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Sustainability in Railways – A Review

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This paper examines the sustainability of railways. A comprehensive international literature review was conducted on railway vehicles, traction, and railway permanent way. The main goal was to find the factors and parameters that affect railway sustainability the most. CO_2 emissions from transportation, mining, raw material production, manufacturing, use, operation and maintenance, and demolition and restoration must be significantly reduced. Naturally, the attention will be on the considerable energy and financial savings. This article's main topics are sustainability, affordable and clean energy, industry, innovation, infrastructure, sustainable cities and communities, responsible consumption and production, climate action, and life on land. Building materials come from quarries and gravel pits, but availability is decreasing. Future pavement construction and maintenance require recycling demolition and industrial waste. Engineers must choose materials and technology that extend track lifetimes to ensure reliability, availability, maintainability, safety, sustainability, and economy in permanent railroad ways. Life-cycle costs can be reduced, e.g., by Building Information Modeling. Electric machinery is preferred for construction equipment, materials, and management. Sustainability, like grassed tracks and recyclable plastics, has improved urban life. Sheet metal forming using recycled materials and sustainability shows how important environmental protection is in car and train design. Electric road and rail propulsion are driven by environmental concerns, while supercapacitors and batteries are studied. In conclusion, by preferring rail for freight and passenger transport, both for private and public transport, energy savings and CO_2 emissions can be up to 2-10 times higher than for other modes of transport.

1. Introduction

Sustainability is "the quality of being able to continue over a period of time, or it is the quality of causing little" or, in another definition, it is "no damage to the environment and, therefore, able to continue for a long time" (Cambridge University Press and Assessment, 2023). In the current paper, the sustainability aspects of railways were considered. In this context, railways mean not only the permanent railway itself; this term was extended to vehicles (rolling stock), railway stations, buildings, catenary systems, etc.

Sustainability has several areas, e.g., (i) no poverty, (ii) zero hunger, (iii) good health and well-being, (iv) quality education, (v) gender equality, (vi) clean water and sanitation, (vii) affordable and clean energy, (viii) decent work and economic growth, (ix) industry, innovation, and infrastructure, (x) reduced inequalities, (xi) sustainable cities and communities, (xii) responsible consumption and production, (xiii) climate action, (xiv) life below water, (xv) life on land, (xvi) peace, justice, and strong institutions, as well as (xvii) partnership for the goals (Széchenyi István University, 2023). From this list related to railways, the six most considerable and most important areas are the following: (vii), (ix), (xi), (xii), (xiii) as well as (xv). Considering the space limitations, this literature review will emphasize and highlight these six segments to make the current study as detailed as possible. Of course, the railways can also be linked to the other eleven areas, but not as closely as the six highlighted priority areas. In the course of the analysis, it is not marked in every place exactly to which segment each chapter or paragraph belongs, but in most cases, it can be clearly identified without these remarks.

In the first instance (1), lowering carbon dioxide and other pollutants and harmful gases, chemicals, and so on can be addressed using specific and appropriate production processes and goods with the smallest possible ecological footprint (Wen and Song, 2022). (a) Fixed-rail transit is generally the most energy-efficient, ecologically friendly, and safe land passenger and freight transportation. When compared to air transport,

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journey and transit times are much longer; when compared to water transport, efficiency is lower. However, ecologically sustainable service and safety are also important considerations. The CO_2 emissions of trucks can reach 7-13 times the level of electric rail freight transport in the 3.5-7.5 t maximum permissible weight category (366...693 g/tkm compared to 52 g/tkm, where "tkm" means ton-kilometers) (KTI, 2014a). In the category above 32 t, the CO_2 emissions are also 1.23-1.96 times higher. For passenger transport, the ratio is at least three times higher than for passenger cars (42 g/pkm compared to 14 g/pkm for rail passenger transport, where "pkm" means passenger kilometers) but can be as high as 11.3 times (KTI, 2014b). For airplanes, the ratio is 20.4 times, with air passenger transport at 285 g/pkm (KTI, 2014b). The average energy demand for electric railways is 18 kWh/100 pkm, compared to 58 kWh/100 pkm for diesel cars, 74 kWh/100 pkm for petrol cars, and 75 kWh/100 pkm for aircraft (KTI, 2007). Another statistical site shows that cars require almost 2.2 times more energy per pkm than buses and seven times more than rail. Inland air transport is twice as energy-intensive as passenger cars and 15 times more energy-intensive than rail transport (Odyssee-Mure, 2019). (b) In the case of building materials, using environmentally friendly materials such as hemp, corn stalk block, reed, and so on, or possibly earthen masonry. Tougher materials offer increased hardness and/or mechanical resistance, resulting in a longer lifespan and lower maintenance requirements; they are more cost-effective and less environmentally harmful. (d) The selection of recyclable materials, such as metals, plastics, glass, paper, and so on.

The following is the second major area (2) identified. Reducing the quantity of energy required and utilizing more efficient technologies, maybe (also) using renewable energy. For example, (a) less usage of fossil fuels, more sophisticated technology, less energy consumed, and hence less pollution. Preference for power facilities that already employ renewable energy to generate energy (mainly electricity), such as solar, wind, and hydropower.

The third major part is a mixed one. (a) Low environmental noise and vibration levels should be considered through specific flexible materials, rail grinding, wheel profiling, noise barriers, and so on. (b) The construction of railway lines that are more attractive to the sight (aesthetic, closer to the environment, more liveable), for example, the construction of imposing viaducts in the countryside, tunnels, or underground railway lines.

The current article aims to present the relevancy of sustainability in railways. So-called five case studies were collected in which the most considerable details are shown; see Sections 2.1-2.5. It should be noted, of course, that the case studies presented do not cover the full spectrum of the subject area due to the six sustainability areas mentioned above and the limited space of the article. The article is intended primarily as a thought-provoking one.

2. Case studies in the sustainability of railways

2.1 Issues of security of supply in the case of railway ballast

For the production and maintenance of railway ballast, the construction industry heavily relies on quarries and gravel pits. The decreasing availability of raw material stocks affects the proportion of raw materials representing the highest quality, making railway ballast production more difficult year after year. Mining companies that produce railway ballast meet aggregate demand for railroad construction and additional road, bridge, and other construction projects. SNAP-SEE and other European surveys ('Sustainable Aggregates Planning in South East Europe (SNAP-SEE)', 2023) demonstrate that primary product production will continue to be the central pillar of raw material supply in the future, with primary raw materials and quarries accounting for more than 80 % of demand.

The Hungarian construction industry uses domestic, state-owned raw materials, particularly in mix production and (railway) ballast bed construction. Imports are negligible, coming primarily from Slovakia and Romania and, to a lesser extent, from Austria. The use of various types of crushed stones in mass-produced asphalt mixtures exacerbates sustainability, requiring an average of 1.5-1.7 t of raw materials to produce one ton of asphalt mixture. (Values are based on unpublished and unofficial sales and production data from Colas Északkő Ltd.).

The production rate of the 32/50 mm fraction for railway construction is approximately 25 %, which strains the raw material's inherent quality limitations. A maximum of 25 % of the processed best-quality raw material can be produced in the case of railway ballast production. Managing stocks of decreasing quantity and varying quality is critical, including increased recycling of demolished road construction materials, industrial byproducts for road construction, and low-quality stone materials in appropriate places.

The continuous development of developed countries' road and railway networks necessitates applying various mineral raw materials, such as stone aggregates, for pavements and railway ballast structures. The management of heterogeneous resources in terms of decreasing quantity and quality is of fundamental national economic interest, as optimized use of these resources is a basic requirement for future pavement construction and maintenance.

Mineral resource accessibility research projects, such as the SaRMA (Blengini et al., 2012) and SNAP-SEE projects, have been carried out. However, the user industry's rules, application criteria, and regional differences were not investigated. Analyzing available results from the user industry's perspective and supplementing special target studies can significantly contribute to optimizing domestic application requirements for available mineral resources, ensuring the mineral resources required for long-term construction and maintenance.

2.2 Sustainability in the design and construction technologies of railway lines

The RAMS principle (Mahboob et al., 2018), which focuses on sustainability and the economy, is crucial in railway track design (RAMS means reliability, availability, maintainability, and safety). The engineer's responsibility is to choose materials and technologies that will extend the life of railway tracks while considering all influencing factors. At the design stage, two important factors to consider are lifetime engineering and life-cycle costs. However, many decisions are based on initial construction costs, which can be significantly higher than more modern, cost-effective, and environmentally friendly alternatives. BIM (building information modeling) should also be used in the design process because it allows various disciplines to create a three-dimensional model of the entire facility and can even serve as a track management system by the operator (Ajtayné Károlyfi et al., 2021).

Construction technologies are discussed in three parts: first, the machinery used, second – the materials used, and third – the construction management solutions. Large machines and machine chains on rails, medium-sized machines, e.g., heavy machines that can be moved by several people or other machines, machines that one or two people can move, and small hand-held machines are all examples of machinery. Machinery can fall into one of three categories: internal combustion engine (petrol or diesel), electric (battery and non-battery – purely solar, for example), or hybrid. Modern, low-emission internal combustion engines, primarily pure electric machines, are the most sustainable solutions. As previously stated, they are powered by electricity or can be solar-powered. The second consideration when discussing machinery is noise and vibration protection; clean electric machines are generally preferred due to reduced emissions (Robel Bahnbaumaschinen GmbH, 2023). The speed of the technology provided, the efficiency of the machinery (time and financial aspects, for which it is best to conduct a cost-benefit analysis, considering the whole life costs), the labor requirements, and accident safety should all be considered when selecting the machinery. Regarding construction technologies, it is crucial to consider whether the work is on the superstructure or the substructure (possibly both), and there are significant differences between earthmoving and big-machine technologies for the substructure.

The current paper can be referred to for materials used and to be incorporated. Due to space constraints, all structural elements and the various solutions that can be used for each element are not discussed.

The organization in terms of space and time has to be summarised. The procurement of materials (considering the distance and time of transport) and the organization of track times are critical factors (night track times are the most difficult for freight trains, while daytime track times are the most difficult for passenger trains). Furthermore, recycling of construction materials and parts in permanent ways, whether on-site or off-site, must play an increasingly important role in materials and function, both in construction technologies and materials.

2.3 Sustainability in the operation and maintenance technologies of railway lines

In recent decades, sustainability has resulted in numerous infrastructure innovations, such as green tracks and recycled plastic bundles. Green tracks have numerous benefits in improving the quality of urban life, such as regulating temperature, evaporation, and condensation, contributing to air cleaning, stormwater capture and drainage, and reducing noise pollution. German urban railways are pioneering grass tracks, which have been popular since the mid-1990s. Green tracks have been adapted to existing ballasted tracks, and their scale has grown significantly since the 2010s during renovations (DVB, 2023). Chen (2017) dealt with the analysis of mechanical characteristics of the polyurethane base plate for ballastless tracks of high-speed railways. Polyurethane, as an advanced composite material, has already been used as a filler in the gap between a high-speed track and a concrete roadbed, and it can not only provide extra elastic force but also repair defects and deformation of the track or concrete roadbed.

Green tracks have also been a focus of tramway reconstruction and line extension projects. Grass(ed) tracks have been a constant focus of reconstruction and line extension projects in the capital (Fuerst, 1999). Plastic sleepers were developed in Japan in the 1970s (Ferdous et al., 2021). Because of their mechanical properties and weight, they have a lifespan of up to 50 years and are suitable for replacing wooden sleepers. The EU Regulation 2011/71/EU (European Commission, 2011) is the primary impetus for their implementation in Europe, bans carbolic acid and creosote, the primary saturant in sleepers.

In neighboring countries, particularly Austria, there is a constant push to increase the use of 100 % renewable energy in infrastructure operations. Foreign small machine manufacturers have created innovative track maintenance and operation solutions, such as battery-powered small machines that can replace gasoline-powered machines. These machines offer lower noise emissions, safety, and ergonomics and can now compete in terms of performance with petrol-engine machines. When designing electric machines, the E^3 principle (economical-ecological-ergonomic) is considered (Keller, 2022). Currently, battery-powered track maintenance machines such as grinding machines, tamping machines, impact wrenches, rail cutting and drilling machines, and rail band saws are available. These innovations help to improve urban life and infrastructure sustainability.

2.4 Sustainability in the design, manufacture, and operation of railway vehicles

Environmental protection has become more critical in automobile and railway vehicle design and production. Consumers and manufacturers want eco-friendly, synthetic-like products. Rail is more environmentally friendly than road, and consumers expect used cars to be greener. Rail vehicles have a longer lifespan than road or air vehicles, so sustainable technologies emerge more slowly (Singh et al., 2022).

Technological advances, market needs, government policies, and constraints affect rail sector development. Railway vehicle design is affected by new materials and manufacturing processes (Blackwood et al., 2022). Faster top speeds require streamlined body shapes for dynamic stability and aerodynamic drag. Travelers want fast, comfortable rides, so axle and suspension systems must be excellent. Additionally, powertrain changes are significant. The government sets fire, accident, vibration, pollution, and noise standards for rail vehicles (Rodrigues et al., 2022).

Government policy, market, operational requirements, and technology are all factors that influence rail vehicle design (Matsika et al., 2013).

The choice of materials plays a key role in the design of railway vehicles. Important factors influencing the type of materials to be used: (i) function/structural, (ii) environment, (iii) cost, (iv) manufacturing/joining technologies, (v) lightweight, (vi) fire smoke and toxicity (Matsika et al., 2013).

Mild steel has traditionally been used for vehicle bodies. Lightweighting is helping other materials gain ground. They include composites, aluminum alloys, and high-performance steels. Lightweight and low fire, smoke, and toxicity (FST) make composites popular. They come in laminates, sandwiches, sheet molding compounds, and fiber-reinforced polymers. Manufacturing and design of rail vehicles aim for full life cycle design.

Vehicle bodies are made from recycled aluminum and steel, and sheet metal forming technologies are also environmentally friendly (Abe, 2021).

Since the late 1990s, technology developers have considered environmental issues like hazardous residues and production waste. Understanding chemical and physical reactions in manufacturing and their effects on humans and the environment is essential for sustainable and environmentally friendly manufacturing. Several studies have examined the environmental impact of forming lubricants (Peppas et al., 2021). Greener lubricants and cleaners should be used. Lubrication is the most crucial issue in "green" metalworking due to the environmental impact on product cleaning and auxiliary materials (Satheeshkumar et al., 2023).

According to the literature review, life cycle analysis needs to model and quantify process environmental impacts. Additionally, calculating the environmental impact of forming technologies is challenging and process-dependent (Gupta et al., 2022). It means that when comparing a conventional and an innovative forming process, for example, some specific aspects that depend on the respective processes must be considered; in fact, they may differ quite significantly in terms of tooling, operating parameters, etc. (Wiesenmayer et al., 2021). There are, therefore, many issues to consider, some of which are (i) process energy consumption, (ii) material wasting, (iii) GHG emissions (greenhouse gas), (iv) forming steps required in a manufacturing cycle, (v) lubricating conditions, (vi) tooling systems (materials and tool-life), (vii) temperature effects.

2.5 Sustainability in railway transport and the operation of railway vehicles according to energy consumption

Internal combustion engine propulsion is being phased out on roads and trains for environmental reasons. In this area, reducing CO_2 emissions is becoming an increasingly important consideration (International Energy Agency (IEA) and International Union of Railways (UIC), 2017); also, for detailed values, see Section 1. Electric traction has been used for a long time (Fischer and Kocsis Szürke, 2023), but some lines are still not electrified, primarily because they are mostly branch lines where electrification is not cost-effective (low-traffic lines). One solution could be using diesel-powered vehicles and storing energy in other forms without an overhead line. Such energy storage could be a supercapacitor (Vilberger et al., 2022) or a battery (Zhao et al., 2022), which can be charged by regenerative braking from a charging point or an overhead line if the vehicle can also run on an electrified section. Fuel cells (including hydrogen cells) can provide energy, and new vehicles and research are continuously being developed (Fakhreddine et al., 2023). Stadler's Eurodual and Siemens' Vectron Dual Mode locomotive are hybrid vehicles. These dual-mode locomotives with electric and diesel-electric propulsion can transport passengers and freight on electrified and non-electrified railway lines. The Bombardier TRAXX Last Mile locomotive also uses the diesel-electric propulsion system. When the stations are being marshaled, only a small diesel engine is installed to allow the vehicle to enter the overhead contactless tracks and sort the wagons. As a result, in diesel mode, this locomotive has limited speed and traction.

Electric multiple units (EMUs) with batteries are available from several major rail vehicle manufacturers, allowing these hybrid vehicles to run on electrified lines and tracks without overhead wires. BEMUs are Battery Electric

Multiple Units. Stadler, in collaboration with the Technical University of Berlin (TU Berlin) and the energy provider EWE AG, launched a research program in 2017 with funding from the German Federal Ministry of Economics and Energy to jointly develop and implement a battery-powered motor train that can run in pure electric mode on overhead lines, resulting in zero local CO_2 emissions (Popovich et al., 2021).

Concerns about the future of current diesel vehicles arise because procurement projects for railway companies are resource-intensive, and hybrid vehicles are typically more expensive than standard vehicles. Retired diesel vehicles may not be sold to other railways, making it challenging to sell them to other companies. One solution is to convert diesel vehicles into zero-local-emission vehicles, which requires a thorough assessment of the conditions and distances involved. The German regional railway company Erzgebirgsbahn, TU Chemnitz, TU Dresden, and the Fraunhofer Institute for Transport and Infrastructure Systems collaborated on the EcoTrain retrofitting vehicle development project (Fichtl et al., 2016). Another option is purely battery-powered high-speed rail vehicles with no other energy-supply systems, which are currently scarce on the market.

Generally, it is worth mentioning that the energy consumption of transportation infrastructure over its lifetime, which includes construction and operation energy consumption, is a significant factor that should be considered during the planning stage. Zhang et al. (2016) presented a superstructure-based mixed-integer programming (MIP) model for the energy consumption optimization of inter-city high-speed transport systems, a network design integration of aviation and high-speed railway, accounting for both energy consumption during infrastructure construction and energy consumption during subsequent operation processes. The goal was to optimize connections between large population centers and connections between modes of transport.

3. Conclusions

Sustainability related to railways was overviewed. The paper concentrated on reducing CO_2 and other pollutants in railway transportation by employing specific production technologies and products with a low environmental impact. Fixed-rail transportation was emphasized as the most energy-efficient, environmentally friendly, and safe mode of passenger and freight transportation. Mining and base material production, railway line design and construction, operation and maintenance, railway vehicle design, manufacture and operation, and energy consumption in railway transport were identified as the five main areas of sustainability. Small case studies are used to demonstrate these examples. The following main conclusions can be drawn based on the completed literature review. Quarries and gravel pits supply the construction industry, but decreased availability harms quality. Demolished materials and industrial waste must be recycled for pavement construction and maintenance. Engineers must choose materials and technologies that extend track lifetimes under the RAMS principle, which emphasizes sustainability and economy in permanent railroad methods. BIM aids life-cycle cost calculation. Construction technologies include equipment, materials, and management, primarily electric. Sustainable infrastructure innovations like green tracks and recycled plastics have improved urban life. Recycled materials and sustainability in sheet metal forming technologies show how important environmental protection is in car and train design and manufacturing. Environmental concerns drive the switch to electric road and rail traction as supercapacitors and batteries are investigated.

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