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Review

Environmental Impact Evaluation as a Key Element in Ensuring Sustainable Development of Rail Transport

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Abstract: The development of railways stands as a pivotal milestone in the history of transportation, transforming the world and revolutionising the movement of people and goods. From their humble beginnings as rudimentary track systems to the sophisticated and interconnected networks we witness today, railways have played a crucial role in fostering economic growth, promoting globalisation, and shaping modern societies. Moreover, as the world grapples with the urgent need to mitigate climate change and transition to sustainable modes of transportation, the role of railways has gained significant attention. Railways have long been recognised as one of the most environmentally friendly means of mass transit, offering lower carbon emissions, energy efficiency, and reduced congestion compared to other transportation modes. However, there are still many challenges to overcome to provide continuous sustainability in the context of environmental impacts, especially related to wildlife and habitat protection. This scientific paper aims to explore the concept of sustainability in the context of railways, providing a comprehensive analysis of their environmental influences. As a result, the authors present a complex analysis of the topic, combining different perspectives—ecological, engineering, and legislative. They present methods of reducing noise pollution—constructional and legal ways; emission pollution reduction associated with combustion engines; and innovative analysis of limiting the impact of transportation on natural habitats and forest animal populations, which is not yet sufficiently elaborated scientifically in the literature. By examining key strategies, technologies, and policy frameworks, this research sheds light on the challenges and opportunities related to sustainability within the railway industry around the world.

Keywords: railway transport; ecology; wildlife; traffic safety

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1. Introduction

The development of rail transportation, including the establishment of new rail lines and the modernization of existing networks, is significantly improving transportation connectivity, both for the transportation of people and material goods. By 2021, the total length of operational railway tracks around the world is estimated to be more than 1.2 million km (745,645 miles) [1]. According to statistics, the United States has the most extensive rail network in the world, covering almost 150,000 km. It is followed by China, India, and Canada. Governments and private entities invest substantial amounts in the rail infrastructure. For example, China has invested heavily in railway development, with a target of reaching a total track length of 175,000 km (108,740 miles) by 2025, according to a plan issued by the National Development and Reform Commission (NDRC) [2].

New transportation corridors are being created with national, international, and transcontinental significance. Furthermore, modern technologies allow for increased travel speeds, resulting in the multiplication of connections. High-speed rail systems have gained prominence in recent years. The fastest operational train in regular service is the Shanghai Maglev, which reaches speeds of up to 430 km/h (267 mph) [3]. Countries such as China, Japan, France, and Germany have developed extensive high-speed rail networks [4].

At the local level, Poland has also been developing its high-speed rail infrastructure. The country's first high-speed rail line, known as the Central Rail Line (CMK), connects Warsaw with major cities such as Kraków and Katowice. The CMK allows trains to reach speeds of up to 250 km/h (155 mph) [5–7]. Poland has plans for further high-speed rail expansion. One of the proposed projects is Rail Baltica, an international high-speed rail line that will connect Poland with the Baltic states of Lithuania, Latvia, and Estonia [8]. The electrification of railway lines is an ongoing effort in Poland. The aim is to electrify more sections of the railway network to improve energy efficiency and reduce emissions [7]. Poland is actively working to integrate its railway system with broader European rail networks, promoting interoperability and facilitating seamless cross-border travel.

The idea of sustainable development was stated by the United Nations; the most well-known is the "Johannesburg Declaration on Sustainable Development" about challenges and the need for commitment [9]. Sustainable transportation refers to a mode of transportation that incorporates practices and technologies aimed at minimising negative environmental, social, and economic impacts while maximising efficiency and long-term viability. In the case of railroad transport, it encompasses various aspects of railway operations, infrastructure, and policies that strive to achieve a balance between meeting transportation needs and ensuring environmental stewardship. Among the key elements of sustainability are environmental impact, energy efficiency, safety, and social accessibility.

In the first case, the development aims to minimise the ecological footprint of trains and rail infrastructure. This includes reducing greenhouse gas emissions, air pollution, and noise pollution via measures such as electrification, the use of renewable energy sources, improved energy efficiency, and effective waste management practices. In the future, it will prioritise energy-efficient operations, focusing on optimising train designs, propulsion systems, and infrastructure to minimise energy consumption. This includes advances in regenerative braking systems, efficient train timetabling, and smart grid integration to maximise energy recovery and minimise energy waste. In the context of safety, sustainability refers to the safety and security of passengers, employees, and infrastructure. This involves the implementation of robust safety measures, modern signalling systems, effective maintenance practices, and security protocols to minimise accidents, disruptions, and risks. Taking into account social accessibility, the main role is to ensure inclusive and equitable access to transportation, which implies affordability, reliability, and accessibility of rail transport to diverse populations. This includes considerations for people with disabilities, senior citizens, and other marginalised groups. It also involves integrating the railways with other modes of transport [10–16].

Although rail transport is considered to be one of the most environmentally friendly modes of transportation in terms of greenhouse gas emissions and electricity consumption [17], the described idea of sustainable transport seems to overlook other aspects of environmental impact. In addition to the adverse environmental effects described in detail in the literature, such as noise, exhaust emissions, and energy consumption, which are and will be further reduced by technological solutions and appropriate regulations, there is also the phenomenon of fragmentation of wildlife habitats and increased mortality of animals due to collisions with vehicles.

The railway lines pass through the habitats of many animals, forcing them to traverse the tracks in order to find food, to breed, and to rest. Hence, animals move perpendicular to the tracks, and they do not consider the oncoming train as a natural enemy or react fast enough to avoid an approaching vehicle [18], which results in a collision. Accidents with large mammals, such as bears or ungulates, or entire herds pose a serious threat to the safety of rolling stock. These can cause significant vehicle damage, traffic delays, and, in extreme cases, train derailments. On the other hand, for some species, the tracks invoke a so-called "behavioural barrier effect" [19,20] that restricts migration and leads to habitat fragmentation, which has severe negative impacts on the balance of the ecosystem [21]. In order to increase traffic safety (thus providing one of the key characteristics of sustainable transportation), especially in woodlands and sparsely populated areas [22], efforts have

been made to reduce the number of train-wildlife collisions in order to reduce environmental and financial losses, but the problem persists. For large animal populations, the single death of individuals in the herd on the tracks is not a major ecological threat, but it poses serious damage to the ecosystem in the case of rare (often protected) species. Analysing from an ecological and environmental perspective, the worst for the ecosystem are fatal collisions between vehicles and rare animal species that live in small groups on a large territory and have low fertility (e.g., lynx, wildcat, bear), because the death of a particular family-group member may endanger entire species in a given habitat, and the vast majority of accidents are fatal for animals [23]. Other species that are sensitive to behavioural barriers and collisions with vehicles are those that often roam in search of food and daily shelters (e.g., cervids, wild boars) or have long seasonal migrations (reindeer, moose). Therefore, taking preventive measures and reducing the number of accidents involving animals is in the interests of both railroad operators and environmental protection.

In this paper, the authors undertake a comprehensive analysis of the environmental impact of rail transportation development, in which, in addition to the recognised dangers of noise pollution and exhaust fumes [16], they also outline the effects on wildlife as well as methods of reducing them to ensure sustainable development.

The next section of this paper describes the environmental aspects of rail transportation. It first describes the problem of noise pollution and methods of reducing it, then addresses the emission of toxic substances into the atmosphere and legislative and construction solutions to counteract this phenomenon. Last but not least, the problem of fragmentation and destruction of wildlife habitat, along with an analysis of increased animal mortality as a result of accidents with rail vehicles, are covered by the authors. Their aim is to prove that consideration of the less-known aspects of environmental protection is one of the key elements of a sustainable development strategy, both from an ecological and a safety perspective.

2. Environmental Aspects of Rail Transport

Noise pollution, toxic emissions, and direct threats to wildlife, such as habitat fragmentation and increased animal mortality, were selected as the three key aspects of rail transportation affecting the environment to be considered in the development of a sustainability strategy. As a methodology for literature research, a typical purpose approach was chosen, which is the most preferable way to do a systematic review of publications on the selected topic, consisting of a synthesis and comparison of information [24], methods, and research results, particularly focusing on presenting the complexity of the issue and its various aspects.

The purpose of this study was to comprehensively analyse the three issues chosen as key in assessing the effectiveness of implementing sustainable transportation development solutions. The research methodology focused on the transparency of these solutions, including their advantages and disadvantages. The main idea of the review was to present it as broadly as possible. It was based on publications available in scientific databases and official documents (concerning legal regulations), and it was decided to present the results descriptively because, in this way, it is simpler to outline the scale and complexity of the problem than briefly describing the most important factors in a tabular manner.

2.1. Noise Pollution

Noise pollution can be considered any disturbing or unwanted sound that affects the well-being and mental, emotional, and physical health of humans or other organisms. Among the symptoms of the effects of noise pollution on organisms, we can distinguish dissatisfaction, anxiety, and irritation. In addition, it can result in the development of conditions such as hypertension [25], sleep problems [26], incomplete functional capacity [27], or even hearing loss [28]. Generated noise also has a negative impact on wildlife; it can negatively affect the habitat of wild species and their behavioural behaviour. Controlling noise pollution is therefore one of the key aspects of making transportation sustainable [29].

One source of noise pollution is rail transport. This phenomenon is particularly troubling in highly urbanised areas where tracks are close to human settlements [30]. Noise levels above 55 dB (A) are considered noise pollution for humans [31]. At the same time, the sound emitted by rail vehicles can be higher, reaching values close to 100 dB(A) [32]. It is estimated that 22 million people are exposed to excessive noise in the European Union alone [33]. Rail noise pollution can be of the nature of an acoustic wave propagating through the air or vibrations emitted onto the ground during the passage of a train set [34]. The sources of noise pollution from rail transport can be described as complex, resulting from both the mode of operation, the construction of the rail vehicle, and the infrastructure. Among the causes that arise from the mode of operation is the use of a train horn in certain situations, such as when passing a level crossing. Noise sources related to the construction of the rail vehicle include the sound emitted in front of the vehicle's propulsion system, its equipment (HVAC), aerodynamic noise at high speeds, braking systems, and the noise emitted by rolling elements such as bearings or wheels [30,35]. The noise generated by the latter is particularly related to the infrastructure of the rail vehicle. One phenomenon with a significant impact on noise pollution is wheel-rail contact [36].

This noise takes various forms. The main one that we can mention is the rolling noise that occurs on a straight track. It is characterised by emissions over a wide frequency range. It is the result of phenomena related to direct contact between the wheel and the rail and is influenced by the wear of both, including the formation of roughness and unevenness. Particularly annoying impulse noise is also generated due to discrete elements such as wheel flats and the passage through rail joints or turnouts [37]. Very high noise levels, especially in urban areas with small radius curves, are caused by the squealing when passing through them due to the increased contact between rail and wheel [36].

Also problematic is the transmission of low-frequency vibrations to the ground during the passage of a rail vehicle, known as ground-borne vibrations [38]. Negative effects include adverse health effects and the degradation of infrastructure in the immediate vicinity of the rail tracks. Studies have shown that, in some cases, vibrations caused by passing trains can increase heart rate during sleep by 3 beats per minute, which, in the long term, can affect cardiovascular function [39]. Evidence was also found of a negative effect of ground-borne vibrations on the body's regenerative capacity, which impairs the long-term stress response [40]. It has also been shown that ground-borne vibrations can negatively affect wildlife [31].

Reducing noise pollution is an important element in ensuring sustainable rail transport. In the European Union, the harmonisation of solutions to reduce noise emitted by rolling stock is realised by the technical specification for interoperability 'Rolling stock—Noise'. Strategies to reduce noise pollution can be divided into solutions to limit its generation at the source and to prevent its propagation (scheme shown in Figure 1) [38].

The first approach requires technological and structural changes to the rolling stock and infrastructure. Rail vehicles can be upgraded with noise-reducing solutions. These include the installation of noise barriers in vehicle traction equipment, optimising wheel geometry, using appropriate suspension and dampers, and, in the case of high-speed trains, improving aerodynamics [41,42]. Another method is to change the materials used to make rail vehicle parts or modify their dynamic properties [43]. A particular type of design solution is the replacement of steel brake blocks with their composite counterparts. According to the TSI Rolling Stock Noise, the use of steel brake blocks will be banned from 2024 on lines defined as 'silent' [30]. Infrastructure solutions can include the modernization of railway tracks via the use of non-jointed rails, such as continuously welded rails that eliminate impulse noise associated with the passage of wheels through joints, the reduction in turnouts, and the use of damping sleepers [36,38]. An important aspect is the maintenance of the already upgraded infrastructure. The grinding of the rails alone can reduce the noise emitted by 3 dB [44]. Another solution is the use of automatic wheel flange and rail lubrication systems to reduce friction and noise, particularly when crossing

curves [30]. The use of elastic pads on the sleeper was highly effective in reducing the vibrations transmitted to the ground, reducing them by 16 dB [45].

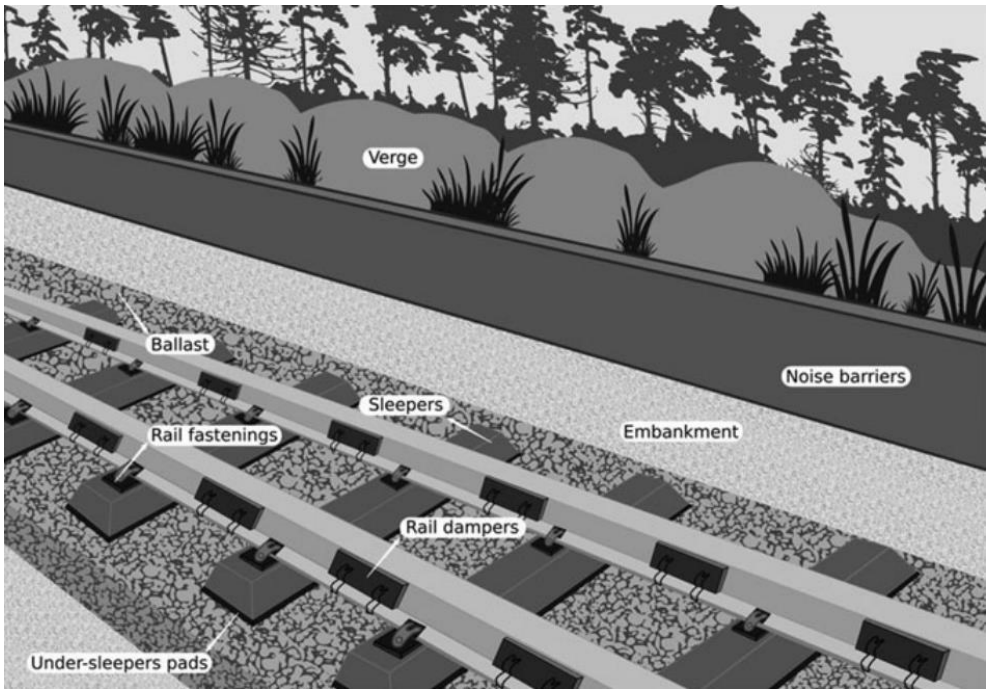


Figure 1. Schematic drawing of a railway showing some measures to minimise noise and vibration: rail fastenings; rail dampers; under-sleeper pads; and noise barriers (not at scale) [30].

Noise propagation is reduced, among other things, by the use of trenches and embankments. Although these solutions require the occupation of a large strip of land, they are environmentally friendly and effective, achieving noise reductions of 25 dB. Noise barriers are also used; these structures can be made of soil, wood, concrete, or metal and can be an important tool to minimise the negative impact of sound on both people and wildlife, especially for species that are extremely sensitive to it. Green barriers, such as dense vegetation, can also be used and, in certain cases, provide an effective barrier against noise propagation [30,31].

Summarising the concerns of this subsection, many studies indicate that rail transportation can contribute to high levels of noise pollution, especially in areas near railroad tracks and stations. The continuous passage of trains, with the accompanying vibration and mechanical noise, can disturb human and wildlife behaviour. Despite legal regulations regarding noise restrictions and the implementation of damping technologies, the problem persists. To address noise pollution, several mitigation measures can be implemented. These include the use of noise barriers, sound insulation for buildings near railway tracks, and the development of low-noise train technologies. Furthermore, adopting quieter maintenance practices, implementing speed restrictions in areas sensitive to noise, and incorporating noise reduction strategies during the planning and design of the railway infrastructure can significantly contribute to minimising the impact of noise pollution.

2.2. Emissions

Atmospheric emissions from rail transport are considered to be lower than those from other modes of transport (see Figure 2). Moreover, it is characterised by its high energy efficiency. For these reasons, the development of railways is eagerly being promoted as a sustainable transport solution [46,47]. However, this does not mean that this branch of transport is completely environmentally neutral and is also characterised by the generation of harmful pollutants [48].

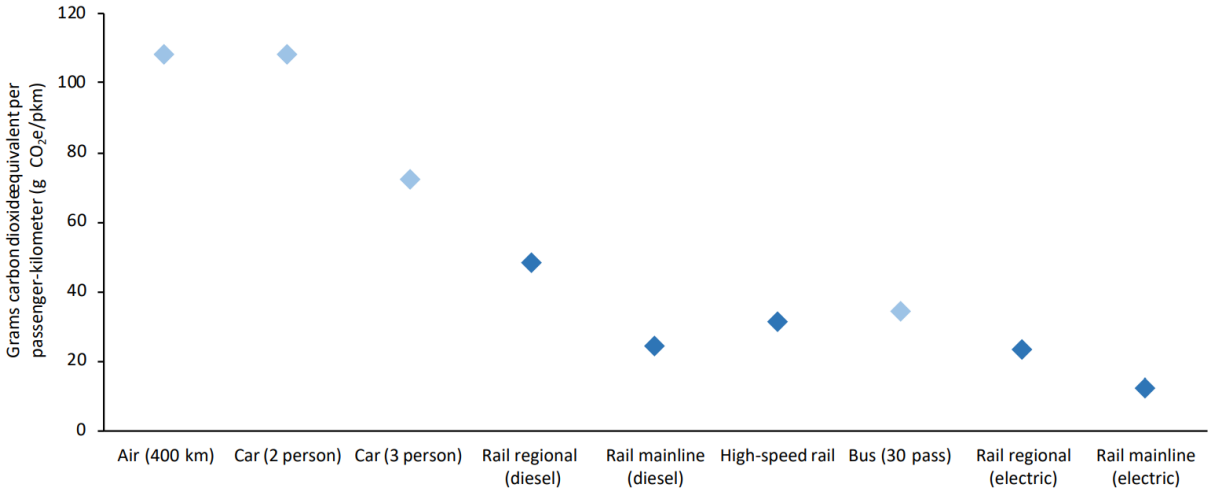


Figure 2. Typical Traction-Related Emissions for Intercity Passenger Trips by Mode (Data assumes carbon emissions of 400 g per kilowatt hour for electric modes) [48].

In the case of rail transport, we can divide emissions into direct and indirect. Direct emissions are associated with the operation of rolling stock, particularly those powered by traditional fossil fuels. They include greenhouse gases such as carbon dioxide (CO_2), hydrogen oxides (HC), and nitrogen oxides (NOx) resulting from the combustion process occurring in diesel vehicles. Additionally, airborne particulate matter (PM) is a pollution problem. PM refers to fine solid or liquid particles suspended in the air. It includes both fine particles (PM2.5) and coarse particles (PM10) [49,50]. PM emissions from rail transport can be due to diesel engine exhaust, brake wear, or abrasion of the track [51].

Indirect emissions in rail transport are related to ensuring the proper operation of infrastructure and rolling stock that are not produced directly by rail vehicles. Examples include the emission of greenhouse gases and particulate matter through power plants that provide energy to electrically powered rolling stock [52], harmful emissions from equipment used to maintain rail transport components, or pollution generated during the rolling stock production and maintenance process [53].

Various methods can be distinguished for reducing the atmospheric emissions of greenhouse gases from rail transport. The European Union has adopted emission standards for the NRMM (Non-Road Mobile Machinery) vehicle category, which includes rail vehicles. The standard provided limits for toxic compounds and PM mass emissions. As a result, rail vehicles were forced to be designed with better emission characteristics [54]. Another method is the transition from train sets consisting of diesel-powered units to those powered by more environmentally friendly energy sources. The primary method is the electrification of railway lines. By investing in a traction infrastructure capable of supplying electricity, the use of diesel units on electrified lines can be eliminated, directly contributing to reducing atmospheric emissions. To achieve total zero emissions, it is also necessary to modernise the sources of electricity that supply the catenary network, among other things, by replacing power plants fuelled by mine gases with plants that use renewable energy or nuclear power [52]. Another example of replacing rolling stock with more environmentally friendly vehicles is the use of hydrogen-powered units [55].

Another measure being taken to reduce the emissions of rail transport is to increase the energy efficiency of rolling stock, which is one of the most important ways to ensure the sustainability of rail transport [56]. This includes the use of lighter materials in trains, the implementation of braking systems that allow energy recovery, and the improvement of the aerodynamic properties of rail vehicles [57,58]. Ensuring adequate energy efficiency can be achieved not only via interventions in the design of the rail vehicle but also via appropriate planning of railway lines and train stops along the route. Studies have shown that, at higher maximum speeds, intercity and express trains have lower energy consumption

per passenger-kilometre than suburban and regional trains. This is due to their different stopping cycles. Accelerating a train when it has reached a complete stop is highly energy-intensive, which, for trains that frequently stop in stations, results in increased overall energy consumption [56]. This shows that emission reductions in rail transport must take into account a wide range of factors and be limited not only to on-site emission reductions but also to ensuring adequate energy efficiency as well as the provision of clean energy at the source, i.e., at power plants.

Although railway transport is known for its relatively low carbon emissions compared to other modes of transport, such as road or air transport, our findings indicate that diesel-powered trains and outdated infrastructure can still contribute to emissions of greenhouse gases and air pollutants. Improving air quality near rail tracks is essential to safeguarding the health of both wildlife and humans. Therefore, implementing effective air quality monitoring, employing emission control technologies, and ensuring proper maintenance of locomotives and rolling stock are critical to minimising the direct impact of emissions on wildlife habitats and urban areas adjacent to rail tracks.

2.3. Direct Threats to Wildlife

Among the direct environmental threats posed by the unsustainable development of transportation networks are environmental fragmentation, leading to the loss of genetic diversity in the area, habitat loss, and increased animal mortality [59–61]. Many studies on that topic concern roads and highways [62,63] instead of railways. The issue remains the same, but the degree of impact differs [64]. Tracks cross wildlife habitats and animal migration routes [65] (often defined as so-called ecological corridors or habitat connectivity corridors), affecting the lives of wild animals in various ways.

The behavioural barrier effect [66,67], also known as the barrier effect or the fragmentation effect, refers to the impact of transportation infrastructure, such as railways, on wildlife populations and their movement patterns. Railroads can act as physical or psychological barriers that impede or disrupt the natural movement and behaviour of wildlife, leading to fragmentation, isolation, and potential negative consequences for ecological connectivity. This barrier can act on large ungulates, birds, reptiles, small mammals, and insects, such as bumblebees [59,67,68].

Railways can divide wildlife habitats, separating populations and fragmenting larger ecosystems [69]. The presence of railways can create isolated patches of habitat, limiting the movement of animals across their natural ranges. This fragmentation can have adverse effects on the ability of wildlife to find suitable resources, mates, and territories, leading to reduced genetic diversity and potentially increasing the risk of local extinction. One of the basic conditions for the preservation of biodiversity is to ensure the continuity and permeability of ecological corridors. Fragmentation caused by rails can impede gene flow among wildlife populations. Limited movement and reduced opportunities for interbreeding can lead to genetic isolation, inbreeding, and a decrease in genetic diversity. This can ultimately affect the long-term viability and adaptability of wildlife populations, making them more susceptible to environmental changes, diseases, and other threats to the balance of ecosystems [21,70].

In addition to genetic threats to biodiversity, railways can disrupt the natural movement patterns of wildlife, which may rely on certain corridors or migratory routes for foraging, breeding, and dispersal. Animals may be reluctant to cross railway lines due to the noise, vibrations, and perceived danger associated with trains. This disruption can result in altered migration patterns, reduced access to critical resources, and increased energy expenditure for wildlife as they seek alternative routes and stress levels. These changes in habitat use, resource selection, and social dynamics can become a lasting behavioural modification [71] that can have cascading effects on the entire ecosystem, including changes in predator-prey dynamics and changes in the composition of the plant community.

This cascading effect is also related to increased mortality caused by collisions between wildlife and trains, which alter the size of animal populations in a particular territory.

Animals, especially those with lower mobility or slower reaction times, such as reptiles, amphibians, and larger mammals, may be at higher risk of collisions with trains or other railway infrastructure. These collisions can result in injuries or deaths for wildlife populations, further exacerbating the impact of railways on their survival. According to research conducted in Montana in the United States, bear-train collisions were twice as frequent on a railway compared to a parallel road and were the second highest cause of mortality after poaching [72]. The significance of mortality correlates with many factors, such as the speed and size of trains, the lack of escape routes, the attraction of animals to the tracks (for example, the warmth of the tracks can attract reptiles seeking heat, and vegetation growing along the tracks may offer a food source for herbivores; litter and food scraps discarded by people on the train can attract bears (Figure 3) or wild boars; and the bodies of animals killed in collisions with the train can result in the presence of scavengers) [23].

Figure 3. A grizzly bear in Banff National Park, Canada, attracted by leftover food thrown from the train [73].

The frequency of collisions between wild animals and trains is influenced by the nature of the landscape, the number and concentration of animals in the area, the height of the railroad embankment in relation to the natural terrain, and seasons of increased animal migration. In addition, it depends on the volume of traffic, the speed of vehicles, the construction technique of the line, and the distance from human settlements [21,74]. A higher frequency of accidents occurs at night, especially at dusk and dawn, as well as in autumn and winter, which may be related to the fact that the population of ungulates increases in autumn, when they then form larger herds in which they migrate to winter feeding grounds [75]. Weather conditions also have an impact: the presence of thick snow cover (in Scandinavian countries and Canada) causes increased moose mortality during the winter months [76]. The blocking of tracks by moose, which use the tracks as a path in snowdrifts, is shown in Figure 4.

Generally, collisions occur in grassland near forests in sparsely urbanised areas. Tourism-related expansion, climate change, and hunting are altering animal behavioural patterns and disrupting animal migration, which can result in increased animal disorientation combined with the unpredictability of their reactions (and a higher likelihood of collisions).

Figure 4. A moose deny to leave the railroad tracks near Caswell, Alaska [77].

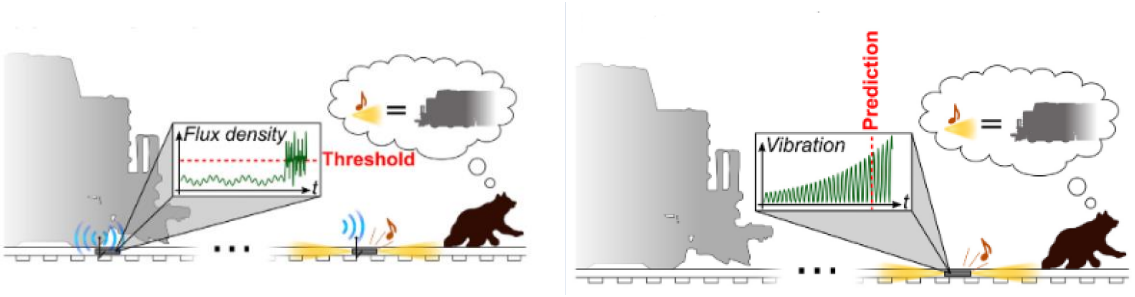
Except for strict collisions, there are also fatal accidents associated with electrocution, rail entrapment, and wire strikes [64]. Negative impacts of the railway infrastructure, specifically tubular poles that support the catenary, were observed in the form of creating pitfall traps for nesting birds and causing their deaths [78].

Another aspect is habitat alternation, related to construction and operation of railways. In addition to the zoning of land for the construction of the line, which involves clearing the forest and cutting down vegetation, the noise factor and traces of human presence are also important, as they disturb the ecosystem.

In the context of driving safety, which is part of the idea of sustainable transport development, attention should be paid to the risks to rolling stock, passengers, and cargo that accidents involving animals raise. Accidents with animals and the consequent measurable damage are especially experienced by passenger trains [22] due to the higher speed of travel and type of vehicle design (electric or diesel multiple units are more prone to collision damage than massive locomotives of freight trains). A collision involving large animals (e.g., deer, bears, elk, and elephants) can cause serious damage to a traction vehicle or locomotive, and a collision with a herd, in extreme cases, results in a train derailment. Among the vehicle components most susceptible to damage are body panels, headlights, windshield, suspension system, cooling, and fluid-containing systems. Furthermore, sudden braking can injure passengers and destroy cargo, especially if it is fragile. However, in most incidents, the arrival of the trains is delayed and schedules are disrupted, which brings financial and image losses to the rail carriers.

Addressing the risk of train-wildlife collisions requires a comprehensive approach that includes identifying high-risk areas, implementing wildlife mitigation measures, imposing speed restrictions and warning systems, and providing public awareness and education. Conducting surveys and analysing collision data to identify locations where wildlife mortality is more prevalent can help prioritise mitigation efforts, such as constructing wildlife crossing structures, installing fencing along tracks, or implementing vegetation management strategies to reduce wildlife attraction, which can help minimise the risk of collisions. Additional enforcement of speed limits in wildlife-sensitive areas and the implementation of effective warning systems, such as sound devices or vibration systems for early detection of the presence of animals near railroad tracks, can provide additional safety measures for both animals and train operators. Methods to reduce the number of collisions and their effectiveness are described in detail in [79]. Among the many different approaches worth mentioning are innovative methods of informing about an approaching train in the zone of potential collision with wildlife based on rail vibrations studied in

Canada [80] (Figure 5) and animal crossing projects studied in Sweden [81] (Figure 6) or Japan [82], combining infrastructural methods with acoustic deterrents.



(**a**) (**b**)

Figure 5. The idea of a wildlife alert system that is activated by trains tested on a freight railway within Banff National Park, Alberta, Canada and Yoho National Park, British Columbia, Canada, Yoho. (**a**) The passing relay relays triggers to a remote warning device using a sensing device to detect trains. (**b**) The approach detector combines integrated warning signals and vibrations in the train to find distant trains [80].

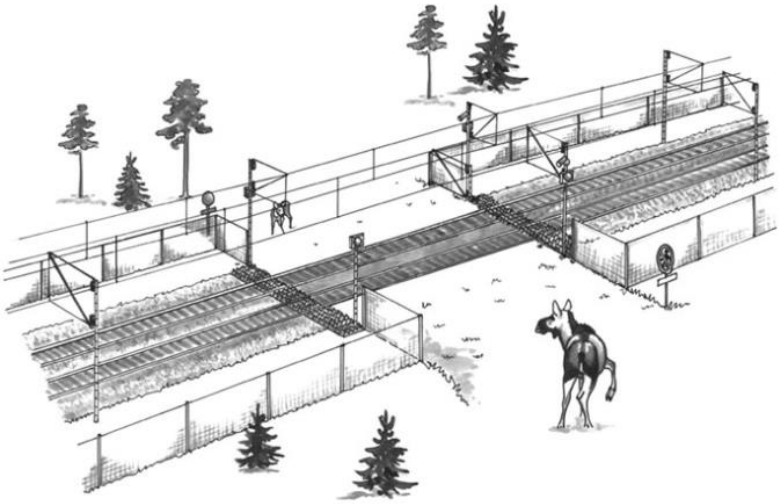


Figure 6. Schematic of an experimental animal crossing at track level, combining infrastructural methods and acoustic animal shooing systems triggered by the signal of an approaching train (investigated in Sweden) [81].

However, despite the use of various technical solutions (e.g., animal crossings, culverts, guide fences), the barrier effect, or the increased mortality of animals due to collision cannot be completely reduced [83]. Without a doubt, by implementing measures and adopting wildlife-friendly practices, it is possible to further mitigate the negative impact of railroads on the environment, protect wildlife populations while increasing the safety and reliability of rail traffic, and promote co-existence between transportation infrastructure and biodiversity conservation.

In discussing this subsection, it is worth observing how railway transport poses direct threats to wildlife populations. Collisions between trains and animals can result in injuries and fatalities, adversely affecting species populations and ecosystem dynamics. Larger mammals, such as deer, moose, and bears, are particularly susceptible to these collisions due to their size and slower movement patterns. The behavioural barrier effect, which leads to fragmentation of ecosystems and disruption of biodiversity, is difficult to minimise. In addition, the construction of railroad lines often causes habitat loss. The establishment of wildlife crossing structures, using animal deterrence systems and signals for early detection of the presence of animals on tracks in hotspot areas, can provide safe passages for animals

to navigate across railway tracks, reducing the risk of collisions. These structures should be appropriately designed, considering the movement patterns and specific needs of the target species.

3. Discussion

Analysing the examples presented, it can be noted that despite numerous solutions of various types—legal, technological, and strategic—the negative impact of railroads on the environment still exists, so the assumptions of sustainable transport are not fully implemented. The implementation of innovative ideas to reduce this impact is time-consuming and cost-intensive and requires the cooperation of many entities and the integration of many perspectives—engineering, political, and environmental—which is a challenge. Moreover, many of the approaches mentioned only superficially affect the assessment of the environmental impact of rail transportation development, allowing them to meet the formal requirements of projects, but the broader perspective and long-term effects are not taken into account.

Table 1 proposes a summary of the subsections described above, highlighting the scale of the impact and the methods used so far to reduce negative impacts (exemplary and most significant).

Table 1. The synthesis of areas of environmental impact of selected aspects of railroads and primary classification of reduction methods.

Chosen Aspect of the Environment Impact of Railway	Areas of Negative Impact	Methods of Reducing the Impact
Noise pollution	Individuals, wildlife habitats	Legal: speed restrictions, TSI Noise regulations Technological: changes in vehicle constructions and designs Infrastructural: track modernization and noise barriers
Emissions of toxic gases	Ecosystems, air quality	Legal: EU emissions standards Technological: construction changes in vehicles, use of clean energy Infrastructural: electrification of railway lines
Direct threats to wildlife	Individuals, wildlife habitats, ecosystems	Legal: eco-friendly railway network development planning, strategies for monitoring wildlife behavior and populations Technological: improving animal deterrence systems Infrastructural: animal crossings

The methods are classified as legal—national and international regulations, but also expansion plans, development strategies, and design assumptions; technological, related to specific structural changes to vehicles, such as changes to the powertrain or vibration damping systems; and infrastructural, which directly change the environment around railroads.

This synthesis of information not only makes it possible to observe the scale of the problem but also allows the development of strategies to reduce its negative impact. Above all, it is necessary to point out the need to integrate solutions of various types in order to thoroughly reduce the environmental impact while maintaining the proper dynamics of development. Furthermore, collaborative efforts between railway operators, ecological organisations, and government agencies are crucial to developing and implementing environmental management plans. These plans should integrate ecological considerations into the planning, operation, and maintenance of the railway infrastructure to ensure the long-term viability of wildlife and human populations in adjacent areas of the railway, pursuing the principles of sustainable development.

4. Conclusions

In conclusion, the development of rail transport can be accepted as a solution to make transport more sustainable in terms of ensuring environmental friendliness. However, simply increasing the proportion of railways in national transport systems without adequate investment in infrastructure may reduce the effectiveness of the objective of ensuring sustainable transport or even nullify it.

Measures to increase the number of railway lines should be combined with measures to modernise rolling stock, auxiliary infrastructure, and energy infrastructure. Increasing the proportion of electrically or hydrogen-powered rolling stock will in itself reduce on-site emissions as the vehicle passes over it, but to reduce global emissions, it is also necessary to make the rolling stock more energy efficient, to modernise the auxiliary vehicles that maintain the railway lines, and to ensure that the power plants feeding the catenary and the centres for the production of alternative fuels such as hydrogen operate on the basis of renewable energy sources. Consideration should also be given to the design of rolling stock and rail infrastructure to the use of solutions to reduce noise pollution and the transmission of vibrations to the environment, as these have been shown to be harmful to both people and wildlife in the vicinity of the rail network.

The impact of the expansion of the rail transport infrastructure on wildlife must also be considered as part of development activities. It has been shown that it can have a negative impact on animal life and behaviour, and therefore the use of solutions to maintain harmony between rail transport lines and wildlife habitats is a key aspect of ensuring sustainable transport. At the design stage of a railway line, consideration must be given both to its alignment so as to disturb wildlife habitats and travel routes as little as possible and to the use of devices that allow both the early detection of track intrusion and the possible deterrence of fauna already on the track.

Due to the wide range of aspects that need to be taken into account in making rail transport more sustainable, the authors of this article point to the need for appropriate investment using structured infrastructure programmes with the participation of rolling stock and ancillary equipment manufacturers, experts, and social and environmental organisations. This broad approach will ensure the development of sustainable transport, taking into account the interests of citizens and wildlife.

5. Future Directions

In the context of environmental sustainability, the future direction of rail transport focuses on further reducing its carbon footprint, minimising resource consumption, and enhancing overall environmental performance. One of the main steps is to accelerate the electrification of railway networks. Transitioning from diesel-powered trains to electric trains can significantly reduce greenhouse gas emissions and air pollution. Additionally, integrating renewable energy sources, such as solar or wind, into the railway infrastructure can further enhance the environmental sustainability of train operations.

In addition, efforts should be made to mitigate the noise and vibration caused by trains to minimise disturbance to nearby communities and ecosystems. Advanced noise reduction technologies, improved track design, and sound barriers can help address the noise pollution associated with railway operations. In addition, the development and maintenance of sustainable rail infrastructure play a crucial role in minimising environmental impacts. This includes using eco-friendly construction materials, implementing green building practices, and integrating nature-based solutions into railway projects to improve biodiversity and reduce ecological disturbances.

These solutions can focus on directions related to wildlife-friendly infrastructure in railway development and expansion projects, wildlife monitoring and research, ecological connectivity, and habitat restoration. This includes the construction of wildlife underpasses, overpasses, and green corridors that allow animals to safely cross railway tracks, reducing the barrier effect and minimising the risk of wildlife-vehicle collisions, including the use of innovative technologies based on the psychology of animal behaviour.

Sustainable development requires establishing a comprehensive perspective right from the beginning. It seems reasonable to provide the right conditions at the level of strategy and planning based on an assessment of the impact on the environment rather than implement corrective measures afterward. However, this approach needs collaboration among engineers, researchers, the public administration, and politicians. Sharing best practices, knowledge exchange, and fostering international partnerships can accelerate the adoption of sustainable technologies and practices in different railway networks and promote a harmonious coexistence between transportation infrastructure and the environment.

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