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Review

Transition Paths towards a Sustainable Transportation System: A Literature Review

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Abstract: In this paper, the challenges inherent in the development of a decarbonized transportation system are thoroughly examined. Sustainable transportation practices that can contribute to the limitation of greenhouse gas emissions and overall sustainability are identified. Furthermore, the most effective and innovative research avenues being pursued by the research community to enhance transportation sustainability are reviewed and discussed. The review framework has been designed to facilitate the identification of key areas of interest through the implementation of a systematic literature review approach. Firstly, an in-depth analysis is provided concerning the main barriers encountered in the realization of sustainable transportation. These barriers are categorized into five dimensions, namely regulatory, technological, financial, organizational, and social. Subsequently, attention is directed towards the emerging approaches that actively support the implementation of sustainable transportation. Lastly, the primary policy measures intended to promote sustainable mobility are the subject of discussion. The findings unveiled in this paper possess the potential to provide managers and policy makers with a comprehensive understanding of transportation sustainability issues. Furthermore, they carry practical implications that can contribute to the construction of sustainable transportation systems.

Keywords: sustainability; transportation modes; energy efficiency; decarbonization

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Citation: Jelti, F.; Allouhi, A.; Tabet Aoul, K.A. Transition Paths towards a Sustainable Transportation System: A Literature Review. *Sustainability* **2023**, *15*, 15457. https://doi.org/10.3390/su152115457

Academic Editor: Armando Cartenì

Received: 22 September 2023
Revised: 24 October 2023
Accepted: 26 October 2023
Published: 30 October 2023

1. Introduction

Transportation is the backbone of local, regional, and global economies, with goods and people continuously moving around the world. However, these capabilities require significant energy demands, which become more critical to ensure better access through more diversified forms of transportation [1]. Transportation includes land (passenger cars, road freight vehicles, buses, and motorcycles), air, rail, and sea transportation. Each transportation mode requires a different energy source/fuel to satisfy the specifications of its propulsion system [2]. This represents a significant factor in the socio-economic development of a country but is a major source of emissions, noise, and environmental pollution and poses risks to human health and safety [3].

The International Energy Agency (IEA) has identified three main contributors to carbon emissions: electricity, industry, and transportation. The largest contributor is electricity generation (42%), followed by transportation (23%) and industrial emissions (19%) [4,5]. Furthermore, transportation is heavily dependent on fossil fuels and accounts for 61.2% of the world's oil consumption [5]. The environmental assessment of transportation systems is generally dependent on carbon intensity (gCO_{2e}/MJ), energy intensity (MJ/km), and total transportation demand (km) [6]. Overall, global emissions from transportation decreased by less than 0.5% in 2019 owing to increased efficiency, electrification, and the use of alternative sources such as biofuels [7]. Currently, there is increased interest in accelerating the technological development of alternative powertrains, and new regulations or subsidy mechanisms to promote alternative fuel vehicles to enhance movement efficiency and reduce emissions [8]. It is important to emphasize that vehicle emissions involve several factors, including vehicle technology, fuel quality, road and traffic management, and maintenance [9].

1.1. Overall Considerations

1.1.1. Climate Change Aspects

The development of an efficient transportation system is critical for the improvement of living standards and can contribute to the mitigation of current environmental concerns, notably climate change [10]. Some of the most significant impacts of climate change on transportation infrastructure and operations arise from severe adverse weather conditions. As these weather incidents increase in frequency and severity, their related damages also increase [11]. This means that careful and effective governance of transportation operations and infrastructure is crucial to limiting disruptions and accidents caused by adverse weather conditions [12]. Simultaneously, the effects of climate change on the transportation sector depend mainly on the transportation mode and the region [13]. Therefore, it is important to consider how transportation systems should be planned, designed, implemented, operated, and maintained.

As stated before, the effects of transportation emissions on climate change are significant. They include greenhouse gases (GHGs), which trap heat in the atmosphere and cause global air temperatures to rise. According to the IEA [14], transportation sector end users reported a share of approximately 37% of the total CO_2 emissions in 2021. As more countries industrialize and transportation demand increases, its environmental impact increases as well. The main cause of transportation emissions is the burning of fossil fuels, such as gasoline and diesel, to power vehicles, which in turn releases CO_2 into the atmosphere [15]. Other causes of transportation emissions include vehicle production, road construction, and air travel. These activities require energy, which emit higher GHGs into the atmosphere. Potential solutions to reduce transportation emissions and mitigate the effects of climate change include switching to electric vehicles, investing in public transportation, and encouraging people to walk or ride bicycles instead of driving [15].

1.1.2. Social and Health Aspects

Different cities differ in how they provide public transportation services, facilities for pedestrians and cyclists, and car usage. Similarly, there are significant differences between reality and the application of policies for speed limits and blood alcohol control. These observations show that the impact of transportation policies on public health and social equity among different groups is diverse [16]. For example, car dependency can be at the root of air pollution and road accidents. However, reducing car dependency, especially by investing in public transportation, can improve public health and provide a more affordable and accessible mode of transport than car travel for people on low incomes or with disabilities [16]. In addition, economic development has led to increased demand for passenger and freight transportation. Increased car use, pollutant emissions, and traffic congestion have given rise to multiple health problems, including traffic-related injuries and respiratory disease risks caused by harmful emissions and noise [17].

Particulate matter (PM) is the most important pollutant in developing countries owing to its exposure, toxicity, and ambient concentrations. Petroleum vehicles and two-stroke gasoline-powered vehicles are the two main contributors to PM exposure. Consequently, air pollution causes respiratory problems, adverse effects on lung function, premature births, and even death [16]. It has been reported that carbon monoxide (CO), hydrocarbons (HCs), nitrogen oxides (NO_x), and PM are among the most harmful substances from motor vehicle emissions into the atmosphere. All of these substances cause varying degrees of toxicity and cancer [18].

Traffic accidents are also a major cause of injuries and fatalities [19]. Given its broad field, this risk is approached differently, depending on the context. There is a traditional paradigm that maintains the perception of safe motor vehicle travel in general and considers that most accidents are caused by certain high-risk drivers or behaviors, such as inexperienced and disruptive driving. Therefore, the focus of safety programs should be shifted towards achieving a safe driving environment for this category of drivers and controlling unsafe practices [20].

1.1.3. Economic Aspects

Transportation is a fundamental part of the global economy, making it possible for people and goods to move across borders. It drives economic growth and development by supporting trade, investment, tourism, global supply chains, and employment. Its economic impact can be measured in a number of ways, including the value of transportation, such as passenger and freight fares, and the value of goods transported [21]. In turn, the economic benefits of transportation are reflected in other sectors of the economy. These include increased economic productivity, investment and trade, and the attraction of new businesses and activities to areas with efficient transportation infrastructure. In addition, transportation can improve cost efficiency by facilitating access to resources and markets around the world. It can also improve people's lives by providing access to jobs, education, health care, and other essential services [22].

However, the transportation sector faces many challenges, including the need for infrastructure, as many countries suffer from inadequate transportation infrastructure, which may hinder economic expansion and development [23]. Other challenges can have a significant economic impact, such as rising fuel prices. Many factors drive higher fuel prices, including the global economy, geopolitics, supply, and demand. Increased fuel prices have a potential impact on the economy as a whole because rising transportation costs lead to higher transportation costs for companies and customers. They can therefore drive up the price of goods and services at the economic level [24].

Overall, transportation is now a key part of the global economy, affecting many sectors and a wide range of activities in our daily lives. It is important to note that the overall economic prosperity and growth of countries and regions depend heavily on the efficiency of transportation systems.

1.1.4. Energy Use Aspects

Energy consumption in transportation has become a major concern for researchers. Accordingly, assessing the relationship between economic development, the transportation industry, and energy consumption in this sector is one of the key issues for investigation. This relationship involves the possibility of improved transportation quality and consequently, a decrease in energy consumption [25]. Other factors have an impact on energy consumption, i.e., passenger-kilometers, fuel efficiency, distance, and emissions from the transportation sector, which all depend on vehicle type, combustion engine, and fuel type [9,26].

Facing such issues, sustainable transportation is a trend that may become inevitable for energy conservation, emission reduction, and air quality improvement [26,27]. Promoting eco-friendly transportation requires the significant involvement of several actors, as follows [21]:

1. Fuel producers: They can shift towards low-carbon fuels, such as biofuels, and other renewable energies.
2. Car manufacturers: There are opportunities for the manufacturers to improve the fuel efficiency of their vehicles, in line with European standards.
3. Vehicle drivers: There are options for vehicle drivers to opt for green mobility based on their travel frequency and distance, as well as on eco-driving practices.

Sustainable transportation systems are also seen as a way to help control accidents, pollution, congestion, and energy consumption, while improving the connectivity, affordability, livability, accessibility, and economic well-being of a business or region [28,29].

1.2. Contribution and Objectives of the Paper

As the field of sustainable transportation evolves rapidly, it is important to remain up to date with the latest research developments that can help drive efficient transportation. A review of the current literature on sustainable transportation provides a good basis for understanding the challenges and opportunities involved in achieving a sustainable transportation system worldwide. However, gaps remain in the literature on effective pathways for transformation in this sector.

In this regard, the contribution of this paper is to advance the field of sustainable transportation by consolidating existing empirical data, highlighting the challenges and opportunities, and suggesting ways forward for developing policy and conducting future research. It also helps to fill some critical gaps in this area of research, thereby making the transition to sustainable transportation more effective at the global level.

The principal objectives of this paper are as follows:

4. Discuss various challenges faced by the development of a sustainable transportation system.
5. Examine how sustainable transportation practices can contribute to limiting GHG emissions and improve sustainability as a whole.
6. Review and discuss the most efficient and novel research pathways to improve the sustainability of the transportation sector.

The remainder of this paper is organized as follows. First, the methodology followed to answer research questions is described. Afterwards, an assessment of the different barriers against the development of sustainable transportation systems is provided. A series of recommendations are proposed to overcome these barriers toward high efficiency and sustainability. Second, novel approaches toward sustainable transportation are highlighted. Finally, relevant multi-aspect policies are discussed to support a sustainable path for the transportation sector.

2. Methodology

In this study, we adopted a systematic literature review approach, recognizing its inherent merits in effectively synthesizing and analyzing the extensive and diverse body of research literature found in challenging areas such as sustainability in transportation. This method's rigor and structured nature are especially advantageous for ensuring comprehensive coverage and objective assessment [30–32]. It was carried out in three phases:

Phase 1: Identification of research questions

The first phase consisted of identifying the research questions. This phase is essential, as it will guide the rest of the analysis process and ensure the relevance of the results. The research questions (RQs) for achieving the study objective were defined as follows:

RQ1: How can the sustainable transportation shift contribute to GHG emissions mitigation goals within the framework of efficient energy use for transportation?

RQ2: Which approaches and policies could be considered to highlight best practices for sustainable transportation?

Phase 2: Search strategy

Once the research questions were identified, the next step was to develop a search strategy to identify the relevant literature covering the research area. The search strategy was developed based on keywords and the search process undertaken to find the most pertinent data.

In terms of keywords, all major concepts used in this study were applied, taking into account PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines to ensure the consistency of the systematic review [33,34]: ("climate change" and "transport"), ("social health" and "transport"), ("governance" and "transport"), ("sustainability" and "transport"), ("emission" and "energy use" and "transport"), ("alternative fuels" and "transport"), ("technologies" and "transport"), ("infrastructure" and "transport"), ("planning" and "transport"), and ("shared mobility" and "transport").

In terms of the search process, the two most relevant academic databases were selected: Web of Science (WoS) and Scopus, because of their multidisciplinary and high-level content.

Phase 3: Procedure for the selection of the articles

After completing the search strategy process and identifying relevant articles, the next step was to select the articles to be included in the study. This required the definition of detailed inclusion and exclusion criteria. Figure 1 illustrates the process used to compile and analyze the relevant data to be included in this study, based on the inclusion and exclusion criteria listed in Table 1.

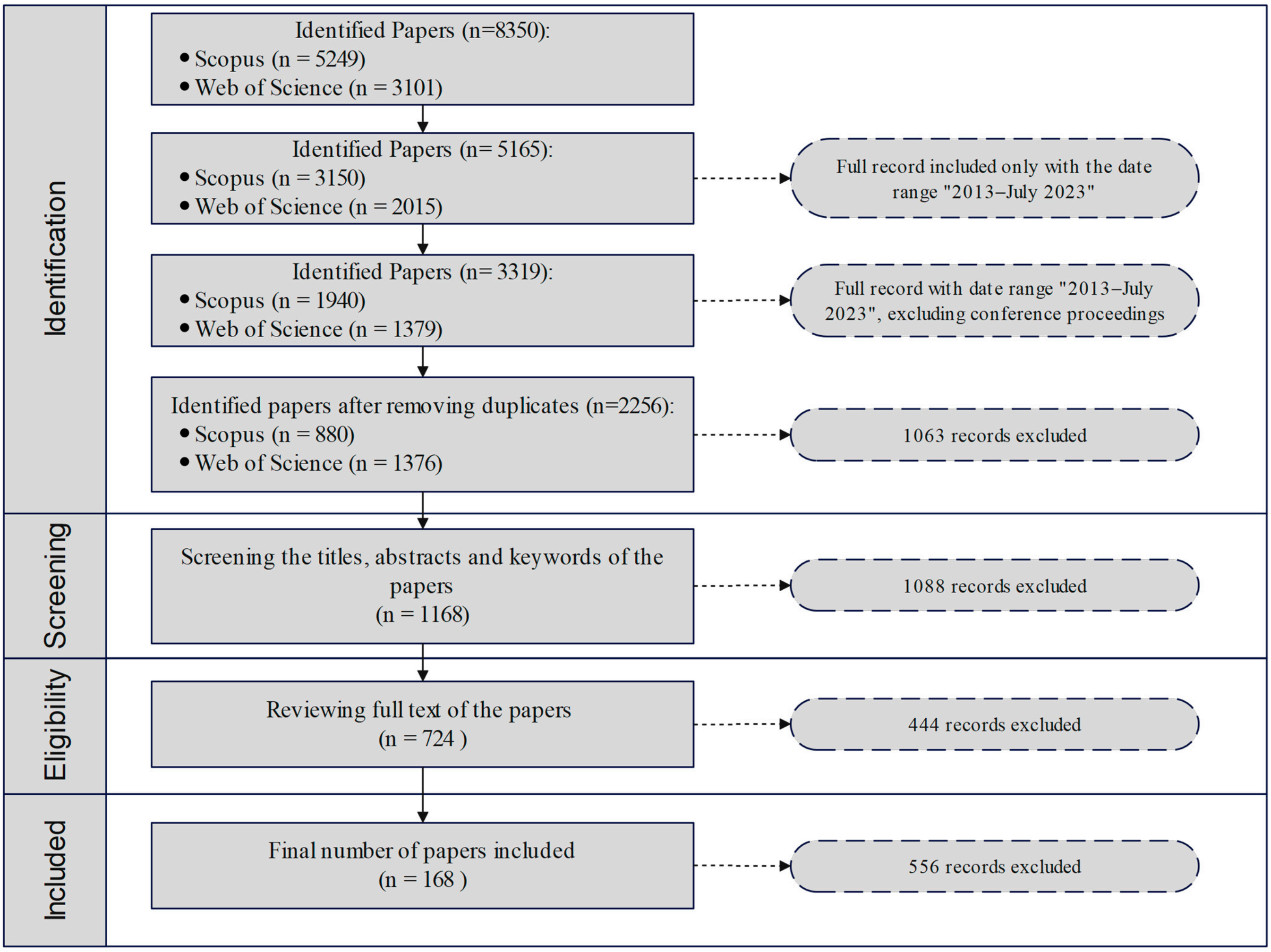

Figure 1. PRISMA flow diagram of the current study.

Table 1. Inclusion/exclusion criteria.

Inclusion	Exclusion
Period: 2013–July 2023 Language: English Articles in scientific journals and books	Duplicates Not including conference proceedings

A literature review was conducted to identify papers that illustrate research lines on current sustainable transportation issues, as well as emerging approaches and policies supporting the transition towards sustainable transportation. Based on the above results, 8350 papers were initially identified and refined according to inclusion and exclusion criteria. This resulted in 2256 records. The second stage involved a close examination of the title, abstract, and keywords of the remaining 2256 papers, discarding all those whose analysis did not match the scope (n = 1088). This stage eventually resulted in the selection of 1168 records. In the third stage, the analysis of 724 papers was completed, with the exclusion of 444 papers that did not meet the objectives of the present study. Finally, 168 papers meeting the research questions and objectives of this study were selected for inclusion. In this way, valuable data were consolidated, ensuring that complementary aspects of the implementation of strategies to promote sustainability in the transportation sector could be explored most effectively, while identifying the main challenges involved in the shift towards sustainable travel.

3. Barriers to a Sustainable Transportation Sector

The main barriers to achieving sustainable transportation are perceived to be a lack of funds, appropriate technologies, and public support. However, institutional barriers also directly affect the implementation process, coupled with inadequate knowledge of the various benefits of sustainable transportation, particularly by policy makers [35]. The increased awareness of these potential sustainable transportation benefits can contribute to the alignment of different stakeholders and institutions in the policy-making process. The most significant barriers to implementing sustainable transportation can be categorized as governance and regulatory, technological, financial, organizational, and social issues [36,37].

3.1. Governance and Regulatory Barriers

The combined growth of population and income has shifted in recent years towards urbanization and has resulted in an increased demand for transportation centered around automobiles, a trend emphasized by a transition to higher employment and services, especially in existing urban areas, and the incapability to ensure sustainable development at the national and regional levels [38]. As a result, an increased disconnect has occurred between the locations where people live and work. This urban phenomenon has led to difficulties in the development of transportation, urban planning, and employment [39]. For example, in an era of rapid urbanization, intense competition in the goods transportation sector in expanding urban areas has resulted in a lack of uptake and an unwillingness to invest in environmentally friendly vehicles [21]. Furthermore, high taxation can create market instability at the planning stage, affecting the competitiveness of national transportation operators. This will result in a reduction in the widespread adoption of modern technologies and alternative approaches in the transportation sector. Commitment levels from the public and policy makers are still unclear, so public acceptance of major changes to achieve sustained transportation objectives remains uncertain. This represents a real problem for policy makers, who cannot implement policies without public support [40].

In this complex landscape of urbanization, transportation, and sustainable development, various stakeholders play important roles. Often, the success of sustainable transportation initiatives relies heavily on the commitment and active participation of political and corporate leaders. Political leaders, whether at the local, national, or international levels, play a pivotal role in promoting sustainable transportation [41,42]. They have the power to enact legislation, allocate funding, and shape policies that can significantly influence transportation choices [43].

Corporate leaders, conversely, wield immense influence over transportation systems through their businesses and industries. They have the power to shape consumer choices and market trends [44]. Corporate leaders in the automotive and transportation sectors have the ability to invest in and produce cleaner and more efficient vehicles, including electric cars and hybrids. Corporate leaders can also set a precedent by implementing sustainable transportation practices within their own organizations, such as offering incentives for employees to use public transportation, carpool, or switch to electric vehicles.

However, commitment levels from the public and policy makers are often unclear, so public acceptance of major changes to achieve sustained transportation objectives remains uncertain. This represents a real problem for policy makers, who cannot implement policies without public support [40].

On the other hand, there are also regulatory gaps resulting from a lack of comprehensive government regulations and incentives, which has created an ineffective operational environment in terms of the existing policy frameworks. This has also resulted in reduced investor interest and consumer demand for cleaner technologies [45]. For example, some countries are encouraging the development of electric mobility and increasing investments in infrastructure to support it. However, the limited standards for these emerging technologies would restrict their potential market penetration [46].

The commitment and actions of political and corporate leaders are vital in the transition to sustainable transportation. Political leaders have the power to shape policies, allocate resources, and raise public awareness, while corporate leaders can influence transportation choices and invest in sustainable technologies. The intersection of these two spheres offers significant potential for accelerating the shift toward more sustainable transportation systems, contributing to economic prosperity, environmental quality, and social equity.

3.2. Technological Barriers

The deployment of technological innovations via advanced engineering in the transportation sector has been outlined as a driving force for achieving sustainability in the field. These innovative technologies have the potential to control environmental pollutant emissions and provide an option for attaining sustainability using renewable resources [47]. However, the key limitations and challenges for the effective transition from traditional to new technologies involve the need for greater flexibility, unlimited access to cleaner sources, lower production costs, feedstock availability, the expansion of fuel stations and their maintenance costs, poor public perception, and low efficiency [48]. Various alternative fuels and vehicles are now commercially viable, including liquid biofuels, biogas, battery-powered vehicles, hybrid electric vehicles, and hydrogen fuel cell vehicles [49]. However, the aforementioned alternative vehicles face acute technological barriers, such as the high viscosity of biofuels, especially when operating at low temperatures, which can affect their performance. Similarly, vegetable oil without modification can lead to engine problems such as excessive combustion, increased sedimentation, and tank deposits; therefore, it should only be used after appropriate filtration [50,51].

Other technological issues also need to be addressed, including limited technological equipment for traffic management and monitoring, notably intelligent transportation systems (ITS), the lack of recharging/fueling facilities for sustained vehicles, poor public transport infrastructure, and network design that fails to adequately manage the vehicle fleet [37,52,53].

3.3. Financial Barriers

A key financial barrier to boosting the effectiveness of sustainable transportation systems lies in the prohibitive cost of a shift towards the sustainable development of the transportation sector. This makes the transition very challenging without solid infrastructure [54]. The requirements for roads and freight networks are important for the successful implementation of greener transportation, which is evident in the visible disparity seen in developing countries [39]. These challenges would lead to the renewal of old infrastructure to meet the current need for sustainable transportation. In this regard, vast investments and considerable commitment from governmental and financial institutions are required to attain cleaner transportation [47,55].

Other financial barriers to developing sustainable transportation exist, making it difficult to switch to greener modes. For example, there are already a large number of companies and government agencies that operate fleets of buses and trucks. Moving these fleets to more sustainable options, such as electric or hydrogen vehicles, can be costly in terms of decommissioning and purchasing new vehicles [37]. Another issue relates to the political and regulatory changes that are often required to develop sustainable transportation. This makes it more costly to implement new laws and standards, including introducing new incentives, rebates and emission reduction targets [45].

3.4. Organizational Barriers

Some organizational issues affecting sustainable transportation relate to the lack of effective stakeholder involvement in designing and implementing policies to promote more sustainable transportation systems, as well as limited cooperation between governmental institutions and other stakeholders in the sector. This results in ineffective harmonization of policies and programs to develop and implement sustainable transportation [36,37]. At the same time, access to comprehensive, reliable, and real-time data and performance metrics related to sustainable transportation initiatives is limited. This makes it difficult for companies to make effective decisions and evaluate the effectiveness of their projects [56].

Other organizational barriers can hinder the adoption of sustainable transportation initiatives, including resistance to change within organizations, particularly among employees, and management that may be reluctant to abandon traditional transportation practices [36]. There may also be a need for a particular level of expertise in the development and management of sustainable transportation projects. A lack of expertise can make it difficult to launch and monitor projects effectively [37].

3.5. Social Barriers

The development of transportation infrastructure (e.g., highways and railroads) is intended to create efficient metropolitan and regional connections. However, it can also lead to disruptions in local pedestrian and bicycle networks, reducing local accessibility and creating social inequalities that, in turn, would affect mobility patterns for meeting in public places. Similarly, these barriers limit access to jobs in lower-income communities over time, leading to the creation of geographic mobility inequalities [57].

Furthermore, some drivers do not behave appropriately towards other road and public transportation users, such as pedestrians, bus lanes, and cyclists [58]. Overall, the public awareness of the benefits of sustainable transportation in urban areas remains low. In particular, perceptions of safety in some urban neighborhoods discourage walking, cycling, and car sharing [37,59,60].

Additional barriers to sustainable transportation in the social arena affect the perception and acceptance of alternative modes and their use. These can be complex and interrelated. They include a lack of awareness, which means that many people are unaware of the sustainable transportation options available to them. This can lead to people habitually continuing to use traditional means when there are greener alternatives [37].

4. Research and Development (R&D) Efforts

Various pressing challenges and opportunities call for global research and development (R&D) efforts in the field of sustainable transportation. These include environmental issues, resource depletion, urban congestion, public health, energy efficiency, economic opportunity, technological advancement, global emission reduction, and accessibility and equity. Meeting the challenges and seizing the opportunities will require continued investment in sustainable transportation research and development by governments, academia, industry, and international agencies. This will make the global transportation sector more sustainable and resilient. The following are some key areas of R&D in sustainable transportation worldwide.

4.1. Alternative Fuels

The transportation sector is one of the most difficult sectors to decarbonize, particularly in areas such as international shipping and long-distance air travel. Petroleum products in particular are rapidly being depleted, and their combustion leads to environmental pollution. It should be noted that there have been efforts to develop energy technologies that are efficient, eco-friendly, and economically viable. The current environmental crisis is addressed by slight and gradual improvements in combustion technology. For instance, alternative fuels are derived from a range of natural resources other than crude oil [61]. Generally, alternative fuels include all fuels used in vehicles, except for gasoline and diesel. Many of them can be used with existing internal combustion engines, with only minor modifications or none at all. The advantages of alternative fuels include cleaner combustion, lower emission levels, and less dependence on fossil fuels. However, alternative fuels do not necessarily represent renewable energy sources. Each fuel type has advantages and disadvantages in terms of cost, availability, environmental impact, vehicle/engine modifications, safety, consumer acceptance, and legislation [62].

The attractiveness of alternative fuels, on the whole, can be enhanced by the many advances being made in the field of alternative transportation fuels to reduce GHG emissions and improve air quality. The most promising technologies are electric vehicles (EVs), hydrogen fuel cells (FCEVs), and advanced biofuels such as biodiesel, produced from renewable organic sources or waste [62]. Apart from these fuel technologies, the efficiency and emission control technologies for vehicles will continue their development. These include new engine and vehicle designs [63].

Today, governments and companies worldwide maintain their efforts to invest in the development of alternative fuels and vehicle technologies. For example, the European Union is committed to phasing out new sales of gasoline and diesel by 2035. Similarly, the United States has ambitious targets for the growth of electric and other alternative fuel vehicles [64].

Accordingly, research on alternative fuels has resulted in an extensive list of proposals that support and develop their characteristics. The suitability of each fuel type for combustion engines has been investigated worldwide. The most important fuels are alcohols (methanol and ethanol), biodiesel, gaseous fuels (compressed natural gas, hydrogen, and liquefied petroleum gas), dimethyl ether (DME), and electricity, as summarized in Table 2 [62].

Table 2. Comparative overview of the main alternative fuels in terms of their technical, environmental, and safety characteristics.

	Technical Concerns	Environmental Concerns	Safety Concerns
Methanol (methyl alcohol)	Methanol is mainly derived from natural gas, but also from coal or biomass [65]. The most common use of methanol as a fuel is a blend with gasoline referred to as M85 (85% methanol, 15% gasoline); however, pure methanol, referred to as M100, can also be used [66].	A key feature that makes methanol vehicles greener than petrol is their improved environmental performance. For example, M85 vehicles are expected to emit 30–50% less harmful ozone-depleting emissions. However, they generally emit about the same amount of CO as petrol cars [67].	Methanol used as a fuel is considered toxic and highly flammable and leads to adverse effects on human health, including skin and eye irritation and respiratory and central nervous system damage [68].
Ethanol (ethyl alcohol)	Ethanol is suitable for automotive fuel. It is produced from sugar as a by-product and can be considered a sustainable fuel due to its use of renewable resources. Ethanol production is based on different production processes, mainly on the energy inputs used during distillation and other processes [62].	It is considered one of the best ways of reducing tailpipe emissions [69]. It is more volatile than gasoline and therefore evaporates more easily. This can lead to the generation of ground-level ozone and smog [70].	The risk of catastrophic burns from ethanol explosions causing skin, facial, and nerve damage is a major concern. Both short- and long-term health effects are also possible with ethanol; in particular, short-term signs of inhalation poisoning, headaches, breathing difficulties, and eye irritation have been observed [71].

Table 2. *Cont.*

	Technical Concerns	Environmental Concerns	Safety Concerns
Biodiesel	Biodiesel refers to synthetic diesel fuel developed from renewable feedstocks, like vegetable oils and animal waste. It is compatible with current diesel vehicles requiring only minor modifications [72]. Biodiesel is classified as a fatty acid mono-alkyl ester and is obtained through transesterification processes. However, one of its main limitations is its higher cost compared with conventional diesel [73].	The use of biodiesel results in higher NO_x emissions than conventional diesel, but less carbon emissions and particulate matter (PM) [74]. Biodiesel is, therefore, considered an alternative to petroleum and coal, as it helps to reduce GHG emissions [75].	The low sensitivity of biodiesel to atmospheric conditions and its high energy content makes it safer than petroleum fuels. However, the higher energy content of all liquid fuels means that there is a risk of ignition when they are stored or transported [76].
Dimethyl ether (DME)	DME is also known as methoxymethane, wood ether, and methyl ether. It is a colorless, non-toxic, and highly flammable gas under ambient conditions and can be transported as a liquid under low pressure [77]. It is particularly suitable for replacing conventional fuels in vehicles because it has similar properties to liquefied petroleum gas (LPG) [78]. DME can be produced directly from synthesis gas made from natural gas, coal, or biomass. It can also be produced indirectly from methanol via dehydration [79].	DME is designed as a clean fuel with improved energy performance and a significant reduction in the amount of PM, SO_x, HCs, CO, and noise when compared to conventional oil-based fuels [80].	DME can have some hazardous effects through inhalation, while liquid DME can cause serious skin burn damage [81]. The risk of leakage is high with DME-based fuel in high-pressure storage systems because DME is kept in the liquid phase and adequate flow is maintained in the fuel system [82].
Liquified petroleum gas (LPG)	LPG refers to a blend of specific hydrocarbons that are maintained in the liquid phase under ambient temperature and pressure. Primary feedstocks include hydrocarbons typically based on refined products, natural gas processing, and lighter hydrocarbon cracking processes [83]. The storage of LPG is carried out in cylinders, mainly in liquid form, under a pressure of ≈760–1030 kPa. These cylinders are manufactured in different sizes to match different vehicles [84].	Using LPG as an alternative fuel is one of the cleanest conventional fuels on the market. It generates fewer carbon emissions than petrol and diesel. So, it does help reduce overall CO_2 emissions [85].	The leakage of LPG can be in the form of a gaseous or liquid leak. In case of a liquid leak, it vaporizes immediately and forms a relatively large gas cloud dropping to the ground, given that it has a higher density than air. If there is a risk of contact with an ignition source, the gas may burn or explode [86].
Compressed natural gas (CNG)	CNG is produced by the compression of conventional natural gas, which consists mainly of methane. It is stored and distributed under pressure at 2900–3600 psi using, usually, metal cylinders [87].	CNG is an alternative fuel for vehicles. Compared to other fuels, it has the lowest emissions and contains significantly fewer air pollutants than diesel. This means that CNG consistently leads to savings compared with diesel [87].	CNG can be used as a safe fuel due to its safety characteristics. The risk of leakage is negligible because it is stored safely in high-quality certified cylinders. In case of a leak, CNG will be released into the atmosphere and will be mixed easily and homogeneously, which affects human health [88].

Table 2. *Cont.*

	Technical Concerns	Environmental Concerns	Safety Concerns
Hydrogen	Hydrogen can be generated from a wide range of primary energies (natural gas, biogas, sewage gas, and others) using different methods, such as electrolysis and natural gas reforming/gasification [89]. The use of hydrogen is considered a future sustainable energy and therefore an innovative and technological development opportunity to achieve energy efficiency [90].	The combustion of hydrogen is practically free of pollutant emissions, especially when using renewable energy [91]. This makes hydrogen a safe energy source and helps prevent harmful GHG emissions within the overall energy system [92].	As with all combustible gases, there are two critical safety considerations with hydrogen. First, adequate ventilation is needed to prevent accumulation, reducing the risk of flammable hydrogen gas being released into enclosed spaces in the event of a leak. Second, effective leak detection is important, involving the installation of flammable gas or hydrogen detectors in storage areas [93].
Electricity	Unlike internal combustion engines, electric vehicles (EVs) are operated by an electric motor. They are powered by a battery that needs to be recharged when the vehicle is not in use [94]. However, the main issues with EVs are their limited range and refueling concerns, which take considerably longer than conventional vehicles [95,96].	The environmental impact of EVs over their lifetime is much lower than that of gasoline or diesel vehicles. However, their impact is not negligible. The operation of battery electric vehicles (BEVs) results in zero emissions during the use phase, but may result in the generation of CO_2 emissions from the electricity source used to power them [97].	The most serious safety concerns associated with EVs relate to the risk of batteries exploding and releasing harmful and toxic chemicals if not maintained and operated according to the manufacturer's standards. Considerable diversity exists in battery design for EVs and hybrid electric vehicles (HEVs) among manufacturers. Therefore, it is important to be aware of specific information regarding manufacturers and vehicles to ensure safe operation [98].

4.2. Innovative Concepts for Sustainable Transportation

4.2.1. Public Transportation

Rapid urbanization and increased population density have led to several problems in urban areas, including transportation infrastructure saturation, traffic congestion, and poor air quality [99]. There are also other issues related to road safety, traffic noise, and global warming [100]. These challenges adversely affect the human quality of life and the environment. At the national level, policy makers and other stakeholders are encouraging a shift from private cars to public transportation, which is vital for sustainable urban development and higher quality of life. This decision is intended to reduce vehicular traffic while ensuring smooth citizen mobility. Simultaneously, it reduces GHG emissions, which makes it crucial to apply the Kyoto Protocol and provides a powerful indicator of economic development and human health in urban areas [100]. Currently, public transportation has a significant impact on the delivery of mass transit and provides affordable and flexible transportation services. They remain the most economically, environmentally, and socially appropriate solution for balanced and sustainable urban development. However, the critical issue facing this mode of mass transit is related to sustainability [101]. From this perspective, the rapid deployment of electric and fuel-cell buses is attracting increased attention in the transportation sector worldwide, which can meet higher environmental requirements in public transportation in terms of emission reduction [100,102]. In addition to these potential improvements in GHG emission reduction, e-buses have significant benefits in terms of energy consumption and noise pollution reduction compared to traditional bus engines [100,103].

Major changes and innovations are currently taking place in the public transportation sector to make it more efficient and better integrated. This includes greater integration with other modes of transportation, such as walking and cycling. This integration includes the provision of bicycle parking at public transportation stops, dedicated cycle lanes and traffic calming measures to make walking and cycling safer [104]. Another aspect concerns data-driven decision making, which involves public transportation agencies using data to make better decisions about their system operations. Data can be used to improve schedules, identify areas for service improvement, and monitor system performance [105]. Working to make public transportation more equitable and inclusive for all users, such initiatives focus on providing more accessible facilities and affordable fares, and designing networks that meet the needs of all users in the community [105].

4.2.2. Eco-Driving Practices

Eco-driving is a set of techniques designed to reduce fuel consumption and emissions. As people have become increasingly aware of the environmental impact of transportation, its popularity has grown in recent years. In essence, eco-driving involves controlling or improving driver behavior to influence fuel consumption and emissions [106]. Important factors influencing efficiency parameters are driving speed, acceleration, deceleration, route selection, idling, and vehicle accessories. Shown in Figure 2 are the most common and useful eco-driving practices that drivers can implement on a daily basis [106,107].

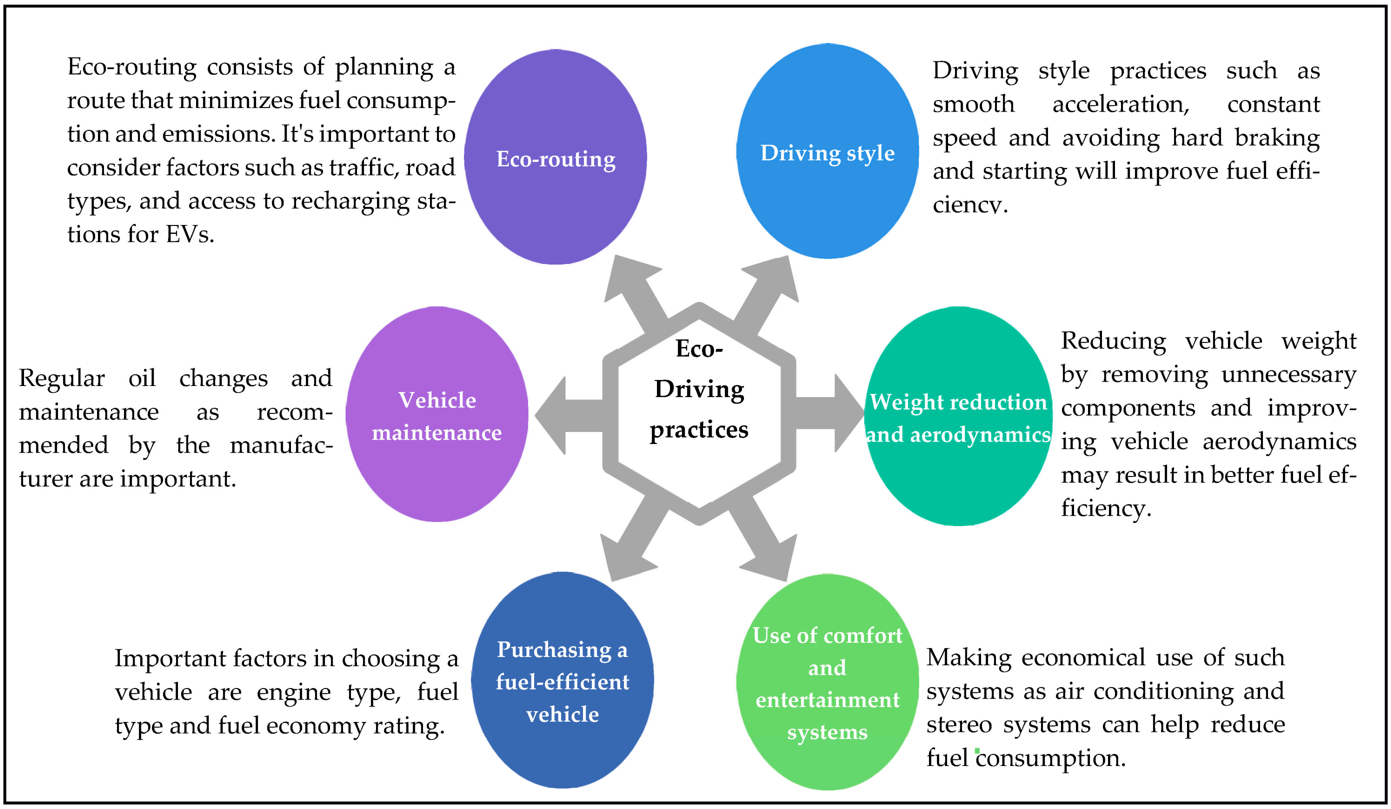

Figure 2. Eco-driving practices.

Eco-driving initiatives have several advantages, including that they are relatively inexpensive to implement. In addition, these initiatives are accompanied by safe driving training programs that are suitable for any vehicle. The results, based on net savings in fuel consumption and reduced emissions, are instantly visible [108].

Other trends in eco-driving include the growing use of telematics and other data-driven technologies. These can provide valuable information for improving fuel efficiency by monitoring vehicle performance and driver behavior. For example, telematics can be used to identify less congested routes and track the effectiveness of different eco-driving techniques [106]. The development of new technologies to improve fuel efficiency is another step forward in eco-driving. For example, many new vehicles are equipped with devices such as stop–start technology, which switches off the engine when the vehicle is at a standstill, and cylinder deactivation, which switches off certain engine cylinders when not in use [106]. Public awareness of the benefits of eco-driving is also important. Today, more people are becoming aware of the benefits of eco-driving, both for the environment and for their budgets. The result is a growing demand for eco-driving training and education [108].

4.2.3. Connected Autonomous Vehicles

A connected automated vehicle (CAV) is a combination of an automated vehicle (AV) and a connected vehicle (CV). That means it can drive without human intervention and communicate with other vehicles and infrastructure (see Figure 3) [109]. CAVs can make intelligent decisions and navigate efficiently, using data from their sensors and data shared by other vehicles. This will improve the overall performance of the transportation system, enhancing safety and efficiency [109]. The transportation sector is currently promoting a number of innovative digital technologies, among which self-driving vehicles are considered one of the most promising options in terms of maturity and technological innovation. For example, passenger transportation has mainly dealt with private cars over the last decades owing to their high flexibility and user-friendly driving processes. This is particularly relevant in large urban areas, where traffic congestion causes drivers to waste time, and environmental and safety issues [110]. The potential of autonomous vehicles (AVs) lies in significantly improving the travel experience of passengers, offering them a greater degree of flexibility, with little effort behind the wheel. In fact, passengers can engage in a wide variety of activities during their travel, and any time previously lost can be exploited for work or entertainment [111]. Additionally, fleets of shared AVs can remain in motion, continuously using algorithms that optimize their routes based on user requirements [112].

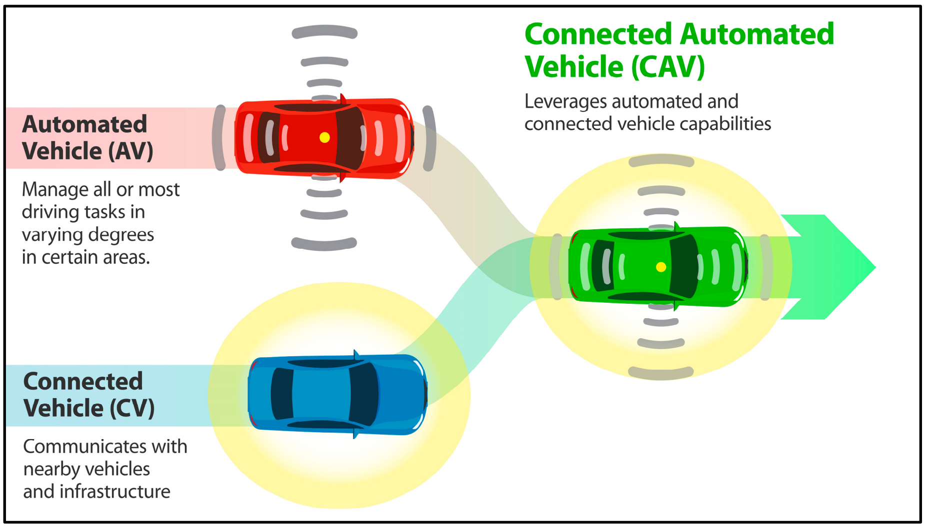

Figure 3. Automated vehicles, connected vehicles, and connected automated vehicles.

A key aspect of supporting AV deployment is improving road safety, as a full shift to AVs can eliminate accidents caused by human error. Self-driving cars can also ensure smoother operations, more efficient drive cycles, and better coordination with other vehicles, thereby reducing congestion [113]. Nonetheless, interactions between computerized vehicles and humans (or cyclists, pedestrians, and animals) may be less tractable because humans are much less predictable, and the lack of eye contact makes human–robot interaction difficult. Consequently, the transition to self-driving cars could be more complicated, and potential problems could prevent the elimination of current conventional cars [114].

Running an AV requires acquiring and processing substantial amounts of data from onboard sensors and constant communication with other vehicles, such as vehicle-to-vehicle (V2V), external infrastructure, and vehicle-to-infrastructure (V2I). This requires significant improvements in the mobile data infrastructure, as connected car deployment leads to exponential data growth. Data communication should also consider privacy issues and potential cyber-security threats. In addition, in-vehicle hardware and software solutions must deal with data volumes that are expected to grow by several orders of magnitude [112,115].

4.2.4. Transportation Infrastructure

Multiple factors determine the overall level of transportation activity, including the size and quality of transportation infrastructure. These factors also affect energy consumption and GHG emissions [116].

In the case of ground transportation, several studies have assessed the impact of new road infrastructure on increasing or decreasing GHG emissions. The majority concluded that newer roads reduce GHG emissions and claim that they reduce congestion and shift traffic patterns towards smoother roads. Therefore, new roads help reduce idling and help vehicles maintain their fuel consumption per distance as low as possible [117]. Additionally, the most prominent factors influencing the development of road transportation systems are mainly based on the accessibility of transportation services, road network quality, and vehicle safety standards [116,118]. In summary, road networks need to be supported on a regional level by funding investments to steadily implement upgrades to the road infrastructure, such as improving the quality of the existing road network, building an extensive road network within different regions, and enhancing local and regional access roads to major transportation routes [116].

On the other hand, intelligent transportation systems (ITSs) can make a significant contribution to the development of a sustainable and cost-efficient transportation system. They may contribute to improving safety, reducing congestion, improving fuel efficiency, and lowering emissions [119]. As shown in Figure 4, there are several examples of ITSs developed in different countries that combine the main classes of ITSs [120]:

- **Infrastructure-based ITS:** Uses sensors, cameras, and other devices to collect transportation data such as traffic, weather, and road conditions. These data are then used to improve the efficiency and safety of the transportation system.
- **Vehicle-based ITS:** Systems on board the vehicle that provide information and services to the driver.
- **Cooperative ITS:** The combination of infrastructure-based and vehicle-based ITS systems to provide even greater benefits. For example, traffic light timing could be adjusted to reduce congestion using data from traffic sensors. Similarly, cooperative ITSs could use vehicle data to warn other drivers of hazards.

Major challenges for widespread EV adoption remain, including the driving range, access to charging infrastructure, and charging times. Therefore, emerging systems and technologies in the field of e-mobility that can help address these challenges include wireless charging, vehicle-to-grid (V2G) integration, and vehicle automation. Wireless charging and V2G facilitate EV charging automation and improve large-scale road electrification by increasing the charging capacity. This, in turn, can help overcome driving range constraints and increase public interest in EVs [121,122]. For example, the widespread use of photovoltaic (PV)-based renewable energy sources for powering EVs is becoming increasingly accessible because of the lower cost of PV systems. Therefore, there is a potential for EVs to be powered by solar PV energy, which can be considered a zero-emission technology; however, it is only suitable for battery electric vehicles (BEVs) (see Figure 5) [123,124].

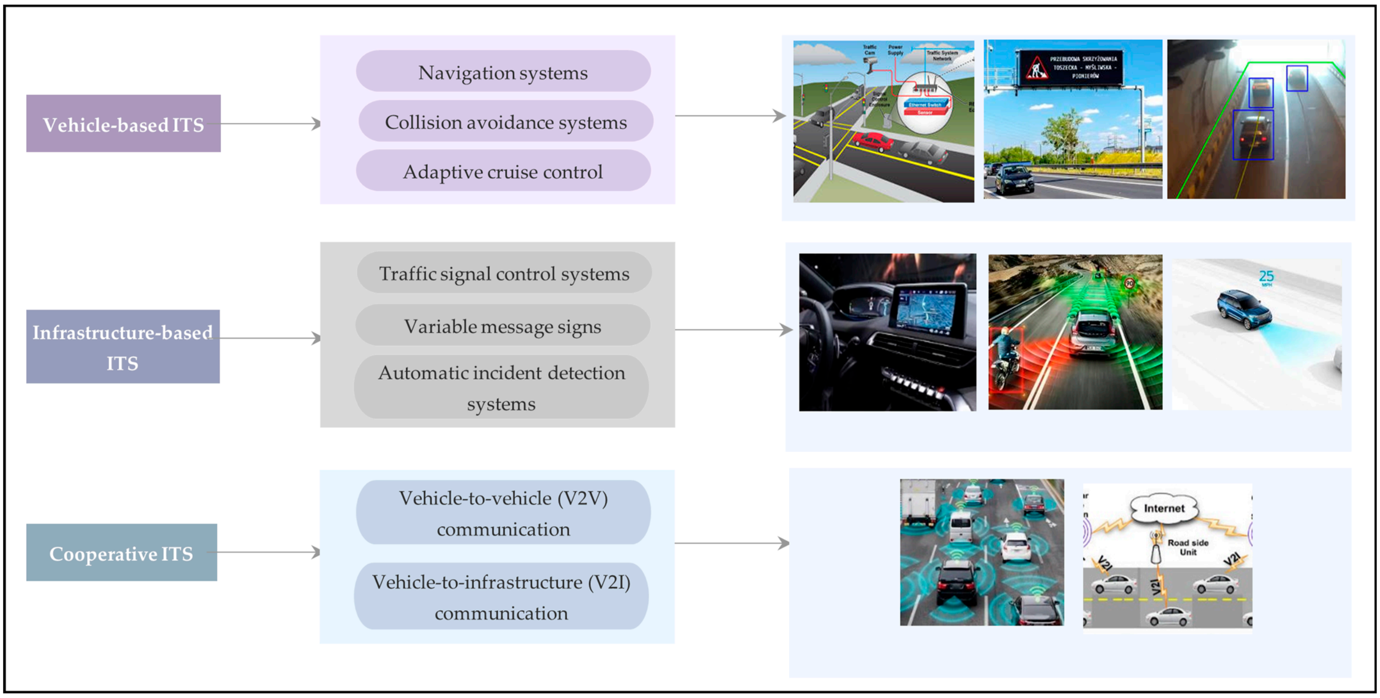

Figure 4. Examples of three classes of intelligent transportation systems.

Figure 5. An example of PV-based parking lots for EV charging.

4.2.5. Shared Transportation Systems

The emerging field of shared mobility, which is based on technological mobility services in a shared economy context, is still in its early stages. However, the scope of shared mobility services is evolving rapidly. They represent new transportation modes, aiming to improve existing service quality as well as sustainable urban transportation [125]. The popularity of shared mobility services has increased significantly worldwide and they are becoming increasingly attractive to customers because of their ability to offer a wide range of services to their clients, such as car sharing, carpooling, and bike sharing (see Figure 6) [126,127]. These services were originally limited to bicycles and cars; however, in recent years, electric scooters and motorcycles have rapidly gained popularity with short-term rental packages. With the deployment of these services, many operators and their mobile applications supporting vehicle rental have emerged [128]. Accordingly, shared mobility can be seen as a way of providing users with access to mobility following their needs, as well as a way of reducing congestion, especially on road networks [125]. Developing shared mobility services is another way of reducing energy consumption, environmental impact, and financial costs compared with owning a private vehicle. The use of any given form of shared mobility can be achieved on trips with a wide range of distances and varying degrees of flexibility [129].

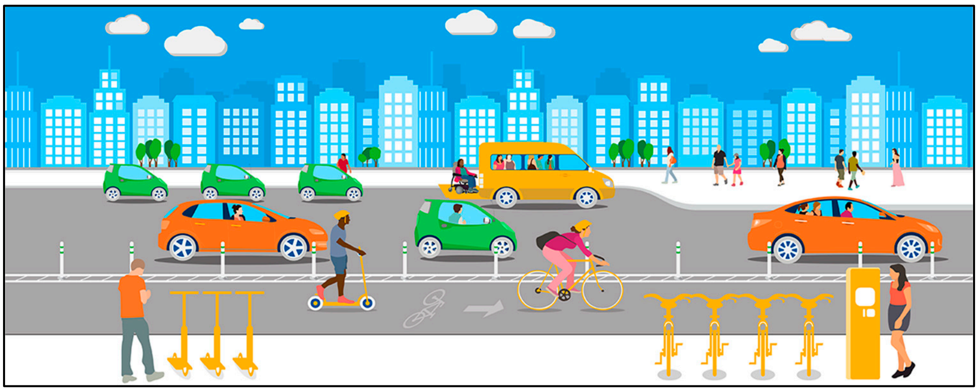

Figure 6. Shared mobility technologies.

A car-sharing service, for example, is an attractive transportation mode for non-commuters and citizens using both public transportation and car-sharing services to meet their mobility needs in urban areas, without the need to own a car. Meanwhile, bike sharing is suitable for users who need to travel to work and other places in the city with an intermediate distance between walking and public transportation, or for individuals who use the bike-sharing service as an alternative to other transportation modes. These particular shared mobility services are encouraged to address private car usage and its negative impacts (e.g., air and noise pollution and land consumption) through restrictive policies (e.g., road pricing, reduced traffic zones, and parking pricing). They are also favored for implementing mobility as a service (MaaS), which means delivering a transportation system that integrates various mobility services, both in terms of structure and pricing [130].

According to [128], important barriers for open innovations in shared mobility systems are related to increased market competitiveness and pressure to interact with pricing policies. In turn, the least important ones are the need to share data with external stakeholders and the lack of attractiveness to various customer groups, such as older people. These findings are significant in challenging the operational perception and major concern regarding implementing open innovation, which is mainly associated with data sharing. Another issue is that shared mobility is not actively encouraged by governments, unlike EV development, owing to the lack of experience with shared mobility in comparison to EVs [131]. Furthermore, poor accessibility is another factor considered by users when choosing a shared mobility system, which could lead to a lack of interest in bike-sharing and carpool services [132].

The potential success of shared mobility services in urban areas depends heavily on well-planned tariffs, adequately sized fleets, a well-functioning integrated public transportation system, and policies that promote sustainable transportation modes [133]. Additionally, researchers and practitioners consider digital infrastructure as a critical component in providing efficient and intelligent mobility in cities that focus on shared mobility as a means of enhancing flexibility rather than on private car use alone. There have been innovations in MaaS systems to facilitate multi- and inter-modal travel, integrating new mobility services with traditional transportation modes.

Other important aspects of shared mobility include autonomous mobility, which can be applied to existing systems. Fully autonomous vehicles are assumed to reduce travel costs and offer safer, more convenient, and more sustainable means of transportation. If these assumptions are realized, then autonomous vehicles can dramatically change the urban environment and transform the future of shared mobility systems [134–136]. Despite their potential benefits, there are some safety concerns related to shared autonomous vehicles. In other words, if AVs are not proven to be safer than human-driven vehicles, then they may not be legally viable for widespread use [136]. According to [137], other service attributes, such as travel cost, travel time, and user idle time, could be critical factors for their adoption.

5. Policy Implications

Several factors contribute to economic and social development when it comes to ensuring sustainable transportation. These include facilitating growth and expansion, as well as improving business opportunities and access to health and education services. The quality of transportation infrastructure is also an important determinant of economic growth, labor mobility, bidding opportunities, and market competitiveness [138]. Above all, achieving sustainability in transportation requires new thinking and drastic mindset changes. Such developments have widespread relevance and affect entire market segments, such as electric vehicles, and their adoption will increase owing to their ever-growing attractive and efficient features. There will also be an increase in car sharing, public transportation, cycling, and walking, leading to a reduction in vehicle usage [45,124]. Operationally, autonomous vehicles will help reduce congestion and accidents, whether for private or business use [139]. Therefore, an important aspect of the eco-friendly transportation system is to promote the sustainable development of cities to meet people's transportation needs and achieve maximum traffic efficiency with significantly reduced social costs [140]. In terms of policy making, a practical approach for governments would be to develop relevant and attractive strategies to encourage individuals to reduce private car usage and transition towards more environmentally friendly transportation modes [141].

It is widely accepted by scientists and governments alike that with increased urban development leading to greater human density in cities, sustainable transportation remains a key requirement to meet the mobility needs of people and goods in the most efficient, safe, smooth, and environmentally friendly way possible [142].

People's willingness to adopt environmentally friendly modes of transportation remains critical to their long-term development and will ultimately accelerate the transition to low-carbon and sustainable pathways [141], as the shift to sustainable modes of transportation can lead to higher levels of overall well-being. However, most people have not yet shown the willingness and commitment to make the switch [143]. Therefore, both policy makers and operators alike need to identify the factors that influence and change people's behavior and encourage shifts to sustained modes of transportation [141].

Based on the analysis of relevant studies, several challenges need to be addressed to effectively develop sustainable transportation policies, especially those aimed at reducing carbon emissions, considering the complexity of the current economic frameworks. Similarly, policy makers should be sensitive to the interaction between policies and their socioeconomic impacts [112,144,145]. The main objective of this section is to examine various policies that support the delivery of an efficient and sustainable transportation industry design. These policies aim to promote modal differentiation and the development of cleaner modes of transportation and cover both passenger and freight transportation:

7. **Incentives for electric vehicles:** Incentivizing electric vehicles (EVs) plays a critical role in encouraging their adoption and accelerating the transition to a more sustainable transportation system. These incentives make EVs more attractive to consumers by helping to offset the higher initial cost of EVs. They include purchase subsidies, tax credits, grants, reduced registration fees, incentives for workplace charging, and support for fleet electrification [146–148]. Such incentives can be tailored to the specific needs and circumstances of each region, taking into account factors such as local charging infrastructure, vehicle availability, and the policy framework.

8. **Reinforcement of public transportation:** As stated before, public transportation plays a key role in decarbonizing the transportation sector, reducing congestion, and promoting sustainable urban development [104]. The promotion of mass transit is supported by a wide range of policies that include improved funding and investment, integrated and efficient networks, land-use planning, real-time information and technology, and public awareness campaigns [105,112]. Improving public transportation performance requires infrastructure funding, effective planning, policy alignment, and community involvement [149].
9. **Fuel efficiency standards:** Fuel efficiency standards for passenger and goods transportation are important steps in achieving global climate change goals and energy savings in transportation [150]. Some practical aspects of fuel efficiency standards and their potential benefits should also be highlighted. These include stimulating technological innovation, delivering cost savings to consumers, enabling market transformation, and promoting international harmonization [151]. As the automotive industry evolves, fuel efficiency standards may need to be regularly updated in line with technological and environmental developments. Meanwhile, regulatory support for electric vehicles and other alternative fuels can complement fuel efficiency standards to achieve broader sustainability goals [152].
10. **Active transportation promotion:** The use of active transportation, such as walking and cycling, is one of the most important strategies for reducing emissions, improving public health, and creating more sustainable and livable cities [153]. There are many approaches and policies to promote active travel. These include infrastructure investment, bike sharing and rental programs, the integration of cycling with public transportation, and multimodal integration [154]. However, promoting active travel requires a comprehensive, holistic approach that takes into account urban planning, infrastructure, and public engagement [155]. For example, a project in New Zealand has demonstrated the potential for implementing cycling and walking initiatives to help reduce carbon emissions. This project resulted in a total cost of 13.1 million USD, of which approximately 85% was spent on infrastructure upgrades, such as improving sidewalks and bicycle lanes, and 15% on promotion and awareness, including campaigns to increase cycling and walking [156].
11. **A modal shift for freight:** The promotion of a modal shift in freight transportation involves encouraging the movement of goods from the most polluting and least efficient modes, such as road and air freight, to more sustainable and environmentally friendly modes, such as rail, sea, and intermodal transportation [112]. Shifting freight will require multiple actions, including investment in rail infrastructure, the development of intermodal facilities, improving last-mile delivery, incentives for sustainable fleet use, green freight certification programs, and regulatory support for freight efficiency [157,158]. In this context, a comprehensive and coordinated effort by a range of stakeholders, in particular government, transportation providers, urban planners, and consumers, is crucial [159,160]. For example, the German government reported in 2018 the approval of a program to support the modal shift of freight transportation from road to rail, with an annual budget of 350 million EUR until 2023. This program will have an environmental impact by significantly reducing carbon emissions. It also reduces congestion by decreasing medium- and heavy-duty vehicles on the roads [112]. Modal diversification combined with more sustainable transportation solutions can make freight transportation less polluting and supply chains more efficient [161].
12. **Carbon-pricing mechanisms:** Carbon pricing aims to reduce GHG emissions by imposing a cost on carbon dioxide and other GHGs emitted into the atmosphere. These costs provide financial incentives for individuals, businesses, and governments to reduce their carbon footprint by reflecting these emissions' environmental and social impacts [112,162]. The two main approaches to carbon pricing are the carbon tax and the cap-and-trade system. Carbon taxes are direct taxes on the carbon content

of conventional fuels, with the aim of making high-carbon fuels less attractive and encouraging consumers and companies to use clean and carbon-free transportation systems [163,164]. By contrast, cap-and-trade or emission trading schemes can be seen as another type of carbon pricing. They set a limit (cap) on the total amount of carbon emissions from vehicles and allow companies to buy and sell allowances within that cap. This provides an incentive for companies to reduce their emissions and encourages the development of cleaner transportation technologies [164,165]. To summarize, carbon-pricing mechanisms may be designed to meet national conditions, emission reduction goals, and economic considerations. Their effectiveness will depend on their design, their enforcement mechanisms, and their alignment with broader climate change and sustainable development strategies [166].

13. **Collaboration and international agreements:** International cooperation and agreements are critical to addressing the challenges and opportunities in the transportation sector, particularly environmental and economic issues with global implications. These include climate change agreements and targets, harmonized standards and regulations, technology transfer and sharing, and the development of global supply chains [167]. Such efforts address the interrelated challenges of transportation and its impact on global sustainability. They also enable countries to promote economic growth and environmental awareness by building on common strengths, sharing knowledge, and developing global solutions to complex transportation problems [168].

6. Conclusions

Sustainable transportation is now a major focus of transportation policy at all levels around the world. A strong commitment to addressing the economic, social, and environmental sustainability of transportation is needed to move towards green transportation. This means that policy makers in both developing and developed countries must include sustainable transportation measures in action plans and prioritize them because they are aware of the challenges of sustainable transportation. The development of a sustainable transportation sector was examined in this paper. In addition, the barriers faced by the transportation sector in terms of five dimensions, namely, regulatory, technological, financial, organizational, and social barriers, in delivering sustainable and carbon-free transportation were identified, as well as recommended actions needed to address these barriers. Finally, a wide range of policies supporting transportation decarbonization were discussed in terms of their different aspects. It was concluded that implementing transportation decarbonization initiatives could promote the adoption of zero-carbon mobility patterns as a means of mitigating climate change, particularly through widespread infrastructure provision to support rail, road, aviation, and maritime networks. In addition, human behavior, which cannot be easily managed in the real world, is largely responsible for both driving behavior and transportation demand. These factors provide policy makers with the necessary toolkit not only to identify actions and policies to address specific human behaviors but also to meet their commitments with regard to climate change.

In this article, we provide a valuable overview of the main ways in which sustainable transportation can be achieved. However, other perspectives can also be considered, including the potential role of digital technologies such as artificial intelligence (AI), big data, and blockchain in achieving a transition to sustainable transportation. Artificial intelligence, for example, offers the potential to optimize traffic flows and reduce congestion, while blockchain brings promising options for creating more secure payment systems for sustainable transportation services. At the same time, the transition to a sustainable transportation system is not just a question of technological and infrastructural change. It is also a question of social innovation and changes in the way people get around. These can include new approaches to designing modes of transportation, such as MaaS and electric shared mobility, as well as alternative ways of financing and managing transportation systems. Overall, a global, integrated approach is needed to solve the challenging world of transportation. This means that developed and developing nations must work together to develop common standards for sustainable transportation technologies.

Author Contributions: Conceptualization, F.J. and A.A.; methodology, F.J.; writing—original draft preparation, F.J.; writing—review and editing, A.A. and K.A.T.A.; supervision, A.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

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

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