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Environmental performance assessment in the transport sector using nonparametric frontier analysis: A systematic literature review

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ABSTRACT

The increasing environmental issues relating to carbon dioxide emissions are a primary concern globally and have triggered excessive research to investigate possible ways to reduce such emissions, especially in the transport sector, as initiated by Sustainable Development Goal (SDG) 13. This study investigates the importance of the nonparametric frontier analysis methodology, particularly Data Envelopment Analysis, in measuring environmental performance in the transport sector, emphasising how EU countries are working on meeting the recommendations of SDG 13. Researchers and policymakers have indisputably identified the transport sector as the primary source of global emissions. This paper aims to underline the significant environmental trends in the transport sector, including research topics, key works, research methods, future research direction, and recommendations to explore possible global or regional research agendas. In this regard, we mainly focus on various techniques used to measure the environmental performance within the transport sector. This research considers 186 articles from 46 journals. The survey's main findings show the ever-increasing attention paid to studying the transport sector's emissions, emphasising road and passenger car CO_2 emissions as the major source of emissions in the transport sector. In the existing literature, the top three frequently adopted methodologies for measuring environmental performance in transportation include Data Envelopment Analysis, emission analysis, and simulation. This study shows research gaps and future directions on environmental performance assessment within the transport sector, particularly maritime and aviation.

1. Introduction

The global transport sector is one of the significant producers of carbon dioxide emissions (CO_2), with about 25% of artificial emissions. International transport emissions fell by 10% in 2020 because of the COVID-19 pandemic, although it is expected to grow by 60% in 2050 (ITF Transport Outlook 2021, 2021). With the fast-growing CO_2 emissions from the transport sectors, it is imperative to research aggressive and sustainable emission reduction strategies. Emissions reduction is of topmost priority among the sustainable development goals (SDG13), which has a broad range of social, economic, and environmental objectives. In the UK, CO_2 emissions from the transport sector recorded 97.7 million metric tons ($MtCO_2$) in 2020, indicating a reduction of about 11% from the previous years. However, a rebound in 2021 to 107.5 $MtCO_2$ (Department for Business Energy & Industrial Strategy, 2021). With this swift increase in the UK's transport CO_2 emissions, more work needs to be done to achieve the UK government's proposition to cut emissions by 78% in 2035 compared to the 1990 levels of emissions (BEIS, 2021).

Similarly, researchers, policymakers, and government bodies are pushing hard to transition from the conventional fossil fuel transport system to a low-emission transport system with a 50% reduction target from 2005 levels by 2030 (UK Department of Transport, 2021). However, several documents published by the European Union, such as the Commission of the European communities and the European Commission Directorate, show that previously proposed EU transport strategies are ineffective enough to slow down the continuous rise in transport emissions (Commission, 2012). Consequently, there is an increased need to identify, evaluate, and promote strategies to reduce global transportation emissions cost-effectively. A considerable number of papers have been published on this topic. For example, Banister et al. (2012) considered experts' opinions on investigating climate change, energy,

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and transport emission challenges from geographers, transport experts, and scholars in the UK. Findings from their review suggest that automobile emission was the priority. At the same time, maritime transport was to be least prioritised. However, compact development patterns (reducing vehicle miles travelled) and effective mobility management were identified as emission mitigation strategies. In addition, they considered the potential barrier to policy implementation as a negative influence on climate change.

Emberger (2017) reviewed the challenges and the mitigation strategy in the European transport sector and emphasised that the transport strategy in the EU is focused on economic growth. If the growth takes place, it might not be sustainable. Furthermore, they advised the EU to look for strategies not dependent on economic growth, such as an innovative multifunction transport strategy capable of functioning in both development and stagnant economic growth. Other researchers who have conducted a literature review on the transport sector emissions include Aloui et al. (2021), Fan et al. (2018), Larsson et al. (2019) and Lee et al. (2016). Fan et al. (2018) presented optimisation as the most commonly used method to address challenges such as data availability, a significant limitation in research on transport sector emissions. However, despite the rich literature in this area, review studies relating to frontier analysis to measure environmental performance in the transport sector need more sufficiency. Therefore, this study investigates the literature in the pertinent area to confirm the importance of the frontier analysis methodology, such as Data Envelopment Analysis (DEA), in measuring environmental performance and CO_2 mitigation strategies in the transport sector with an emphasis on European countries. The rest of this study is organised as follows; Section 2 presents the survey plan and analysis procedure of the environmental performance measurement in the transport sector. Other Sections include an analysis of the literature survey, the findings and future research suggestions, conclusions of this study, and finally, the policy implication of the current research.

2. Survey plan and analysis process

This section presents the systematic framework considered in the current literature review, including the databases, journals, and articles section criteria.

2.1. Journal selection process

This study considers journals listed under the science and social science citation indexes aligned with Lee et al. (2016)'s approach. The journals are evaluated using peer-review processes, timelines, and citation criteria. The leading journal selection criteria for this study are as follows; (a) journals under transportation categories of the science and social science indexes list, (b) journals under environment categories, (c) journals under energy categories, and (d) journals names with sustainability, logistics, and shipping or Freight or ports. These four journals selection criteria were selected because they contain at least ten articles published in the field of transportation emissions, enough to allow a critical analysis of the research trend. After applying these criteria, we include 56 articles under the transportation journals category, 26 articles from the environmental journals category, 76 articles from the energy journals category, and 30 articles from other categories, including logistics, climate, sustainability, and others, making a total of 186 articles from 46 journals (see Tables 1 and 2). In addition, some journals, such as the European Journal of Operation Research (EJOR) and the Review of Policy Research journal, are included among journals with a specific name in (d) above. The data show more journals published under environmental journals because of the issue responsible for environmentally related research.

Another noteworthy point is the lack of publication of transportation-related emission papers in top-tier journals such as the Journal of Operations Management, International Journal of Operations and Production, Supply Chain Management, Operations Research, and European Journal of Operation Research. The reason is that the high-impact journals are not explicitly related to environmental issues. Consequently, the current study included 46 journals for analysis to cover the practical, theoretical, and policy trends relating to environmental performance in the transport sector.

Table 1
Journal Categorisation.

Keywords	Selected Journals
Transportation	Transportation Research Part A, B, C, D, and E, Transport Policy; Transport Reviews; Transportation; European Transport Research Review; Journal of Air Transport Management; Research in Transportation Economics; Transportation Research Procedia; Transportation Research Interdisciplinary Perspectives; Transport.
Environment	Journal of Environmental Research and Public Health; Journal of Environmental Economics and Management; Environmental Research Letters; Environmental Science and Pollution Research; International Journal of Environmental Research and Public Health; International Journal of Environmental Research and Public Health; Journal of Environmental Research and Public Health; Environmental and Resource Economics; Environment, Development, and Sustainability; Environment and Planning A; Environmental and Resource Economics; Environmental Sciences Europe; Environmental and Resource Economics; Clean Technologies and Environmental Policy; Frontiers in Environmental Science.
Energy	Energy Policy; Energies; Energy; Applied Energy; Energy Economics; International Journal of Energy Research; International Journal of Energy Production and Management; International Journal of Sustainable Energy; Energy Efficiency; Progress in Energy and Combustion Science; Energy Procedia; Renewable and Sustainable Energy Reviews; Frontiers in Energy Research; Mathematical Problems in Engineering.
Other names	European Journal of Operational Research; International Journal of Physical Distribution and Logistics Management; International Journal of Logistics Management; International Journal of Operations and Production Management.

2.2. Article selection and analysis process

This paper is based on literature identified from an initial search of databases, review article bibliography, searches of authors' citations, and web-based resources. Some of the databases include Science Direct and Web of Science, among the leading databases for academic journals in the sciences citation index (SCI-X) and social sciences citation index (SSCI), emphasising transportation and the environment. A combination of keywords was used for the search to target articles directly related to environmental performance management. The keywords adopted for the search include "ENVIRONMENT" AND "CARBON EMISSIONS", OR "CO_2 EMISSIONS" OR "CLIMATE CHANGE" OR "DECARBONISATION" AND "LOGISTICS" OR "TRANSPORTATION" OR "TRANSPORT" AND "DATA ENVELOPMENT ANALYSIS" OR "DEA" AND "EUROPEAN COUNTRIES" OR "SIMULATION". Note that DEA is a widely used technique for assessing the relative efficiency of a group of entities with multiple inputs and multiple outputs, while simulation is a proficient tool for modelling complex systems and analysing their behaviours over time. Applying these specific keywords is necessary because the study focuses on carbon efficiency evaluation and modelling in the transport sector, making DEA and simulation a fundamental part of this study.

The searches specifically cover articles published between 2005 and 2022 because of the increase in publications within this period. After a critical search using these keywords, 965 papers are from journals related to the abovementioned topics. The search period is between November 2021 and December 2022. The current research focuses on articles about environmental performance in the transport sector published in transportation, environmental, and energy journals. However, after thoroughly screening the titles and abstracts of the articles, 186 articles were selected for further screening in the next stage (full-text

Table 2
Journals with a minimum of four articles and others.

Journal name	Authors	No. of publication
Applied Energy	Al Baroudi et al. (2021), Hammond et al. (2008), Schulte-Fischedick et al. (2021), Zahraee et al. (2021)	4
Energy	Liu et al. (2021), Zhao et al. (2022), Song et al. (2019), Heinrichs et al. (2014), Smith (2010a), Cui et al. (2022)	6
Energies	Brdulak et al. (2020), Charalampidis et al. (2019); Deschle et al. (2022), Djordjević and Krmac (2019), Jaworski et al. (2021), Mądziel et al. (2021), Roh et al. (2020), Statharas et al. (2019), Taljegard et al. (2019), García-Mariaca and Llera-Sastresa (2021), Bata et al. (2019), Djordjević and Krmac (2019), Durajczyk and Drop (2021), Ghandriz et al. (2021), Grijalva and López Martínez (2019), Jaworski et al. (2021), Jereb et al. (2021), Kisielińska et al. (2021), Konečný (2020), Mądziel et al. (2021), Ortega et al. (2021), Palander et al. (2021), Palander and Kärhä (2019), Rokicki et al. (2021), Akbar et al. (2020), Dillman et al. (2021), García et al. (2022), Palander et al. (2021), Palander and Kärhä (2019)	30
Energy Economics	Marrero et al. (2021), Ryan et al. (2009), Voltes-Dorta et al. (2013), Yeh et al. (2021)	4
Energy Policy	Baptista et al. (2012), Berggren and Magnusson (2012), Bristow et al. (2008), Daly and GallachÓir (2012), Eom et al. (2012), Fontaras and Dilara (2012), Fontes and Pereira (2014), Fritz et al. (2019), R. González et al. (2019), González and Marrero (2012), Gössling and Metzler (2017), Haq and Weiss (2016), Kok et al. (2011), Krause et al. (2020), Ma et al. (2012), Meleo et al. (2016), Miola et al. (2011), Morrell (2007), Papagiannaki and Diakoulaki (2009), Pérez-López et al. (2013), Plötz et al. (2019), Schipper and Fulton (2013), Seixas et al. (2015), Siskos et al. (2015), Siskos et al. (2018), Smith (2010b), Thiel et al. (2016), Tietge et al. (2017), Zacharof (2016)	32
Environmental Science and Pollution Research	Danish et al. (2018), Danish and Baloch (2018), Hasan et al. (2019), Hassan et al. (2019), Hossain et al. (2021), Lei et al. (2021), Lian et al. (2020), Mohsin et al. (2019), Rasool et al. (2019), Sohail et al. (2021), Ullah et al. (2021), Wang et al. (2020), Wang et al. (2019), Zhang and Chen (2021)	14
European Transport Research Review	Gómez et al. (2019), González et al. (2019), Islam et al. (2016), Jonkeren et al. (2019), Lah (2015)	4
Environmental and Resource Economics	Gerlagh et al. (2018), Hulshof and Mulder (2020), Krautzberger and Wetzel (2012)	3
International Journal of Environmental Research and Public Health	Dong et al. (2019), Jiang et al. (2022), Jiang et al. (2020), Lim et al. (2020), Ma et al. (2019), Meireles et al. (2021), Połom and Wiśniewski (2021), Ren et al. (2020b), Shen et al. (2019)	9
International Journal of Physical Distribution and Logistics Management	Liimatainen (2015), Pålsson and Kovács (2014), Pålsson et al. (2017), Pujawan et al. (2015)	4
International Journal of Logistics Management	Kengpol et al. (2014), Liljestrand et al. (2015), Nilsson et al. (2017), Rigot-Muller et al. (2013)	4
Journal of Air Transport Management	Alonso et al. (2014), Carlos Martin and Roman (2001), Güner et al. (2021), Ko et al. (2017), Omrani and Soltanzadeh (2016), Prussi and Lonza (2018), Scheelhaase (2019)	7
Transportation Research Part A: Policy and Practice	Carling et al. (2017), Brand et al. (2013), Jochem et al. (2015), Logan et al. (2021), Siskos and Moysoglou (2019), Holden et al. (2016), Jochem et al. (2015), Llorca and Jamasb (2017)	8
Transportation Research Part D: Transport and Environment	Alam et al. (2017), Chang and Park (2016), Cui and Li (2014), Hájek et al. (2021), Karkatsoulis et al. (2017), Kousoulidou and Lonza (2016), Leenders et al. (2017), Liu et al. (2016), Morfeldt et al. (2021), Nocera and Cavallaro (2016a), Palmer et al. (2018), Park et al. (2016), Wild (2021), Zhu et al. (2018), Lodi et al. (2018)	15
Transportation Research Part E: Logistics and Transportation Review	El Yaagoubi et al. (2022), Hihara (2011), Lättilä et al. (2013), Yu and Fan (2009)	4
Transport Policy	Cavallaro et al. (2018), Lerida-Navarro et al. (2019), Liimatainen and Pöllänen (2013), Lo et al. (2020), Nocera and Cavallaro (2016b), Sajid et al. (2019), Tapio (2005), Yan et al. (2021)	8
Others	Ajanovic et al. (2016), Nocera et al. (2018), McKinnon (2016), Nocera and Cavallaro (2017), Robaina and Neves (2021), Albuquerque et al. (2020), Aloui et al. (2021), Brzeziński and Pyza (2021), Jiang et al. (2020), Paltsev et al. (2018), Fageda and Teixidó (2022), Lamb et al. (2021), Märtz et al. (2021), Andong and Sajor (2017), Gray et al. (2017), Clairotte et al. (2020), Paddeu and Denby (2022), Ajanovic et al. (2016), Bal and Vleugel (2021), Fontaras et al. (2017), Giannakis et al. (2020); Kujanpää and Teir (2017), Mardani et al. (2017), Osorio-Tejada et al. (2017), Ren et al. (2020a), Sharma and Maréchal (2019), Solaymani (2022), Tolón-Becerra et al. (2012), Vleugel and Bal (2018), Zhou and Kuosmanen (2020)	30
Sum		186

screening). The list of articles and the published journals are presented in Table 2, showing journals with a minimum of four articles and those with articles less than four are classified as others. It shows that articles on transportation emissions are mainly published in academic journals, including Energies, Energy Policy, Environmental Science and Pollution Research, Transportation Research Part D: Transport and Environment, International Journal of Environmental Research and Public Health, Journal of Air Transport Management, Transportation Research Part A: Policy and Practice, and Transport Policy, with eight and above article in the search. This analysis could help us understand the trend of environmental issues in the transport sector. Furthermore, this study investigates the topic survey to understand the top environmental concerns of researchers in the transport sector. Finally, we explore the methodology to analyse the application of frontier analysis in transport sector emissions research and identify potential future research directions.

3. Literature survey results

This section presents the results from the literature review with emphasis on articles relating to the environmental challenges in the transport sector, net-zero challenges in the transport sector, and the trending methodologies in the transport sector.

3.1. Environmental challenges in the transport sector

Research on environmental emissions within the transport sector has garnered significant attention. Table 2 provides a summary of articles from selected journals, focusing on those with more than four related articles to ensure a critical analysis of research trends in the field. We chose only the journals with more than four related articles listed to ensure a critical analysis of the research trends. Nine journals were selected and divided into two groups. The first group was related to journals specifically interested in transportation research, including Transport Policy, Transportation Research Part D: Transport and Environment, Journal of Air Transport Management, and Transportation Research Part A: Policy and Practice. The second group relates to journals interested in energy and the environment, such as Energy, Energies, Energy Policy, Environmental Science and Pollution Research, and International Journal of Environmental Research and Public Health. As presented in Table 3 and Fig. 1, the number of articles published in the two groups of journals increased swiftly over the year, indicating a continuous rise in research on transport sector emissions.

Among the selected journals, the Energy Policy (EP) in group (2) contributed the most articles (approximately 25%) on global transportation emissions, with a steady rise in publications from 2011. The Energies in the same group also recorded a significant number of articles (23%) with a rise in publication from 2009. Finally, for group (2), Environmental Science and Pollution Research (ESPR), International Journal of Environmental Research and Public Health (IJERP), and Energy recorded 10%, 7%, and 4% of the selected articles, respectively.

In group (1), Transportation Research Part D: Transport and Environment (TRD) recorded 15 articles on global transportation emissions. The second journal in this group, Transport Policy (TP) and Transportation Research Part A: Policy and Practice, has a record of 6% of publications from respective journals. Finally, the Journal of Air Transport Management recorded the lowest number of publications, with 4%. Fig. 2 depicts the cumulative percentage of articles published in the selected journals within the transport sector emissions research. The upward trend in cumulative research publications in the Energy Policy (EP), Energies, and Transportation Research Part D (TRD) journals provides valuable guidance on preferred outlets for publishing transportation emission research. Sequence with the study of Bakker et al. (2019), Kraus and Proff (2021), and Ortega et al. (2021), who further recommend policymakers and decision-makers consider the proper use of alternative fuel, prioritise a sustainable urban transport policy and investigate new sustainable development measures.

3.2. Selected keywords to explore environmental challenges in the transport sector

This review investigates the significant challenges in reducing emissions in the transport sector by considering the most frequently used keywords in this literature. The reason for considering keywords, in this case, is because keywords provide a clear view of the context and a potent way to explore the topics examined in a research paper. Table 4 summarises the original or conventional keywords the selected research papers adopted. The keywords analysis shows that some of the keywords overlap with the same meaning. For example, CO_2 emissions, carbon emissions, and greenhouse gas emissions; Transport and transportation; or Data Envelopment Analysis and DEA. Consequently, the original keywords are presented in Table 4, and the overlapping keywords are in

Table 3
Selected journals with more than four articles relating to transportation and environmental emissions.

	Group (1)				Group (2)					Total
	TP[F]	TRD	JAT	TRA	Energy	EP	Energies	ESPR	IJERP	
2005	1©	x	x	x	x	x	x	x	x	1
2007	x	x	x	x	x	1	x	x	x	1
2008	x	x	x	x	x	1	x	x	x	1
2009	x	x	x	x	x	1	x	x	x	1
2010	x	x	x	x	1	1	x	x	x	2
2011	x	x	x	x	x	2	x	x	x	2
2012	x	x	x	x	x	7	x	x	x	7
2013	1	x	x	1	x	2	x	x	x	4
2014	x	1	1	x	1	2	x	x	x	5
2015	x	x	x	2	x	2	x	x	x	4
2016	1	5	1	1	x	5	x	x	x	13
2017	x	3	1	2	x	2	1	x	x	9
2018	1	3	1	x	x	2	x	2	x	9
2019	2	x	1	1	1	3	9	5	3	25
2020	1	x	x	x	x	1	4	3	3	12
2021	1	3	1	1	1	x	10	4	2	23
2022	x	x	x	x	2	x	6	x	1	9
Total	8	15	6	8	6	32	30	14	9	128

[F]TP: Transport Policy, TRD: Transportation Part D: Transport and Environment, JAT: Journal of Air Transport Management, TRA: Transportation Research Part A: Policy and Practice, EP: Energy Policy, ESPR: Environmental Science and Pollution Research, IJERP: International Journal of Environmental Research and Public Health.
©The numbers within the table show the number of papers published in the selected journals for a specific year.

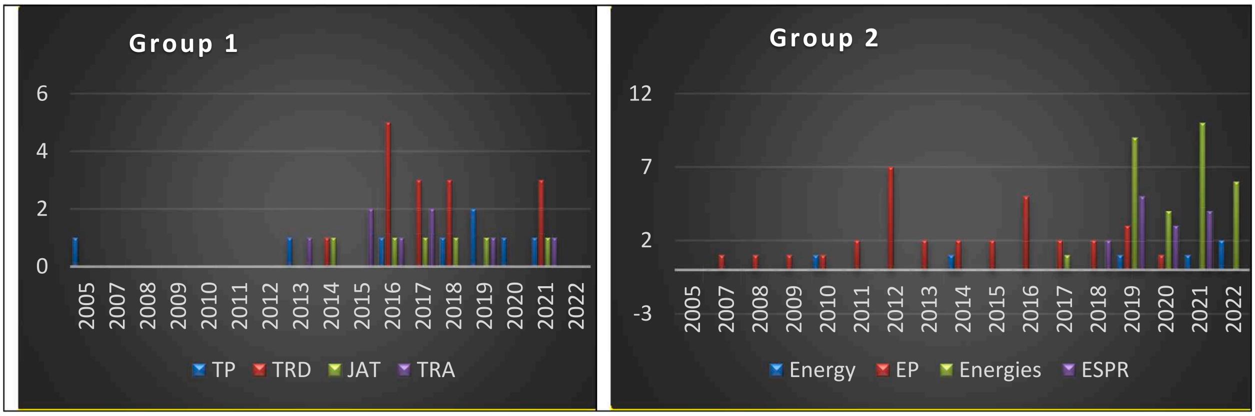

Fig. 1. Growth in transportation and environmental emissions (over 4 papers) published in journals of Groups (1) and (2).

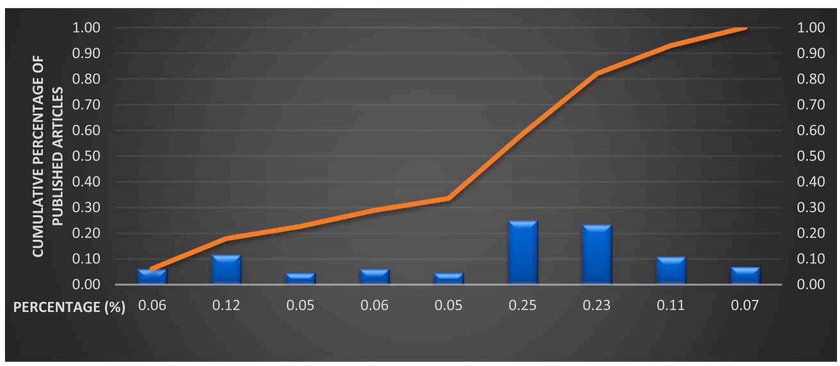

Fig. 2. Cumulative percentage of published environmental emissions in the transport sector.

Table 5.

Comparing the top 5 keywords in Tables 4 and 5, those issues relating to transport (original keyword) and transport and transportation (adjusted keyword) are the most used, with a frequency of 82 and 99, respectively. These indicate that the searched articles are closely related to research on the transport sector and CO_2 emissions. Besides, the keyword ranking three in the adjusted keywords (Table 4) is 'policy,' which implies that researchers are investigating policies that could reduce transportation emissions. Another note is that most selected articles are researched in the EU. The keyword ranking 5 (Table 4) also shows that the policies to reduce emissions in the transport sector drive toward electric vehicles (Smith, 2010a; Grijalva and López Martínez, 2019). Relating these findings to real-life situations, the government continuously increases policies that could encourage the production and use of electric cars, such as the free charging system and incentives for electric vehicle production companies. Keywords such as Data Envelopment Analysis (DEA) and Simulation did not appear in the top ranking but seems to be among the most used method. To identify the most researched mode of transportation, Road and Road transport ranked (7th) in the adjusted keywords and Road transport (9th) in the original keywords (See Tables 3 and 4), making it the most researched transportation mode among the selected articles.

3.3. *Trendy methodologies to address transportation emissions*

The contemporary demands for massive reductions in CO_2 emissions caused by the transport sector, especially in large urban settlements, compel local and national authorities to propose, develop, and implement policies to reduce (or eliminate) pollution significantly. On the researcher's part, several methodologies have been adopted to address transport sector emissions. This section presents the methods used in the selected articles to address transportation emissions. Table 6 summarises the survey results for the approach adopted in the selected papers with the above five papers.

Table 4
Original search result of keywords shown more than five times.

Ranking	Keyword (Non-Adjusted)	Frequency
1	Transport	82
2	CO_2 emissions	58
3	Carbon emissions	18
3	Transportation	18
5	Electric vehicles	14
6	Greenhouse gas emissions	13
7	Decarbonisation	10
8	Climate change	9
8	Energy efficiency	9
10	Road transport	8
11	Simulation	6
12	Aviation	5

Table 6 shows that DEA[1] is the most frequently used methodology among the selected papers. In this context, DEA is used primarily for measuring carbon performance, energy and carbon efficiency, and evaluating emission trends in the transport sector. We recall that transportation and CO_2 emissions are the hottest topics identified in the keyword search (See Tables 4 and 5); these imply that researchers are investigating ways to improve transportation CO_2 emissions by identifying the emission trend and the emission performance in the transport sector. It is important to note that the current research also explores the use of frontier analytical tools in the transport sector emission, which influenced the selected keywords used in the present study. Therefore,

[1] DEA and frontier analysis are briefly reviewed in the ensuing sections.

Table 5
Adjusted search result of keywords shown more than five times.

Ranking	Keyword	Frequency
1	Transport and transportation	99
2	Energy	25
3	Policy	22
4	Greenhouse gas emissions and greenhouse gasses	21
5	EU and European Union	19
5	Logistics	19
7	Environment	17
7	Data envelopment analysis (DEA)	17
9	Mathematical modelling	13
9	Road and road transport	13
9	Sustainable transport, logistics, and development	13
12	Sustainability	12
13	Energy consumption and fuel consumption	9
14	Emission factor and emission trading	8
15	Inland Freight and road freight	7

DEA is the most used frontier analytical tool in transportation emission research projects.

Scenario-based approaches are ranked second in the most frequent methodology applied in the literature in areas such as exploring the types of vehicle taxation, accelerated fuel technology, and purchasing behavioural transition (Brand et al., 2013; Dillman et al., 2021; García et al., 2022). Others include comparing emission configurations (Lättilä et al., 2013). In addition, Fontes and Pereira (2014) examined the impacts of fleet composition changes on emissions because of different road transportation policies in Portugal. Their study compares baseline and counterfactual scenarios to understand what would occur without policies. Meleo et al. (2016) proposed a calculator of the European Union Emission Trading Scheme (EU-ETS) direct cost of Italian companies under the scheme between 2012 and 2014. Relative to forecasting the EU emission trading scheme relative to three scenarios of emission permit price. Morfeldt et al. (2021) used the vehicle turnover model and prospective life cycle assessment with a decarbonisation scenario to analyse the effect of the carbon footprint of a passenger car in Sweden. The scenario-based method has also been combined with other techniques, including scenario and energy-based models (Thielet al., 2016) and simulation and scenario-based methods (Kickhöfer et al., 2019). These indicate that the scenario-based analysis is mainly used to compare cases to suggest policies and mitigation strategies to reduce carbon emissions from the transport sector.

Simulation has also frequently come to the fore and ranked third. The widespread use of simulation methods in addressing emissions is because of the complexity of modelling the effect of emissions and climate change (Cortés et al., 2008; Marcilio et al., 2018). The findings also show that methods such as DEA, simulation, and optimisation models are more analytical and are among the leading methods (see Table 6) in the current research. It implies that environmental research could be more objective when critically analysed. This study compares the top 5 most frequent methodologies (DEA, scenario analysis, simulation, regression models, and optimisation models) with previous review studies. Lee et al. (2016) suggested that emission analysis, survey, simulation, environmental impact analysis, and emission measurement development are the top 5 most frequent methodologies adopted, with simulation appearing in the third position in both studies. In addition, Lee et al. (2016) suggested that DEA is a less popular method in the environmental issue paper and needs to be harnessed. However, between 2016 and 2022, DEA gained significant attention in transportation CO_2 emissions, evidenced in the current research findings.

4. Environmental performance of the transport sector using frontier analysis

Traditionally, frontier analysis attempts to estimate the efficiency of an entity from a sample of observations (Charnes et al., 1978). The

Table 6
Survey result for the top 8 methods adopted in the selected papers (>5 times appearance).

Ranking	Method	Frequency	Authors
1	Data Envelopment Analysis (DEA)	22	Su and Rogers (2012), Voltes-Dorta et al. (2013), Krautzberger and Wetzel (2012), Cui and Li (2014), Chang and Park (2016), Park et al. (2016), Holden et al. (2016), Mariano et al. (2017), Mo and Wang (2019), Wang et al. (2022), Djordjević and Krmac (2019), Dong et al. (2019), Gomes and Lins (2008), Gupta et al. (2021), Klumpp (2017), Li and Cui (2017), Llorca et al. (2017), Llorca and Jamasb (2017), Lu et al. (2019), Mariano et al. (2017), Vukić et al. (2020), Wang et al. (2017)
2	Scenario-based approach	15	Schulte-Fischedick et al. (2021), Waisman et al. (2013), Jereb et al (2021), Heinrichs et al. (2014), Krause et al. (2020), Hájek et al. (2021), Kousoulidou and Lonza (2016), Nocera and Cavallaro (2016a), Zhu et al. (2018), Alonso et al. (2014), Scheelhaase (2019), Statharas et al. (2019) Krause et al. (2020), Paddeu and Denby (2022), Fontes and Pereira (2014)
3	Comparative analysis	13	Taljegard et al. (2019), Durajczyk and Drop (2021), Kisielińska et al. (2021), Škultéty et al. (2021), Yue and Byrne (2021), Cavallaro et al. (2018), Ajanovic et al. (2016) Brzeziński and Pyza (2021), Sharma and Maréchal (2019), Prussi and Lonza (2018), Scheelhaase (2019), Połom and Wiśniewski (2021), Eom et al. (2012)
3	Optimisation model	14	Statharas et al. (2019), Charalampidis et al. (2019), Mądziel et al. (2021), Grijalva and López Martínez (2019), Ghandriz et al. (2021), Pérez-López et al. (2013), Castaneda et al. (2022), Tordecilla-Madera et al. (2018), Jochem et al. (2015), El Yaagoubi et al. (2022), Lättilä et al. (2013), Ko et al. (2017), Thiel et al. (2016), Shen et al. (2019)
5	Regression models	9	Konečný (2020), Lim et al. (2020), Tietge et al. (2017), Mądziel et al. (2021), Alam et al. (2017), Zhou and Kuosmanen (2020), Mohsin et al. (2019), Lim et al. (2020)
6	Simulation	9	Zahraee et al. (2021), Brdulak et al. (2020), Hihara (2011), Yan et al. (2021), Karkatsoulis et al. (2017), Lättilä et al. (2013), Plötz et al. (2019) Bal and Vleugel (2021), Boehm et al. (2021)
7	Econometric	8	Lam et al. (2018), Liu et al. (2016), Carling et al. (2017), González et al. (2019), Siskos et al. (2015), Giannakis et al. (2020), Meireles et al. (2021), Daly et al. (2012)
8	Life cycle assessment (LCA)	6	Albuquerque et al. (2020), Kawamoto et al. (2019), Lodi et al. (2018), Märtz et al. (2021), Baptista et al. (2012), Dallemand et al. (2010)

literature on frontier analysis has been classified into two categories, parametric and nonparametric frontier approaches (Charnes et al., 1978). Although both methods are designed to estimate frontier technology, they use different assumptions regarding the functional form of the best practice frontier (Makieła and Mazur, 2022). In this section, we briefly describe the parametric and the nonparametric frontier approaches to enable the discussion on applying frontier analysis in the transport sector's CO_2 emission research. Parametric frontier methods are based on statistical techniques to estimate the best possible performance of a production process or decision-making unit (DMU) based on input variables (Coelli et al., 2005). According to Coelli et al. (2005), these methods assume that the production process can be modelled using a specific mathematical function, such as a linear or nonlinear regression model. The three main parametric frontier methods described in the literature include the Stochastic Frontier Approach (SFA), the Distribution-Free Approach (DFA), and the Thick Frontier Approach (TFA) (Berger and Humphrey, 1997; Murillo Zamorano, 2004; Weill, 2004). Unlike parametric frontier approaches, nonparametric approaches do not assume a specific mathematical function for the production process. Instead, they use mathematical programming techniques to estimate the frontier based on observed data and some axioms (Charnes et al., 1978; Cook and Seiford, 2009).

The most common nonparametric frontier approach is DEA, first proposed by Charnes et al., (1978). DEA assumes that DMU is efficient if it produces the maximum output for a given set of inputs or uses the minimum amount of inputs to produce a given output level. In other words, efficient DMUs specified by DEA construct the best practice (Charnes et al., 1978). There are several variants of DEA, such as radial DEA, additive DEA, and network DEA, each with specific assumptions and applications (Cook and Seiford, 2009). This review paper focuses on DEA, which has been widely used (Chang and Park, 2016; Holden et al., 2016; Mo and Wang, 2019). The current study finds DEA and SFA as the most popular nonparametric and parametric frontier analysis methods to measure the transport sector's environmental performance. Table 7 shows published articles on transport sector emissions using frontier analysis. Remarkably, the application of frontier analysis methods to measure the environmental performance of the transport sector is relatively low. The leading frontier method used in the current literature survey is DEA, with a few papers on SFA. DEA futures in almost all the selected frontier methods and environmental performance and efficiency measurement are the key research areas except for two papers using SFA (see Table 7).

4.1. DEA in the transportation emissions performance

Environmental issues in the transport sectors are becoming more critical and require swift action. The Sustainable Development Goals (SDG) 13 suggests global emissions of CO_2 have increased by almost 50% since 1990, with a stiff increase in emissions between 2000 and 2010. Consequently, SDG Target 13.2 emphasises integrating climate change measures into policies, strategies, and organisational planning (UN Environmental Programme-SDG 13, 2015). The quest by the SDGs to reduce CO_2 emissions increases the need to explore more suitable methodological applications to enhance CO_2 reduction decisions. For example, DEA is widely used for business and management decision-making (Coelli et al., 2005; Velasquez and Hester, 2013).

DEA is the leading methodology that can be used to assess environmental performance. This section investigates the methodological application of DEA to measure environmental performance in the transport sector, emphasising European countries. DEA is a nonparametric linear programming technique for evaluating the relative efficiency of entities or decision-making units (DMUs) with similar characteristics (Charnes et al., 1978). With a combination of multiple inputs and outputs, DEA can be used to evaluate the relative efficiency of DMUs. There are two main types of DEA models, including the Constant Returns to Scale (CRS) or Charnes, Cooper, and Rhodes (CCR) model introduced by Charnes et al. (1978) and the Variable Returns to Scale (VRS) or BCC model initiated by Banker et al. (1984). The CRS model assumes the proportional variation in inputs will eventuate the same proportional variation in outputs while the VRS model assumes a proportional variation in inputs will not result in the same proportional variation in outputs (Cooper et al., 2007).

The main objective of the DEA model is to maximise the ratio of weighted outputs to weighted inputs for the selected DMUs. DEA can be used as a framework to evaluate the environmental performance of DMUs or entities. Assume that a policymaker evaluates the environmental performance of n homogenous transporters (DMUs) where each transporter $j = 1, 2, \cdots, n$ consumes m inputs $x_{ij}(i = 1, \cdots, m)$ to produce n outputs $y_{rj}(j = 1, \cdots, s)$. Note that revenue generation could be the good output, while CO_2 emissions could be the bad output. For the sake of brevity, the following mathematical programming model is formulated to measure the relative efficiency of the o^{th} transporter:

$$
\begin{aligned}
&\max \sum\nolimits_{r=1}^{s} u_r y_{r_o} \\
&\text{s.t.} \\
&\sum\nolimits_{i=1}^{m} v_i x_{i_o} = 1, \\
&\sum\nolimits_{r=1}^{s} u_r y_{rj} - \sum\nolimits_{i=1}^{m} v_i x_{ij} \leq 0, \quad \forall j, \\
&v_i, u_r \geq 0, \quad \forall i, r,
\end{aligned}
\tag{1}
$$

where u_r and v_i are weights associated to the r^{th} output and i^{th} input, respectively.

One of the significant advantages of DEA models in the environmental performance of the transport sector is that it considers the relationship between performance factors at once, such as fuel consumption, type of fuel, and the related CO_2 emissions. At the same time, other methods may not have this upside. Moreover, DEA models can be used to compare the environmental performance of entities (Djordjević & Krmac, 2019; Dong et al., 2019; Lu et al., 2019). Consequently, DEA can support the realisation of SDG 13 because, from the beginning of the 21st century, environmental sustainability or sustainable development has been at the forefront of societal goals to meet the three pillars of sustainable development. The three pillars of sustainable development include social, economic, and environmental sustainability. These pillars are interconnected and interdependent and must be balanced for long-term sustainable development. Social sustainability refers to the ability of a society to meet the needs of its current and future members while promoting social well-being, equity, and inclusion by addressing issues such as poverty, education, health, gender equality, and social justice (World Bank, 2012). The United Nations defines social sustainability as "the ability of a social system, such as a country, to function at a defined level of social well-being indefinitely" (United Nations, 2017). Economic sustainability refers to the ability of an economy to support long-term growth and development while ensuring equitable distribution of resources and benefits (United Nations, 2018). Economic sustainability promotes economic growth, productivity, innovation, and competitiveness while addressing income inequality, poverty, and unemployment (OECD, 2018). Finally, environmental sustainability is the ability of the natural environment to support life and meet the needs of current and future generations while maintaining ecological balance and biodiversity. Environmental sustainability addresses climate change, pollution, resource depletion, and habitat loss (UNEP, 2012). Therefore, adopting innovative methods such as DEA to analyse environmental sustainability issues would contribute immensely to achieving the SDGs. In this regard, Domagała and Kadłubek (2022) suggested that DEA is increasingly used for sustainability assessment because it allows the inclusion of economic, energy, and environmental factors in the efficiency analysis. Similarly, Hermoso-Orzáez et al. (2020) revealed that DEA is a reliable tool to measure the effectiveness of environmental policies in a specific area or region. However, DEA has some drawbacks, including inadequate discrimination power in some

Table 7
DEA and SFA applications in the transport sector considering emission issues.

Reference	Perspective	Method	Inputs	Outputs (D/U*)
Su and Rogers (2012) Published in International Journal of Sustainable Transportation	Economic and CO_2 emissions efficiencies of national transport systems in the OECD countries	DEA-CCR model	Employee fuel consumption	Gross value added, Total freight transport, CO_2 emissions
Krautzberger and Wetzel (2012) Published in Environmental and Resource Economics	CO_2-sensitive productivity development of the 27 European countries' commercial transport industry	Malmquist-Luenberger index	Energy materials and Services, Capital stock, Employees	Gross domestic product, CO_2 emissions
Voltes-Dorta et al. (2013) Published in Energy Economics	Present and future emission targets with existing technological trends with an in-depth analysis of the Spanish car market	DEA-Malmquist method	Engine power, Volume range	Mass, Fuel consumption, CO_2 emissions
Cui and Li (2014) Published in Transportation Research Part D: Transport and Environment	The transportation energy efficiency of thirty Chinese PARs from 2003 to 2012 to verify its rationality	Three-stage virtual frontier DEA	Labour, Capital energy	Passenger turnover volume, Freight turnover volume, Emissions
Chang and Park (2016) Published in Transportation Research Part D: Transport and Environment	Measuring the impact of environmental regulations in the Korean port industry transport sector	DEA-based model	Labour, Quay length, Terminal area, Energy consumption	Cargo handled, CO_2 emissions
Park et al. (2016) Published in Transportation Research Part D: Transport and Environment	Environmental efficiency changes in the USA transport sector	Non-Radial SBM-DEA model	Capital expenses, Energy use labour	GDP added value, CO_2 emissions
Holden et al. (2016) Published in Transportation Research Part A: Policy and Practice	Monitoring fright transport key performance indicators using the emission benchmarking approach that integrates weight utilisation, volume utilisation, distance travelled, and associated GHG emissions in the global freight transport sector in the UK	DEA model under VRS.	Weight to drop, Volume to drop, Travel distance, Fleet size, Max vehicle weight, Max vehicle volume, Distance travelled, Fuel factor	Emissions
Mariano et al. (2017) Published in Journal of Cleaner Production	Evaluating the efficiency in the relationship between logistic performance index and CO_2 emissions in 104 countries, including EU and BRICS.	SBM-Malmquist index	GDP, Customers, Infrastructure, Quality of logistic service, Tracking and tracing timeliness	CO_2 emissions
Mo and Wang (2019) Published in Energies	Investigating the environmental sustainability of road transport of OECD countries over 2000–2014	Radial DEA-VRS output-oriented model	Length of road, Investment	Passenger, Freight, Emissions
Wang et al. (2022) Published in Sustainability (Switzerland)	Performance measurement of land transportation of 25 organisations in OECD countries	A DEA-based model with Undesirable inputs	Infrastructure investment, Maintenance, Length of transport routes, Labor, Energy consumption	Freight transport, Passenger transport, CO_2 emissions
Gupta et al. (2021) Published in Resources Policy	A multi-objective optimisation model for sustainable transport including economic, environmental, and cooperate social responsibility in Jharkhand, India	AHP-DEA-Fuzzy approach	Time reliability of the vehicle rate of production damage	Operating revenue, Freight turnover, Accident rate
Djordjević and Krmac (2019) Published in Energies	Energy and environmental efficiency in the European road, rail, and air sector	Non-radial DEA-Topsis	Energy consumed assets, Labour	The volume of passenger and Freight, CO_2 emissions
Mariano et al. (2017) Published in Journal of Cleaner Production	Evaluation of CO_2 emissions and logistics performance of 104 selected countries	SBM-Low carbon logistic performance index (LCLPI)-Malmquist index	Customer infrastructure, Quality of logistic service, Tracking and Tracing, Timeliness	GDP, CO_2 emissions
Dong et al. (2019) Published in the International Journal of Environmental Research and Public Health	Evaluating and comparing the environmental performance and operational efficiency of a container port along the maritime silk road with undesirable outputs	Inseparable DEA with SBM	Number of container berths, Container berth length, Number of query cranes	Investment growth, Production, Consumption, CO_2 emissions

(*continued on next page*)

Table 7 (*continued*)

Reference	Perspective	Method	Inputs	Outputs (D/U*)
Gomes and Lins (2008) Published in the Journal of the Operational Research Society	Evaluating the global (country data) CO_2 emissions based on the Kyoto Protocol statement	Zero-sum gains DEA (ZSD-DEA) models	Population, Total energy consumption,	GDP, CO_2 emissions
Klumpp (2017) Published in Sustainability	A review of the application of the DEA Malmquist index technique to evaluate sustainable logistics and supply chain of the European market	DEA Malmquist index technique	Assets and revenue volume	EBIT, dividend volume, GHG emi#ssions, Employment, Women in management
Li and Cui (2017) Published in Transportation Planning and Technology	An evaluation of the efficiency Emission Trading scheme of 22 international airlines in the EU from 2008 to 2012	DEA multi-stage network structure	Stage 1: Number of employees, Aviation kerosene Stage 2: Available seat kilometre, Available ton kilometre, Fleet size Stage 3: Revenue passenger kilometre, Revenue ton kilometre, Sales cost	Stage1: Available seat kilometre, Available ton kilometres Stage 2: Revenue passengers' Kilometres, revenue ton kilometres Stage 3: Total business income
Lu et al. (2019) Published in Sustainability (Switzerland	An environmental performance index for assessing the Performance in green transportation and logistics of 112 countries	Range adjustable measure of DEA	Customer, Infrastructure, Tracking, Shipment, Service quality, Timeline (six components of service quality)	CO_2 emissions, Oil Consumption
Vukić et al. (2020) Published in Journal of Marine Science and Engineering	Proposing a model for determining the optimal transport routs among alternatives in the European Union	DEA	Sum of the total cost of transport, The external cost of transport, Transit time, and Sum of the Length of sea and rail route	The increase in transport routes, CO_2 emissions
Wang et al. (2017) Published in Energies	An evaluation of the energy efficiency of seven countries selected countries	SBM and Malmquist productivity index	Gross capital, Labour Force, Total Energy consumption	GDP, CO_2 emissions
Llorca et al. (2017) Published inEnergy Journal	To estimate the energy demand functions of Latin America and the Caribbean transport sector	SFA	Variables: Thousands of toes 6 Millions of US dollars Thousands of inhabitants Energy price index Thousands of inhabitants/km^2	N/A
Llorca and Jamasb (2017) Published in Transportation Research Part A: Policy and Practice	Analysing the energy efficiency and rebound effects for road freight transport in 15 European countries from 1992 to 2012	SFA	Variables: Total fuel consumption, Diesel consumption, Gasoline consumption, Price of diesel, Price of gasoline, Transitive multilateral price index, Gross domestic product, Stock of trucks, Stock of light vehicles, Stock of trucks and light vehicles, Road freight transport, Rail goods traffic, and Logistics performance index	N/A

* D: desirable output, U: undesirable output.

circumstances. In this respect, Cooper et al. (2007) postulated that the number of DMUs to be analysed should be at least a multiplication of the number of input and output or triple the sum of the number of inputs and output variables, ensuring sufficient discrimination power of DEA. Therefore, we acknowledge the drawbacks of DEA (see, e.g. Zhu (2021), Chen and Liang (2021), and An and Liu (2022)). Still, because of the simplicity of DEA models and the easy-to-access computer support, it is highly recommended for corporate and government use.

Integration of DEA in measuring environmental performance has attracted enormous interest in the past years, specifically in the transport sector. The current research attempts to study how DEA is integrated into the environmental performance evaluation of the transport sector. Therefore, we explore and identify the relevant papers and research priorities, including the transport sector's environmental efficiency, measuring environmental regulations, transportation and logistics performance evaluation, and evaluation of global CO_2 emissions. For instance, Wang et al. (2022) tried to support SDG 13 by evaluating the environmental performance of land transport to improve operational efficiency, save energy, reduce greenhouse gas emissions, and enhance environmental protection. Their study considers the DEA model with the undesirable output to address CO_2 emissions as a bad output. However, there is evidence that DEA models' undesirable outputs are the most used in the evaluation of environmental performance in the transport sector among the selected papers.

Regarding ranking the efficiency of land transportation in 25 OECD countries, Wang et al. (2022) considered factors such as differences in infrastructure investment, the demand for transport, and the Length to rank DMUs for effective decision-making. Su and Rogers (2012) demonstrated how DEA can be used to compare the national transport systems' economic and CO_2 emissions efficiencies using the CCR-DEA model. The authors considered the transportation systems from OECD countries as the DMUs and analysed the panel data from 2000 to 2007. Their model includes the economic variables, fuel consumption, and CO_2 emissions to examine the transportation efficiency of the selected countries. In addition, the economic performance relative to CO_2 emissions and the success in emissions control is evaluated by calculating the economic and ecological indices.

Another significance of DEA is its ability to combine with other approaches to compare or obtain a more robust solution for transportation efficiency. For example, Wang et al. (2017) combined the super slack-based model (super SBM) and the Malmquist productivity index (MPI) to evaluate the energy efficiency of the selected countries during a specified period. In the first instance, the SBM model compares the energy efficiency with and without undesirable output (CO_2 emissions). Next, the MPI was applied to evaluate the selected countries' energy and environmental efficiency by measuring their productivity, technological efficiency, and technical efficiency. Interestingly, DEA models can also combine with other multi-criteria tools such as ELECTRE, AHP, and TOPSIS to evaluate the environmental performance in the transport sector (Liu et al., 2019; Jozala et al., 2021). For example, Djordjević and Krmac (2019) applied the non-radial DEA to evaluate the energy and environmental efficiency of the European rail, road, and air sectors on a macro level. Their evaluations consider energy and non-energy inputs, including desirable and undesirable outputs of the selected transport mode (road, rail, and air). However, TOPSIS was used to rank the transport modes (DMUs) and check the non-radial DEA model's aptness when evaluating the transportation industry's energy and environmental efficiency. Similarly, Jozala et al. (2021) proposed a framework to evaluate the sustainability of public transportation systems using a combination of DEA, AHP, and TOPSIS.

The selected DEA papers also show that the DEA output-oriented model is not popular in calculating environmental sustainability in the transport sector because it assumes increasing output while keeping input constant. For example, policymakers would want to control input variables, such as energy consumption, which would regulate output variables, such as CO_2 emissions. Nevertheless, some key models popular in applying DEA models for evaluating environmental performance in the transport sector include input-oriented DEA models, DEA models with undesirable outputs, SBM, and the MPI.

4.2. DEA models with undesirable outputs

Some DEA models are able to handle the unwanted or bad outputs during energy and environmental analysis in the transport sector or other related sectors with high environmental inefficiencies. DEA assumes that efficiency can be better maintained with more desirable output resources compared to undesirable output and input resources (Halkos and Petrou, 2019). For example, let's consider the transport sector, where CO_2 emissions are produced as undesirable outputs. If inefficiency exists in the production function of a particular transporter, the undesirable variables, such as CO_2 emissions, should be reduced to achieve efficiency. This implies when evaluating the energy and environmental performance of the transport sector, desirable and undesirable outputs must be treated differently (Seiford and Zhu, 2002). There are other cases pointed out by Seiford and Zhu (2002) where the undesirable output (input) needs to decrease (increase) for a particular DMU to improve its efficiency. This case could result in treating the undesirable output (input) as input (output) which does not reflect the traditional production process. The concept of the undesirability of DEA models operates under two alternatives: cases of strong disposable technology and weak disposable technology due to the strength of regulations in the case of CO_2 emission cap. However, researchers have provided various ways to treat the undesirability of output (input) variables (Yang and Pollitt, 2010; Chen et al., 2017).

To treat undesirable variables, Färe et al. (1989) proposed a model with enhanced hyperbolic output efficiency measure that can evaluate the performance of DMUs by ensuring an equal proportionate increase (reduction) in the desirable outputs (inputs) and a reduction (increase) of the undesirable outputs (inputs). Their methodology was applied in the study of Färe and Grosskopf (1996) using strong and weak disposable technology. The concept of the strong disposable technology of undesirable outputs was also applied by Seiford and Zhu (2002) to improve the efficiency of DMUs with undesirable outputs by increasing the desirable outputs and reducing the undesirable outputs. An example illustrating the strong disposability of undesirable outputs is evident in the transport sector, where CO_2 emissions are a notable instance. However, weak disposability is a case where a reduction in transportation emissions could result in a lower production of desirable outputs due to pollution regulations. Consequently, reducing undesirable outputs is possible but comes with an additional cost to the organisation (Zhu & Cook, 2007).

A practical illustration of the undesirability of the output variables is presented here. Assume that a transporter (DMU) consumes a certain amount of energy as the input, the transport turnover or added value is considered the desired output, while the CO_2 emissions are the undesirable output. An example of weak disposability is when a reduction in CO_2 emissions is possible with a proportional reduction in the added value or dividends where the input vector is constant (Zhu & Cook, 2007).

Suppose that there are n independent DMUs, denoted by $DMU_j(j = 1, 2, \cdots, n)$. Each DMU consumes m inputs $x_{ij}(i = 1, 2, \cdots, m)$ to produce s desirable outputs $y_{rj}(r = 1, 2, \cdots, s)$ and k undesirable outputs $b_{tj}(t = 1, 2, \cdots, k)$.

In the case of strong disposable undesirable outputs, the production possibility set (PPS) is defined as a set of all feasible production combinations that a DMU can produce given its available resources. The PPS is expressed using input and output variables, showing the maximum amount of output that a DMU can produce from a given set of inputs or the minimum amount of inputs required to produce a given output. The PSS can be expressed as:

$$T^s = \left\{ (x,y,b) \middle| \sum\nolimits_{j=1}^{n} \eta_j x_j \le x, \sum\nolimits_{j=1}^{n} \eta_j y_j \ge y, \sum\nolimits_{j=1}^{n} \eta_j b_j \le b, \ \ \eta_j b_j \ge 0, \ \ j = 1, 2, \cdots, n \right\} \quad (2)$$

For the weak disposable undesirable outputs suggested by Shephard (1970), the PPS is considered as follows:

$$T^s = \left\{ (x,y,b) \middle| \sum\nolimits_{j=1}^{n} \eta_j x_j \le x, \sum\nolimits_{j=1}^{n} \eta_j y_j \ge y, \sum\nolimits_{j=1}^{n} \eta_j b_j = b, \eta_j b_j \ge 0, j = 1, 2, \cdots, n \right\} \quad (3)$$

It is important to note that the weak and strong disposability are related to the internal DMUs technology. At the same time, the issues of regulation of the undesirability of variables are externally imposed upon the DMUs (Dar et al., 2021).

5. Environmental research trend in the EU transport sector

The EU transport sector accounts for about 10 million employees and generates about 5% of the EU's GDP; consequently, most EU companies' efficiency heavily depends on the transport sector. Transportation and storage account for about 10–15% of the cost of finished goods in EU countries. Concerning environmental efficiency, the Department of Transport in the UK suggests that the transport sector is the largest emitter of greenhouse gas (GHG) emissions, accounting for 24% of the UK's total emissions in 2020, amounting to 406 $MtCO_2$ emissions. (Department for Transport, 2022). Moreover, the EU hosted about 251 million passenger cars on the road in 2015 and generated 770 $MtCO_2$ emissions, 22% of the overall EU CO_2 emissions of 2015 (Zacharof et al., 2016). Therefore, the EU needs to investigate potential strategies to reduce CO_2 emissions from passenger cars, including other modes of transportation in order to achieve its abatement targets. The issues of Brexit relative to climate change have been established under the Climate Change Act 2008, seeking to maintain the commitment regarding all emissions as stated in Article 7.2 of Chapter 7 (Climate and Environment). However, chapter 8 of the UK-EU Trade and Cooperation Agreement (TCA) emphasises the trade and sustainable development of the EU and UK commitment to effectively implement the United Nations Framework Convention on Climate Change (UNFCCC). The Paris Agreement aims to limit the global average temperature below 2°C above pre-industrial levels and pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels, as stated in Article 8.5. Their attempt to maintain the climate change agreement includes the commitment to remove all obstacles to trade and investment in goods and services relevant to climate change mitigation and adaptation, including cooperation in trade-related aspects of climate change policy.

In this context, researchers in the EU and the UK are actively exploring strategies to mitigate transport emissions and achieve significant reductions. For instance, Smith (2010a) and Grijalva and López Martínez (2019) attempted to determine the factors needed to transition from the conventional transportation system to electric vehicles to minimise transportation emissions. Furthermore, Nocera et al. (2018) proposed using technology to address imperfect information for accurately quantifying CO_2 emissions. Besides, Taljegard et al. (2019) proposed applying the cost minimisation investment model and an electricity dispatch model of the European electricity system with an assumption of charging systems. Robaina and Neves (2021) classified the contributing factors for CO_2 emissions intensity in the EU. Their classification suggests that CO_2 emissions intensity from the transport sector can be divided into two classes; (i) CO_2 emissions compared to fossil fuels consumption, and (ii) fossil fuel consumption compared to electricity consumption. Others include total energy consumption compared to the capital, capital compared to the population, and the inverse of the average productivity of the population, which is a ratio between the added value of the transport sector and the population. However, the findings from their study suggest that the total energy consumption compared to the capital and the capital compared to the people are the most significant factors in explaining the intensity of emissions. They indicate the importance of population and capital on CO_2 emission reduction in the transport sector.

Wild (2021) presented an overview of the standards, tools, methods, frameworks, and programs for calculating emissions in the transport sector. Their study used expert interviews to compare the existing guidelines, including ISO IWA 16, focusing on Carbon Care EN16258. However, their study recommends global emissions standards such as simplicity, accuracy, flexibility, feasibility, and transparency. To review transport policies, Brzeziński and Pyza (2021) explored the impact of the organisation transport processes on carbon emission reduction using the theory of organic fuel combustion of a chemical reaction. Their study surveyed expert opinions on how diesel locomotive consumes much fuel and energy. However, apart from the financial cost, their study recommends considering environmental costs in their transport management policy.

Krautzberger and Wetzel (2012) compared the commercial transport industry's CO_2 emission sensitivity productivity development in 17 EU countries between 1995 and 2006. Their study compared the best-practice frontier-based MPI. The findings show a positive productivity development for about 50% of the sample, while the rest demonstrate higher productivity growth values in the CO_2-sensitive model compared to the economic model. Su and Rogers (2012) demonstrated the application of the DEA-CCR model to compare the economic and CO_2 emissions of national transport systems of OECD countries from 2000 to 2005 and 2007; the data set does not include 2006 because OECD did not report data for that year. Their study confirmed that the current structure of the supply chain in the selected countries is oil-based and prevents significant improvements in reducing CO_2 emissions. Future improvement could be possible with significant changes in how products and services are sourced and sent to the market. Finally, Tolón-Becerra et al. (2012) proposed a method for calculating the weighted coefficient for transport GHG emission reduction to analyse the transport emission pattern of the transport sector in the EU.

Gray et al. (2017) contrasted policy development in three European cities, including Aberdeen, Bermen, and Malmo, to share an innovative methodology for carbon reduction in the transport sector. Their study identified government-related uncertainties, including the approach to policy formulation and implementation, consensus, and cohesion as the main factors in achieving sustainability in the transport sector. Karkatsoulis et al. (2017) assessed carbon emission's macroeconomic and sector impact by simulating a transition toward low-carbon transport in the EU. Pålsson et al. (2017) analysed the expected impact of CO_2 and socio-economic factors on transportation systems.

Palander and Kärhä (2019) considered the fixed-effect panel regression model to analyse the impact of logistic performance on CO_2 emissions of the Balkan countries. Their findings reveal a positive relationship between logistic performance and the CO_2 emissions performance of the Balkan countries. Škultéty et al. (2021) proposed a two-step cluster analytic method for for segmenting the logistic performance of the capital cities in the EU-27. Their findings suggest improving city logistics could enhance transportation methods, inventory management, handling and storage of products, waste, return, and delivery services. Hájek et al. (2021) discussed how the individual policy instrument could reduce transportation carbon emissions in a group of EU countries. The result suggests that national legislation in the form of tax revenue varies within the EU member countries. However, the finding reveals that the rising allowance reduces CO_2 emissions.

Similarly, researchers and scholars also attempt to contribute to decarbonization efforts, aiming to minimise environmental impact and

Table 8
Summary of the research trends in the general transport sector.

Authors	Research Trend	Journal
Smith (2010a), Grijalva and López Martínez (2019)	Transition from conventional transportation systems to electric systems	Energy
Nocera et al. (2018)	Imperfection in quantifying CO_2 emission	Transportation Research Part C: Emerging Technologies
Taljegard et al. (2019)	Cost minimisation investment model and an electricity dispatch model	Swiss Journal of Economics and Statistics
Robaina and Neves (2021)	CO_2 emissions intensity	Research in Transportation Economics
Wild (2021)	Standards, methods, frameworks, and programs for calculating emissions in the transport sector	Transportation Research Part D: Transport and Environment
Karkatsoulis et al. (2017)	Simulating a transition toward low-carbon transport	
Hájek et al. (2021)	Carbon reduction policy	
Brzeziński and Pyza (2021)	Organisation transport processes on carbon emission reduction	Transport
Krautzberger and Wetzel (2012)	Commercial transport industry's CO_2 emission sensitivity productivity development	Environmental and Resource Economics
Su and Rogers (2012)	Economic and CO_2 emissions of national transport systems of OECD	International Journal of Sustainable Transportation
Tolón-Becerra et al. (2012)	Weighted coefficient for transport GHG emission reduction and transport emission pattern	International Journal of Energy Research
Gray et al. (2017)	Policy development to share an innovative methodology for carbon reduction	Environment and Planning A
Pålsson et al. (2017)	Impact of CO_2 and socio-economic factors on transportation systems	International Journal of Physical Distribution and Logistics Management
Palander and Kärhä (2019)	Impact of logistic performance on CO_2 emissions	Energies
Charalampidis et al. (2019)	Regional transport restructuring	
Škultéty et al. (2021)	Logistic performance	Sustainability (Switzerland)

improve the economic consequences of transport operations through effective traffic flow management (Jereb et al., 2021). Charalampidis et al. (2019) proposed a regional macroeconomic model for assessing the effects of regional transport restructuring on the regional economies of the EU. Reviewing the existing literature in this area shows that research is investigating the contributing factors of transportation emissions across various transportation modes and the required strategies to reduce emissions using multiple methods presented in this review. The findings from the selected papers also suggest that researchers are working on developing more efficient methods to achieve the sustainable development goals of the SDGs. The literature shows DEA is one of the most popular and effective methods for assessing environmental performance because of its dynamic sustainability dimension to consider separate entities and its ability to handle robust data. On a more serious note, DEA has gained significant attention in the EU as a method for assessing environmental performance because of its ability to evaluate multiple inputs and multiple outputs. The European Environment Agency (EEA) suggests that DEA can be used to analyse firms' environmental performance efficiency to promote sustainable development. The EEA notes that DEA can help identify best practices and inform policy-making to improve environmental performance in the EU (European Environment Agency, 2018).

Similarly, the EU's Joint Research Centre (JRC) also recognised DEA as a good method for evaluating the environmental performance of various industries. The JRC highlights that DEA can assess the efficiency and performance of different firms within the same industry, providing information on best practices that could be adopted to reduce environmental impacts (Joint Research Centre, 2019). Traditional methods for assessing environmental performance rely on subjective assessments, which can be biased and unreliable. In contrast, DEA uses mathematical programming to objectively determine the most efficient DMUs and identify the best practices other units could adopt to improve their environmental performance. In summary, DEA offers a comprehensive approach to evaluating environmental performance by considering multiple dimensions and separate entities and handling robust data. These advantages have made DEA a popular method in sustainability research. The coming sections will discuss the research trends in the various transportation modes of the EU and the UK. Table 8 summarises research trends in the general transport sector and the related journals.

5.1. *Road transportation sector*

Most studies have focused on reducing fuel and energy consumption to evaluate environmental performance in the road transport sector indicating that energy consumption plays a major role in climate change. Consequently, the selected papers show a significant attempt by researchers to explore the dimensions of SDGs in the transport sector such as De Castro Camioto et al. (2014) study on the efficiency of Brazil's industrial sectors in energy sustainable development. However, in road transportation environmental performance research, Kisielińska et al. (2021) conducted a comparative assessment of the use of renewable energy sources in EU road transportation. Furthermore, Morfeldt et al. (2021) estimated the impact of a carbon footprint on banning internal combustion engines in the sales of new cars in Sweden. Finally, Konečný (2020) proposed a methodology to calculate direct and indirect urban public bus emissions. Their approach evaluates the extent to which urban public transport fleet renewal in the EU can contribute to reducing or increasing CO_2 emissions, recommending the consideration of various energy sources, fuel, or power trains and the type of operations during environmental energy assessment in the transport sector.

In a review of the environmental policies and DEA methodology in the road transport sector emissions, Stefaniec et al. (2021) used Shannon entropy and DEA models to examine the social sustainability performance of the EU members between 2004 and 2017 in a cluster of old (EU-15) and new (EU-13) EU members. Their findings suggest that considering social factors in the measurement eliminates the bias from economic factors. Wang et al. (2022) proposed a model to evaluate the environmental efficiency of land transportation by using the DEA method with undesirable outputs in 25 Organization for Economic Co-operation and Development (OECD) countries from 2015 to 2019. The result shows that countries with the best efficiency score for land transportation include Switzerland, Spain, Italy France, Japan, Australia Korea, Lithuania, The Netherlands, Sweden, the USA, and Poland.

Zhou and Kuosmanen (2020) proposed a decomposition methodology to break down CO_2 emissions in the EU's new passenger car using data from Finland between 2022 and 2014. Bhat and Garcia (2021) explored the Paris Agreement's recommendations, aiming to limit the increase in global temperature to less than 2°C. Their study considered the Intergovernmental Panel on Climate Change (IPCC) mobile source methodology to evaluate the CO_2 emissions of a selected class of

Table 9
Summary of the research trends in the road transport sector.

Authors	Research Trend	Journal
Kisielińska et al. (2021)	Assessment of the use of renewable energy sources	Energies
Konečný (2020)	Direct and indirect urban public bus emissions	
Djordjević and Krmac (2019)	Electric vehicles needed to meet emission reduction target	
Brdulak et al. (2020)	Emission policies	
Fontaras and Dilara (2012)	Reported emissions reduction	Energy Policy
Pérez-López et al. (2013)	Reduction and mitigation of emissions	
Krause et al. (2020)	Vehicle efficiency improvement	
Liu et al. (2016)	Weather conditions and CO_2 emissions from road passenger transport	Transportation Research Part D: Transport and Environment
Alam et al. (2017)	Extrapolation of CO_2 emissions	
Lodi et al. (2018)	Average productivity of vehicle-mounted photovoltaic roofs	
Morfeldt et al. (2021)	Carbon footprint and banning internal combustion engines in the sales of new cars	
Palmer et al. (2018)	The economic and environmental benefits in the fast-moving consumer goods	
Haas and Sander (2020)	Emission performance standards	Sustainability (Switzerland)
Wang et al. (2022)	Environmental efficiency of land transportation	
Zhou and Kuosmanen (2020)	Average CO_2 emissions reduction	European Journal of Operational Research
Gerlagh et al. (2018)	National fiscal policies on decarbonisation	Environmental and Resource Economics
Yan et al. (2021)	Transport demand, energy consumption, and emissions	Transport Policy
Stefaniec et al. (2021)	Social sustainability performance	Socio-Economic Planning Sciences
Bhat and Garcia (2021)	Paris Agreement's recommendations	Applied Sciences (Switzerland)
Brand et al. (2013)	Vehicle type and taxation to accelerate fuel, technology, and purchasing behaviour	Transportation Research Part A: Policy and Practice
Fontaras et al. (2017)	Fuel consumption and the realistic estimate of the in-use CO_2 emissions	Progress in Energy and Combustion Science
Voltes-Dorta et al. (2013)	Car manufacturers and emission targets	Energy Economics

automobiles in the EU. The decomposition is based on fuel consumption and fossil fuels' net calorific value (NCV). The result suggests that most EU members consistently increased diesel GHG emissions and decreased gasoline GHG emissions between 2000 and 2018. The diesel records are highest in Poland, the UK, Germany, Spain and France and lowest in Cyprus, Malta, Greece, Netherlands, and Estonia. Finally, Fontaras and Dilara (2012) examined how the reported emissions reduction translates under realistic operations and the effectiveness of the adopted measurement standards using a simple dynamics CO_2 emissions model. Their study used a sample of vehicle modelling data from the official monitoring database, literature sources, and qualified assumptions in the EU. The researchers focused on information on gasoline and diesel passenger car characteristics in the EU, vehicle characteristics, and real-world emissions and correction factor evaluation. However, findings from their research show a significant improvement in vehicle characteristics of the average passenger car's CO_2 emissions.

Other researchers within European countries, such as Brand et al. (2013), considered vehicle type and taxation to accelerate fuel, technology, and purchasing behaviour. To investigate the most tailpipe and life cycle GHG emissions saving, the potential revenue neutrality, and no adverse effects on car use and ownership. The findings suggest that policy choice, design and timing can be crucial in meeting multiple goals. However, CO_2 grading and tightening of CO_2 limits over time are crucial in the shift to low carbon mobility. Pérez-López et al. (2013) analysed the main factors that condition the evolution of Spanish motorway GHG emissions using tier 3 methodology with a focus on factors that involve the reduction of emissions and the mitigation of emissions. The average daily traffic was the most significant parameter affecting the environment besides the average fleet age and vehicle size. Voltes-Dorta et al. (2013) explored the ability of major car manufacturers to meet the present and future emission targets using existing technological trends in the Spanish market using the Malmquist method over a reasonable sample of car models sold in Spain between 2004 and 2010. The findings show that gasoline cars from the US have lower technical efficiency than European cars. However, there is no significant difference in the efficiency between European and Japanese manufacturers. In addition, the price level of cars has a direct relationship with technological change. Consequently, policymakers should try to improve the fuel efficiency in low-priced cars because of their market share.

Concerning the amount of CO_2 emissions from road passengers, Liu et al. (2016) surveyed the Swedish National Travel to quantify the amount of CO_2 emissions by examining which weather conditions correspond least (most) CO_2 emissions from road passenger transport. Haq and Weis (2016) considered the mandatory labelling scheme to analyse the relationship between CO_2 emissions and fuel consumption of new cars within the EU. Fontaras et al. (2017) investigated the factors affecting fuel consumption and the realistic estimate of the in-use CO_2 emissions of European passenger cars. Alam et al. (2017) proposed a framework to improve the estimation and back extrapolation of CO_2 emissions from the Irish road transport sector using a bottom-up data modelling technique. Finally, Lodi et al. (2018) proposed a methodology to analyse the average productivity of vehicle-mounted photovoltaic roofs and quantify the resultant benefit for traditional passenger cars in the EU. Their study revealed that assuming the average CO_2 emissions from the passenger car fleet is reduced to the average of the newly registered passenger car in 2013 (120.7 g/km of CO_2 emissions), there would be a 16.1% reduction in the total CO_2 from road transportation in 2013, which is a significant amount. Zhou and Kuosmanen (2020) considered a frontier-based decomposition (nonparametric CNLS) of the Malmquist index and the index decomposition analysis (IDA) to break down the change in the average CO_2 emissions of new passenger cars in Finland from 2002 to 2014. The breakdown includes components such as available technology, carbon efficiency of customer choice, vehicle attributes, the gap between type approval and onroad CO_2 emissions of passenger cars, and fuel mix. The findings demonstrate that technical change was the most important pathway to decreasing CO_2 emissions. In addition, technical progress in new cars remains the most potent driver even when the test manipulation is adjusted.

Similarly, Gerlagh et al. (2018) studied how national fiscal policies have decarbonised newly sold passenger cars in 15 EU countries from 2001 to 2010. Their result shows that the increased sensitivity of CO_2 registration taxes has significantly reduced the CO_2 intensity for the average new car to about 1.3%, such that higher fuel taxes could lead to the purchase of fuel-efficient cars. However, the study recommends that institutional alignment explore more appetite for low-carbon policies and implement policy transfer such as the EU collaboration framework. Finally, Haas and Sander (2020) analysed the debate surrounding emission performance standards of cars adopted in the 2019 spring to strengthen the decarbonisation of the EU passenger cars in 2019. Their study urges mobility research to engage in lobbying power in the EU to incorporate environmental leadership to enhance environmental performance.

Research also attempted to analyse the efficiency and emission performance of the road transport sector. For example, Palmer et al. (2018) demonstrated how real-world data can be modelled to quantify the economic and environmental benefits in the fast-moving consumer goods (FMCG) sector. Their study reveals a 23% reduction in cost with 58% fewer road kilometres and a 40% reduction in CO_2 emissions. Wang et al. (2022) measured the performance of land transportation in the 25 OCED countries between 2015 and 2019 using DEA. Their model suggests an effective method to determine the environmentally efficient DMUs in the land transport sector of the OCED countries. However, emission policy can contribute effectively to the reduction of carbon emissions. Brdulak et al. (2020) considered emission policies to examine the EU countries that will achieve 95% Zero Emission Buses (ZEB) by 2030. Their study simulates the number of zero-emission buses in the EU countries in 2025 and 2030 to forecast the number of clean vehicles. Further, their finding demonstrates that with the prediction of clean buses, it is most likely that only Norway will reach a 95% level of ZEBs share in all buses proposed. However, most EU members, including the UK, Spain, and Turkey, will have a 95% share of ZEBs in a fleet of all buses after 2050. In addition, Krause et al. (2020) considered a measure for vehicle efficiency improvement, transport reduction, transport smoothing, and transport fleet composition to evaluate the European road transport CO_2 emissions reduction by 2050. Furthermore, Yan et al. (2021) proposed a freight transport model to simulate transport demand, energy consumption, and emissions in Ireland with scenarios up to 2050. Their study discussed that light and heavy-duty vehicles have the potential to significantly reduce the growth of energy consumption between 2015 and 2050. However, it recommends that policymakers could strengthen compliance to ensure efficiency. Finally, Djordjević and Krmac (2019) applied a non-radial DEA model to investigate the potential electric vehicle needed to meet CO_2 targets of emission reduction.

Despite the campaign for sustainable transport and its importance to economic growth and prosperity, there are visible concerns relating to the sustainability of road freight transportation in terms of safety, efficiency, and health implications, including emissions. However, it is observed that policy-driven mechanisms are featured mostly, with urban freight dominating the academic literature in the road transportation sector, indicating an opportunity for future research direction. Table 9 provides a succinct overview of the research trends in the road transport sector as illuminated in the literature.

5.2. Maritime transportation sector

Maritime transport remains the most cost-effective method for moving products globally. Although it witnessed a slight decline in 2018, it remains the backbone of international trade. According to the United Nations Conference on Trade and Development (UNCTAD), about 80% of global trade by volume and 70% by value is carried by sea (UNCTAD, 2020). By 2050, the International Maritime Organization (IMO) aims to reduce GHG emissions from the shipping industry by 50% compared to 2008. In this regard, researchers and policymakers have been working on more efficient methods to reduce maritime GHG emissions. For instance, a review of operational measures shows that adopting slow steaming yields significant CO_2 emission reductions, e.g., a speed reduction of 10% corresponds to a 27% decrease in engine power (Faber et al., 2017). In support, Halim et al. (2018) examined the technical probability of reaching the 1.5°C goal of the Paris Agreement and the expected supporting policy measures. Their findings suggest that the appropriate deployment of available technologies could enhance decarbonisation by 2035. Finally, the authors recommended policies to support the shift to zero-carbon operations, including more stringent energy efficiency targets, a speed limit, and a low-carbon fuel standard. In addition, Serra and Fancello (2020) provided a critical overview of the measures to reduce emissions in the global shipping industry. Their study suggests emission reduction strategies include implementing substantial changes in fuels, technologies and operations. Touratier-Muller and Jaussaud (2021) proposed a mixed-method research approach, using surveys and interviews, to evaluate the sustainable freight transport indicators for shippers when selecting their criteria. Their study assessed the feasibility and pertinence of indicators based on the opinions of shippers and the future technological innovation required by shippers' carriers, as highlighted by the French Ministry of Ecology. The findings suggest the need to increase inter-organisational collaboration between shippers and carriers—transparent data transmission using trunk telematics to reduce disappointment in information flow within the shipping industry.

Efficiency evaluation is crucial in the maritime transport sector. DEA is at the forefront of marine transport performance evaluation. For instance, Barros (2006) applied DEA with a combination of operational and financial variables to evaluate the performance of Italian seaports from 2002 to 2003. Their studies examined indicators such as size, containerisation, and labour to determine the efficiency of the Italian seaport. Their finding suggests that seaport with fewer employees by sales tends to be more efficient than seaport companies with more employees by sales. DEA demonstrates proficiency in efficiency evaluation, most significantly in the maritime sector emissions. Zahran et al. (2017) demonstrated how DEA can be used to assess the efficiency of landlord Pas using two separate models, including the number of vessels called, the total throughput and the number of passengers (throughput) and the activity of the port as inputs for the first model. The second model considered the area of open yards, the number of berths and cargo handling equipment related to the infrastructure and operating characteristics of the port as inputs. However, both models consider revenue as the single output. Their findings suggest that relatively few ports are efficient in both models. The results imply that the Pas of these ports follows optimal resource utilisation practices for their revenue generation. This approach is also proficient in the evaluation of maritime sector environmental sustainability. Nguyen et al. (2022) proposed a two-stage DEA approach to examine the proficiency of the nonparametric DEA and parametric method in terms of differentiation power when measuring the maritime transportation efficiency of European countries from 2016 to 2019. The first stage considers the DEA Malmquist model to measure productivity changes, and the second stage includes the Epsilon-Based Measure (EBM) model to assess the effectiveness and inefficiency of each maritime transportation system: short sea shipping, energy usage, containerisation, and vessels' number and gross tonnage are the inputs. The passengers and gross weight of goods are the two outputs. Findings suggest Estonia, Croatia, Latvia, Malta, Netherlands, and Norway rank among the countries with the top efficiency scores for maritime transportation sustainability. Kujanpää and Teir (2017) reviewed the EU regulation on maritime CO_2 emissions. Their findings proposed monitoring and verifying cargo are the main issues in detecting leaked emissions during a ship's voyage. Leenders et al. (2017) considered allocating CO_2 emissions to a specific shipment in routing transportation. They implied that a traditional cost allocation of CO_2 emissions is inefficient and could be improved with modern mechanisms to achieve better efficiency, indicating the need to advance CO_2 emissions research, specifically in the transport sector. However, the authors highlighted a gap that researchers in the aviation sector could consider, studying the effect of allocation rules on routing decisions. Rigot-Muller et al. (2013) proposed an optimisation model to minimise logistics-related CO_2 emissions for an end-to-end supply chain based on two real-life situations in the UK. The analysis of the cases reveals end-to-end logistics carbon emissions as a significant factor in the UK through direct delivery rather than transhipment through the EU ports. Finally, Bal and Vleugel (2021) proposed measures for emission reduction in the bulk

Table 10
Summary of the research trends in the maritime transport sector.

Authors	Research Trends	Journal
Halim et al. (2018)	1.5°C goal of the Paris Agreement and supporting policy measures	Sustainability (Switzerland)
Touratier-Muller and Jaussaud (2021)	Criteria for a sustainable freight transport indicator	
Barros (2006)	Operational and financial variables in transport performance	Maritime Economics and Logistics
Zahran et al. (2017)	Efficiency of landlord Pas	
Nguyen et al. (2022)	Maritime transportation efficiency	Axioms
Kujanpää and Teir (2017)	Regulations on maritime CO_2 emissions	Energy Procedia
Leenders et al. (2017)	Cost allocation of CO_2 emissions	Transportation Research Part D: Transport and Environment
Rigot-Muller et al. (2013)	Logistics-related CO_2 emissions for an end-to-end supply chain	International Journal of Logistics Management
Bal and Vleugel (2021)	Emission reduction in the bulk freight service	International Journal of Energy Production and Management

freight service between Germany and France and made them compliant with emission targets. However, this study suggests it takes concerted actions to achieve such emission reduction objectives.

The review shows few studies assessing the required policy measures to achieve the decarbonisation target in the maritime sector. Without robust national policies offering strong motivations and mechanisms that support the adoption of low-carbon technologies, ambitious targets and stringent regulations in the maritime transportation sector may encounter resistance from industry stakeholders. Table 10 shows a summary of research trends in the maritime transport sector.

5.3. Aviation transportation sector

The aviation industry is a significant polluter, causing an increase in environmental impacts on a global scale. According to the International Energy Agency (IEA), aviation transport accounted for more than 11% of the transport sector's energy consumption and was responsible for about 3% of the worldwide CO_2 emissions as of 2020. The IEA further projected that aviation emissions might increase by 3% per year if no additional measures to reduce emissions. Therefore, to ensure the reduction in aviation emissions, one of the SDGs is to combat climate change and its impacts, including reducing greenhouse gas emissions from all sectors. Similarly, in 2016, ICAO adopted the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), aiming to stabilise net carbon emissions from international aviation at 2020 levels through carbon offsets.

According to the International Air Transport Association (IATA), air cargo transports account for over US $6 trillion worth of goods, accounting for approximately 35% of world trade by value. Therefore, adopting methods capable of enhancing the sustainability of the aviation industry could significantly reduce emissions from global trade. DEA is the advanced descriptive and prescriptive analytical tool among the various approaches for modelling environmental performance in the air transport sector. For instance, Cui et al. (2022) used DEA to calculate the Pollution Abatement Costs (PAC) index and regulated profits of the global aviation industry. Their study emphasises the selected airlines' recovery times from COVID-19 to predict the data of 25 international benchmark airlines from 2021 to 2027, grounded on the actual data from 2012 to 2019. The discussion and findings confirm that Air France-KLM recorded maximum regulated profits, but EasyJet has minimal gains. In addition, they revealed that setting route conditions impacts whether airlines can achieve a win-win situation. Güner et al. (2021) proposed a Fuzzy Double-Frontier Network DEA (FDFNDEA) model to investigate the relationship between desirable (freight and passenger turnovers) and undesirable (pollutant emission levels) outputs against infrastructure usage, fuel consumed, and movements of the 23 Eurasian airports from 2000 to 2018. Results established a negative impact of income inequality and a positive impact of private engagement on technological progression in the Eurasian airports. Li and Cui (2021) presented a dynamic DEA cross-efficiency model to explore the impact of cooperation or competition on the environmental efficiency of 29 international airlines from 2010 to 2016. The results establish that cooperation is better than competition for the benchmarking airlines. However, competition will likely embody the airline with the lowest environmental efficiency.

Besides DEA, researchers have explored the area of aviation emission using other methods; for example, Alonso et al. (2014) explored the structure of air traffic and its distribution among different EU countries. Their study highlights that the five major countries (France, Germany, Italy, Spain and UK) account for approximately two-thirds of the EU CO_2 emissions as with the traffic. Kousoulidou and Lonza (2016) considered the future growth of aviation fuel demand and biofuel development based on scenarios conducted by the European Commission's Joint Research Centre. Their finding regarding CO_2 emissions projection to 2030 shows a steady increase of 3%, 1%, and 4% average for the three scenarios, including the future growth of aviation, the resulting fuel demand, and biofuel deployment in the European aviation sector. Furthermore, Scheelhaase (2019) scrutinised the cost associated with an EU-ETS (EU Emission Trading Scheme) for regulating air transportation CO_2 and non-CO_2 environmental impact on an individual airline. In addition, Lo et al. (2020) focused on the non-emission-specific decision on the amount of CO_2 generated by the aviation sector. They discussed that although aircraft size increases total CO_2 emissions, it reduces emissions per available seat kilometre. In addition, the route distance increases total emissions and decreases emissions per available seat kilometre. Therefore, the authors implied that CO_2 is less of a problem in long hull connections. Yan et al. (2021) identified the determinant of air passenger flows and flight frequency in 150 international European air routes. Their study adopted a freight transport model to simulate transport demand, energy consumption, and emissions applied in Ireland's transport sector. The authors recommended a comprehensive policy agenda in areas such as technology standards and pricing mechanisms to promote low-emissions vehicle technology. Fageda and Teixidó (2022) studied the impact of the EU carbon market on aviation emissions using data from 58,239 airline-route pairs for 44 EU countries every quarter between 2010 and 2016. Their study showed that the airlines reduced CO_2 emissions by 4.7% within the research period. Finally, Kanellou et al. (2018) studied the environmental performance of European airports, in which they suggested that DEA is suitable for assessing airports' environmental performance. It allowed for the inclusion of multiple input and output variables and provided a clear picture of the relative performance of different airports. An overview of research trends in the aviation transport sector is presented in Table 11.

5.4. Rail transportation sector

Freight transport and logistics play crucial roles in driving economic development. The novel COVID-19 pandemic demonstrated the importance of rail transport and logistics in ensuring the interconnections between national economic systems and guaranteeing the sustainability of supply chains during the lockdown. Therefore, the application of DEA to evaluate the performance of rail transport in the EU is gaining increasing attention. Lerida-Navarro et al. (2019) developed a model to analyse the efficiency frontiers of 27 European rail systems using

Table 11
Summary of the research trends in the aviation transport sector.

Authors	Research Trends	Journal
Scheelhaase (2019)	Air transportation CO_2 and non-CO_2 environmental impact regulations	Journal of air Transport Management
Güner et al. (2021)	Relationship between freight and passenger turnovers and pollutant emission levels against infrastructure usage, fuel consumed, and movements in the airports	Journal of air Transport Management
Alonso et al. (2014)	Structure of air traffic and its distribution among different EU countries	Journal of air Transport Management
Cui et al. (2022)	Pollution Abatement Costs (PAC) index and regulated profits of the global aviation industry	Journal of air Transport Management
Li and Cui (2021)	Impact of cooperation on the environmental efficiency of airlines	International Journal of Sustainable Transportation
Kousoulidou and Lonza (2016)	Future growth of aviation fuel demand and biofuel development	Transportation Research Part D: Transport and Environment
Lo et al. (2020)	Non-emission-specific decision on the amount of CO_2 generated by the aviation sector	Transport Policy
Yan et al. (2021)	Air passenger flows and flight frequency	
Fageda and Teixidó (2022)	EU carbon market on aviation emissions	Journal of Environmental Economics and Management
Kanellou et al. (2018)	Environmental performance	Procedia Computer Science

different tools, including DEA, SFA, deterministic frontier (DFA), and a distance function (DIST). The study suggests a weak positive link between EU rail liberalisation. In addition, higher efficiency and effective competition are the most relevant factors in achieving efficiency gains. Baran and Górecka (2019) introduced a DEA-based model to determine the efficiency of road and rail freight transport in EU countries. Their research assessed the correlations between transport efficiency, economic development, and environmental externalities. Moreover, factors influencing rail transport efficiency in the EU members differ in terms of vehicle fleets, the volume of goods transported, infrastructure intensity, and employment rate in the transport sector, all of which should be taken into consideration. Findings demonstrate that Belgium, Slovakia, Slovenia, and Latvia were the leaders in the technical efficiency of both road and rail transport. However, ineffective road and rail transportation is recorded in Croatia, the Czech Republic, Romania, Hungary, and Estonia. Kleinová (2016) estimated the technical effectiveness of the EU railway performance from demand using DEA. The authors concluded that in the case of country comparison, Eastern European countries, including Poland, the Czech Republic, and Slovenia scored low.

Researchers in the rail transport emission using methods other than DEA believe that the key environmental research trends in the EU and UK rail transportation sector are the development and implementation of sustainable transport strategies to reduce the environmental impact of rail transportation. Similarly, the European Union Agency for Railways (ERA) also suggests that sustainable transport is a key priority for the rail sector in the EU. Sustainable transport strategies are crucial to achieving the EU's climate and environmental objectives. In addition, the UK Rail Safety and Standards Board (RSSB) has identified sustainable development as a key priority for the rail sector. It has developed a Sustainable Development Strategy to guide the industry in reducing its environmental impact. Recent research on the EU and UK rail transport has emphasised various topics, including the development of low-carbon rail technologies, the reduction of emissions from existing rail infrastructure and the development of sustainable transport policies to encourage a modal shift towards the rail. For instance, Prussi and Lonza (2018) considered data from various datasets to assess the environmental impact of modal substitution with high-speed rail. Their study focuses on three scenarios proposed in 2017–2025, including aircraft types, distance bands, and occupancy rates. The results indicate the advantage of high-speed trains in direct CO_2 emissions per passenger km. Compared to a neutral scenario, with an annual passenger increment of 3.5%, the high-speed rail substitution of 5% and the 25% of this increment allow a GHG saving of 4% and 20%, respectively. Some analysed routes (e.g., Frankfurt Main, Paris CDG, Madrid Barajas, and Amsterdam Schiphol) have attractive GHG savings.

To examine the economic response to the 2008 recession regarding sustainable transport system development in Europe, Islam (2018) reviewed and identified the need to improve investments in transport infrastructure, notably rail, to encourage a sustainable multimodal transport system. The study includes eight EU countries based on their length of rail infrastructure; France, Italy, Poland, Romania, Sweden, Spain, Germany, and the UK. The findings show that the "austerity" policy was implemented for investment in the rail infrastructure, with a modest policy investment in road infrastructure. However, results also indicate that considering the approaches in the recent recession, European rail transport appears to have fared less. El Yaagoubi et al. (2022) investigate the obstacles limiting the growth of European rail freight. Findings show a 5% profitability and return on investment for reasonable volumes with intermediary margins (5%). Islam et al. (2016) developed a vision of an efficient European rail freight system in 2050 to fulfil the modal shift targets set in the EU White Paper 2011 (double rail's market share from today's 18% by 2050). The findings indicate that the service quality of rail transport improved through appropriate planning and application of ICT systems, including adopting an integrated supply chain method. However, an assessment of the effects of a modal shift to rail transport, by applying the world's 'best practice', shows a reduction in EU land transport GHG emissions of 20–30%. Thus, rail can substantially contribute to the EU target to reduce GHG emissions in the transport sector by 60%, compared to 1990 levels. Table 12 provides an overview of the current research trends within the rail transport sector.

In summary, Fig. 3 presents a number of published articles highlighting environmental issues in transport sector emissions and the respective journals of publication. This visualisation aids researchers in identifying the most pertinent journals for publishing related research.

Table 12
Summary of the research trends in the rail transport sector.

Authors	Research Trends	Journal
Lerida-Navarro et al. (2019)	Efficiency frontiers	Transport Policy
Baran and Górecka (2019)	Efficiency of road and rail freight transport	Economic Research-Ekonomska Istrazivanja
Kleinová (2016)	Technical effectiveness of railway performance	Journal of Rail Transport Planning and Management
Prussi and Lonza (2018)	Environmental impact of modal substitution with high-speed rail	Journal of Advanced Transportation
Islam (2018)	Sustainable multimodal transport system	Benchmarking
El Yaagoubi et al. (2022)	Obstacles limiting the growth of rail freight	Transportation Research Part E: Logistics and Transportation Review
Islam et al. (2016)	Rail freight efficiency	European Transport Research Review

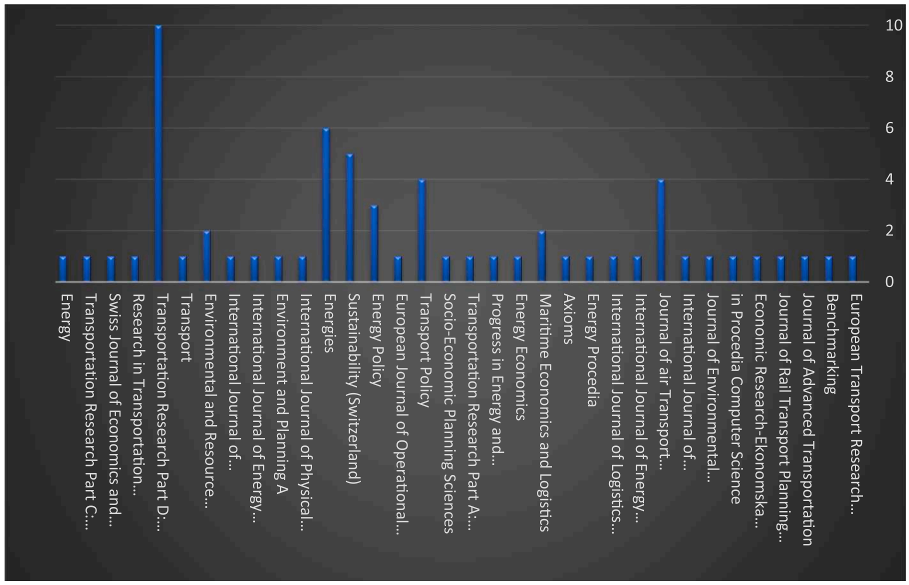

Fig. 3. Number of articles relating to environment trends in the transport sector emissions and the journals of publication.

Notably, the Journal of Transportation Research Part D: Transport and Environment emerges as the most prolific, featuring eight (8) published papers among the selected works.

6. Conclusion and future research directions

Research on transportation emissions has gained continuous attention amid global efforts to reduce greenhouse gas (GHG) emissions. This study investigates major research trends, including the application of frontier methods to measure environmental performance in the transport sector. A review of 186 papers from 46 journals is conducted, and findings are presented in detail. The study indicates that the sustainability and energy journals recorded the highest number of publications.

The review highlights several significant areas that have garnered widespread attention, including transport, CO_2 emissions, GHG, decarbonisation, energy efficiency, electric vehicles, policy implications, problem modelling, road transport, simulation, and climate change. The findings of this review indicate a predominant focus on research trends in the transport sector emissions, particularly in reducing CO_2 and GHG emissions in road transportation through various policies, models, and decision-making tools. Furthermore, this study explores the application of frontier analysis (i.e., DEA) in researching transport sector emissions, acknowledging its significance for planning and optimising transportation emissions. Among the selected papers for this survey, DEA is the most applied frontier analytical tool, recording ten articles, making up 4% of the selected articles. This suggests a potential for increased exploration of DEA in environmental performance research within the transport sector. Notably, specific aspects of DEA, including productivity growth, a measure of efficiency, and performance measurement, are gaining heightened attention. One of the significant limitations of the application of DEA in this study is the availability of data. For example, Zhou and Kuosmanen (2020) highlighted challenges such as inadequate and dependable data for measuring mileage the mileage, the inability to obtain data separately from passenger transport and freight transport, and the difficulty in decomposing energy consumption and CO_2 emissions by other transportation modes besides land transport in the OECD countries (Wang et al., 2022). The research gap in environmental sustainability in the transport sector is broad and requires further research and development. We discover potential opportunities for future research by analysing the existing literature as follows:

The first research direction specified in the current study is to expand the data variables to cover all indicators relating to environmental sustainability and carbon emissions in the transport sector. In addition, future research could consider big data, for example Khezrimotlagh et al. (2019), to allow broad discrimination and analysis for performance measurement using the DEA approach.

There is a notable gap in the literature that specifically addresses the measurement of environmental efficiencies across a supply chain using combined transport modes.

The United Nations appealed to all governments around the globe to develop national strategies and actions to pursue the SDGs. Although most of the research has predominantly focused on CO_2 emissions, little empirical research on the SDGs has been investigated in the field of DEA. In light of this, we recommend future research to explore ways to improve the understanding of SDG13 in the transport sector. Moreover, we suggest directing more attention towards the interplay of SDGs concerning transportation emissions and advocating for a comprehensive evaluation that synergizes related SDGs in future research.

Many methods have been used in the literature to analyse and evaluate the environmental performance of transportation sectors by assuming that observations are deterministic, precise and non-negative data while real-world applications may be characterised by observations that are uncertain, vague or even with negative and ratio values. Further work could extend the formulation to tackle this issue by including fuzzy sets theory (Hatami-Marbini et al., 2022a, Ignatius et al., 2016, Hatami-Marbini et al., 2011), interval approach (Toloo et al., 2021, Hatami-Marbini et al., 2018, Entani et al., 2002), robust optimisation (Arabmaldar et al., 2024, Hatami-Marbini et al., 2022b, Hatami-Marbini and Arabmaldar, 2021), and ratio measures (Hatami-Marbini and Toloo, 2019, Olesen et al., 2017) to quantify imprecise, uncertain, vague and ratio data in DEA models.

Future research could build on the existing literature by following a similar research trajectory but applying different multidimensional methods or a combination of other methods to improve performance analysis. For example, DEA could be combined with multi-criteria decision-making such as VIKTOR, TOPSIS, AHP, and ELECTRE to compare and validate results.

The type of fuel used significantly impacts CO_2 emissions. In light of this, we suggest that future research should consider the existing regulations and the amount of fossil fuels consumed relative to CO_2 emissions generated in producing equivalent sustainable energy sources. Therefore, it is worthwhile to explore the relationship between environmental regulation intensity and the environmental efficiency of various modes based on CO_2 emissions.

Another vital point to consider is that existing research focuses chiefly on policy design and evaluation without incorporating diverse regulatory perspectives. Therefore, we recommend a simulation study in future research to explore the behavioural characteristics of different regulatory bodies and expand emissions policies to cover both road and non-road emissions.

Further study could investigate the factors influencing energy efficiency in the transport sector, including destination, average passenger distance, and degree of distribution hubs. It should be noted that optimisation of data sets of the freight and passenger transport's environmental efficiency decomposition would enhance the overall efficiency of logistics systems.

Finally, research has emphasised the use of performance index to reduce CO_2 emissions. It is worth investigating and comparing the Logistic Performance Index (LPI) scores and carbon performance of all European countries due to variations in economic development levels among them.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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