Spectrum of Mechanical Engineering and Operational Research

Journal homepage: www.smeor-journal.org
eISSN: 3042-0288

Sustainability and Smart Systems in Transportation Infrastructure: A Mini-Review

Szabolcs Fischer[1,*], Bálint Molnár[1], Bence Hermán[1], Klaudia Madarász[1], Csaba Tóth[2], Ádám Titrik[1]

[1] Central Campus Győr, Széchenyi István University, Győr, Hungary
[2] Department of Highway and Railway Engineering, Faculty of Civil Engineering, Budapest University of Technology and Economics, Budapest, Hungary

ARTICLE INFO

Article history:
Received 3 January 2026
Received in revised form 6 March 2026
Accepted 11 April 2026
Available online 20 April 2026

Keywords:
Sustainable transportation; Green infrastructure; Low-carbon materials; Intelligent Transport Systems (ITS); Decarbonization

ABSTRACT

Road and railway systems are fundamental to modern mobility, yet they also generate considerable environmental impacts through fuel consumption, greenhouse gas emissions, material production, land use, and recurring maintenance needs. This mini-review examines recent advances in sustainable and smart transportation infrastructure, with particular emphasis on both road and rail applications. The analysis is organized into four thematic areas: sustainable materials, sustainable construction, sustainable power systems, and smart infrastructure technologies. For road transport, the review covers recycled and porous pavements, low-energy asphalt solutions, intelligent pavement structures, and the infrastructure implications of electric and hydrogen mobility. For railways, it discusses regenerative braking, renewable-energy integration, low-emission track-related materials, energy storage solutions, and digital maintenance systems. The study also addresses intelligent transport systems that improve traffic efficiency, reduce energy demand, and mitigate emissions through monitoring, automation, and data-driven decision-making. The reviewed literature indicates that the most promising sustainable solutions are not always the most technologically advanced. In several cases, well-established approaches such as recycled asphalt, warm-mix asphalt, regenerative braking, and predictive digital maintenance currently show greater practical maturity than emerging smart infrastructure concepts, which remain largely experimental and are only selectively applied. Overall, the findings highlight the need for broader implementation of sustainable materials, cleaner energy systems, and smart operation and maintenance strategies. The review also emphasizes the importance of life-cycle assessment, effective deployment, and long-term field-performance monitoring to support the successful transition toward low-carbon and resource-efficient transportation infrastructure.

---

[*] *Corresponding author.*
E-mail address: fischersz@sze.hu

https://doi.org/10.31181/smeor31202658

1. Introduction

Transportation infrastructure is a key element in modern society and a basic component of its social and economic development. The main part of this infrastructure consists of roads and railways. In addition to being a technological system, transport infrastructure is an important infrastructure for regional and global access. The building, use, and maintenance of transport infrastructure are resource-intensive and have considerable environmental impacts, including CO_2 emissions, energy and material consumption, land use, and waste generation. To assess the sustainability of transport infrastructure, one must consider the infrastructure's entire life cycle, not just the vehicle-use phase.

Maintaining transport infrastructure designed for long-lasting performance has become an important challenge. The effects of design and construction choices throughout the lifetime of structures can be far-reaching for environmental and economic performance. Sustainable transport development is heavily dependent on structures, materials, maintenance and rehabilitation technologies used in transport infrastructure. Hence, it is important to develop designs, materials, and maintenance technologies that are efficient in terms of structural performance, resource use, and, therefore, greenhouse gas emissions and consumption. More efficient structural and maintenance technologies should be part of the overall strategy to reduce energy consumption and enhance the effectiveness of maintenance work.

It is necessary to implement a range of complementary solutions, including new products, recycled products, low-carbon, energy-efficient construction methods, alternative propulsion and energy technologies, and digital technologies for remote monitoring and management of infrastructure. By limiting the environmental impact of transport infrastructure and improving the performance and durability of infrastructure networks, it is possible to implement a truly systemic approach to sustainability. Indeed, a sustainable approach requires analysis of the connections among materials, construction processes, energy consumption, and structural management.

The majority of environmental effects from infrastructure occur before it is in use. In the production, transportation and maintenance of the structure, large quantities of materials and energy are consumed. Such materials include cement, steel, asphalt and aggregates. Future maintenance for heavily used structures should also be considered. It is not enough to consider only the efficiency of infrastructure use. In addition, the embodied environmental effects and the future maintenance needs should be taken into account.

This article provides a mini-review of recent developments in sustainable road and railway infrastructure, covering four major areas: advanced materials; low-carbon technologies; alternative fuels and energy-generating technologies; and intelligent infrastructure technologies. It seeks to highlight the opportunities offered by recent developments in infrastructure technologies that are enabling advancements in sustainable transport systems. It also explores the environmental advantages of these developments, which contribute directly to improved safety, serviceability and reliability of transport infrastructure, which is the backbone of transport systems. This mini-review aims to summarize the opportunities and challenges of applying new materials and technologies to transport infrastructure.

This study is based on the assumption that sustainable transport infrastructure can only be achieved if the entire value chain, from resource extraction to operation and maintenance, is optimized. Consequently, sustainable transport infrastructure development must be an integrated effort that combines material innovations, sustainable construction methodologies, and low-energy infrastructure solutions, with smart, data-driven infrastructure management throughout the whole life cycle, rather than a patchwork of individual actions.

As shown in Figure 1, all stages of the infrastructure lifecycle offer opportunities for sustainable solutions. Reviewed solutions can contribute to several sustainability targets, including resource efficiency, reduced greenhouse gas emissions, long-term performance, and closed-loop systems. This paper supports the assertion that the transport sector must adopt a holistic approach to transport systems that covers the full lifecycle, and that the scope for individual improvements and spot optimizations is very limited.

Fig. 1. Lifecycle framework of sustainability interventions in transportation infrastructure (own figure composed on the basis of the current entire paper)

The structure of the paper is as follows. Sections 2 and 3 provide brief overviews of sustainable innovations in road and railway transportation, respectively, while Section 4 compares them in terms of sustainability. The main technological, economic, and regulatory obstacles to implementing these innovative sustainable transport solutions are discussed in Section 5. The main conclusions and recommendations for further research are summarized in Section 6.

2. Sustainable innovations in road transportation

Road transport is by far the most prevalent mode of transport for passengers and, to a significant degree, for freight. Even small improvements in the road network could deliver enormous cumulative benefits. Potential opportunities for improvement in the road sector reported in the literature include the use of recycled pavements, low-temperature asphalt mix production, connected vehicles, and smart lighting. Although many of the opportunities referred to above are becoming more prevalent, there is no reason to believe that their delivery would be unsustainable in the contexts in which they are required.

Figure 2 illustrates a possible technological roadmap for materials, structure, propulsion, and intelligent systems, based on [1-8]. It is very useful to determine the maturity level of each technology. Figure 2 indicates that:

i. Recycled asphalt, selected secondary additives and permeable pavements are widely used in several regions of the world.

ii. Warm-mix asphalt and cold in-situ recycling are under development to reduce energy consumption while maintaining the general structure of well-established road-building processes for hot-mix asphalt.
iii. Smart lighting, connected mobility, and distributed roadway-energy systems are developing a new generation of smart, data-driven infrastructure, moving away from the passive infrastructure of traditional roads.

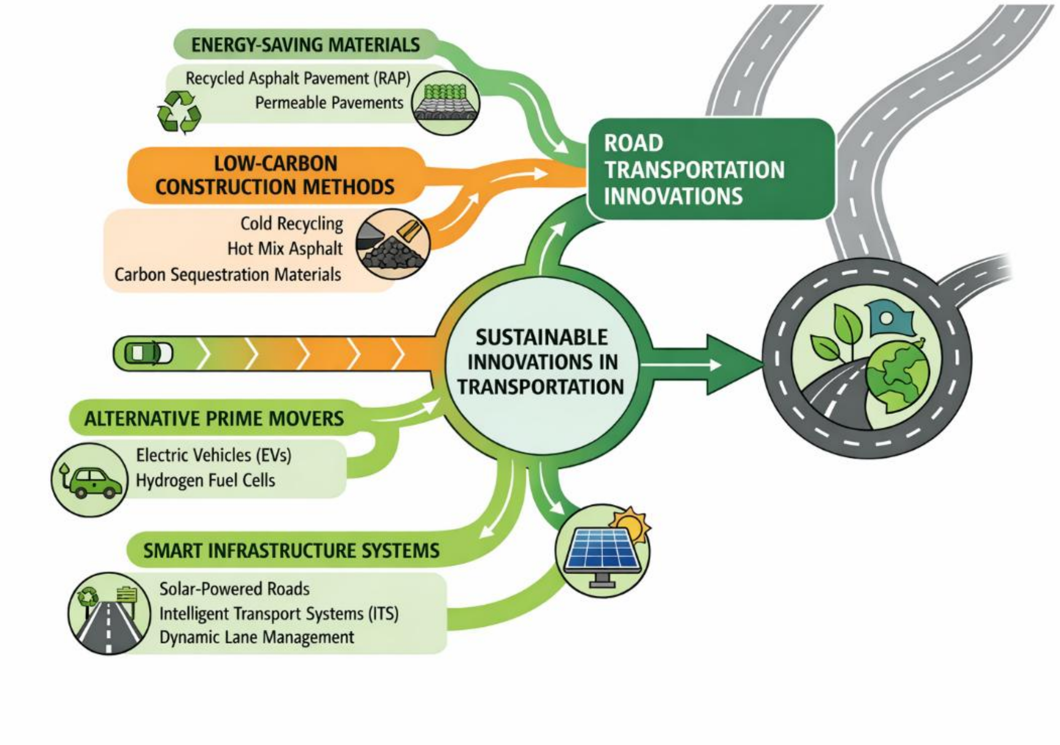

Fig. 2. A technological roadmap of sustainable innovations in road transportation systems (own figure composed on the basis of Section 2)

There is no parity in the volume of reliable information available for alternative fuels and technologies. Some have the advantage of a substantial body of accumulated engineering design and in-use performance information, whereas others are based on single feasibility studies, conceptual designs, and a few field trials or small-scale on-road demonstrations that have been reported as successful but have neither been replicated nor proven to be sustainable. Therefore, this review is intended to serve as a catalog of ideas proposed for the road transport sector, with notes on their maturity and potential for near-term development and application, as either improvements to existing conventional technology or more radical replacements.

2.1 Recycled Materials and Pavement Engineering

The growing awareness of environmental protection within sustainable development has made the use of recycled materials a priority, especially in pavement engineering. The use of Recycled Asphalt Pavement (RAP) provides an effective means of conserving natural resources, such as aggregates and bitumen, and reducing solid waste. The effectiveness of RAP use depends heavily on its application. While RAP is a good conservation tool, it is equally important to ensure the mix design is appropriate and that binder degradation, increased brittleness, and early thermal cracking are avoided.

The paper by Amakye *et al.,* [1] focused on the surface course and subgrade performance. The paper discussed sustainable road pavements on clay subgrade stabilized with eco-friendly cementitious materials. The pavement foundation is where problems most often occur. Even with the best-designed and constructed surface layers, problems with the subgrade are almost inevitable. Premature pavement failure will always occur if the subgrade is weak, saturated, or unstable. So, the eco-friendly stabilization method, which helps reduce embodied carbon and costs, is often rewarded with structural improvements to pavements and their longer life [1].

Sharma *et al.,* [2] applied a life-cycle perspective to study the use of recycled and secondary materials in road construction using LCA. This study is relevant because it goes beyond the common assumption that using recycled materials in road construction is inherently sustainable. The authors argue that the climate benefits of using recycled materials can vary depending on several factors, including energy consumption during processing and transportation, performance within the pavement structure, and the materials' reusability. Hence, recycled mix designs that require extensive processing and have a short pavement life will lose most of their embodied climate benefits. Use of recycled materials in pavement engineering is therefore recommended, but only under certain conditions, such as when a lifecycle assessment is carried out, the pavement structure is adapted to the expected traffic load, and the area's climate is known. Targets such as "reusing 80 % of old materials in new pavements" are therefore not relevant in scientific literature.

In practice, the most effective recycled mixes are usually those designed in the distress mode. That is rutting in one case and fatigue and cracking in the other. Mix design considerations in these cases involve the mix aggregate structure and the mix binder stiffness in the first instance, and, in the second, avoiding excessive stiffness and brittleness. It is increasingly recognized in literature that the performance of recycled materials can be viewed more positively, in an engineering-based manner rather than in a simplistic "downgrade and accept" mode. This trend is critical to considering sustainability beyond a mere marketing context, and hence in a more truly structural design context.

Recent literature on reused pavement materials generally focuses on laboratory characteristics and short-term laboratory comparisons. There are no detailed long-term field studies of reused materials. This does not mean that reused materials cannot be sustainable, but only that new materials cannot be considered sustainable in an engineering sense if the reuse of old, often highly reliable, materials is ruled out a priori.

2.2 Low-Energy Construction and Sequestration

As discussed earlier, using recycled materials reduces the environmental impact of the road structure itself. Reducing energy consumption in the production of new materials is also important. Cold in-situ recycling (CIR) is an example of a low-energy approach to road construction. Tabaković *et al.,* [3] also noted that CIR can have a lower environmental impact than hot-mix recycling due to lower energy consumption. CIR is a good method for rural roads far from asphalt plants. Transporting hot mix to the construction site is not only expensive but also harmful to the environment.

This result may seem more important than it appears. Material transport is often considered a relatively minor factor in assessing the sustainability of materials and systems. However, in the context of distributed road networks, the impact of material transport can be significant, particularly when transportation costs and emissions account for a high proportion of total costs and impacts. In-place and near-place re-use of materials can also provide additional benefits beyond energy savings at the plant. Less trucking is required, site disruption is reduced, and work zones are on the road for a shorter time. These are important considerations in network rehabilitation projects where network access must be maintained for users.

Warm-mix asphalt (WMA) is an alternative that reduces the environmental impacts of asphalt pavement construction. In this study, Calabi-Floody *et al.,* [4] assessed the environmental impact of five warm-mix asphalt mixes composed of natural zeolite and reclaimed asphalt pavement (RAP). The comparison baseline was a 155 °C hot-mix asphalt (HMA). The results revealed that using WMA significantly reduced fuel consumption and emissions while maintaining equivalent performance to hot-mix asphalt. Low carbon emissions, along with compatibility with current pavement infrastructure and processes in the asphalt pavement industry, are key factors influencing the adoption of sustainable materials and practices in pavement structures.

Wörner and Stöckert [5] present an operational perspective, demonstrating how data analytics can improve processes in asphalt road construction. They think that, in addition to using new materials and binders, sustainability should also mean less waste, less variation between processes, less rework, and less inefficiency. So, even "theoretically" sustainable roads can lose much of their potential in practice due to inadequate control of compaction, construction instability, and unnecessary maintenance [5].

The use of permeable pavements and carbonation-related materials is another way to further enhance sustainability in the built environment. Permeable pavement refers to a pavement or surface that allows stormwater to pass through and filter out sediment and other debris. Uses of permeable pavements include reducing stormwater runoff, allowing stormwater to percolate into the soil and aiding in stormwater management. There is increasing interest in using materials that undergo carbonation and waste materials derived from industrial processes. The purpose of using these materials is either to reduce net greenhouse gas emissions or to increase carbon storage in the material. However, these claims also require verification. There are several issues associated with permeable pavement materials, including clogging, maintenance and severe weather. Similarly, the potential for carbonation to result in carbon storage has not yet been proven, and performance and actual environmental benefits require validation. Nonetheless, the most reliable information currently suggests that low-carbon construction can be comparable across a variety of metrics, including lifecycle analysis, cost, and process performance [2-5].

2.3 Future Powertrains and Grid Integration

An environmentally friendly pavement alone does not make a road system sustainable. The development of new types of vehicle power-trains, including electric and possibly hydrogen, is also important. According to Liu *et al.,* [6], the transition toward a more intelligent energy system in the transport sector will affect not only vehicle energy consumption but also the broader management and coordination of transport systems. For electric vehicles in particular, this shift involves multiple challenges, including powertrain design, charging infrastructure deployment, smart grid management, battery integration, and the operation of transport network management systems.

If the emissions from charging an electric vehicle are not managed, they will simply be shifted from the tailpipe to the power station. This system's perspective is a recurring theme in our literature review. A clean vehicle is not necessarily clean transport if the transport and energy systems are not aligned.

Song *et al.,* [7] analyzed the relationships between the propulsion and traffic. The study of L2 CAVs found that they could reduce average travel time and individual fuel consumption in most cases, except in cases with negative energy effects due to increased effective road capacity, which may lead to rebound effects.

The prevailing view is that hydrogen will be used as an auxiliary fuel alongside battery-electric powertrains. Typically, the advantages of hydrogen are described in scenarios where battery performance is a hurdle for battery-electric long-range heavy-duty vehicles. e.g., due to high battery weights, slow charging times, or long vehicle travel routes. This issue has already been noted in numerous literature sources: the environmental impact of hydrogen depends heavily on production, compression/liquefaction, gas transport, and the corresponding storage and refueling infrastructure. Thus, hydrogen itself is not a clean energy carrier, as the production methods and their impacts are neither fully transparent nor well understood. Therefore, in most scenarios, rather than battery-electric or hydrogen vehicles, different vehicles and energy carriers will be needed for various heavy-duty applications. This means there is no single technology that would suit all road applications. Still, the right technology mix for the application will be determined by the composition of the future energy system for transport, depending on the vehicle class, the operating profile, and the possible fuel and energy carrier options, as well as the technology mixes that can be chosen for each application [6,7].

Above all, one thing needs to be said: the technology of the future cars is being discussed almost exclusively in isolation from the infrastructure on which they will operate. This is not right. Just as important as the vehicles' technology will be the charging grid, the energy mix, motorists' driving behavior, logistics structures, and traffic management systems.

2.4 Intelligent Infrastructure Systems (ITS)

The term smart infrastructure is frequently met in the context of transport. However, what is "smart" and who will benefit from it? Sensors are installed on the roads to monitor traffic and environmental conditions. The data they collect is sent via wireless communication technologies to other vehicles, smart roadside units, and central management stations. Ultimately, the control system makes the necessary decisions to respond optimally to the current situation through measures such as smart traffic lights, traffic lane management, and speed adjustments.

An interesting example in [8] illustrates the potentially dramatic effect of a very simple act of intelligence. The subject of this paper is the intelligent control of road lighting. Bozorg and Bullough [8] describe several static, semi-dynamic, and dynamic lighting regimes that can be used to save energy without compromising road safety. Again, the actual savings appear modest compared with some of the more far-reaching ideas for smart roads. Nevertheless, the potential benefit is real and non-trivial. An everyday roadside asset can be made more efficient through control and control systems, with a perfectly intelligible control mechanism, without the need for more exotic or visionary designs of road infrastructure, as illustrated in [8].

Optimizing real-time traffic signal control can benefit from a network-wide operational strategy that leverages Smart Corridors' network-wide connectivity and sensor infrastructure. This strategy can also be applied to other intelligent transportation systems (ITS) devices and infrastructure, such as adaptive signal control, variable speed-limit signage, dynamic lane management, and vehicle-to-infrastructure communications, to reduce acceleration and braking, improve signal coordination across the network, and maximize infrastructure use. Reducing stop-and-go driving and idling also provides a range of sustainable transport benefits, such as reducing driver and passenger energy consumption, improving travel reliability and reducing individual trip emissions [7,8].

This paper is not an endorsement of Intelligent Transport Systems (ITS), but rather an attempt to analyze the sustainability of ITS in a more critical manner. The prevalent view that transport management and technology can do a great deal to promote sustainable transport is not always valid, and it has been shown that the expected benefits of improved traffic management and control can be readily undermined by increased travel activity, which often arises as a consequence of the improved conditions. Some of the innovative ideas proposed for the intelligent road are perhaps more sensational than they are technically or economically sound. Problems with structural integrity, skid resistance, and high cost have plagued some first-generation experiments with solar roads, and new versions of the technology are currently being tested on low-traffic roads, such as bike paths and entrance roads to parking lots. The potential for ITS to contribute to sustainable transport is therefore limited and is currently realized mainly through the more established technologies of dynamic traffic management and operations in transport networks, rather than through some of the more ambitious and perhaps less feasible ideas for creating the "smart pavement".

3. Sustainable innovations in railway transportation

Low rolling resistance and high transport capacity make rail transport more sustainable than road transport for two physical reasons. The high mechanical efficiency of a steel wheel on a steel rail allows the transport of large numbers of passengers and freight over short distances. However, building the infrastructure is carbon- and resource-intensive and expensive to maintain, especially in tunnels, stations, structures, and electrification. The literature is large and aims to prevent the simplification that rail transport is always sustainable.

Railway papers and publications within the scope dealt with the following five topics:

i. regenerative braking and energy recovery;
ii. sustainable materials and structures;
iii. electrification and alternatives to hydrogen;
iv. new concepts for energy storage;
v. digitalized life cycle management.

The broad scope of topics clearly shows that the development of railway sustainability does not merely concern the more efficient operation of the traction system.

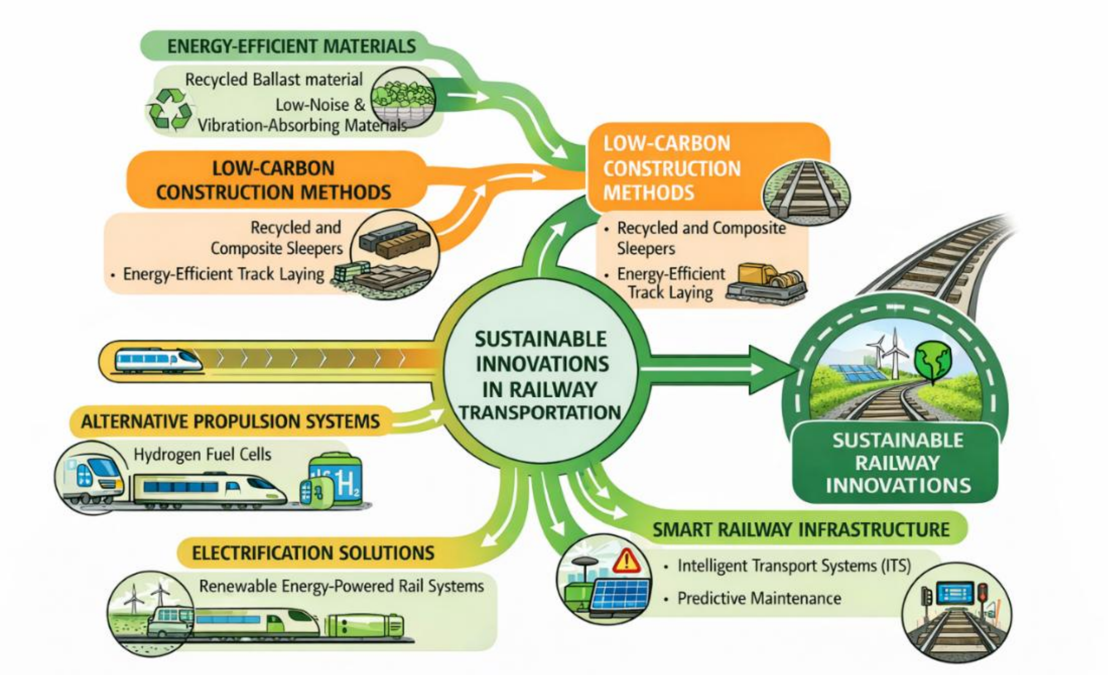

Fig. 3. A technological roadmap of sustainable innovations in railway transportation systems (own figure composed on the basis of Section 3)

Figure 3 presents the materials, construction technologies, propulsion technologies, electrification systems, and infrastructure technologies that enable sustainable railway transportation.

It is important to note that this figure organizes the main innovation fields into interlinked domains that significantly impact the environmental performance of railways. For example, recycled ballast, low-noise and vibration-reducing materials, and recycled or composite sleepers have already enabled more resource-efficient railway track construction. On the other hand, hydrogen-fueled propulsion and renewable-energy-powered rail are considered technologies in the transition phase toward sustainable railways, with the understanding that the use of fossil fuels for traction will be reduced, especially on lines where electrification is not yet established or is only partially established. In the same way, intelligent transport systems and predictive maintenance are considered part of the transformation of conventional railway management toward more intelligent, digitalized and resource-efficient infrastructures.

3.1 Energy Recovery and Thermal Protection

Regenerative braking is one of the many environmental benefits of rail. On electrified lines, during braking, the train converts part of its kinetic energy into electric current. This current can be used by other trains passing through the section, injected into the grid, or simply stored in batteries. In particular, regenerative braking is highly effective in urban and suburban mass transit systems with frequent stops [9].

In the Addis Ababa Light Rail study by Nkurunziza *et al.,* [10], the regenerative braking effect is quantified rather than just discussed in theoretical terms. The main objective of this study was to assess the amount of regenerative energy that is recovered as a percentage of the total train energy consumption for both east-west and west-east directions. Although the percentages vary with line characteristics and the timetable, regenerative braking is not a marginal improvement but plays a significant role in traction and energy management in urban rail systems with high stopping frequency [10].

The recovered energy in the traction power system has economic value only when there are corresponding use systems, such as smart substations, near-train demand, and wayside storage. As Zhou [11] shows, technologies and institutions need to be improved to achieve energy efficiency in the railway system. If there is no corresponding system in the power network, the recovered energy will be wasted if the train is equipped with a regenerative braking system.

The advantages of smart rail microgrid management are remarkable. Thus, it is possible to achieve reductions in energy consumption along the entire railway infrastructure of up to 30%. The quantitative assessment by Nkurunziza *et al.,* [10] of the Addis Ababa Light Rail Transit demonstrates, by its own evidence, that regenerative braking is a fundamental energy management function and not merely an insignificant improvement.

One of the significant elements of the sustainable rail track structure is thermal protection. Although thermal protection systems on rail track structure are not energy recovery systems, they are very important. Ižvolt *et al.,* [12] conducted experiments and simulations on new thermal insulation materials for railway track structures and showed that sensitive structures at risk of ground frost can be better protected through optimization. The main reasons for the high amount of maintenance work, material and resource consumption, and train disruptions are damage caused by freeze-thaw processes, track structure instability due to deviations from design dimensions, and failures in the substructure. Stable temperature in the rail track structure also means a more sustainable rail track system, since it does not require the resource-intensive maintenance work from time to time [12].

Tang *et al.,* [13] discuss the green degree of railway engineering from a system perspective using a dynamic strategic framework. The authors point out that rail sustainability cannot be achieved through a single technology. Instead, it has to be achieved through a series of decisions made throughout the processes of material, design, construction, operation, and management of the rail.

3.2 Sustainable Binders and Recycled Components

The track structure is a major opportunity to reduce the railway system's carbon footprint. The current structure of the track is largely based on high-carbon-content products, such as cement, concrete, steel, and quarried materials. The use of recycled ballast materials, perhaps with lower-carbon binders, and alternative sub-ballast materials is becoming increasingly topical.

The papers considered dealt with the structural behavior of the rail track. These papers dealt with various sub-ballast alternatives in relation to track loading and sustainability. Castro *et al.,* [14] have related sub-ballast behavior to drainage, load distribution, deformation-zone behavior, and long-term structural stability. The paper confirms that the study investigated the materials and quantities used in a maintenance train with a ballast recycling system, and concluded that soils stabilized with fouled recycled ballast can be used as a sustainable sub-ballast for heavy-haul tracks.

Huang *et al.,* [15] studied the life cycle of construction and demolition waste (CDW) from railway engineering activities. Although the rail sector has not been thoroughly investigated for sustainability assessment, which mainly focuses on the operational stage, the management of CDW resulting from ground excavation, the dismantling of railway facilities, and the demolition of auxiliary buildings and other infrastructure has not yet been effectively addressed. As the authors indicate, excavated materials, dismantled railway structures, and demolition products will increasingly be considered secondary resources. Given the long asset lifetimes and the extensive maintenance and renovation work in the rail sector, life-cycle thinking is highly relevant. Material-flow management is therefore crucial for implementing the principles of the circular economy.

Also, in the Korean urban railway assessment [9], the choice of material is of significant importance. A life-cycle analysis of different alternatives, such as asphalt and cement concrete tracks, showed that an asphalt concrete track results in around 2.65 times lower CO_2 emissions and around EUR 29,000 per kilometer less. High material consumption of rail structures explains this. The amounts of different materials in rail structures can vary widely, but, for example, [9] reports that up to 1,998 tons of asphalt mixture, 1,820 m^3 of cement concrete, and 59 tons of reinforcing steel are needed per kilometer.

Krishankumar *et al.,* [16] have attempted to broaden the material selection process by demonstrating the feasibility of ranking zero-carbon structural materials for construction applications. The paper has no relation to the railway sector. Still, it is important to recognize that material selection for low-carbon products must consider several parameters. Parameters such as durability, availability, cost, safety, compatibility with maintenance materials, and design performance are equally important [16].

This is an important aspect. Materials cannot be chosen solely based on their environmental characteristics. Railway infrastructure is a safety structure under high loading conditions and must provide long-term structural performance. Low-carbon or recycled railway materials will therefore require more thorough, longer-term validation than is currently provided in the initial stages of sustainability discussions. A few promising developments are underway, but the engineering criteria for the use of such products on the railways remain sufficiently high.

3.3 Electrification and Hydrogen Rail

Electrification of railways is considered one of the most efficient measures to reduce operational emissions in the transport sector. As mentioned earlier, electrified tracks provide high performance, enable the use of large amounts of renewable energy, and are free of local air pollution. However, full electrification of railway lines is not economically viable in many cases, especially on low-density regional rail lines, light rail networks with fragmented routes, and in situations where topography and infrastructure conditions are poor. In this context, there has been significant interest in battery-electric and hydrogen-fueled trains in recent years.

Battery Electric Multiple Units (BEMUs) are intended for routes where catenary-supplied electric traction is used on electrified sections and battery-electric traction on non-electrified sections [17]. So, full electrification of the corridor is not required, and diesel is not needed. Battery trains can therefore be used where electrification is not economical for conventional trains, thereby creating significant decarbonization potential [17].

In addition to battery-powered trains, hydrogen fuel-cell trains can also be zero-tailpipe-emission [17]. Hydrogen trains will be an alternative when battery technology is not suitable. For example, when the route lacks charging points or is longer, and the refueling stations are in urban centers. Just like with transport, the carbon sustainability of hydrogen will also be a determining factor. So that hydrogen trains are low-carbon if the hydrogen is produced and supplied in a low-carbon way [17].

Zhang *et al.,* [17] aim to investigate carbon emissions across various stages of the life cycle of urban railways. The authors examine emissions generated during the construction and operation of rail-transit infrastructure, identifying the various stages in the life cycle of urban rail transport and their effects on carbon emissions [17,18]. They further add that the propulsion systems of rail transit vehicles account for only a small proportion of the entire railway system, and that emissions from structures such as stations, depots, power distribution rooms, and civil construction cannot be ignored. The study's findings confirm those of a previous study on carbon emissions from Korean urban railways: the type of trackbed material can significantly affect carbon dioxide emissions and costs.

The choice between batteries and hydrogen in rail transport is not absolute and will depend on local conditions. Several parameters will have to be taken into account, such as the length, slope, and layout of the lines; the organization of railway stations (depots); the schedules and frequencies of trains; and access to the network. The majority of the literature suggests that this is not a question of a single solution for the railways.

3.4 Advanced Energy Storage and Storage Physics

Regenerative braking performance can be improved by efficiently storing and reusing braking energy. Energy storage is currently a hot topic in the railway sector. Nkurunziza *et al.,* [10] indicated that assessing the recoverable braking energy in urban railway operations is important. Fischer and Kocsis Szürke [19] introduced a method for identifying energy losses in electric railway vehicles. The main aim of this work is to investigate the conversion, transmission, and other onboard energy losses to enhance braking energy recovery.

Khodaparastan and Mohamed [20] compared flywheels and supercapacitors as wayside storage for electric rail transit. The choice of energy storage technology depends on cycling characteristics, power requirements, the system's time constant, and overall performance criteria. The supercapacitor is suitable for high-cycle charge/discharge applications, such as frequent station-to-station stops in electric rail transit. The flywheel may apply to some high-power, repetitive applications. This work advances the discussion of energy storage in rail transit from general concepts to an engineering level by identifying the appropriate energy storage technology for the required applications.

Allen and Chien [21] have also validated that regenerative braking performance can be improved by adjusting the speed curve, showing that storage is not the main factor and that train control is also important. Li *et al.,* [22] have further advanced research on the application of superconducting energy storage technology in urban rail transit, indicating that this field is now developing toward technology improvement and innovation [21,22].

Many of the proposed energy-efficiency storage solutions are now being implemented. However, it is important to remember that there are costs and material consumption associated with energy storage systems (ESS), as well as increased complexity in control, operation, and maintenance. Therefore, the sustainability value of storage systems should not be taken for granted, but evaluated on a net lifecycle basis. Research in this area is strongest when storage, control and system losses are considered as a system rather than as assumed benefits of storage.

3.5 Digitalization and the "Digital Twin" Framework

The buzzword in the field of infrastructure management for sustainable structures is digitalization. Predictive maintenance, smart operations, digital twins, and lifecycle management of structures are examples of digitalization in the railway sector. The purpose of digitalization is to prevent unnecessary maintenance stops, ensure operational reliability, and support long-term decision-making. The true sustainability effects of digitalization, however, are achieved only when operations are based on it. A highly developed model does not contribute to sustainability if it is not utilized in maintenance practices.

Kaewunruen *et al.,* [23] reported that, through a digital-twin-aided lifecycle assessment of a downtown subway station in Bangkok, 78% of the structure's total cost is incurred during construction. Also, 67% of the structure's total carbon footprint results from the operational and maintenance stage. They also calculated the carbon footprint of each material: 43.66% of the total carbon footprint is attributed to concrete, 29.73% to steel bars, 17.64% to aluminum alloy, etc. This study uses the digital twin approach to determine which lifecycle stage of a structure requires greater attention for sustainable performance.

Kaewunruen *et al.,* [24] is another study on the cost and life-cycle assessment of tunnels for a high-speed railway in China, which includes calculations of CO_2 emissions and energy consumption throughout the tunnel's life. This work also points out that the infrastructure of low-carbon transport systems has a significant environmental impact due to the large amount of resources required for its maintenance and, above all, for its design and construction, a fact that is particularly striking in the case of long infrastructure works such as tunnels.

The work by Wu *et al.,* [25] and Mohamed Fadzil *et al.,* [26] supports the view that structural behavior and materials are very significant for sustainable railways. A digital system can be efficient and productive only if it accurately and fully reflects the physical aspects of engineering. Consequently, the use of digital twins is recommended to connect structural knowledge with lifecycle costs, maintenance activities, and carbon audits [23-26].

One of the many factors to consider is the perception that digitalization is a sustainable tool. Although data quality, interoperability, calibration and organizational capacity may be obstacles to digitalization, they are not the only challenges. The use of technology does not guarantee a sustainable solution; a high level of understanding is therefore required.

4. Comparative analysis of sustainable technologies

A more detailed examination of road and rail transport sustainability than the "rail is greener" soundbite reveals several structural advantages for rail, including lower rolling resistance, a higher payload, and greater opportunities for electrification. However, rail transport sustainability also depends heavily on a range of other factors, including transport volume, load factor, average passenger occupancy, infrastructure utilization, energy mix, and transport corridor characteristics.

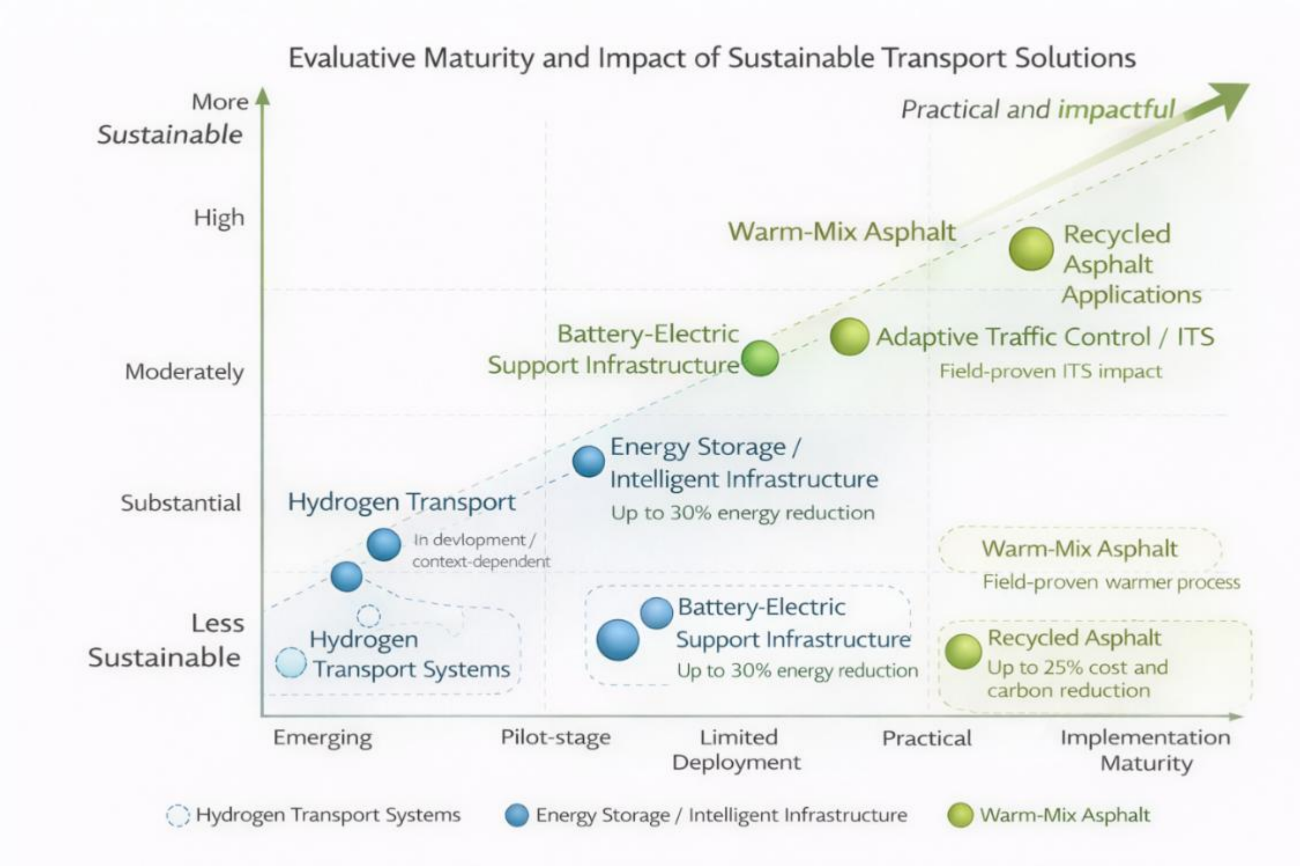

Fig. 4. Indicative positioning of reviewed sustainable transportation technologies by implementation maturity and sustainability benefit (own figure composed using Section 4)

Figure 4 presents a comparative synthesis of sustainable transportation technologies by technology maturity and environmental benefits. As shown, recycled asphalt, warm mix asphalt, and regenerative braking are close to practical maturity and offer significant environmental benefits. On the other hand, hydrogen-based transport technologies, energy storage, and smart infrastructure are less mature but have significant long-term potential. Therefore, sustainable transportation technologies vary in their technology readiness levels (TRLs), and the implementation of sustainable transport infrastructure will depend on environmental benefits, technology maturity, cost-effectiveness, and site-specificity.

4.1 Environmental efficiency comparison

The environmental impact of railways is lower for high-density freight and passenger transport than for road transport, especially on electrified lines. Other studies on the sustainability of railways can also be found, including the review by Ézsiás *et al.,* [27] and the review on the integration of railways with renewable energy by Alshoufi *et al.,* [28]. The latter mentions that sources of renewable energy suitable for railways include solar, wind, bioenergy, and kinetic energy harvested from rail tracks. Furthermore, intelligent multi-agent control of rail microgrids can lead to energy savings of up to 30%, a tangible, real-world effect rather than a purely symbolic one.

Studies on the sustainability and competitiveness of rail freight [29-31] also confirm that it must be part of a comprehensive, corridor-based infrastructure approach. Li *et al.,* [30] and Liu *et al.,* [31] have confirmed that the environmental and economic benefits of rail freight are greater when rail infrastructure is integrated into a corridor.

The environmental advantage of rail does not apply under all circumstances. The conditions for applying this advantage are not always fulfilled. In cases of low utilization of railway infrastructure or major infrastructure works combined with low train frequency, the disadvantages of rail are no longer offset by its advantages. In an optimized road network with alternative fuels, the use of rail in exceptional cases is also not rational [32]. The reasonable conclusion is not that one mode of transport is permanently the low-carbon transport mode. Rather, rail will, in many cases, be the low-carbon transport mode for heavy traffic under appropriate conditions for transport volumes, distances, and infrastructure.

4.2 Economic performance and logistics integration

One of the major challenges in increasing awareness of the economic benefits of railways is that significant rail infrastructure investments are required and are therefore not immediately visible. The positive environmental effects and the reduction of congestion, which are important to the long-term success of railways, are not always considered in cost-benefit analyses. When external effects and corridor performance are taken into account, the economics of railways improve. In research literature, many studies examine the external effects of road transport and evaluate the pros and cons of railways in achieving the intended modal shift. An example of this is a bilevel planning model for assigning freight transport to railways, proposed by Liu *et al.* [33] to shift freight from roads to railways. The model considers the costs of road congestion, railway capacity, and freight station capacity, as well as handling and transfer costs. EU targets include replacing at least 30% of road freight transport over 300 kilometers with alternative modes such as railways or waterways by 2030, and at least 50% by 2050 [33].

Morihladko and Dolinayová [34] provide an excellent contribution to the field of freight transport when they show, with proper coordination of transportation, that the transportation of one-off single wagon consignments is possible. Therefore, using the rail for block trains or oversized cargo is not always necessary. This can also be confirmed through further reading of other corridor studies, such as those by van Staden *et al.,* [35] and Li and Hilmola [36]. Introducing intermodal and synchromodal transport solutions leads to lower costs and reduced environmental impact; therefore, the most sustainable freight transport system is not on the road or on the railways, but in the combination of both.

The basis for comparison may change depending on the boundary conditions assumed. Based solely on capital costs, rail appears to be the most expensive option. However, when lifecycle costs are included alongside costs of congestion, air quality, land use, and the potential for future-proofing, the relative merits and disadvantages of transport infrastructure may be very different.

4.3 Scalability, regional development, and spatial effects

Scalability is a long-term rail advantage. A rail corridor can carry large volumes of activity in a small area of land. On the surface of the road network, it is often difficult to achieve a significant increase in capacity because the road must be widened repeatedly, and large areas of land must be cleared and set aside for the new lanes. Shabani and Safaie [37], Fageda and Olivieri [38], and Lin *et al.,* [39] and others, provide several arguments about how transport infrastructure can influence the development, accessibility and convergence of regions, so that the short-term conditions of transport in a place, are not as important as the long-term impacts on sustainable transport and spatial development.

Rail transport is appropriate for concentrated demand and offers opportunities for land-use planning in the surrounding area. While roads are required to serve isolated demand points and provide the flexibility needed in the distribution network, they also cause urban problems and increased travel. While energy efficiency is not a major factor for an individual trip, the benefits of rail transport can be realized by creating dense, land-efficient forms of urbanization at the landscape level, provided that the planning, demand, and institutional frameworks are appropriate.

4.4 International examples and modal-shift evidence

A brief survey of some international examples may provide some perspective for our discussion. For instance, the success of China's Belt and Road rail projects, achieved through high productivity using a network approach, shows that long-distance freight transport need not be uneconomic [30,32]. Similar issues of intermodality and service network design arise in freight transport planning in Europe [31,35,36]. This can also be illustrated with respect to electrification and rail development in Southern Africa; in these cases, railways have a clear advantage in terms of environmental and economic sustainability for long-distance, high-volume heavy transport [40]. An example of high-capacity, low-carbon transport at a very large scale is also provided by Japan's high-speed rail network [41].

There is a lot of scope for misunderstanding in the transport debate, and foreign examples are often cited without proper regard for the differing conditions in other countries. Thus, a successful fast bus system in a concentrated, highly coordinated, and demand-responsive urban artery in Brazil is no guarantee of success in a more fragmented, demand-responsive urban environment with weaker institutions. Case studies do not provide blueprints for action, but can only illustrate what is possible when transport policy, infrastructure, services and demand are all brought into a compatible relationship.

5. Challenges and barriers to implementation

Sustainable transport innovation is not a "frictionless activity". One of its roles is to identify the technological, economic, and regulatory barriers likely to impede the adoption of sustainable transport technologies and systems [42-58]. These barriers are interdependent: the more technical obstacles there are, the higher the costs of technologies and services are likely to be, the more uncertain the policy framework for investment is, the greater the obstacles to harmonized standards, etc. Sustainable transport innovation is therefore both a technological and a societal challenge.

Please see Figure 5 for the relevant categories of barriers identified for the deployment of innovative sustainable transport infrastructure solutions, interlinked and including technical and legacy system barriers, as well as economic and institutional barriers.

For the transport infrastructure itself, the relevant barriers are identified as being:

i. complex to retrofit into existing infrastructure;
ii. non-compatible with other forms of transport infrastructure;
iii. old, and;
iv. high capital cost with low expected returns.

The deployment of sustainable transport infrastructure solutions is, however, not simply a matter of the technology itself, but also a question of the institutional, economic and operational context.

Fig. 5. Interacting barriers to the implementation of sustainable transportation infrastructure innovations (own figure composed on the basis of Section 5)

5.1 Technological and Legacy Issues

Legacy infrastructure is one obstacle to modernizing infrastructure and services through new technologies and systems. The infrastructure has evolved over the years, and the current state of roads, railways, bridges, tunnels, depots, and control systems was not designed for electrification, smart sensors, connected automation, or the digital twin. Adapting legacy structures to new systems and technologies through retrofits is often technically and economically complex. The rail-damper studies by Kuchak *et al.,* [42,43] demonstrate that even local improvements require a good understanding of the current structural behavior. Therefore, reliable, sustainable maintenance and upgrading can only be expected if the current state of the infrastructure is properly assessed.

Gui *et al.,* [44] and Salim and Husain [50] both believe that the development of the modern digital and autonomous mobility systems is becoming increasingly complicated. Ma *et al.,* [45] also point out that technological innovation in smart transport will lead to unbalanced development across regions and cannot fundamentally solve transportation problems in all regions. Girma *et al.,* [46], Shu [47], and Zhao [48] believe that the efficiency of construction technology, green innovation, and smart transportation is closely related to enterprises' organizational capacity and the actual conditions of the demand area.

The core argument is that sustainable technologies fail more often due to ease of use and integration than to actual technological failure. Technology can be a fantastic sustainable innovation, but it may have associated issues that make it difficult to deploy, commission, maintain, and control.

5.2 Economic and Fiscal Constraints

The economics of the situation have not yet changed. Low-carbon technologies such as electrification of rail, energy storage, smart technologies, and materials are more expensive than their high-carbon alternatives, even though the variable and perhaps the total lifetime costs are lower [49,50]. Our current accounting, budgeting, and procurement practices tend to favor the lowest initial cost and discriminate against higher-cost, lower-lifetime-cost, low-carbon alternatives.

In recent studies, Zhao and Tang [51] conclude that economic policy uncertainty negatively affects green technology innovation in new-energy vehicle enterprises. Apruzzese *et al.,* [52] find that 5G and related technologies open up new opportunities for new business models in logistics and the supply chain. For this, companies must have confidence in future returns, and investors must act accordingly. Finally, regarding communication, Scholten *et al.,* [53] and Jha [54] find that attitudes toward innovation and ICT capability are also important for the conditions surrounding the adoption of sustainable transport. In other words, the economic feasibility of sustainable transport is not simply a matter of bookkeeping; rather, it also depends on incentives, governance and trust in institutions [51-54].

The distribution of costs and benefits from sustainable innovation among stakeholders is often uneven. High costs are borne by one group, while the main benefits accrue to another. Without appropriate mechanisms to balance the interests of different stakeholders, even highly advanced products will not be adopted.

5.3 Regulatory and Legal Hurdles

Regulation is mainly seen as a tool for restriction. However, it also plays a crucial role in sustainable transport, ensuring road safety, interoperability between infrastructure and vehicles, cybersecurity, and accountability of transport service providers. The main obstacle to regulation, as with prices, is the lack of coordination and obsolete legislation. Tsakalidis *et al.,* [55] pointed out that, with adequate policy support and monitoring, as those referred to in TRIMIS and European Green Deal, the promotion of sustainable transport technologies can be achieved. Shi *et al.,* [56] showed that the effect of transport innovations on carbon emissions is not uniform across regions and that regulatory differentiation should therefore be implemented.

A large number of new legal problems have arisen in the digital age. Babu [57] thinks that the transport innovations are closely related to transport security and accident prevention. As infrastructure becomes more connected, it is also important to consider data protection, privacy, terms of use, related liabilities, and cybersecurity. Kurushina *et al.* [58] suggest conducting technology audits to assess innovation within portfolios. It is particularly relevant for transport infrastructure owners, who need to assess the technology's maturity, its compatibility with existing systems, and the risks and impacts on the transport system before making any decisions [57,58].

Future-ready governance is a key component of sustainable transport engineering. The absence of future-ready governance will limit the adoption of technologies, keeping them confined to successful pilot projects and preventing them from scaling.

6. Conclusions

A significant step forward in the development of sustainable transport infrastructure is expected to result from the cumulative effects of new materials, low-energy construction, low-emission traction technologies, and digital lifecycle management, rather than from a few major innovations. Several quantitative analyses highlight the potential for such developments. Transport infrastructure is responsible for about 24% of direct CO_2 emissions from burning fossil fuels. Road transport is responsible for some 75% of these direct emissions. Consequently, even modest improvements to transport infrastructure can have a very significant impact on reducing transport infrastructure's environmental impacts.

Resource-efficient, sustainable road transport technologies are already mature and proven. The use of secondary materials (recycled materials) to reduce the use of primary materials, such as aggregates and binders, has not been fully explored, and existing research has not provided clear-cut conclusions on their substitution due to the complexity of their life-cycle assessment. Cold-in-situ recycling of asphalt pavement has been shown to reduce fuel consumption and emissions, particularly on rural roads far from production plants. Warm-mix asphalt (WMA) is considered a low-carbon technology for the transition period. The study presented here assesses the performance of five different warm-mix additives when used to produce mixtures at temperatures below the standard 155 °C hot-mix asphalt temperature. The results show clear potential to reduce fuel consumption, greenhouse gas emissions, and local air pollutants while maintaining structural and surface performance compared to hot-mix asphalt. Hence, without any changes to current road construction and maintenance practices, it is possible to reduce greenhouse gas emissions.

The purpose of this article is to present the findings related to the material efficiency of the structures in the railway sector. The literature on rail transport indicates that the operational efficiency of the structures cannot be the decisive factor in this sector. Instead, the design stage and the structures' lifetimes are more important. To confirm this, the material efficiency of the Korean urban rail was studied. The study revealed that an asphalt-concrete track has 2.65 times lower CO_2 emissions than a cement-concrete track, and the total cost savings for the whole structure were about EUR 29,000 per kilometer. The material consumption for the rail track structure was 1,998 tons of asphalt concrete mixture, 1,820 m^3 of cement concrete and 59 tons of reinforcing steel per kilometer. It is clear from the information provided that the material efficiency of structures must also be considered in rail transport to achieve sustainability in train operations. This is because material efficiency not only reduces CO_2 emissions but also decreases costs. In addition, the study applied the digital twin method for assessing the material efficiency of a subway station. The findings confirmed that the construction stage accounted for up to 78% of the structure's total lifecycle cost. In addition, the operation and maintenance of the structure formed 67% of the lifecycle CO_2 emissions. The material breakdown of the CO_2 emissions was 43.66% concrete, 29.73% steel bars and 17.64% aluminum alloy.

Figure 6 presents the main conclusion of this paper. That is, creating sustainable transport infrastructure is not technically feasible. The creation of transport infrastructure is a dynamic process that involves key technologies throughout the life cycle, numerous policy frameworks, financial mechanisms and incentives, and the coordination of many sectors and processes for disseminating knowledge and best practices. Figure 6 highlights that the long-term sustainability of technological, financial, institutional, and managerial measures for transport infrastructure will only be possible within a comprehensive system that enables the creation of a resource-efficient, low-carbon, and safe transport system.

Railway energy systems have begun to be investigated in scientific literature, with many works on renewable energy. It has been shown that power consumption in the railway system can be reduced by up to 30% through the smart, intelligent management system of the rail microgrid, including renewable energy resources. In addition, the Addis Ababa light rail study indicated that regenerative braking under high-stop-frequency conditions, such as those in urban tramways, is a fundamental energy management principle rather than an option. Therefore, railways are more sustainable when traction, braking, energy storage, and grid connection are integrated into a single system rather than as stand-alone technologies.

Fig. 6. Integrated pathway toward sustainable transportation infrastructure through coordinated material, construction, energy, digital, and governance interventions (own figure composed on the basis of Conclusions)

Evidence was found for the following three conclusions:

i. The most sustainable transport solutions are those for which lifecycle or operational evidence is available, for example, warm-mix asphalt, cold in-situ recycling, regenerative braking and renewable-energy-supported railway power systems, and digital lifecycle assessment.
ii. That promotional material describing the environmental benefits of new infrastructure and transport technologies should be based on quantitative evidence of reductions in emissions, energy consumption, and costs, and should not be based on the promotion of technology's unique features.
iii. There is consensus in the road and rail infrastructure sector that sustainability is a system property that depends on a large number of factors, including infrastructure construction, materials, energy and resource consumption in processes, and asset management.

Recommendations for future research are: to develop more harmonized and standardized life cycle analysis (LCA) methodologies and tools for assessment of the sustainability of infrastructure and transport solutions; to proceed with the field testing of innovative sustainable infrastructure and transport solutions; and to develop integrative assessment frameworks covering environmental, technical and economic aspects to enable a holistic performance assessment of sustainable solutions.

Author Contributions

Conceptualization, S.F., B.H., K.M., C. T. and Á.T.; writing—original draft preparation, S.F., B.H., K.M., C. T. and Á.T.; writing—review and editing, S.F., B.H., K.M., C. T. and Á.T.; visualization, S.F., B.H., K.M., C. T. and Á.T.; supervision, S.F.; project administration, S.F. All authors have read and agreed to the published version of the manuscript.

Funding

This research received no external funding.

Data Availability Statement

This study did not report any data.

Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

This paper was supported by the János Bolyai Research Scholarship of the Hungarian Academy of Sciences. This paper was technically supported by the research team entitled "SZE-RAIL".

References

[1] Amakye, S. Y. O., Abbey, S. J., Booth, C. A., & Oti, J. (2022). Performance of sustainable road pavements founded on clay subgrades treated with eco-friendly cementitious materials. *Sustainability*, *14*(19), 12588. https://doi.org/10.3390/su141912588.

[2] Sharma, S. N., Lodhi, A. S., Dehalwar, K., & Jaiswal, A. (2024). Life Cycle assessment (LCA) of recycled & secondary materials in the construction of roads. In *IOP Conference Series: Earth and Environmental Science* (Vol. 1326, No. 1, p. 012102). IOP Publishing. https://doi.org/10.1088/1755-1315/1326/1/012102.

[3] Tabaković, A., McNally, C., & Fallon, E. (2016). Specification development for cold in-situ recycling of asphalt. *Construction and Building Materials*, *102*(1), 318-328. https://doi.org/10.1016/j.conbuildmat.2015.10.154.

[4] Calabi-Floody, A., Valdés-Vidal, G. A., Sánchez-Alonso, E., & Mardones-Parra, L. A. (2020). Evaluation of gas emissions, energy consumption, and production costs of warm mix asphalt (WMA) involving natural zeolite and reclaimed asphalt pavement (RAP). *Sustainability*, *12*(16), 6410. https://doi.org/10.3390/su12166410.

[5] Wörner, C., & Stöckert, U. (2024). Learning from data to improve asphalt road construction processes. In *MATEC Web of Conferences* (Vol. 396, p. 02003). EDP Sciences. https://doi.org/10.1051/matecconf/202439602003.

[6] Liu, S., He, K., Pan, X., & Hu, Y. (2023). Review of development trends of transportation energy systems and energy usages in China considering influences of intelligent technologies. *Energies*, *16*(10), 4142. https://doi.org/10.3390/en16104142.

[7] Song, H., Zhao, F., Zhu, G., & Liu, Z. (2023). Impacts of connected and autonomous vehicles with level 2 automation on traffic efficiency and energy consumption. *Journal of Advanced Transportation*, *2023*(1), 6348778. https://doi.org/10.1155/2023/6348778.

[8] Bozorg, S., & Bullough, J. D. (2022). Perspectives on intelligent road lighting control. *Journal of Science and Technology in Lighting*, *45*, 7-21. https://doi.org/10.2150/jstl.IEIJ200000644.

[9] Jeong, W., & Park, H. (2024). Economic and environmental assessment of the Korea urban railway and its greenhouse gas mitigation potential. *Environmental Research Communications*, *6*(9), 095009. https://doi.org/10.1088/2515-7620/ad5a6b.

[10] Nkurunziza, J. M. V., Nizeyimana, J. D., & Turabimana, P. (2021). Quantitative estimation of railway vehicle regenerative energy saving: A case of Addis Ababa Light Rail Transit (AALRT). *International Journal of Engineering Technologies (IJET)*, *7*(1), 9-19. https://doi.org/10.19072/ijet.839666.

[11] Zhou, X. (2022). Path selection and mechanism innovation of improving railway energy efficiency – From foreign experience and Chinese practice. *Railway Sciences*, *1*(2), 324-344. https://doi.org/10.1108/RS-10-2022-0026.

[12] Ižvolt, L., Dobeš, P., Drusa, M., Kadela, M., & Holešová, M. (2022). Experimental and numerical verification of the railway track substructure with innovative thermal insulation materials. *Materials*, *15*(1), 160. https://doi.org/10.3390/ma15010160.

[13] Tang, J., Wang, M., Tang, X., & He, Z. (2022). The promotion strategy analysis for green degree of railway engineering based on a system dynamic flow diagram. *Journal of Environmental and Public Health*, *2022*(1), 2579922. https://doi.org/10.1155/2022/2579922.

[14] Castro, G., Saico, J., de Moura, E., Motta, R., Bernucci, L., Paixão, A., Fortunato, E., & Oliveira, L. (2024). Evaluating different track sub-ballast solutions considering traffic loads and sustainability. *Infrastructures*, *9*(3), 54. https://doi.org/10.3390/infrastructures9030054.

[15] Huang, J., Yin, Y., Zheng, L., Zhang, S., Zhao, Q., & Chen, H. (2022). Life cycle assessment of construction and demolition waste from railway engineering projects. *Computational Intelligence and Neuroscience*, *2022*(1), 6145755. https://doi.org/10.1155/2022/6145755.

[16] Krishankumar, R., Mishra, A. R., Cavallaro, F., Zavadskas, E. K., Antuchevičienė, J., & Ravichandran, K. S. (2022). A new approach to the viable ranking of zero-carbon construction materials with generalized fuzzy information. *Sustainability*, *14*(13), 7691. https://doi.org/10.3390/su14137691.

[17] Zhang, R., Li, L., Cui, L., Liu, T., Zhang, B., Wang, S., Zhao, Y., Hu, W., Liao, C., & Song, K. (2024). Strategy and methods for carbon emission mitigation during construction of rail transit. *ACS Omega*, *9*(32), 34175-34184. https://doi.org/10.1021/acsomega.4c04064.

[18] Sun, J., Guan, X., Yuan, S., Guo, Y., Tan, Y., & Gao, Y. (2024). Public health perspectives on green efficiency through smart cities, artificial intelligence for healthcare, and low-carbon building materials. *Frontiers in Public Health*, *12*, 1440049. https://doi.org/10.3389/fpubh.2024.1440049.

[19] Fischer, S., & Kocsis Szürke, S. (2023). Detection process of energy loss in electric railway vehicles. *Facta Universitatis, Series: Mechanical Engineering*, *21*(1), 81-99. https://doi.org/10.22190/FUME221104046F.

[20] Khodaparastan, M., & Mohamed, A. (2019). Flywheel vs. supercapacitor as wayside energy storage for electric rail transit systems. *Inventions*, *4*(4), 62. https://doi.org/10.3390/inventions4040062.

[21] Allen, L., & Chien, S. (2021). Application of regenerative braking with optimized speed profiles for sustainable train operation. *Journal of Advanced Transportation*, *2021*(1), 8555372. https://doi.org/10.1155/2021/8555372.

[22] Li, W., Yang, T., Li, C., Li, G., & Xin, Y. (2023). Exploration on the application of a new type of superconducting energy storage for regenerative braking in urban rail transit. *Superconductor Science and Technology*, *36*(11), 115013. https://doi.org/10.1088/1361-6668/acf902.

[23] Kaewunruen, S., Peng, S., & Phil-Ebosie, O. (2020). Digital twin-aided sustainability and vulnerability audit for subway stations. *Sustainability*, *12*(19), 7873. https://doi.org/10.3390/su12197873.

[24] Kaewunruen, S., Sresakoolchai, J., & Yu, S. (2020). Global warming potentials due to railway tunnel construction and maintenance. *Applied Sciences*, *10*(18), 6459. https://doi.org/10.3390/app10186459.

[25] Wu, X., Shen, G., Xing, G., Ling, Z., & Chen, W. (2018). Experimental and analytical behavior of a new type of concrete-filled steel tube tied-arch bridge with a trough girder. *Stahlbau*, *87*(3), 256-267. https://doi.org/10.1002/stab.201810575.

[26] Mohamed Fadzil, F. S., Koay, M. H., Selamat, M. A., Abu Othman, E., & Mahaidin, A. A. (2024). Effects of carbon type and composition on the properties of carbon-copper composite as pantograph slide in railway application. *Journal of Mechanical Engineering*, *13*(1), 105975. https://doi.org/10.24191/jmeche.v13i1.3753.

[27] Ézsiás, L., Brautigam, A., Kocsis Szürke, S., Szalai, S., & Fischer, S. (2023). Sustainability in railways – A review. *Chemical Engineering Transactions*, *107*, 7-12. https://doi.org/10.3303/CET23107002.

[28] Alshoufi, K., Al-Nagar, K., & Fischer, S. (2024). Integrating renewable energy into railway systems: A path to sustainable transportation – A review. *Chemical Engineering Transactions*, *114*, 817-822. https://doi.org/10.3303/CET24114137.

[29] Kovalenko-Marchenkova, Y., Martseniuk, L., & Andryeyeva, N. (2023). Railway tourism in providing the sustainable and smart population mobility. In *IOP Conference Series: Earth and Environmental Science* (Vol. 1269, No. 1, p. 012021). IOP Publishing. https://doi.org/10.1088/1755-1315/1269/1/012021.

[30] Li, S., Lang, M., Yu, X., Zhang, M., Minghe, J., Tsai, S. B., Wang, C-K., & Bian, F. (2019). A sustainable transport competitiveness analysis of the China Railway Express in the context of the Belt and Road Initiative. *Sustainability*, *11*(10), 2896. https://doi.org/10.3390/su11102896.

[31] Liu, S., Lin, B., Wu, J., & Zhao, Y. (2018). Modeling the service network design problem in railway express shipment delivery. *Symmetry*, *10*(9), 391. https://doi.org/10.3390/sym10090391.

[32] Xyugan, W., & Lysochenko, A. (2023). Improving the supply chain management of China's rail logistics system. In *E3S Web of Conferences* (Vol. 403, p. 07030). EDP Sciences. https://doi.org/10.1051/e3sconf/202340307030.

[33] Liu, C., Lin, B., Wang, J., Xiao, J., Liu, S., Wu, J., & Li, J. (2017). Flow assignment model for quantitative analysis of diverting bulk freight from road to railway. *PLOS ONE*, *12*(8), e0182179. https://doi.org/10.1371/journal.pone.0182179.

[34] Morihladko, P., & Dolinayová, A. (2023). Increasing the efficiency of the transport of single wagon consignments – A tool for sunsaitable freight transport. *Transport Technic and Technology*, *19*(2), 13-17. https://doi.org/10.2478/ttt-2023-0009.

[35] van Staden, H. E., Yee, H., & Boute, R. N. (2024). Evaluating the cost-emissions trade-offs of a modal shift in intermodal and synchromodal transportation planning. *IMA Journal of Management Mathematics*, *35*(2), 221-245. https://doi.org/10.1093/imaman/dpae010.

[36] Li, W., & Hilmola, O.-P. (2019). Belt and Road Initiative and railway sector efficiency – Application of networked benchmarking analysis. *Sustainability*, *11*(7), 2070. https://doi.org/10.3390/su11072070.

[37] Shabani, Z. D., & Safaie, S. (2018). Do transport infrastructure spillovers matter for economic growth? Evidence on road and railway transport infrastructure in Iranian provinces. *Regional Science Policy & Practice*, *10*(1), 49-64. https://doi.org/10.1111/rsp3.12114.

[38] Fageda, X., & Olivieri, C. (2019). Transport infrastructure and regional convergence: A spatial panel data approach. *Papers in regional science*, *98*(4), 1609-1632. https://doi.org/10.1111/pirs.12433.

[39] Lin, B., Wu, J., Wang, J., Duan, J., & Zhao, Y. (2018). A bi-level programming model for the railway express cargo service network design problem. *Symmetry*, *10*(6), 227. https://doi.org/10.3390/sym10060227.

[40] Lungomesha, E. M., & Zu, A. (2017). Environmental and economic benefits of railway electrification of Southern African countries. *International Journal of Transport Development and Integration*, *2*(2), 136-145. https://doi.org/10.2495/TDI-V2-N2-136-145.

[41] Solomatina, I. (2022). Implementation of sustainable passenger mobility principles in rail transport. *Vadyba Journal of Management*, *38*(2), 43-56. https://doi.org/10.38104/vadyba.2022.2.04.

[42] Kuchak, A. T. J., Marinkovic, D., & Zehn, M. (2020). Finite element model updating – Case study of a rail damper. *Structural Engineering and Mechanics*, *73*(1), 27-35. https://doi.org/10.12989/sem.2020.73.1.027.

[43] Kuchak, A. T. J., Marinkovic, D., & Zehn, M. (2021). Parametric investigation of a rail damper design based on a lab-scaled model. *Journal of Vibration Engineering & Technologies*, *9*, 51-60. https://doi.org/10.1007/s42417-020-00209-2.

[44] Gui, Z., Wang, X., & Li, W. (2024). Dynamic perception-based vehicle trajectory prediction using a memory-enhanced spatio-temporal graph network. *ISPRS International Journal of Geo-Information*, *13*(6), 172. https://doi.org/10.3390/ijgi13060172.

[45] Ma, Q., Jia, P., & Kuang, H. (2022). The impact of technological innovation on transport carbon emission efficiency in China: Spillover effect or siphon effect? *Frontiers in Public Health*, *10*, 1028501. https://doi.org/10.3389/fpubh.2022.1028501.

[46] Girma, S., Chimdi, J., & Mosisa, A. (2020). Challenges of using prefabrication technology in Oromia Regional State. *Journal of Civil Engineering, Science and Technology*, *11*(1), 22-27. https://doi.org/10.33736/jcest.2020.2020.

[47] Shu, L. (2024). Green innovation among transportation enterprises in Guangdong, China – Basis for sustainable development model. *Frontiers in Business, Economics and Management*, *17*(2), 370-379.

[48] Zhao, C. (2024). The power of technology innovation: Can smart transportation technology innovation accelerate green transportation efficiency? *Smart and Resilient Transport*, *6*(2), 94-114. https://doi.org/10.1108/SRT-12-2023-0015.

[49] Fischer, S., Harangozó, D., Németh, D., Kocsis, B., Sysyn, M., Kurhan, D., & Brautigam, A. (2024). Investigation of heat-affected zones of thermite rail weldings. *Facta Universitatis, Series: Mechanical Engineering*, *22*(4), 689-710. https://doi.org/10.22190/FUME221217008F.

[50] Salim, S. B., & Husain, M. T. (2024). The role of artificial intelligence in autonomous vehicles: Challenges and opportunities. *International Journal for Multidisciplinary Research*, *6*(5), 28224. https://doi.org/10.36948/ijfmr.2024.v06i05.28224.

[51] Zhao, Q., & Tang, C. (2024). The impact of economic policy uncertainty on green technology innovation of new energy vehicle enterprises in China. *Sustainability*, *16*(10), 4206. https://doi.org/10.3390/su16104206.

[52] Apruzzese, M., Bruni, M. E., Musso, S., & Perboli, G. (2023). 5G and companion technologies as a boost in new business models for logistics and supply chain. *Sustainability*, *15*(15), 11846. https://doi.org/10.3390/su151511846.

[53] Scholten, V., van den Hoven, J., Cuppen, E., & Flipse, S. (2016). Science communication and responsible research and innovation: How can they complement each other? *Journal of Science Communication*, *15*(06), C04. https://doi.org/10.22323/2.15060304.

[54] Jha, G. J. R. (2023). Exploring the impact of information and communication technology (ICT) on innovative businesses: An investigative analysis. *International Journal of Scientific Research in Engineering and Management*, *7*(9), 25854. https://doi.org/10.55041/IJSREM25854.

[55] Tsakalidis, A., van Balen, M., Gkoumas, K., & Pekar, F. (2020). Catalyzing sustainable transport innovation through policy support and monitoring: The case of TRIMIS and the European Green Deal. *Sustainability*, *12*(8), 3171. https://doi.org/10.3390/su12083171.

[56] Shi, T., Si, S., Chan, J., & Zhou, L. (2021). The carbon emission reduction effect of technological innovation on the transportation industry and its spatial heterogeneity: Evidence from China. *Atmosphere*, *12*(9), 1169. https://doi.org/10.3390/atmos12091169.

[57] Babu, A. V. S. (2024). Reviewing innovations: Advances in transportation, security, and accident detection. International *Journal of Scientific Research in Engineering and Management*, *8*(3), 29884. https://doi.org/10.55041/IJSREM29884.

[58] Kurushina, V., Kurushina, E., & Shabarov, A. (2016). Technology Audit: Assessment of Innovative Portfolio. In *MATEC Web of Conferences* (Vol. 73, p. 07028). EDP Sciences. https://doi.org/10.1051/matecconf/20167307028.