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Review

Sustainability Assessment Methods for the Transport Sector Considering the Life Cycle Concept—A Review

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Abstract: This paper presents a summary and review of life cycle sustainability assessment (LCSA) methods for the transport sector. The paper provides a comprehensive overview of articles that employ a variety of methods for assessing sustainable development in the transport sector, taking into account the economic, social, and environmental dimensions. In the sustainability assessment of transport, three methods were evaluated: life cycle assessment (LCA), life cycle cost analysis (LCC), and social life cycle assessment (SLCA). An overview of sustainability assessment methods in transport and a review of the indicators used in the life cycle sustainability assessment was conducted. It was found that the selection of indicators within the LCSA for assessing various aspects of sustainable development is dependent on various geographic and policy contexts. An overview of the application of multi-criteria decision analysis (MCDA) methods to assess LCSA in the transport sector was performed. MCDA methods are used to support decision-making regarding the selection of the most sustainable transport options and allow for the simultaneous consideration of multiple criteria, enabling a more sustainable assessment of different transport options. MCDA methods help to rank alternative transportation fuels and help decision-makers consider indicators encompassing economic, environmental and social aspects.

Keywords: sustainable development; sustainable transport; multi-criteria decision analysis; life cycle sustainability assessment

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1. Introduction

Sustainable development has become one of the key challenges of the contemporary world, and its significance is growing as new guidelines from the European Commission emphasize the necessity of transforming various economic sectors, including the transport sector. Transport is responsible for a significant portion of greenhouse gas emissions, which poses a serious challenge for environmental protection and public health. In the European Union in 2021, transport accounted for approximately 24.1% of all greenhouse gas emissions, with the largest share coming from road transport emissions, constituting 76% of total transport emissions [1–3].

In 2022, global CO_2 emissions from the transport sector amounted to approximately 8 gigatons (Gt), representing a 3% increase compared to the previous year [1,4]. Planners and transport service providers must constantly grapple with the trade-offs between the economic and social benefits of transport and its sustainable impact on the environment, safety, health, ecosystem, and equity.

In the face of growing challenges related to climate change, environmental degradation, and the depletion of natural resources, sustainable development becomes not only a necessity but also an imperative. Adopting sustainable practices in the transport sector can contribute to significant reductions in greenhouse gas emissions, improvement in air quality, and increased energy efficiency. Therefore, it is necessary to develop methods for evaluating and optimizing transport systems that consider environmental, economic, and social aspects.

One method that enables the analysis of sustainability aspects is life cycle sustainability assessment (LCSA), which incorporates a life cycle approach. The LCSA method provides a comprehensive approach that allows for the analysis of the impact of various modes of transport on the environment, economy, and society throughout their entire life cycle—from raw material extraction, through production and use, to disposal. This approach enables the identification and assessment of sustainability impacts at each life stage, which is crucial for effectively managing its impact on the surroundings.

The aim of this article is to present a review of methods for analyzing the sustainable development of transport, taking into account the life cycle approach. A comprehensive overview of methods for assessing the sustainability of transport is presented: life cycle assessment (LCA), life cycle costing (LCC), and social life cycle assessment (SLCA), which can be implemented for the transport sector. Each of these methods plays an essential role in evaluating different aspects of sustainable development and is necessary for creating comprehensive assessment models. The paper performs both a review of LCSA models, sustainability indicators and a review of MCDA methods used for LCSA in the transport sector.

2. A Summary of the Sustainable Development Assessment Method Considering the Life Cycle Approach

Sustainable development is one of the main challenges of the century, and economic, social, and environmental policies play an important role in developing and implementing transport policies. The modern approach to sustainable development encompasses three main aspects: environmental, economic, and social.

A method that enables the analysis of all the essential aspects of sustainable development using a life cycle approach is the life cycle sustainability assessment (LCSA) method. It includes the methods LCC, LCA, and SLCA [5]. Figure 1 shows the three main components of the LCSA method. The life cycle assessment (LCA) method focuses on environmental impact, considering factors such as emissions of particulate and gaseous pollutants, consumption of renewable and non-renewable resources, and impact on ecosystems and human health. It includes all stages of the life cycle, such as production, distribution, use, and disposal. The LCA methodology, concentrated on assessing the environmental impact of products and processes, was one of the first life cycle assessment techniques developed since the end of the 20th century. It became the basis for the development of more advanced and comprehensive methods, such as LCSA [6].

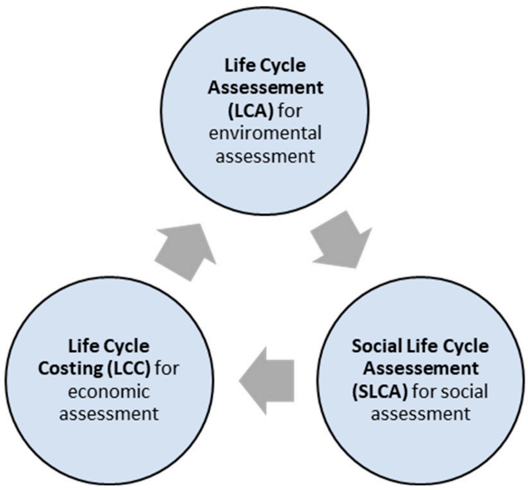

Figure 1. Structure of the LCSA—integration of the three dimensions: LCC, LCA and SLCA methods.

Another component of the LCSA method, life cycle costing (LCC), refers to the total financial aspects related to a product, service, or process, including purchase, operation, maintenance, and disposal costs. This aspect helps to demonstrate sustainable economic development from a financial perspective [6]. Social life cycle assessment (SLCA) refers to the analysis of social and socio-economic aspects of products and processes that affect stakeholders, such as employees, local communities, and consumers. It can include factors such as working conditions, human rights, remuneration, or unemployment [6].

LCSA allows for understanding and minimizing the negative impact of products and processes on the environment, society, and economy by engaging all phases of their life cycle. By assessing and comparing various impacts, LCSA supports the development of more sustainable products and technologies, promoting approaches that are environmentally beneficial, economically viable, and socially responsible.

This approach provides the necessary information for making informed decisions in design, production, and management, considering the full spectrum of impacts on sustainable development. The LCSA method consists of four stages, presented in Figure 2.

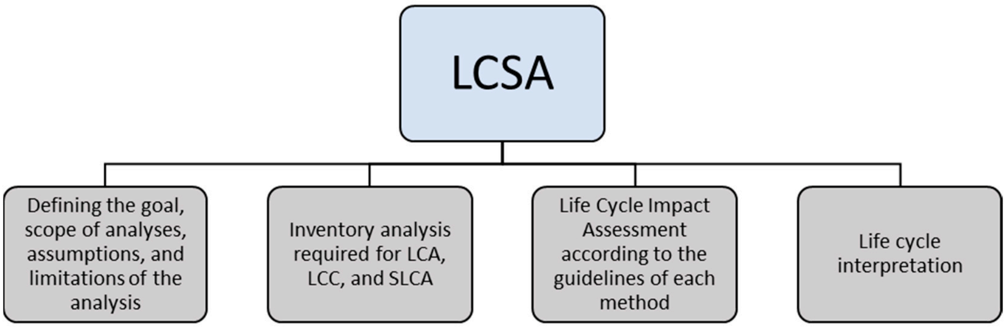

Figure 2. Stages of life cycle sustainability assessment.

In the first stage, "Goal and Scope Definition", the purpose of the analysis, the scope of the study, the assumptions made, and any limitations that may affect the outcome are defined. This is a crucial step that sets the framework for the entire assessment process and ensures clarity about what is to be evaluated and how. The second stage, "Inventory Analysis", involves collecting and evaluating input data (e.g., raw materials, energy) and output data (e.g., emissions, waste) throughout the life cycle of the product, process, or system. In the next stage, "Impact Assessment", the environmental impact, costs, and social aspects are evaluated according to the guidelines and methodologies appropriate for LCA, LCC, and SLCA. Each of these methods has its specific criteria and approaches for impact assessment. In the final stage, "Life Cycle Interpretation", the results obtained in the previous stages are analyzed and interpreted to draw conclusions and recommendations. This interpretation aims to understand and utilize the analysis results to make decisions that can lead to the improvement of sustainable transport development.

3. Application of Sustainable Development Assessment Methods in Transport—A Review of the State of Knowledge

Table 1 provides a comprehensive overview of 20 academic articles that employ a variety of methods for assessing sustainable development in the transport sector, taking into account the economic, social, and environmental dimensions. A set of keywords was used to search for articles to identify publications on transport sustainability. Phrases used included life cycle sustainability assessment (LCSA), sustainable transport, alternative vehicle, transport system, alternative fuels, and electric vehicles. The detailed analysis of these publications enables a deeper understanding of the diverse indicators used to evaluate sustainable transport development. This evaluation includes identifying the primary advantages and limitations associated with each approach. From the review, it becomes evident that multi-criteria decision-making (MCDM) methods are frequently applied to analyze specific aspects of sustainable development, in alignment with the life cycle sustainability assessment (LCSA) methodology. This approach enables a holistic assessment of sustainable transport development by considering the full life cycle of transport systems and infrastructure.

Table 1. Overview of sustainability assessment methods in transport.

№	Author	Aspects of Sustainable Development			Area of Transport
		Economic	**Social**	**Environmental**	
1	Yedla S. and Shrestha R. M. (2003) [7]	Levelized service cost (LSC)	-	Emission reduction potential (ERP)	Selection of alternative options for transport system
2	Brey J. J. et al., (2007) [8]	Purchase cost, Environmental cost, Fuel cost	-	Acoustic emissions	Alternative fuel-based vehicles (HEV, FCEV)
3	Tisita K. G. and Pailacachi P. A. (2012) [9]	Implementation cost, Technology maturity cost, Cost of energy	Energy security, Employment, Social welfare	CO_2 Emissions	Alternative fuels for road transport (biofuels, hydrogen, electricity)
4	Shiau T. and Liu J. (2013) [10]	Modal split of transit	Traffic accidents, Mobility and transport for older adults and disabled persons, Transport infrastructure in remote areas, Transit subsidy in remote areas.	Emission intensity of greenhouse gases (GHG), Emission intensity of air pollutants, Proximity of transport infrastructure to designated environmentally sensitive areas (ESAs), Recycling of end-of-life vehicles.	Urban passenger transport solutions
5	Onat N. C. et al. (2014) [11]	LCC	SLCA	LCA	Alternative passenger electric vehicles (BEV, PHEV, HEV)
6	Maimoun M. et al. (2016) [12]	Fueling station availability, Fuel price stability, Fuel price, Vehicle cost	-	Power Density, Water footprint, Tail-pipe emissions, Life cycle emissions	Alternative fuels for waste collection vehicles (natural gas, biodiesel, hydraulic-hybrid)
7	Kicinski M. and Solecka K. (2018) [13]	Investment costs	Travel time, Standard of travel, Level of integration, Availability, Safety and security, Reliability	Profitability of the urban public transportation system; Environment friendliness	Urban public transportation system
8	Ekener E. et al., (2018) [14]	LCC	SLCA	LCA	Alternative fuels for road transport (biomass based and fossil fuels)
9	Ullah K. et al. (2018) [15]	Project initial cost, Tariff, Fuel cost, Job creation	Social acceptance, Loss of life expectance	External cost, Land requirement	Alternative fuels for road transport (CNG, LPG, LNG)
10	Liang H. et al. (2019) [16]	Fuel cost, Vehicle cost	Social acceptability, Compliance with policy	GHG, PM10, NOx, CO and HCs	Alternative-fuel vehicles (based on LPG, CNG, biodiesel)
11	Balieu R. (2019) [17]	-	-	LCA	Electrified road systems
12	Broniewicz E. and Ogrodnik K. (2020) [18]	-	-	Occupied area, Length of investment, Number of vascular plant species destroyed, Length of sections with high pollution risk, Number of demolitions of residential buildings and others	Transport infrastructure projects

Table 1. *Cont.*

№	Author	Aspects of Sustainable Development			Area of Transport
		Economic	Social	Environmental	
13	Gulcimen S. et al. (2021) [19]	LCC	SLCA	LCA	Light rail transit system
14	Barke A. et al. (2021) [20]	LCC	SLCA	LCA	Battery systems for electric aircraft
15	Du H. and Kommalapati R. R. (2021) [21]	LCC	-	LCA	Public transportation fleet (electric buses)
16	Nour N.M. et al. (2022) [22]	LCC	SLCA	LCA	Selection of alternative fuel taxis (HEV, CNG, BEV)
17	Hasse M. et al. (2022) [23]	LCC	SLCA	LCA	Technologies and alternative fuels for road transport (synthetic biofuel, electricity, hydrogen)
18	Barke A. et al. (2022) [24]	LCC	SLCA	LCA	Comparison of conventional and electric passenger aircraft
19	Gutierrez L. R. (2022) [25]	Depreciation costs, Traction costs, Maintenance costs, Operating cost	Social criterion of service by kilometers travelled by each vehicle	NOx emissions, Particulate matter emissions, CO2 emissions.	Management of the public transportation system
20	Popien J. et al. (2023) [26]	LCC	SLCA	LCA	Electric vehicle traction battery

Moreover, the reviewed publications primarily focus on case studies and empirical research, which investigate particular solutions, technologies, or transport systems. These studies often provide insights into how sustainable transport measures can be implemented in real-world settings, offering valuable evidence for both policymakers and practitioners. A noticeable trend in the increasing use of such sustainability assessments has been observed since 2018. This rise is likely linked to the growing number of international and European regulatory frameworks and initiatives, such as the European Green Deal, which underscore the critical importance of incorporating sustainable development principles into transport policy and planning.

The most frequently studied transport areas are: alternative fuels (five articles), urban public transport (four articles), and means of transport (four articles). These areas reflect growing interest in key sectors that significantly contribute to achieving sustainable transport solutions. Other scientific studies have addressed transport systems, infrastructure projects, and electric batteries, showcasing the diversity of topics within sustainable transport research. Studies on transport systems often focus on optimizing entire networks to improve efficiency, reduce emissions, and promote equitable access. Infrastructure projects delve into sustainable design and construction methods that minimize environmental impacts while supporting long-term transport needs, such as the development of charging stations for electric vehicles or the creation of smart grids for more efficient energy use.

Most of the cited publications considered economic, social, and environmental aspects, highlighting the comprehensiveness of these studies. This multi-dimensional approach underscores the need to balance various factors, such as cost-effectiveness, environmental impact, and social equity, in order to create truly sustainable transport systems. For instance, the economic feasibility of alternative fuels is often weighed against their environmental benefits and the infrastructure investments required for their implementation.

In the reviewed literature, as presented in Table 1, seven articles focus on case studies from Europe, five from Asia, three from North America, and five have a global scope. These studies analyze sustainable transport solutions within diverse geographical and socio-economic contexts, reflecting the varied challenges and opportunities in different regions. In the publications by Yedla S. and Shrestha R. M. (2003) [7], Brey J. J. et al. (2007) [8], Maimoun M. et al. (2016) [12], and Du H. and Kommalapati R. R. (2021) [21], the research primarily focuses on economic and social aspects, particularly within the context of developing countries. These studies aim to evaluate the impact of various transport systems, alternative fuels, and transport technologies on the economies and societies of these nations. In this context, key considerations include implementation costs and long-term economic feasibility, as well as the potential for job creation and the stimulation of local economies.

For example, in the study by Yedla S. and Shrestha R. M. (2003) [7], which investigates India, the priority was the analysis of transport service costs and the potential for emission reductions in the context of choosing a transport system that would support both economic growth and improvements in the quality of life for residents. In developing countries such as India, this study acknowledged the presence of limited financial resources, necessitating the identification of optimal solutions that are both economically viable and effective in enhancing living standards and environmental quality.

The economic aspects of these publications are often analyzed within the context of regional constraints and the potential for the development of transport technologies in countries with limited financial resources. Another important topic is infrastructure availability, as the implementation of transport technologies in developing nations frequently necessitates substantial investment in infrastructure, which is often lacking. Consequently, these studies often emphasize the need for long-term planning and strategic investments to gradually introduce environmentally friendly yet economically viable solutions.

From a geographical perspective, these publications underscore the specific challenges faced by developing countries. For instance, the transport infrastructure in these regions is often underdeveloped, influencing the choice of optimal transport technologies and the availability of alternative fuels. Additionally, access to advanced technologies and sustainable fuels is often limited, requiring a technology selection process that considers local resources and constraints.

In contrast, the studies by Broniewicz E. and Ogrodnik K. (2020) [18] focus primarily on environmental aspects and pertain to more developed countries like Poland. These studies prioritize minimizing negative environmental impacts, especially in the context of advanced transport infrastructure, including electric systems and complex infrastructure projects. These studies address the more affluent European countries, where transport networks are well-developed, and infrastructure investments are primarily aimed at modernization toward sustainable development. The LCSA method develops various indicators for different aspects of sustainability. Section 4 presents the most important indicators for the transport sector.

4. Indicators Evaluated in LCSA in the Transport Sector

Table 2 provides an overview of the indicators used in the life cycle sustainability assessment (LCSA) method in different areas of road transport and the automotive industry. LCSA allows for a holistic assessment of the sustainability impact of transport, enabling the identification and implementation of more environmentally and socially responsible practices and technologies. This makes it possible to make informed decisions about the future of transport based on real data and analysis of impacts throughout the life cycle of transport systems.

Table 2. Overview of the LCSA indicators applicable to road transport and the automotive industry.

№	Author	Indicators			Area of Transport
		LCC	SLCA	LCA	
1	Schau E. M. et al. (2012) [27]	Transport cost, Cost for warranties, Labor cost, Cost of energy for cleaning parts, Cost of spare parts, Used alternator acquisition cost, Fuel use cost for power production, Weight induced fuel use cost, Cost of repair and maintenance, Generator acquisition cost, Salvage value	Adopting labor Conventions, Percentage of population living on less than USD 2/day, Child labor, Fragility of legal system, Fragility of gender equity, Access to improved sanitation, Access to improved drinking water, Potential for high conflict, Gender equity	Abiotic depletion potential (ADP), Freshwater aquatic ecotoxicity potential (FAETP), Marine aquatic ecotoxicity potential (MAETP), Eutrophication potential (EP), Human toxicity potential (HTP), Ozone layer depletion potential (ODP), Photochemical ozone creation potential (POCP), Terrestrial ecotoxicity potential (TETP), Global warming potential (GWP), Acidification potential (AP) Radioactive radiation (RAD)	Remanufactured alternators
2	Onat N. C. et al. (2014) [11]	Import, Gross operating surplus, Gross domestic product (GDP), Air emission cost	Employment, government tax, Injuries, Income, Human health	Global warming potential (GWP), Water withdrawal, Energy consumption, Hazardous waste generation, Particulate matter formation potential (PMFP), Fishery, Grazing, Forestry, Cropland, CO2 uptake land	Alternative passenger electric vehicles (BEV, PHEV, HEV)
3	Onat N. C. (2019) [28]	Operating surplus, purchase, Gross domestic product (GDP), Price, Annual fuel costs, Average maintenance costs	Human health, Total tax, Compensation, Employment	Global warming potential (GWP), Particulate matter formation (PMF), Photochemical ozone formation (POF), Land use, Energy inputs from nature, Water consumption, Water withdrawal	Electric vehicles (BEV, PHEV, HEV)
4	Wang Y. et al. (2019) [29]	Purchase tax, Licensing fee, Government subsidy, Charging pile fee, Energy cost, Maintenance cost, Tax and insurance, Resale value, Battery recycling price	Freedom of association and collective bargaining, Child labor, Fair salary, Forced labor, Equal opportunities/discrimination, Health and safety, Feedback mechanism, Access to material resources, Local employment, Contribution to economic development, Technology development, Policy, Subsidy	Abiotic resource depletion potential (ADP), Global warming potential (GWP), Acidification potential (AP), Eutrophication potential (EP), Ozone layer depletion potential (ODP), Photochemical oxidant creation potential (POCP)	Battery electric vehicles

Table 2. *Cont.*

№	Author	Indicators			Area of Transport
		LCC	SLCA	LCA	
5	Noque N. et al. (2020) [30]	Carbon reduction credit, Life cycle cost of fuel, Life cycle cost of vehicle, Net benefit	Local job creation, Conservation of fossil fuel (CFF), Occupational health and safety (OHAS), Human health based on vehicle exhaust emission	Global warming potential (GWP), Fossil fuel depletion (FFD), Water consumption (WC), Land use (LU)	Alternativeenergy sources for transport sector (electricity, hydrogen, ethanol-gasoline blend E55)
6	Masilela P. and Pradhan A. (2021) [31]	Net present value, Internal rate of return, Payback period, Operation and management costs, Fixed capital investments	Availability of resources, community engagement, knowledge and skill development, safe and healthy living condition, monetary savings, Responsibility of the technology, Existence of infrastructure, health and safety regulations, Energy efficiency	Climate change, Fossil depletion, Freshwater ecotoxity, Freshwater eutrophication, Human toxicity, Ionizing radiation, Metal depletion, Ozone depletion, Particulate matter formation, Photochemical oxidant formation, Terrestrial acidification potential, Terrestrial ecotoxicity	Alternative fuels for vehicle (biomethane, biohydrogen)
7	Elagouz N. et al. (2022) [32]	Operating surplus, Gross domestic product (GDP), Initial costs, Annual fuel costs, Maintenance costs, Insurance costs	Human health, Total tax, Compensation, Employment	Global warming potential (GWP), Particulate matter formation (PMF), Photochemical ozone formation (POF), Land use, Water consumption, Water withdrawal	Alternative fuel bus technologies (CNG buses, electric buses, diesel buses)
8	Hasse M. et al. (2022) [23]	Total costs	Domestic value	Acidification, Climate change, Human toxicity, Ionizing radiation, Marine eutrophication, Freshwater eutrophication, Freshwater ecotoxicity, Photochemical ozone formation, Particulate matter, Resource depletion, Terrestrial eutrophication, Ozone depletion	Technologies and alternative fuels for road transport (biofuel, electricity, hydrogen)
9	Nour N.M. et al. (2022) [22]	Total tax, Operating surplus, Gross domestic product	Compensation, Employment, Human health	Global warming potential (GWP), Particulate matter formation (PMF), Photochemical ozone formation (POF), Water withdrawal, Water consumption, Energy use, Land use	Selection of alternative fuel taxis (HEV, CNG, BEV)

Table 2. *Cont.*

№	Author	Indicators			Area of Transport
		LCC	SLCA	LCA	
10	Popien J. et al. (2023) [26]	Total battery cost	Risk of child labor, Risk of corruption, Risk of forced labor	Namely climate change (CC), Human toxicity (HT), Mineral resource depletion (MRD), Photochemical oxidant formation (POF).	Electric vehicle traction battery
11	Ostojic S. and Traverso M. (2024) [33]	LCC, Gross domestic product (GDP)	Local employment, Safe and healthy living conditions, Fair salary	Global warming potential (GWP), Photochemical ozone creation potential (POCP), Abiotic depletion potential (ADP)	Automotive sector

Examples of the indicators listed in Table 2 include, among others, the selection of sustainable vehicles, which means assessing different propulsion technologies in terms of their environmental impact, such as electric vehicles, hybrid vehicles, and those powered by alternative fuels. Such assessments help to identify the most favorable technological solutions that not only minimize emissions but also contribute to improving energy efficiency. Ostojic S. and Traverso M. (2024) [33], in their publication, listed the seven most commonly used indicators in assessing sustainability in the automotive sector. These indicators include both economic, social, and environmental aspects, such as LCC, gross domestic product (GDP), local employment, safe and healthy living conditions, fair wages, as well as global warming potential (GWP), photochemical ozone production potential (POCP), and abiotic depletion potential (ADP). Other indicators include optimization of operational costs, improvement of working conditions and safety, emission reduction, and sustainable transport infrastructure planning.

A very detailed compilation of numerous indicators is presented in the publications by Schau E. M. et al. (2012) [27], Wang Y. et al. (2019) [29], and Masilela P. and Pradhan A. (2021) [31]. Social indicators can be particularly significant here due to the authors' analyses that consider developing countries or those where human rights are at risk. The authors emphasize aspects such as child labor, fair wages, and safety regulations. Moreover, the integration of social indicators highlights the critical role of corporate social responsibility (CSR) within global supply chains, particularly in the automotive industry, where labor conditions can vary significantly depending on the region. Publications based on examples from developed countries focus particularly on environmental and economic indicators. In developed countries, stricter environmental regulations and higher consumer awareness have led to a greater emphasis on reducing emissions and optimizing resource use, driving innovation in sustainable transportation technologies.

LCC allows for a detailed analysis of all costs associated with vehicle use, including fuel, maintenance, and repair costs. This makes it possible to find the most economical solutions that are also environmentally friendly. An example is a study conducted by Schau E. M. et al. (2012) [27], which analyzes various costs associated with remanufactured alternators, enabling cost optimization while simultaneously reducing emissions. This type of analysis helps manufacturers and service providers balance the economic benefits of remanufacturing with the environmental benefits, contributing to both cost savings and resource efficiency.

The application of LCSA also shows the different priorities and research goals of various authors. The analysis of indicators such as "Human health based on vehicle exhaust emission" (Noque N. et al., 2020) [5] and "Global warming potential (GWP)" (Onat N. C. et al., 2014) [2] provides essential data for evaluating the long-term impacts of different transportation options. These indicators are particularly relevant in urban areas, where the concentration of emissions has a direct impact on public health and contributes to climate change.

The integration of various indicators allows for balancing economic, social, and environmental aspects, which is crucial for making decisions that are both effective and responsible. Decision-makers can use this integrated approach to prioritize solutions that provide long-term sustainability benefits, ensuring that future transportation systems are not only efficient but also equitable and environmentally sound. It is important to note that sustainable development assessment methods incorporating the life cycle concept in every aspect—economic, social, and environmental—apply to the analysis of vehicles and alternative fuels. This highlights that, in the analysis of alternative fuels used in transport, applying life cycle assessment is critical for sustainable transport development analyses. By extending the analysis to the full life cycle, it becomes clear that certain fuels may have hidden environmental costs during production or disposal, even if they are considered zero-emission during use. Given that alternative fuels are considered zero-emission during the vehicle use phase, it is essential to conduct an analysis throughout the entire life cycle to assess their impact in other life cycle stages. This approach ensures that any unintended environmental trade-offs are identified, such as increased water or energy use in fuel production, enabling a comprehensive evaluation of sustainability.

5. Review of LCSA Models for the Transport Sector

With reference to the review of life cycle sustainability assessment models used for vehicles and transport fuels, the models presented in Figure 3 and Table 3 have been identified.

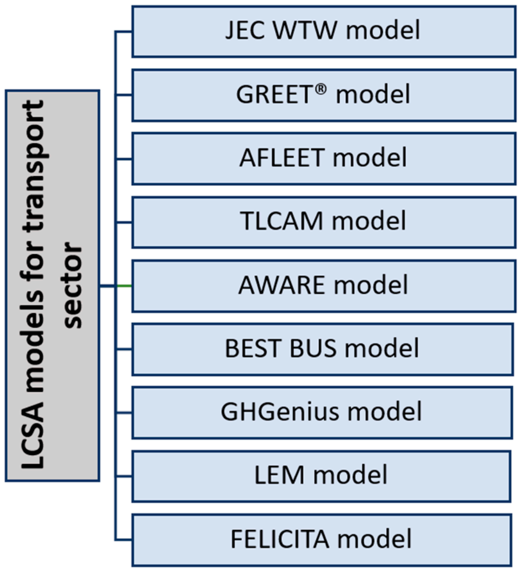

Figure 3. Life cycle sustainability assessment models.

The JEC WTW model is commonly used for conducting well-to-wheel (WTW) analysis of future vehicle fuels and powertrains in European countries. JEC is a long-standing collaboration between JRC, EUCAR, and CONCAWE. This collaboration has resulted in the development of the well-to-wheel analysis, which is applied to assess energy consumption and greenhouse gas emissions for different fuel and powertrain configurations in Europe, covering both current conditions and projections for 2030 [34].

In the United States, the GREET® model (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) is utilized for the WTW analysis of automotive fuels and powertrains. GREET is a comprehensive life cycle model developed by the U.S. Department of Energy at Argonne National Laboratory. This model evaluates the energy consumption and emission impacts of both emerging and conventional transport fuels, as well as the well-to-wheel fuel cycle, considering the vehicle cycle throughout material recovery and disposal [35]. GREET provides a full evaluation of vehicles and fuels, encompassing the entire life cycle.

The AFLEET (Alternative Fuel Life cycle Environmental and Economic Transportation) model was developed to assess greenhouse gas emissions, air pollutants, and the costs of ownership for light-duty and heavy-duty vehicles using straightforward spreadsheet inputs. The AFLEET model was created by Argonne National Laboratory and utilizes data from models such as GREET and MOVES to provide assessments based on simplified data inputs.

In China, the TLCAM (Tsinghua University Life Cycle Analysis) model is applied to calculate the life cycle fossil energy consumption and greenhouse gas emissions associated with different vehicle fuel pathways, such as gasoline, diesel, coal-based fuels, natural gas-based fuels, and electric vehicles [36]. This model is used specifically to assess the Chinese market and vehicle fuel pathways, offering tailored insights into energy use and emissions in the Chinese transport sector.

Table 3. Overview of LCSA models in the transport sector.

№	Author	Models	Indicators	Application in the Transport Sector
1	Lahaussois D. et al. (2017) [34]	JEC WTW	Greenhouse gas emissions (GHG), Primary energy consumption, Fuel efficiency	Assessing the total impact of fuel on greenhouse gas emissions and energy consumption
2	Xu Y. et al. (2015) [35]	GREET	Greenhouse gas emissions (GHG), Primary energy consumption, Emissions of pollutants, Energy efficiency	Life cycle assessment of fuels and propulsion technologies in the context of greenhouse gas emissions, pollutant emissions, and energy consumption.
3	Song H., et al. (2017) [36]	TLCAM	Greenhouse gas emissions (GHG), Air pollutant emissions, Primary energy consumption, Natural resource consumption, Public health impact, Environmental impact, Life cycle costs.	Assessing the environmental impact and life cycle costs of various technologies and fuels
4	Boulay A. M., et al. (2017) [37]	AWARE	Water consumption, Water availability, Impact on water resources, Water stress	Assess the impact of water consumption on available water resources in different regions
5	Xu Y., et al. (2015) [38]	BEST BUS	Greenhouse gas emissions (GHG), Air pollutant emissions, Fuel consumption, Operating costs, Purchase and depreciation costs, Energy efficiency, Passenger comfort.	Evaluation of environmental and economic parameters of different types of buses
6	Stanciulescu V. and Fleming J. S. (2006) [39]	GHGenius	Greenhouse gas emissions (GHG), Air pollutant emissions, Primary energy consumption, Fuel consumption, Life cycle analysis, Environmental costs.	Assessing the total greenhouse gas emissions and energy and environmental impacts of various transportation fuels and propulsion technologies
7	Ranhman M. (2015) [40]	LEM	Greenhouse gas emissions (GHG), Air pollutant emissions, Primary energy consumption, Natural resource consumption, Environmental impact, Life cycle analysis (LCA), Environmental costs.	Assessment of greenhouse gas emissions, air pollutants, and energy and natural resource consumption over the full life cycle of fuels and vehicles
8	Kouloumpis V. and Azapagic A. (2018) [41]	FELICITA	Ozone layer depletion potential, Acidification potential, Eutrophication potential, Photochemical ozone creation potential, Recyclability of materials, Capital costs, Operating and maintenance costs, Fuel costs, Worker injuries, Large accident fatalities, Direct employment	Assess the sustainability and environmental impact of transportation technologies by analyzing emissions, energy use, resource consumption, public health effects, and overall environmental impact.

The AWARE (Available WAter REmaining) model measures the water stress impact of new water consumption, expressed as a water scarcity footprint. This footprint is calculated by multiplying monthly water consumption by monthly county-level water-stress characterization factors. The AWARE model, developed by Argonne National Laboratory within the WULCA (Water Use in LCA Working Group) framework, enables cross-regional comparisons of water stress impacts in different water consumption scenarios [37]. The AWARE model evaluates water stress caused by water consumption in the production of vehicles and biofuels. Further details regarding its applications can be found in additional publications [38].

In addition to these models, several fuel-based models are widely used. These include BEST BUS (Life Cycle Cost and Emissions Model), GHGenius, GREET, and LEM (Life Cycle Emissions Model). BEST BUS is specifically designed to assess greenhouse gas (GHG) emissions from pump to wheel, focusing on emissions from transit buses [38,39]. GHGenius is another model that applies a fuel cycle approach to analyze emissions from different fuels. Meanwhile, the LEM model includes evaluations of fuel cycles, vehicle cycles, and infrastructure cycles. LEM estimates energy use, pollutant emissions, and CO_2-equivalent greenhouse gas emissions from a wide variety of transport and energy life cycles. It accounts for multiple modes of passenger and freight transport, electricity generation, and other energy-related systems such as heating and cooking. LEM is comprehensive, representing the life cycles of fuels, vehicles, materials, and infrastructure, and it considers both energy use and all regulated air pollutants, including greenhouse gases. Models like GREET and LEM have been widely applied to analyze technical pathways for transport fuels in both North America and Europe [40].

The EMFAC (EMission FACtors) model was developed by the California Air Resources Board (CARB) to calculate either country-wide or regional emission inventories by multiplying emission factors by the total distance traveled by all motor vehicles, including passenger cars and heavy-duty trucks, across highways, freeways, and local roads in California. The EMFAC model plays a crucial role in air pollution control and the effort to meet both national and state ambient air quality standards. EMFAC is actively used by CARB to evaluate emissions from on-road vehicles, such as cars, trucks, and buses, in California and to assist in CARB's regulatory and air quality planning, meeting Federal Highway Administration requirements for transportation planning.

Finally, the FELICITA model is used to assess sustainability in the context of transport, integrating environmental, economic and social aspects. It uses a life cycle approach, allowing analysis of the environmental, operational cost and safety impacts of different transport technologies. The model uses fuzzy logic to analyze uncertain data, which is particularly useful in situations where precise information is lacking. FELICITA helps to evaluate alternative transport technologies and solutions, enabling more sustainable decisions related to transport infrastructure investment, fuel choice or transport risk assessment [41].

6. Overview of the Application of MCDA Methods to Assess LCSA in the Transport Sector

In sustainable development assessment models for transport, the combination of MCDA (multi-criteria decision analysis) methods with LCA, LCC, and SLCA is increasingly used. MCDA is a method that allows the consideration of multiple decision criteria in the assessment process, enabling a comprehensive analysis and decision-making based on diverse aspects. In the context of transport, MCDA can encompass various criteria, such as pollutant emissions, operational costs, impact on public health, energy efficiency, and social issues like accessibility and equity. This method is particularly useful when different criteria have different units of measurement and require balancing.

MCDA enables the comparison and balancing of these criteria, which is particularly important in situations where decisions must consider trade-offs between different goals and values. This method allows for the integration of quantitative and qualitative data and the inclusion of preferences from various stakeholders, leading to a more transparent and justified decision-making process. As a result, MCDA supports the creation of more sustainable and holistic transport strategies that can contribute to achieving long-term sustainable development goals.

In addition, MCDA also has significant applications in economic and political studies focused on reducing greenhouse gas emissions in transport, particularly by promoting the electrification of vehicles to achieve net-zero emissions. MCDA helps evaluate options like electric vehicles (EVs), taking into account multiple factors such as cost, environmental benefits, and social impacts. This aligns with policies supporting EV adoption through financial incentives, infrastructure development, and tax breaks. By facilitating the comparison of alternative fuels and technologies, MCDA plays a key role in encouraging the shift from traditional internal combustion engine vehicles to electric vehicles, thereby supporting the broader goal of reducing greenhouse gas emissions [42,43].

Multi-criteria decision analysis includes many methods that help in making decisions considering diverse criteria. There are many multi-criteria methods, like TOPSIS, ELECTRE, VIKOR, AHP, and PROMETHEE. Each of these methods has its advantages and limitations, and the choice of the appropriate one depends on the specifics of the decision problem, the available data, and the preferences of the decision-makers.

In order to select MCDA methods that can be applied for multi-criteria analysis of sustainable transport, a review of these methods was conducted. Based on the review of multi-criteria decision analysis (MCDA) for transportation fuels and vehicles, methods previously used for the analysis of transportation fuels were gathered. The application of multi-criteria decision analysis for transportation fuels and vehicles is presented in Table 4. The table compiles multi-criteria decision analysis (MCDA) techniques that can be used to rank alternative transportation fuels and provide information to support decision-making. MCDA methods help decision-makers consider criteria encompassing economic, environmental, social, and technological aspects.

Table 4. Overview of applications of multi-criteria decision analysis in transportation.

Reference	MCDA Methods	The Objectives of the Study
Yavuz M. et al. (2015) [44] Hayashi T. et al. (2014) [45] Pilavachi P.A. et al. (2009) [46] Quintero J.A. et al. (2008) [47] Zhou Z. et al. (2007) [48]	WSM (weighted sum model)	Home health care service provider Biodiesel fuel production Hydrogen production Ethanol production Light vehicles
Brey J. J. et al. (2007) [8]	DEA (data envelopment analysis)	Alternative-fuel based vehicles (HEV, FCEV)
Maciol A. and Rebiasz B. (2018) [49] Büyükozkan G. et al. (2018) [50] Oztaysi B. et al. (2017) [51] Mukherjee S. (2017) [52] Maimoun M. et al. (2016) [12] Onat N.C. et al. (2016) [53]	TOPSIS (technique for order preference by similarity to ideal solution)	Light vehicles Buses Light trucks and vans for utility company Road sector in general Alternative fuels for waste collection vehicles (natural gas, biodiesel, hydraulic-hybrid) Light vehicles
Vahdani B. et al. (2011) [54]	Fuzzy TOPSIS, PSI (preference selection index)	Buses in urban areas
Yedla S. and Shrestha R.M. (2003) [7] Dinh L.T.T. et al. (2009) [55] Shiau T. and Liu J. (2013) [10] Aydın S. and Kahraman C. (2014) [56] Osorio-Tejada J.L. et al. (2017) [57] Tsita K.G. and Pilavachi P.A. (2012) [9] Tsita K.G. and Pilavachi P.A. (2013) [58] Mardani A. et al. (2015) [59] Ullah K. et al. (2018) [15]	AHP (analytical hierarchy process)	Conventional fuel vs. CNG cars Biodiesel production Urban passenger transport solutions Buses Road freight transport Various fuel types The road sector in general Transportation systems Alternative fuels for road transport (CNG, LPG, LNG)

Table 4. *Cont.*

Reference	MCDA Methods	The Objectives of the Study
Sehatpour M.-H. et al. (2017) [60]	PROMETHEE (preference ranking organization method for enrichment evaluation)	Light vehicles
Ziolkowska J.R. (2013) [61]	Fuzzy PROMETHEE	Biodiesel, ethanol
Stević Ž. et al. (2020) [62]	MARCOS (measurement of alternatives and ranking according to compromise solution)	Supplier selection
Ghose D. et al. 2019 [63]	COPRAS (complex proportional assessment)	Material for electric vehicle
Kicinski M. and Solecka K. (2018) [13]	ELECTRE III	Urban public transportation system
Ekener E. et al. (2018) [14]	MAVT (multi-attribute value theory)	Biomass based and fossil transportation fuels

These articles demonstrated the application of multi-criteria decision analysis (MCDA) to analyze individual sustainability indicators, in line with the life cycle sustainability assessment (LCSA) method. This integration of MCDA and LCSA may indicate a relatively new and innovative approach to sustainability assessments in transport, as both methods allow for a more detailed evaluation by considering a wide range of indicators. The complexity of studies using both methods simultaneously reflects the growing recognition that sustainable transport requires addressing multiple challenges, such as life cycle emissions, resource use, and social impacts, in an integrated manner. Each author prioritized sustainable transport differently.

7. Conclusions

The challenges of sustainable development through managing environmental, social and economic indicators in the transport sector are becoming increasingly important. Due to the fact that ESG (environmental, social and governance) sustainability reporting is obligatory in many organizations of the European Union, sustainability assessment methods for the transport sector should be developed considering the life cycle concept. The importance of sustainability appraisal methods needs to be emphasized in view of the European Commission's new guidelines on ESG reporting under the CSRD Directive [64]. The literature to date has outlined the potential and challenges of applying LCSA to the automotive industry [5,65]. Therefore, this article presents an overview of sustainability appraisal methods taking into account the life cycle for the transport sector. Different methods for assessing sustainability in the transport sector are presented, taking into account economic (life cycle costing), social (social life cycle assessment) and environmental (life cycle assessment) dimensions.

Based on a review of methods and indicators for assessing sustainability in transport, it was shown that the choice of indicators within the life cycle sustainability assessment method for assessing different aspects of sustainability depends on different geographical and political contexts. Furthermore, it was found that most models dedicated to the transport sector only address environmental issues, and there are few LCSA models in the literature that cover all three aspects of sustainability.

Based on a review of the application of multi-criteria decision analysis (MCDA) methods for assessing LCSA in the transport sector, it was concluded that these methods are used to support decision-making regarding the selection of the most sustainable transport options and allow multiple criteria to be considered simultaneously.

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