fields, this work presented successful results through achieved specific goals such as energy efficiency or ecological consequences, and it presented broader information so that readers can understand the context and successfully indicate the possible successful compatibility of the researched technology. In this context, the role of Industrial Internet of Things was presented with a particular emphasis on wireless communications and remote sensor networks for railway transportation supervision and management. Special emphasis was also given to narrow-band remote sensor networks for the monitoring of railway infrastructure and atmospheric conditions at the track as key prerequisites for intelligent transport management. Two characteristic cases were presented, wherein remote sensors were successfully used with expert systems and artificial intelligence for railway traffic management, resulting in increased traffic throughput and improved management under adverse weather conditions. It is likely that the new 5G radio network paradigm is going to make notable inroads into railway transportation due to its flexibility, versatility, and support for both narrow-band structured data transfer for smart remote sensor networks and massive broad-band communications, which could support future autonomous railway transport. The integration of technologies that have proven to be successful through research projects is moving in the direction of digitisation, which is key to the competitiveness of the railway industry, and that is why it has become one of the priorities that stakeholders in the railway system deal with in order to use technological opportunities to improve operational processes, i.e., the quality of the provided transport services. The modern information and communication systems mentioned in the paper are focused precisely on applications in different business verticals, where transport in general, especially environmentally friendly rail transport, plays a major role. Modern railway systems will largely apply communication technologies of the latest generations paired with new data sources and the application of data science, including artificial intelligence (e.g., fuzzy logic) in order to optimise processes and provide a competitive, reliable, safe, and environmentally sustainable transport service. The digitisation of railway processes, driven by the application of mobile communication networks and information-communication systems, generates a sufficient amount of data on the basis of which it is possible to extract and use those that are important for the improvement of operational processes in railway systems.

Finally, the role of the Industry 4.0 concept was investigated within the framework of railway transportation. In that respect, the role of information and communication technologies was investigated for the case of autonomous trains and automated railway traffic, wherein big data analytics and latest next generation communication technologies ought to play key roles in future railway transportation. The same conclusion can also be drawn in the case of multimodal transportation combining railways with other modes of transport, with a particular emphasis on the role of new technologies in improving the energy, economic, and ecological indices. In that sense, the utilisation of optimisation tools may be the key to achieve more efficient, economic, and cleaner transport. On the other hand, when transportation safety is concerned, the predictive maintenance of railway vehicles and infrastructure represents one of the key prerequisites for future transportation safety. In that sense, intelligent sensor networks coupled with big data analytics and artificial intelligence may provide timely information about equipment and infrastructure condition deterioration. Obviously, this may also have a profound effect on the railway network and transportation system resilience. In that sense, the utilisation of specialised sensors, machine learning and artificial intelligence, and innovative platforms for the inspection and surveillance of critical railway infrastructure should play key roles in future intelligent transport. The utilisation of intelligent Industrial IoT sensors and smart metering is also vital for the introduction of the smart grid concept into the railway transportation sector. Such synergy between intelligent transport and intelligent energy management is likely to usher many improvements in energy efficiency and transportation security and safety. For that to happen, it is crucial that ICT systems for railways can support both narrow-band and broad-band communications with enhanced security features to support the integrated smart railway transport and energy infrastructure.

Author Contributions: Conceptualisation, M.N. and D.P.; methodology, M.C., Z.K., and T.J.M.; investigation, Z.K., D.P., M.T., M.C., and M.N.; resources, D.P.; writing—original draft preparation, Z.K.; writing—review and editing, D.P., M.C., M.T., and M.N.; visualisation, Z.K., D.P., and M.C.; supervision, T.J.M.; project administration, D.P.; funding acquisition, D.P. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the European Regional Development Fund (ERDF) under the grant KK.01.1.1.01.0009 (DATACROSS).

Data Availability Statement: This is a review article, so no new data were created or analysed in this study. Data sharing is not applicable to this article.

Acknowledgments: The authors would like to express their appreciation of the efforts of the journal's editor and the anonymous reviewers whose comments and suggestions have helped to improve the quality of the presented subject matter.

Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

3D	Three-Dimensional
4G	Fourth Generation New Radio Network
5G	Fifth Generation New Radio Network
5G-R	Fifth Generation New Radio Network for Railways
AC	Alternating Current
AI	Artificial Intelligence
ANN	Artificial Neural Network
ARRT	Autonomous Rail Rapid Transit
CNN	Convolution Neural Network
R-CNN	Region-Based Convolution Neural Network
CO_2	Carbon Dioxide
DC	Direct Current
DC/DC	Direct Current to Direct Current (power converter)
DER	Distributed Energy Resource
DGs	Distributed Generators
DME	Dimethyl Ether
DOEM	Dynamic On-Board Energy Management
DP	Dynamic Programming
EC	European Commission
ECo	External Consumer
EEE	Energy, Economic, and Ecological (indicator)
EMO	Electricity Market Operator
EMS	Energy Management System
ERA	European Railway Agency
ERTMS	European Rail Traffic Management System
ESO	Electrical System Operator
ESS	Energy Storage System
EU	European Union
FACTS	Flexible Alternating Current Transmission Systems
FBMC	Filter Bank Multi-Carrier (modulation technique)
FFT	Fast Fourier Transform
FLIR	Forward-Looking Infra-Red (thermal imaging camera)
H_2	Hydrogen
HD	High Definition (video camera)
HESS	Hybrid Energy Storage System
HIL	Hardware-in-the-Loop
HPT	Hypercomplex Fourier Transform (model)
HVDC	High-Voltage Direct Current
IFFT	Inverse Fast Fourier Transform
GHGs	Greenhouse Gases
GIS	Geographic Information System
GNSS	Global Navigation Satellite System
GSM	Global System for Mobile Communication
GSM-R	Global System for Mobile Communication—Railways
I2V	Infrastructure-to-Vehicle (communication)
ICT	Information and Communication Technologies
IoT	Internet of Things
IIoT	Industrial Internet of Things
IoV	Internet of Vehicles
IMU	Inertial Measurement Unit
IP	Ingress Protection
ISST	Intelligent Sub-Station
IT	Information Technology
ITC	Information and Telecommunications
ITS	Intelligent Transportation System
LCA	Life Cycle Assessment
LIDAR	Light Detection and Ranging

$LiFePO_4$	Lithium Iron Phosphate (batteries)
LNG	Liquefied Natural Gas
LP	Linear Programming
LSTM	Long Short-Term Memory (neural network type)
LTE	Long-Term Evolution (radio networks)
LTE-R	Long-Term Evolution (radio networks) for Railways
LTO	Lithium-Titanate (battery chemistry)
M2M	Machine-to-Machine (communications)
MILP	Mixed-Integer Linear Programming
ML	Machine Learning
MPC	Model-Predictive Control
NB	Narrow-Band
NB-IoT	Narrow-Band IoT
NB-LTE	Narrow-Band LTE (network)
NiMH	Nickel-Metal-Hydride (batteries)
NR	New Radio
OFDM	Orthogonal Frequency Division Multiplex (modulation technique)
QAM	Quadrature Amplitude Modulation
PI	Proportional-Integral (control)
PV	Photovoltaic
PWM	Pulse-Width Modulation
R&D	Research and Development
REM-S	Railway Energy Management System
RESs	Renewable Energy Sources
RN	Radio Network
RSO	Railway System Operator
RSST	Reversible Sub-Station
SG	Smart Grid
SGAM	Smart Grid Architecture Model
SIL	Safety Integrity Level
SoC	State-of-Charge (of a battery or an ultracapacitor energy storage)
SST	Sub-Station (non-reversible)
SUMO	Simulation of Urban Mobility (traffic simulation software)
SVM	Support Vector Machine (machine learning model)
SVR	Support Vector Regression (machine learning model)
UAV	Unmanned Aerial Vehicle
V2I	Vehicle-to-Infrastructure (communication)
V2P	Vehicle-to-Pedestrian (communication)
V2V	Vehicle-to-Vehicle (communication)
V2X	Vehicle-to-Anything (communication)
WANs	Wide-Area Networks
WLAN	Wireless Local-Area Network
ZEBRA	Sodium-Nickel Chloride (batteries)

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