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Review Article

A review of transportation carbon emissions research using bibliometric analyses

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HIGHLIGHTS

- The number of articles on TCEs has grown rapidly since 2010.
- TCEs research focuses on theory and methods, low-carbon travel, green supply chain management, and carbon emission drivers.
- Scenario analysis, data envelopment analysis, and vehicle routing problem are popular keywords.

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ABSTRACT

The transportation sector is one of the major sources of global carbon emissions. In this study, a bibliometric analysis was conducted using CiteSpace and VOSviewer for articles published in the field of transportation carbon emissions (TCEs) between 1997 and 2023. From this analysis, our research shows that: (a) the number of articles on TCEs has grown rapidly since 2010; (b) China, the United States, and the United Kingdom are important research forces, with the Helmholtz Association of German having the highest number of publications; (c) Transportation Research Part D: Transport and Environment is the most cited journal in this field; (d) the current research hotspots mainly focus on theory and methodological approaches, low-carbon travel, green supply chain management, and carbon emission drivers; (e) while, scenario analysis, data envelopment analysis, and vehicle routing problem are popular keywords that have been used in the research field of TCEs in recent years. Finally, using current research trends, our study also proposes a series of future research endeavors for the field of TCEs.

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1. Introduction

Global climate change and the adverse effects that have been caused by increases in carbon emissions have attracted widespread attention from the international community, with the transition to a low-carbon growth agenda forming the heart of contemporary economic development debates (Sikder et al., 2022a,b). According to the International Energy Agency, the transportation sector accounts for about a quarter of total global carbon emissions and has become the second largest carbon emitting sector in the world. Along with accelerated rates of urbanization, the transportation sector is set to further contribute to growing levels of energy demand and carbon emissions in the future (IEA, 2022). As such, the need to reduce carbon emissions reflects one of the most pressing issues of our times and something that must be tackled immediately. It is therefore important that we deepen our understanding of the current status of transportation carbon emissions (TCEs) research and explore the potential of carbon reduction within the transportation industry in order to achieve global carbon reduction targets.

Existing studies agree that the transportation sector is one of the most challenging areas from which energy savings and emissions reductions can be achieved (Wang et al., 2020a,b). Studies on transportation CO_2 emissions have been widespread, with research conducted on the popularity of electric vehicles (Vilchez and Jochem, 2020; Wang et al., 2022), shifts in travel modality (Wang et al., 2022; Wang and Yuan, 2018), green vehicle routing problems (Asghari and Al-e-hashem, 2021), transportation and climate change (Pal et al., 2023), and energy consumption and emission reduction measures in the transport sector (Sikder et al., 2022a,b; Ulengin et al., 2018).

The methodological approaches used in conducting research on transportation CO_2 emissions have mostly focused on statistical analysis, life cycle evaluation, and model simulations. Statistical analysis has proven an instrumental means of assessing the research domain, with the relevant transportation CO_2 emission data, providing a highly effective means of illustrating the patterns and factors that influence transportation CO_2 emissions. At present, there are several statistical analysis methods for empirically assessing transportation carbon emissions, such as regression analysis, factor analysis, and path analysis, etc. (Ao et al., 2019; He et al., 2020). Other techniques include the life-cycle approach, which has been widely used as a comprehensive evaluation method. By evaluating the whole life cycle of transportation activities, the actual impact of transportation CO_2 emissions can be revealed (Tuan and Wei, 2019; Yue et al., 2015). In addition, in order to measure the benefits of low-carbon policy initiatives, some scholars are now gradually simulating the impact of urban planning and transportation management policy measures on CO_2 emissions through simulation approaches, such as the use of coupled multi-intelligence models and complex models of system dynamics (Chaves et al., 2021; Jiang et al., 2020).

Systematic analysis of transportation CO_2 emissions research can identify the strengths and weaknesses of existing research. Furthermore, it is possible to explore research hotspots and trends in this area. Most of the existing literature reviews on TCEs adopt a content analysis approach, i.e., they provide an overview and commentary on the internal mechanisms, key drivers, and important low-carbon pathways of TCEs based on a comprehensive and systematic collection of relevant literature (Liu and Qiu, 2023; Lyu et al., 2021). In terms of energy efficiency, with a particular focus on passenger cars, light commercial vehicles, air transportation, and rail transportation in China's transportation sector, Zhao and Heywood (2017) provided a comprehensive review of their energy efficiencies and areas of potential improvement across the specified modes of transportation. From a green vehicle routing perspective, Lin et al. (2014) provided a systematic summary of the research methods for green vehicle routing and provided an outlook for future research. While in the broader field of sustainable transportation research, Velazquez-Martinez et al. (2016) discussed the different sustainable transport strategies and practices adopted by countries around the world. However, in these examples, most of the existing literature is limited to only one area of TCEs, making it difficult to provide a detailed overview of the overall research landscape. Therefore, this research combines the bibliometric software VOSviewer and CiteSpace for visualization and analytical purposes. On the one hand, the basic information of the literature on TCEs was analyzed, such as the annual change of the total number of papers, the major national/regional cooperation networks, the distribution of research institutions, and the important journals in the field. On the other hand, in order to identify the key research content and research hotspots, co-citation analysis of the literature, keyword co-occurrence clustering analysis and burst detection analysis were conducted, so as to illustrate the current development and future trends of the field and provide a more comprehensive overview of TCEs research.

This study makes three contributions. First, it directly reflects the current status and content of TCEs research, making tracing the origins of the field clear and understandable. Second, it demonstrates the trajectory and research hotspots of TCEs research, and provides a detailed review of relevant studies to highlight future research trends. Third, the most important institutions, journals, and references in TCEs research are shown, which helps scholars improve their ability to accurately search for relevant journals and industry studies.

The remaining sections are organized below. Section 2 describes the data collection and research methodology. Section 3 provides a visualization of the results and analysis. Finally, Section 4 provides further discussion and draws several key conclusions.

2. Data collection and research methodology

2.1. Data collection

The data selected for this study were extracted from the Web of Science (WOS) core collection database, with the following process adopted. First, we set the search formula to be: TS = (transport* OR traffic*) AND TS = (“carbon emission*” OR

"CO_2 emission*" OR "carbon dioxide emission*") in the advanced search option of the WOS core database, from which 14,343 documents were retrieved. Then, the type of literature was limited to "article" and 12,922 documents were obtained. In addition, the refined research directions were transportation, environmental sciences ecology, energy fuels, business economics, engineering, etc. Further, biochemistry, spectroscopy, mechanics, biotechnology and other apparently unrelated categories were excluded, resulting in 2211 English articles being retrieved. The deadline for the literature search was set as April 10, 2023.

2.2. *Data screening*

The titles and abstracts of the retrieved literature were identified and read in detail, and screened according to the following conditions: (1) related to the field of transportation; (2) the research content involves transportation carbon emissions or one of its directions; and (3) the full text is available. Manual screening was performed based on the above conditions to exclude irrelevant subjects and research content, with 1185 articles finally being used as the dataset for this study. In order to facilitate the bibliometric analysis using CiteSpace and VOSviewer software, all the documents were exported in the format of "full record and reference" text files.

2.3. *Research methodology*

Bibliometric analysis refers to a method of visualizing and analyzing the quantitative relationship and distribution structure of literature through statistical and mathematical theories based on the characteristics of literature attributes (van Eck and Waltman, 2010). By presenting the current status and hot spots of research in a certain field, the approach is able to predict future evolutionary research trends. CiteSpace and VOSviewer are the most widely used software tools for visualizing literature information. Visual graphs can be generated for country, institution and author collaboration network analysis, keyword co-occurrence analysis, citation analysis and the co-citation analysis of relevant literature (Wood and Khan, 2015; Zou et al., 2018). The latter can provide superior visualization of literature information, especially co-occurrence network and cluster density analysis. The advantage of CiteSpace over VOSviewer comes from the analysis of scientific trends provided by the mutation detection function. Keyword mutation detection as well as temporal trend analysis can be implemented to reveal the evolution, research frontiers and development trends of hotspots in related fields. Therefore, this study summarizes the research on TCEs systematically based on the bibliometric analysis tools CiteSpace and VOSviewer.

3. Visualization of results and analysis

3.1. *Annual change in the total number of papers published*

The change in the number of publications is an important indicator of the developmental trends of a field. In order to facilitate the analysis, the distribution of the TCEs studies in the WOS core collection was plotted. Fig. 1 shows that the field of TCEs research has developed rapidly since 1997, with areas development occurring in two distinct phases: an initial period of relatively slow growth from 1997 to 2009; before a more dramatic phase of growth occurring between 2010 and 2022, with a significant increase in the number of published studies, up from 14 in 2009 to 167 in 2021. The average annual growth rate in publications is 34.28%, with particularly rapid growth after 2016.

Further analysis suggests that the growth trends among the number of TCEs publications was particularly prevalent in 1997, 2009, and 2015, which may be related to important international climate policies and initiatives. For example, the Kyoto Protocol was signed in 1997 by 179 nations and regions, opening a new era in the global effort to reduce CO_2 emissions.

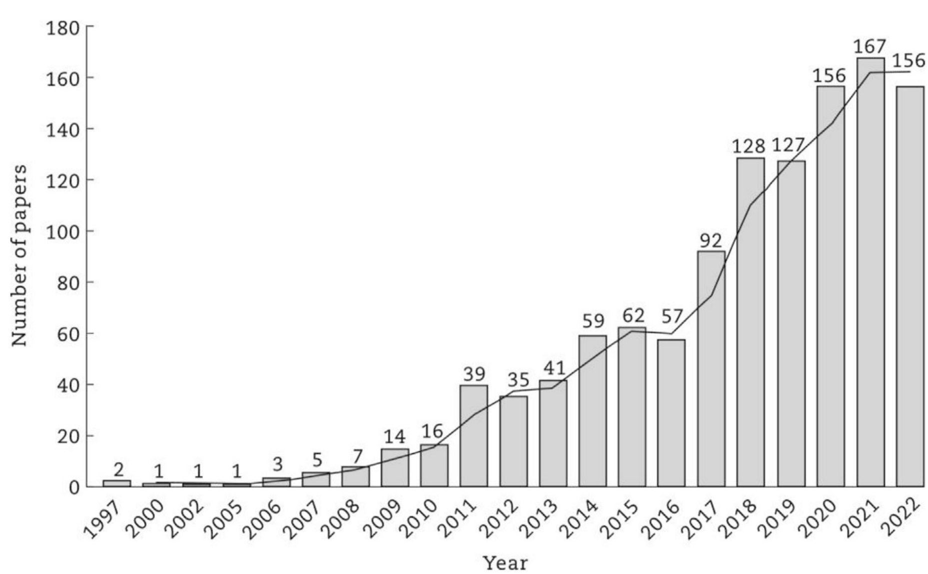


Fig. 1 – Distribution of the number of published papers from 1997 to 2022.

The Copenhagen World Climate Conference in 2009 formulated the Copenhagen Accord, which made arrangements for the mandatory reduction in emission levels by developed countries and the offering of autonomous mitigation actions by developing countries. In 2015, another landmark climate agreement was reached, which sought to take meaningful global action against climate change. 195 nations adopted the first-ever universal, legally binding global climate agreement at the Paris Climate Conference. These events help to illustrate the fact that the study of TCEs is closely related to the implementation of global climate change initiatives, and as such reflects an area of significant contemporary research focus. Given the appeal, it is foreseeable that the number of publications in this field will continue to increase moving forward.

3.2. *Quantitative analysis of major countries/regions*

Our quantitative analysis reveals that 80 countries/regions have participated in TCEs research across the review period. Table 1 shows the top 10 major research countries/regions. China, the United States, and the England were the top three nations in terms of publications.

China published 280 articles, while the United States and the England published 220 and 121 articles, respectively. The total contribution of the three countries accounted for 52.41% of all published works, indicating that the three countries have a significant influence on TCEs research. Additionally, it was discovered that nations in West Asia, South America, and Africa published fewer articles.

Fig. 2 shows the distribution of countries/regions focusing on TCEs, and the collaboration network among them. The analysis is visualized using CiteSpace, with the respective nodes representing the number of TCEs focused studies published in the country/region. The greater the number of papers published, the larger the node. The connection between the two nodes reflects the strength of the cooperative relationship between countries/regions. The color of the node corresponds to the publication time of the article. The darker the color, the older the article. In our study, the network is highly interconnected, indicating a high degree of cooperation between countries/regions. It is simple to see that China, the United States, Germany, and the England all have significant nodes in this network, which illustrates that these nations are active in the field of TCEs research. In terms of the time dimension, we show that there is a heavy concentration of studies published across the 2016 to 2022 period. While, when compared with the USA and England, the number of studies published in China has increased dramatically over the past two years. These developments illustrate the fact that the issue of transportation CO_2 emission reduction is not only related to environmental issues but also socio-economic structural changes to the energy sector. As a country that is keen to be more environmentally responsible, China has established two key goals that would seek it firstly reach "carbon peaking" by 2030, and secondly be "carbon neutral" by 2060. As an important part of achieving the goal of low-carbon emission reduction targets, the TCEs has become the research focus of Chinese scholars.

Table 1 – Top 10 major research countries/regions.

Rank	Country	Citation	Quantity	Percentage (%)
1	China	7086	280	23.63
2	USA	6622	220	18.57
3	England	4621	121	10.21
4	Germany	1599	80	6.75
5	Italy	1159	62	5.23
6	Australia	927	52	4.39
7	France	1097	52	4.39
8	India	879	47	3.97
9	Spain	730	47	3.97
10	Sweden	745	45	3.80

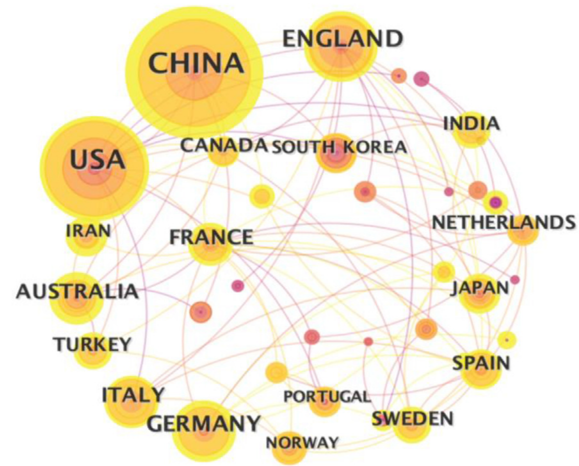


Fig. 2 – Co-authorship network among the main research countries/regions.

3.3. *Quantitative analysis of the main research organizations*

Table 2 shows the distribution of major institutions involved in TCEs research. In this regard, the Helmholtz Association of Germany ranks first in terms of the number of publications. From a global perspective, five of the top ten research outlets are Chinese institutions, with a combined percentage of 7.42% of publications among them. This indicates that many institutions in China are interested in field of TCEs research. In Europe and the UK, the key research institutions are the Helmholtz Association in Germany, the University of London in the UK, the European Commission Joint Research Centre in the EU, which together account for 5.24% of the total number of publications in the field of TCEs. Among the U.S. research institutions, the University of California System is in third place, accounting for 1.94% of the total number of publications, followed by the United States Department of Energy and the Massachusetts Institute of Technology.

Fig. 3 illustrates the distribution of different institutions of TCEs and the connections between institutions. The size of the nodes indicates the number of publications for

Table 2 – Top 11 major research institutions.

Rank	Organization	Country	Counts	Total
1	Helmholtz Association	Germany	24	2.03%
2	Tsinghua University	China	23	1.94%
	University of California System	USA	23	1.94%
4	United States Department of Energy	USA	21	1.77%
5	Beijing Jiaotong University	China	20	1.69%
	European Commission Joint Research Centre	EU	20	1.69%
7	Massachusetts Institute of Technology	USA	19	1.60%
8	University of London	UK	18	1.52%
9	Hong Kong Polytechnic University	China	17	1.43%
10	Chang'an University	China	14	1.18%
	Chinese Academy of Sciences	China	14	1.18%

institutions, and the number of connection lines between each node represents the number of collaborative studies that have been published between different research institutions. The current status of the collaborative research work that is being done among institutions can be seen from the figure. Of note, is the significant importance the academic hubs that Tsinghua University, Helmholtz Association, Hong Kong Polytechnic University, and the United States Department of Energy have become in this field. Moreover, Table 2 shows that these institutions are not only leaders in terms of the number of published papers but are also highly active in establishing close cooperation with other institutions through co-publications. Fig. 3 highlights that the U.S. and Chinese organizations have a clear advantage in the network in terms of the size of nodes and the number of connections. This indicates that these two countries lead the field in terms of TCEs research with high levels of cooperation occurring between institutions and strong research networks among researchers in the field.

3.4. *Quantitative analysis of the main source journals*

Table 3 lists the top 10 journals in the WOS database according to the quantity of TCEs-related research articles published as well as their academic impact metrics. The top 10 journals account for 56.61% of the total amount of papers published. Firstly, in terms of the number of articles, Transportation Research Part D: Transport and Environment is the top journal with 265 articles, accounting for 22.36% of the total number of articles, which is much higher than other journals. The Transportation Research Record had the second-highest number of articles, accounting for 6.24% of the total. Secondly, in terms of academic impact, Table 3 shows two indicators. The first indicator of the academic influence of journals is the H-index, which stands for "high citations". The higher the H-index, the greater the academic influence (Hirsch, 2010). From the top 10 journals in terms of the number of publications, Transportation Research Part D: Transport and Environment has the highest H-index, which indicates that it has a high score in terms of both the quantity and quality of publications. The impact factor (IF) of journals is also an important indicator of academic influence. The highest is the Journal of Cleaner Production with 11.016 and the lowest is the Transportation Research Record with 2.005.

In order to show the distribution of various journals in the field of TCEs, a journal citation network graph was developed by CiteSpace (Fig. 4). The size of the nodes indicates the number of citations for each journal, and the color transition

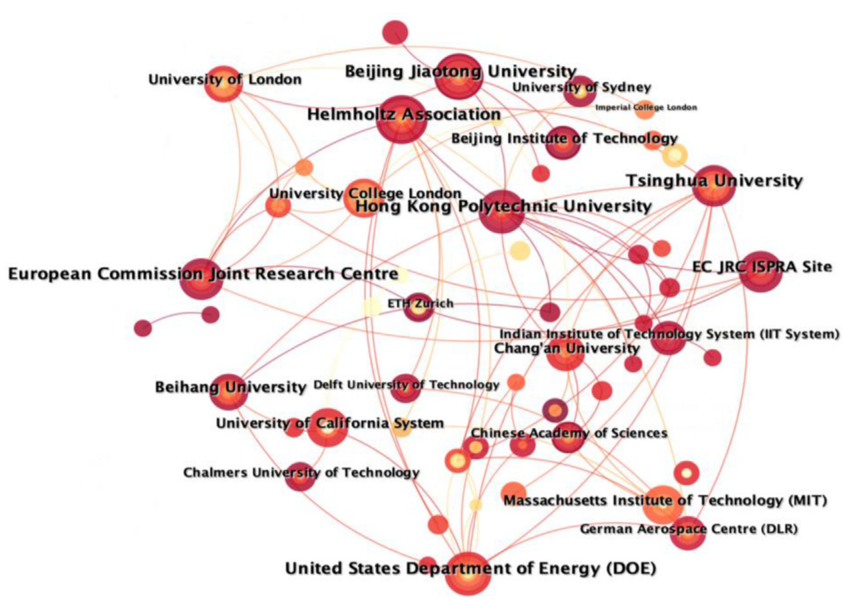


Fig. 3 – The cooperation network of research institutions in TCEs.

Table 3 – Top 10 source journals ranked by total publications.

Rank	Journal	Total publication	Percentage (%)	Citation	H-index	IF
1	Transportation Research Part D: Transport and Environment	265	22.36	7211	43	7.624
2	Transportation Research Record	74	6.24	474	12	2.005
3	Transportation Research Part A: Policy and Practice	66	5.57	3398	31	7.462
4	Journal of Cleaner Production	54	4.56	2084	25	11.016
5	Energy Policy	51	4.30	2431	29	7.88
6	Transport Policy	44	3.71	783	16	6.228
7	International Journal of Sustainable Transportation	39	3.29	473	12	4.26
8	Transportation Research Part E: Logistics and Transportation Review	28	2.36	1048	19	9.333
9	Journal of Advanced Transportation	25	2.11	170	7	2.502
10	Transportation Research Part C: Emerging Technologies	25	2.11	875	14	10.323

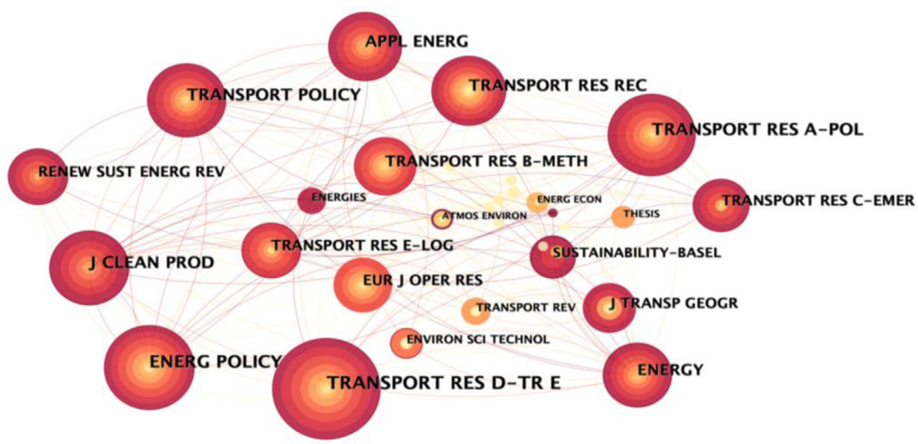


Fig. 4 – Journal citation network of TCEs studies.

of the nodes indicates the temporal evolution of each journal on the research topic of TCEs. Based on the node size, we find that the journals with the highest levels of citation frequency are the journals, Transportation Research Part D: Transport and Environment, Transportation Research Part A: Policy and Practice, the Journal of Cleaner Production, and Energy Policy. These journals have made outstanding contributions to the field of TCEs. Combined with Table 3 and Fig. 4, we show that several of the journals with larger numbers of publications have more colors, indicating that relevant articles from these journals have been published throughout the study of TCEs. The number of citations in the journal Transportation Research Part C: Emerging Technologies has increased in recent years, which reflects a recent shift in the research focus towards pathway optimization and fuel consumption model development within the broader CO_2 emissions domain (Jia et al., 2022; Wang et al., 2020c).

3.5. *Literature citation analysis*

A citation analysis helps to objectively identify influential articles in each field and explore the relationship between citations or co-citations of analysis objects such as sources, documents, and authors (Hota et al., 2019). The number of citations within the literature can reveal both its importance to the field of study and the status of the researchers themselves. Table 4 shows the top 10 articles cited on TCEs topics in WOS (sorted by citations in WOS, recorded as of April 10, 2023). The highest-ranked article is "help or hindrance? The travel, energy and carbon impacts of highly automated vehicles", which has been cited 476 times. The study examined the specific impacts of automation on mobility, energy demand and greenhouse gas emissions. It proposed that automation can help reduce GHG emissions and energy consumption (Wadud et al., 2016). The second-ranked paper is "an adaptive

Table 4 – Highly cited articles in WOS (top 10, April 10, 2023).

Rank	Title	Source journal	Year	Citation
1	Help or hindrance? The travel, energy and carbon impacts of highly automated vehicles	Transportation Research Part A: Policy and Practice	2016	476
2	An adaptive large neighborhood search heuristic for the pollution-routing problem	European Journal of Operational Research	2012	401
3	Mainstream consumers driving plug-in battery-electric and plug-in hybrid electric cars: a qualitative analysis of responses and evaluations	Transportation Research Part A: Policy and Practice	2012	396
4	Energy and emissions impacts of a freeway-based dynamic eco-driving system	Transportation Research Part D: Transport and Environment	2009	379
5	Predicting consumers' intention to adopt hybrid electric vehicles: using an extended version of the theory of planned behavior model	Transportation	2016	337
6	Transport sector CO_2 emissions growth in Asia: underlying factors and policy options	Energy Policy	2009	243
7	Electric vehicles' energy consumption measurement and estimation	Transportation Research Part D: Transport and Environment	2015	237
8	Scientific research about climate change mitigation in transport: a critical review	Transportation Research Part A: Policy and Practice	2011	190
9	Optimizing the locations of electric taxi charging stations: a spatial-temporal demand coverage approach	Transportation Research Part C: Emerging Technologies	2016	179
10	Effect of carbon emission regulations on transport mode selection under stochastic demand	Flexible Services and Manufacturing Journal	2014	176

large neighborhood search heuristic for the pollution-routing problem" with 401 citations. Demir et al. (2012) designed the adaptive large neighborhood search algorithm to solve the pollution-routing problem (PPR). The third-ranked article is "mainstream consumers driving plug-in battery-electric and plug-in hybrid electric cars: a qualitative analysis of responses and evaluations" with 396 citations. In this instance, Graham-Rowe et al. (2012) used semi-structured interviews to explore the attitudes of mainstream consumers towards plug-in electric vehicles. They proposed that governments need to enhance infrastructure investment, while manufacturers and promoters should consider the convenience, cost performance, endurance mileage, aesthetics, and other factors of electric vehicles.

Some studies have explored the optimization of emission reduction pathways from the perspective of modeling algorithms (Demir et al., 2012; Hoen et al., 2014). Others have examined the willingness to use electric vehicles and their development (Graham-Rowe et al., 2012; Wang et al., 2016). In addition, other research has focused on the measurement and control of CO_2 emissions, including the transportation sector (Timilsina and Shrestha, 2009), autonomous vehicles or systems (Barth and Boriboonsomsin, 2009; Wadud et al., 2016), the siting of charging stations (Tu et al., 2016), and the energy consumption levels of electric vehicles (Wu et al., 2015), etc. Such efforts have undoubtedly laid the foundation for further research in the field of TCEs.

To determine the relevance and characteristics of these studies, we used VOSviewer to analyze the co-citation relationships of the cited references, from which four clusters were obtained (Fig. 5). The weight of the "co-citations" indicates the number of times an article has been cited in the co-citation network, and the larger the weight, the larger the corresponding node. Articles in the same cluster are similar in terms of research topics. These articles constitute a knowledge base for the research field of TCEs, and their results and methods provide a reference for other scholars. The following section analyzes the clustering results in conjunction with the information illustrated in Fig. 5.

3.5.1. *Cluster 1 (red)-36 items: green vehicle routing problem (GVRP) research*

Cluster 1 contains 36 articles, of which the highest weighted article is "the pollution-routing problem", published in Transportation Research Part B: Methodological. It has 658 citations in the WOS. The total number of co-citations is 57, and the total link strength is 322. It has the highest number of co-citations in the whole network, indicating an important impact in the research field of TCEs. Bektaş and Laporte (2011) proposed the pollution routing problem (PRP), which investigated the influence of travel distance, greenhouse gas (GHG) emissions, fuel, travel time, and cost on vehicle travel efficiency.

The main topic of Cluster 1 is the green vehicle routing problem (GVRP). Xiao et al. (2012) introduced the fuel

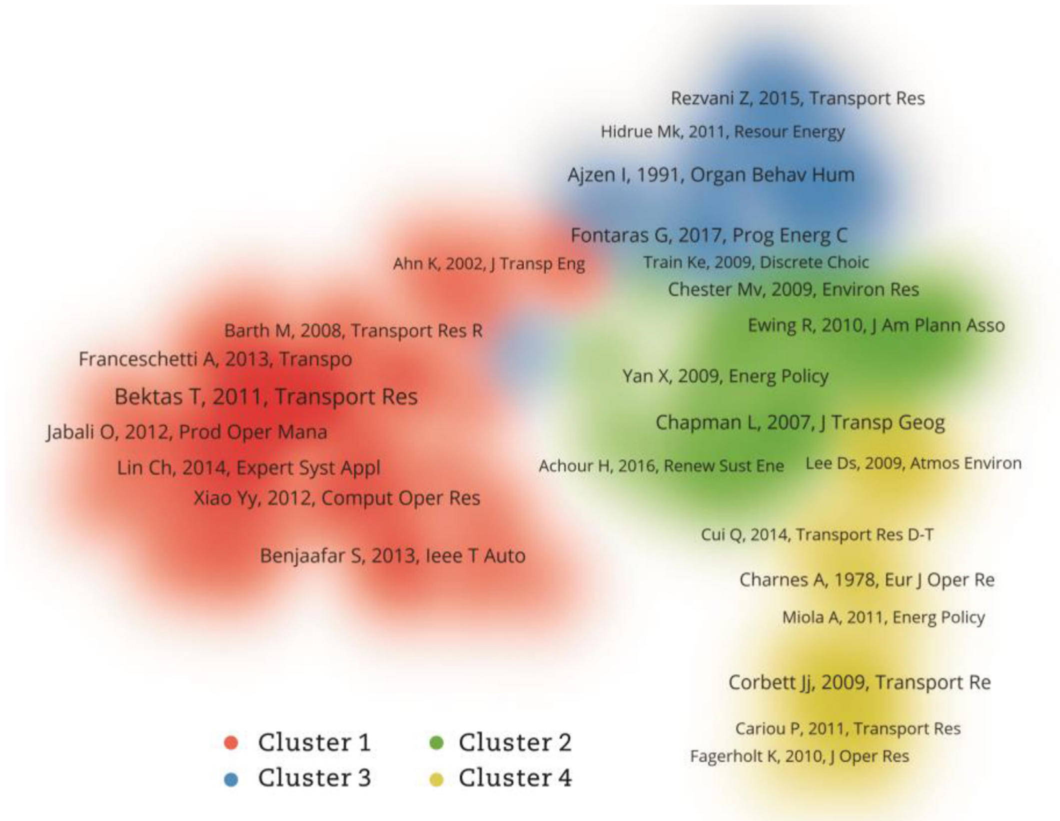


Fig. 5 – Visualization of the co-citation density of references.

consumption rate (FCR) to extend the classical capacitated vehicle routing problem (CVRP) to form the FCVRP model and proposed a simulated annealing algorithm based with a hybrid exchange rule. The study pointed out that this algorithm shows good performance for both the CVRP and FCVRP, and the comparison revealed that the FCVRP model can reduce fuel consumption by 5% on average. As people's awareness of the greater need for environmental protection increases, based on the consideration of reducing fuel consumption, scholars have begun to focus on the factors that affect transportation efficiencies as the object of study (e.g., traveling time, time window, emission, fuel, etc.), and carry out an in-depth study on the GVRP (Franceschetti et al., 2013). Liu et al. (2023) considered the traveling time and time window constraints and designed an adaptive large neighborhood search algorithm to solve the time-dependent GVRP using time windows.

3.5.2. *Cluster 2 (green)-33 items: transportation and environmental research*

Cluster 2 includes 33 articles, and the highest weighted paper is "transport and climate change: a review", which was published in the Journal of Transport Geography and has some 617 citations in the WOS. Its co-citation number is 24, and the total link strength is 38. This paper reviewed the CO_2 emissions of the transportation industry. It investigated the impact of growth in car ownership, aviation, and freight on greenhouse gas emissions. Furthermore, methods of reducing greenhouse gas emissions in various modes of transportation are explored (Chapman, 2007).

Articles in Cluster 2 explore the impact of transportation on climate and the drivers of CO_2 emissions from multiple perspectives. Chester and Horvath (2009) considered CO_2 emissions from infrastructure and supply chains when studying the environmental impact of transportation. After evaluating the CO_2 emissions of the life cycle of a vehicle, it was pointed out that the non-operating components of an automobile often produce very high emission levels. Based on a panel of household activity and travel data from Quebec City, Barla et al. (2011) argued that individual and household characteristics, as well as urban transportation trends affect GHG emissions and predicted that emissions may decrease significantly as a country's population ages. In addition, many scholars quantitatively analyzed the impacts of different factors including economic growth, transport infrastructure (railroads and highways), energy structure, and transport energy consumption on transport CO_2 emissions from national macro data, which can help to further explore the initiatives to achieve a low-carbon pathway for transport (Achour and Belloumi, 2016; Fan and Lei, 2016).

3.5.3. *Cluster 3 (blue)-26 items: theoretical basis and green travel research*

Cluster 3 contains 26 articles, and the highest weighted paper is "fuel consumption and CO_2 emissions from passenger cars in Europe–laboratory versus real-world emissions". This is a highly cited paper with 328 citations in the WOS. Its co-citation number is 30 and total link strength is 29. This article reviewed and compared the different influencing factors that affect fuel consumption and CO_2 emissions in real road and laboratory environments. The research confirmed that driving behavior, vehicle configuration and traffic conditions are the most influential factors. Some neglected factors (e.g., side winds, rain, road grade) can significantly affect fuel consumption when driving (Fontaras et al., 2017).

The articles in this cluster primarily focus on green travel research. Consumer intentions for electric vehicles have been studied based on the theory of planned behavior (TPB) and its extensions (Wang et al., 2016). TPB is one of the classic theories of social psychology, which proposes that human behavioral patterns are influenced by attitudes, subjective norms, and perceived behavioral control, and has been widely used in many social science studies (Ajzen, 1991). Rezvani et al. (2015) outlined the drivers and barriers to consumer adoption of electric vehicles. The study also sorted out the theoretical perspectives used to understand consumer intentions and adoption behaviors towards electric vehicles. Other scholars concentrate on CO_2 emissions from electric vehicles. Petrauskiene et al. (2020) evaluated electric and conventional vehicles in Lithuania from an environmental impact perspective. The study predicted the expected GHG emission reductions from electric vehicles at different points in time and for different electricity combinations from 2015 to 2050.

3.5.4. *Cluster 4 (yellow)-18 items: carbon emission reduction in aviation and shipping research*

Cluster 4 contains 18 articles, and the highest weighted paper in this cluster is "the effectiveness and costs of speed reductions on emissions from international shipping", which is published in Transportation Research Part D: Transport and Environment. The study had 381 citations in the WOS, with 25 co-citations and 61 total link strength. Corbett et al. (2009) studied the impact of deceleration directives and fuel taxes on ship CO_2 emission policies by constructing a profit maximization function, and the analysis indicated that an increase in fuel taxes could reduce speed-related CO_2 emissions.

Articles in this cluster focus on carbon emissions from aviation and maritime transportation. Scholars have studied the climate impacts of air transport, emission reduction measures and their effectiveness (Bouman et al., 2017). Lee et al. (2010) analyzed the impacts of aviation on climate change and ozone depletion and assessed the carbon emissions from the aviation industry. They summarized the types of carbon emissions from air transport such as kerosene, CO_2, H_2O, NO_x, soot, sulfur dioxide, carbon monoxide, hydrocarbons (HCs), etc. At the same time, taking environmental impacts into account, studies have proposed and compared methods and initiatives to reduce CO_2 emissions in shipping and air transportation with a view to achieving economic and environmental sustainability (Psaraftis and Kontovas, 2013; Scheelhaase et al., 2018).

3.6. *Keyword co-occurrence analysis*

As a highly condensed and summarized core content of a paper, keywords usually include research interests, research fields, research objects, research methods, etc., and play an important role in revealing research trends in related fields. Keyword co-occurrence analysis (KCA) is a common research method in bibliometrics (Khan and Wood, 2015; Thirumaran et al., 2022; Zou et al., 2018). In this paper, the VOSviewer software was used to generate the keyword co-occurrence network for TCEs study, as shown in Fig. 6. The figure shows the distribution of keywords, with each node representing a keyword, while the size of the node represents the frequency of the keyword, and the color represents the different clusters. The first 15 high-frequency keywords are shown in Table 5.

From Fig. 6 and Table 5, we show that the keywords of TCEs mainly include CO_2 emissions, impact, electric vehicles, model, and demand. Further analysis shows that most of the studies focus on CO_2 emission models, energy consumptions, impact factors, and environmental assessment. All the literatures were screened with a keyword co-occurrence value of 15 and above as a screening criterion. A total of 95 keywords meeting the criteria were obtained and the keyword co-occurrence network is shown in Fig. 6. The popular topics of TCEs have formed four clusters, and the keywords in the same cluster have a high degree of similarity with the research topics. The analysis of the key research content in the four clusters can demonstrate the research hotspots contained within a field. The framework of literature analysis of research hotspots is shown in Fig. 7.

3.6.1. *Cluster 1 (red): theory and methods*

The first cluster has 26 nodes, and the co-occurring keywords mainly include CO_2 emissions, energy consumption, China, sustainability, road transport, energy efficiency, transport sector, data envelopment analysis, etc. This cluster focuses on the theoretical and methodological approaches of studies within the TEC research domain, which involves the measurement of CO_2 emissions and the evaluation of energy efficiency. Liu et al. (2022) has conducted a systematic review of existing research on carbon dioxide emissions during the road life cycle. The study shows that the road life cycle is usually divided into five stages: material production, construction, use, maintenance and end-of-life (EOL) phases. The contribution of different road life cycles to carbon dioxide emissions varies, with the use stage and initial construction stage contributing the most to carbon dioxide emissions. This provides evidence for the carbon emissions and measurement methods of road traffic in different life cycles.

A large number of studies have analyzed energy consumption and emission reductions in the transportation sector. Some studies focus on different modes of transportation. (1) Aviation: Liu et al. (2020) and Hassan et al. (2018) investigated the factors influencing changes in carbon emissions in China's civil aviation and the United States' aviation systems, respectively, and Monte Carlo simulations were used to predict emission trends. (2) Ports: Tovar and Wall (2019) calculated the CO_2 emissions efficiency of 28 Spanish port administrations, assessing the potential for ports to cut emissions by improving operational efficiency. (3) Urban rail transit: a bottom-up modeling approach was used to calculate the energy efficiency and environmental

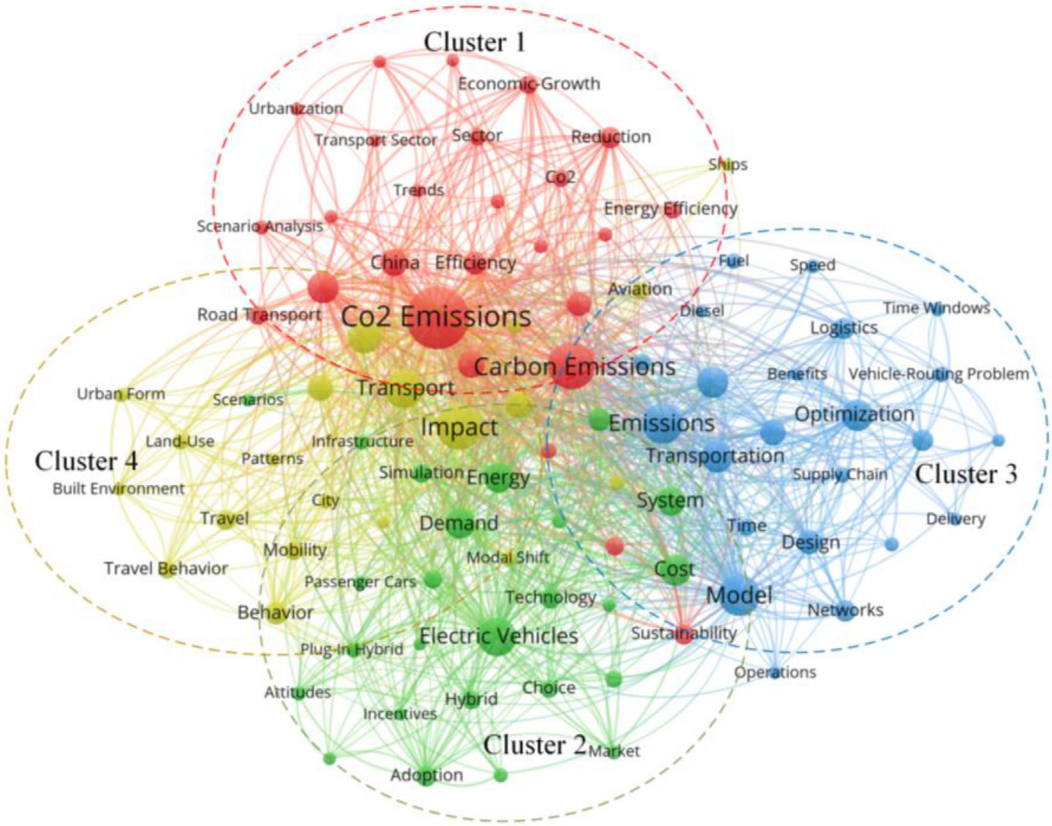


Fig. 6 – Keyword co-occurrence network of TCEs.

impacts of high-speed rail transportation in China, using the Beijing–Shijiazhuang high-speed rail as an example (Chang et al., 2019). (4) Private cars: Long et al. (2020) analyzed the spatial and temporal trends and influencing factors of CO_2 emissions from private vehicle use by Japanese households. These studies measured the CO_2 emissions and energy use efficiency from different modes of transportation and further analyzed their influencing factors.

Table 5 – High-frequency keywords for the WOS TCEs-related papers.

No.	Keyword	Occurrence	Total link strength
1	CO_2 emissions	309	1170
2	Carbon emissions	174	630
3	Impact	167	679
4	Model	140	523
5	Emissions	125	460
6	Electric vehicles	118	449
7	Transport	117	482
8	Greenhouse-gas emissions	94	424
9	Cost	82	309
10	Optimization	81	267
11	Fuel consumption	78	274
12	Energy consumptions	77	381
13	Transportation	76	299
14	Demand	70	293
15	Energy	69	280

There are five main research methods involved in this cluster (Table 6). (1) A bottom-up approach. A modified bottom-up approach (Alam et al., 2017) was adopted using vehicle mileage data and specific vehicle class data to estimate CO_2 emissions. Chang et al. (2013) used intelligent transportation system (ITS) technology and proposed a bottom-up vehicle emission model for the real-time estimation of CO_2 emissions. (2) A top-down approach. Lu et al. (2017) adopted a top-down approach based on urban big data to provide a forecast for transportation CO_2 emission information of the whole city in real-time. (3) Indicator decomposition analysis. This method is widely used to study the factors that influence total energy consumption and carbon emissions in the transportation sector over time. Wang and Liu (2015) took Beijing as an example, and constructed a structural decomposition model, which analyzed the main factors affecting the changes in emissions using LMDI. (4) The system optimization method. Jiang et al. (2020) used a system dynamics method to develop a Beijing urban passenger transportation carbon model, including the economic subsystem, population subsystem, transportation subsystem, energy consumption, and CO_2 emission subsystem, to evaluate the energy consumption and CO_2 emission levels of urban passenger transportation in Beijing. (5) The life cycle approach. Yue et al. (2015) studied the environmental impacts of the Beijing–Shanghai high-speed railway using a life cycle approach. From their analysis, they found that the top-down

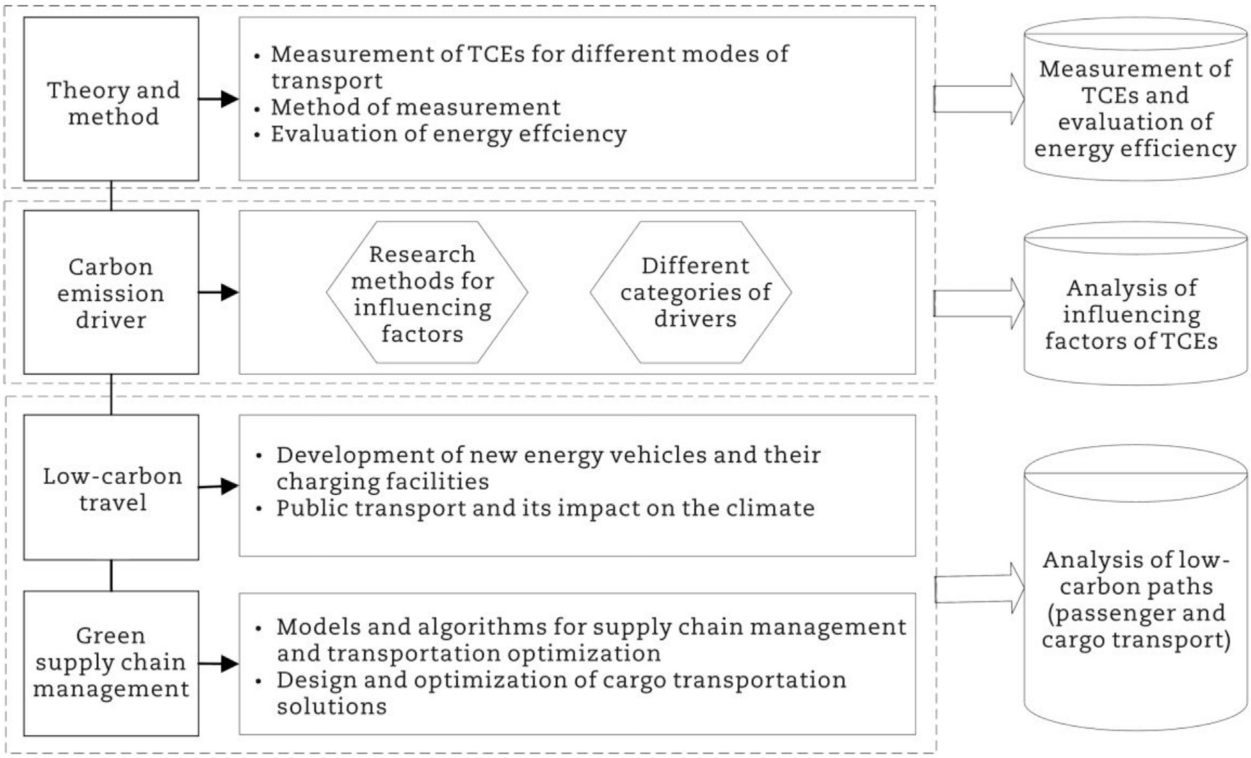


Fig. 7 – The framework of literature analysis of research hotspots.

Table 6 – Summary of accounting methods of TCEs.

Research method	Method introduction	Literature source
Bottom-up approach	The CO_2 emissions of each vehicle are estimated by combining the carbon emission factors of each energy source through the vehicle's mileage, unit energy consumption, energy consumption structure, etc. Besides, detailed vehicle technology (i.e., vehicle type, engine size, fuel type, vehicle age, transmission type, and air conditioning system) and driving patterns (i.e., speed, acceleration, and road gradient) need to be explicitly considered in this approach.	Alam et al. (2017), Chang et al. (2013)
Top-down approach	On a large spatial and temporal scale, carbon emissions are calculated based on the carbon emission coefficient of the means of transportation and the total energy consumption data. Transportation carbon emissions are calculated at large spatial and temporal scales (e.g., national annual levels) based on the carbon emission factors for various energy sources used in transportation versus data on total consumption of various energy sources. (e.g., daily emissions for a city)	Hassan et al. (2018), Lu et al. (2017)
Index decomposition analysis (IDA)	IDA is a commonly used method to quantify the internal drivers of energy/emissions change, and to some extent avoids the arbitrariness in the determination of influencing factors.	Isik et al. (2020), Wang and Liu (2015)
System optimization methods	Based on computer simulation technology, this method dynamically simulates quantitative data through some linear or non-linear mathematical methods to obtain information of the system feedback structure, function and behavior. All system parameters are obtained based on historical data.	Jiang et al. (2020), Wang and Liu (2015)
Life-cycle approach	In the estimation of CO_2 emissions, carbon emissions from fuel use, manufacturing and transportation processes are usually measured over the entire life cycle of a single product (or corporate product) and regional carbon emissions. The use of the life-cycle approach usually needs to be combined with an input-output approach.	Chang et al. (2019), Yue et al. (2015)

and bottom-up approaches are commonly adopted by scholars.

In addition, the evaluation of a transportation system's energy efficiency is also the focus of many scholars. The DEA model, which is most commonly used in the evaluation of a transportation system's energy efficiency, is a non-parametric model for measuring the relative efficiency of multi-input and multi-output decision units (Charnes, 1978). However, traditional DEA models have been unable to deal with a range of undesirable factors and require further development. To solve this problem, some researchers have developed DEA models for non-desired inputs and outputs (Liu et al., 2017a). Seiford and Zhu (2002) confirmed that increasing desired outputs and decreasing non-desired outputs in the traditional DEA model could improve the performance, and proposed the use of linear monotonic decreasing transformation for non-desired outputs to convert to desired output data. Omrani et al. (2018) evaluated the energy efficiency of the transportation sector in 20 provinces of Iran based on a game cross-efficiency DEA model. Wei et al. (2021) combined the stochastic multicriteria acceptability analysis (SMAA-2) with data envelopment analysis to evaluate the energy and environmental efficiency of the transportation sector in China under the uncertainty of CO_2 emission data.

3.6.2. *Cluster 2 (green): low-carbon travel*

The second cluster has 25 nodes, and the co-occurring keywords mainly include electric vehicles, cost, demand, energy, system, technology, life-cycle assessment, plug-in hybrid, incentives, public transport, planned behavior, etc. Yu et al. (2021) used an extended structural decomposition analysis model and input-output analysis to study the structural emission reduction of transportation in China. The energy intensity effect is the main factor in reducing carbon emissions in China's transportation sector, which is caused by the improvement of energy efficiency. The energy structure effect suppresses the growth of carbon emissions. In order to reduce the destructive impact of transportation systems, sustainable economies and carbon-free transportation systems are the main trends (Koengkan et al., 2022). A review of the existing literature shows that research on low-carbon mobility can be divided into 2 categories: (1) the development of energy consumption of new energy vehicles and their charging infrastructure services; (2) public transport modes and their impact on climate.

For the first category, the adoption of new energy vehicles is a promising strategy for mitigating climate change and improving the road transportation environment (Hao et al., 2022). Existing studies have mainly explored the cost-effectiveness and environmental benefits of plug-in hybrid electric vehicles (PHEVs) and battery electric vehicles (BEVs) for consumers (Fulton, 2020). Other studies use a life cycle assessment method to comprehensively evaluate the environmental impacts of different vehicle powertrain technologies.

In addition, with the increasing penetration of electric vehicles, the construction of charging infrastructure has become an important aspect of electric vehicle development, especially the use of DC fast charging stations (DCFCS) (Gjelaj et al., 2020). Arias et al. (2018) proposed the optimal location of charging stations considering the electric power transmission network. Zhuang and Liang (2017) recommended an energy equivalent model-based prediction method for centralized and decentralized charge loads. Sheppard et al. (2016) proposed a method to optimize the size and siting of fast charging stations to reduce infrastructure construction costs.

For the second category, the development of public transportation networks represents one of the most critical measures for addressing the increase in both private vehicle use and CO_2 emission levels. He et al. (2013) calculated that promoting public transportation and limiting car use could reduce total energy use in China's transportation sector by 21%, by 2030. In a subsequent study, based on the changing trend of public travel behavior after rapid urban expansion and development, Yang et al. (2019) conducted a comparative analysis of Beijing and Xi'an to explore the impact of metro services on urban carbon dioxide emissions. Among the methods to calculate CO_2 emissions of various public transportation systems, the life cycle assessment method is widely used. Ghate and Qamar (2020) compared the CO_2 emissions of metro systems and bus rapid transit (BRT) systems based on a life-cycle assessment approach. The study concluded that although metro systems produce more CO_2 emissions, they are more energy efficient than BRT systems over their entire life cycle.

As traditional public transportation such as buses and subways are limited by fixed routes and schedules, new transportation services that are more flexible and personalized such as ridesharing and ride hailing are attracting attention. Tikoudis et al. (2021) found that in 247 cities belonging to Organization for Economics Co-operation and Development (OECD) countries, the widespread use of carpooling services could reduce transportation-related carbon dioxide emissions by an additional 6 percent, and that this figure differed markedly from city to city. Zhu and Mo (2022) modeled two different modes including carpooling and hailing and obtained that carpooling reduces the total vehicle kilometers traveled (VKT) by 8.21% compared to the standard hailing mode. And it can reduce oil consumption and greenhouse gas emissions accordingly, which brings environmental benefits.

3.6.3. *Cluster 3 (blue): green supply chain management*

The third cluster has 23 nodes, and the co-occurring keywords include model, missions, transportation, optimization, management, design, networks, algorithm, supply chain, vehicle-routing problem and operations, etc. With the high globalization of supply chains in many industries, longer supply chains increase the flow of freight internationally and domestically, resulting in an increase in carbon emissions.

In the existing research content of green supply chain problems, many scholars have measured and designed the optimal cargo transportation scheme from the perspective of the cargo transportation mode (Wang et al., 2020d) and order management methods (Tran and Lam, 2022) to achieve a green supply chain system with minimal carbon emissions. Mallidis et al. (2014) proposed an optimization method to minimize the expected total cost and emissions of the alternative network schemes by considering the key logistics network and the regular replenishment cost. Further, considering that traffic congestion is also an important factor leading to an increase in CO_2 emissions, Chen et al. (2021) proposed a time-varying green vehicle routing scheme from the perspective of low-carbon economy by adding traffic congestion and CO_2 tax indicators.

In addition, in terms of research methods, many scholars adopt games, econometric models and their differential equations to analyze specific data to solve the problem of low-carbon supply chain resource allocation. Li et al. (2008) made the first attempt to assess the impact of facility location decisions on the environment. A mixed integer linear programming (MILP) model with profit maximization and emission minimization was proposed to determine the location of the optimal distribution center and transportation mode selection. Harris et al. (2014) determined the optimal number of operating facilities based on multi-objective evolutionary algorithm (MOEA) and the Lagrangian relaxation method. The optimal allocation of these facilities, the minimization of transportation costs and carbon dioxide emissions were discussed. Konur and Schaefer (2014) proposed an EOQ modeling approach for bicycles, from an inventory management and transportation perspective, and finally determined the optimal order quantity for minimizing holding, ordering, and assessing transportation costs.

Besides, benders algorithm (Pishvaee et al., 2014), the whale optimization algorithm (Dewi and Utama, 2021), and the genetic algorithm in strategic network design (Fatemi-Anaraki et al., 2022; Wolff et al., 2021), and the newsvendor model in inventory decision cost (Arias et al., 2018) have been all applied in this clustering. The main research contents and definitions of various algorithms and models are summarized as follows (Table 7).

3.6.4. *Cluster 4 (yellow)-20 items: CO_2 emission drivers*

The fourth cluster has 20 nodes, and the co-occurring keywords mainly include impact, transport, greenhouse-gas emissions, policy, climate change, land-use, travel behavior, urban form, built environment and modal shift. The clustering themes focus on the study of carbon emission drivers. The transportation CO_2 emission system is a high-order dynamic and complex system. Identifying the basic factors and systematically dissecting the internal and external drivers of TCEs are beneficial to sort out the influence mechanism and reduce CO_2 emissions. The commonly used research methods of TCEs influencing factors are as follows. (1) The fixed panel regression model (Guo et al., 2022). A multiple linear regression model is established to find the significant influencing factors by considering the influence of multiple independent variables on CO_2 emissions. (2) The stochastic impacts by regression on population, affluence, and technology model (Andres and Padilla, 2018), or STIRPAT for short, has been one of the mainstream tools for studying

Table 7 – Research model and algorithm summary of supply chain management and transportation optimization.

Research content	Model/algorithm	Model/algorithm introduction	Literature source
Strategic networks design decisions costs and environmental impacts	Mixed integer linear programming (MILP)	Algorithms where the objective function and constraints are linear, but some of the decision variables must be required to be integers.	Chaabane et al. (2012), Konur and Schaefer (2014)
	Benders algorithm	An algorithm that decomposes a planning problem with complex variables into linear programming and integer programming, decomposes the master problem and subproblems by the method of cutting plane, and solves the optimal value by iterative method.	Pishvaee et al. (2014)
	Multi-objective evolutionary algorithm (MOEA)	Algorithms for solving complex optimization problems with multiple objectives.	Harris et al. (2014)
	Whale optimization algorithm	A new type of swarm intelligence optimization algorithm in the field of swarm intelligence algorithm other than the ant colony algorithm and the particle swarm algorithm.	Dewi and Utama (2021)
	Genetic algorithm	The algorithm searches for the optimal solution by simulating the natural evolutionary process. In solving more complex combinatorial optimization problems, it is usually possible to obtain better optimization results more quickly.	Fatemi-Anaraki et al. (2022), Wolff et al. (2021)
Costs of tactical inventory planning decisions and environmental impacts	Economic order quantity (EOQ)	It is a type of fixed order lot model that can be used to determine the quantity of a single order (outsourced or homemade) for a company. When a company orders according to the economic lot size, the sum of the ordering cost and the storage cost can be minimized.	Konur and Schaefer (2014)
	Newsvendor model	The algorithm studies the procurement problem with optimal order quantity and optimal lead time under strict assumptions to study the procurement problem closer to real-life enterprises.	Arikan and Jammernegg (2014)

environmental issues. It is able to integrate three human-driven factors, population, wealth, and the technology level, with environmental issues into one analytical framework, and to study the direction and intensity of the impact on CO_2 emissions. (3) The system dynamics model (Chaves et al., 2021; Sim, 2017). Based on the system theory and information feedback control theory, four subsystems of socio-economic, energy, environment, and transportation are simulated, with the results obtained providing some reference for policymakers. (4) Structural equation modeling (SEM) is commonly used to explore the complex relationship that exists between the built environment and travel behavior (Ashik et al., 2023). The advantage is that it can avoid the problem of endogeneity between variables. (5) Spatial econometric models take spatial factors into account, with the approach often used to analyze the evolution of spatial patterns of transportation CO_2 emissions, regional differences in urban transportation CO_2 emissions, etc. (Long et al., 2020). These methods can effectively identify the influencing factors of TCEs and are widely used in a variety of fields.

With the widespread application of spatial geographic analysis techniques, an increasing number of scholars have conducted in-depth analysis of the drivers of TCEs from numerous perspectives, including land use, travel behavior, urban form, built environment, and climate. Ashik et al. (2023) examined the direct and indirect effects of the built environment (BE) on CO_2 emissions associated with commuting and found that such effects differ in developed and developing countries. Existing research suggests that the factors influencing TCEs are numerous and complex. Considering the common characteristics of related factors, the drivers can be gathered into the following categories: economic development, transportation policy and management, residents' travel behavior, urban form, and environmental factors, etc. (Table 8).

The impact mechanisms of TCEs has been the focus of academic attention. Scholars mainly investigate the changes of regional CO_2 emissions under the combined effect of multiple factors, and propose measures to reduce emissions accordingly (Wang et al., 2020e). By using the ARDL model, Sikder et al. (2022a,b) found that energy use, industrialization, economic growth and urbanization have a positive impact on CO_2 emissions in 23 developing countries, and made recommendations for relevant policy makers from a policy perspective. As technology continues to evolve, scholars have also considered combining geographic and human factors to build models that better match realistic scenarios. There is no doubt that research on this topic will continue in the future.

3.7. *Research trend analysis*

3.7.1. *Keyword clustering timeline*

CiteSpace is used to cluster the keywords according to time, and 8 main clusters reflecting the research content of TCEs are identified (Fig. 7). The keyword clustering timeline graph begins in 2010 and concludes in 2023, even though the literature search reveals papers published as early as 1997. However, there were not enough studies published before 2010 to produce clusters. The literature under each clustered theme based on the timing of keyword clustering is analyzed below (Fig. 8).

The research on "CO_2 emissions" (2010–2023) is included in the whole process of TCEs, with more articles published during the early part of this period, the likes of which mainly explored the basic theory of carbon emissions, however, the number of articles on this topic gradually decreases as the level of research progresses. "Vehicle routing problem" is the most common keyword that appears from 2010 to 2023 and contains the largest number of studies and a prominent topic in the overall field of research. The models, techniques, and scenarios are continuously updated throughout the research process, and the green vehicle routing problem is derived since the advent of new energy vehicles (Hu et al., 2016; Murakami, 2018). "Transportation and sustainability" (2010–2023) is also a relatively long-lasting research question within the field of TCEs research, indicating that sustainable transportation has been the focus of attention. However, the number of total research outputs is low, with the existing literature mainly exploring the issue of how to reduce emissions in the transportation sector, such as battery production, and research on alternative fuels for vehicles. In recent years, studies have been conducted using discrete choice models to analyze the choice of transportation at the individual level (Okada et al., 2019).

Table 8 – Overview of research on the drivers of TCEs.

Factor classification	Literature source
Economic development	GDP (Guo et al., 2022); transportation industry scale (Xu and Lin, 2015); population (Andres and Padilla, 2018); car ownership (Ashik et al., 2023)
Transportation policy and management	Fuel tax (Gupta and Dhar, 2022; Pettit et al., 2018); technological progress (Sim, 2017); emissions tax (Hu et al., 2021); transport mode shift (Saltykova et al., 2022)
Residents' travel behavior	Choice of travel mode (He et al., 2013); commuting distance (Yang et al., 2019); travel attitude (Ding et al., 2014)
Urban form	Urbanization rate (Liu and Feng, 2020); road infrastructure (Hu et al., 2021); building area scale (Yang et al., 2019); land use and density of urban road network (Ou et al., 2013)
Environmental factors	Architectural environment (Ashik et al., 2023); energy intensity and energy structure (Isik et al., 2020)

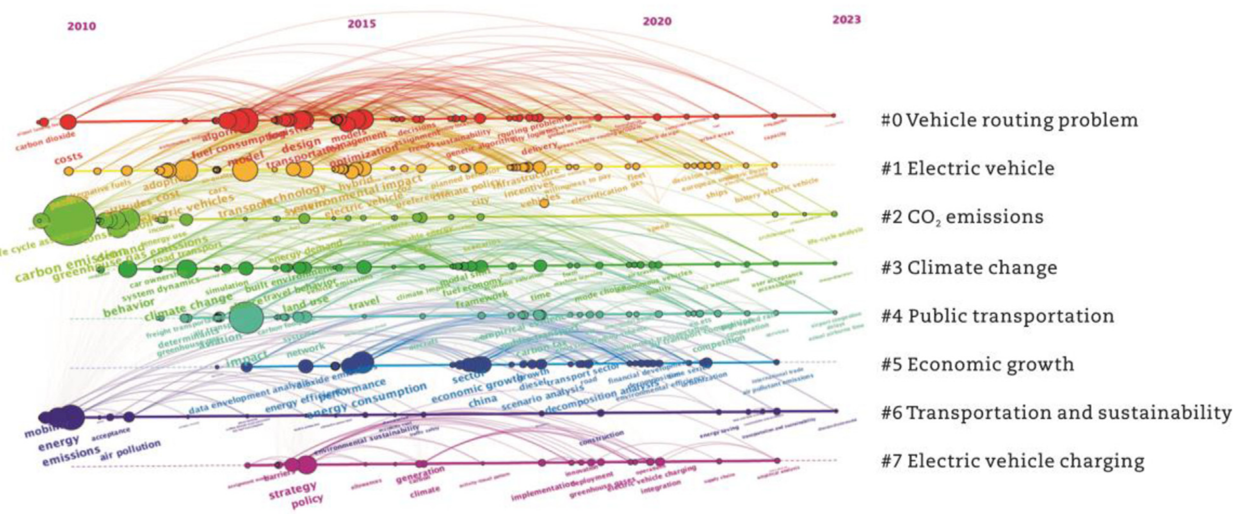


Fig. 8 – Keyword clustering timeline graph.

CO_2 emissions from transportation and climate change are closely related, so "climate change" (2012–2023) has been a key theme throughout the TCEs research that has been conducted. However, during this period, the exact focus has gradually shifted from the climate impact of road, rail, and air transportation through to the willingness of individuals to pay for CO_2 emissions and the role of electric vehicles in mitigating climate change.

Low-carbon travel is an important aspect of TCEs research, which includes three clusters: "electric vehicle" (2010–2022), "electric vehicle charging" (2013–2022), and "public transportation" (2013–2023). During this period, electric vehicle sector research has evolved from something that focused primarily on vehicle power models to one that examines consumer purchase intentions, decisions, and support strategies (Schmidt et al., 2021). With the boom in electric vehicle research came research on electric vehicle charging issues. In 2014 many scholars began to explore consumer perceptions of electric vehicles from a charging perspective (Schmidt et al., 2021) as well as the barriers to electric vehicle development (Tarei et al., 2021). Public transportation is also part of green mobility, and research on TCEs has been progressively involved in better understanding, since 2013, the air transportation sector (Chao, 2014; Cheze et al., 2013) and railroads (Logan et al., 2020).

The "economic growth" (2013–2022) cluster has developed over a relatively short period, but the number of studies have been abundant, particularly in regard to the causal relationship that exists between transportation carbon emissions and regional economic development. The initial studies explored energy efficiency and energy consumption. Since 2016, numerous scholars have studied the relationship between transportation-related greenhouse gas emissions and economic growth in different countries (Wang et al., 2023). With the accelerated urbanization process, the effect of urban density on transportation CO_2 emissions has also been further studied (Liu et al., 2017).

From 2010 to 2012, theoretical research on CO_2 emissions was the clear focus, while from 2013 to 2015, the integration of algorithms and models into path optimization problems started to become the mainstream area of research. During this period, many scholars started to explore the connection between TCEs and economic development, and research on electric vehicles also started to emerge. In 2015, we found that the types of research that were being carried out across all clusters were still in development, for instance, the optimal path design problem in the "vehicle routing problem" cluster, the study of hybrid vehicles in the "electric vehicle" cluster, the study of energy efficiency measures in the "economic growth" cluster, and the study of public attitudes and electric vehicle policies in the "electric vehicle charging" cluster.

Since 2015, each cluster's size and distribution of nodes have been more evenly distributed, demonstrating that TCEs research has been advancing in each area and exhibiting a balanced development trend.

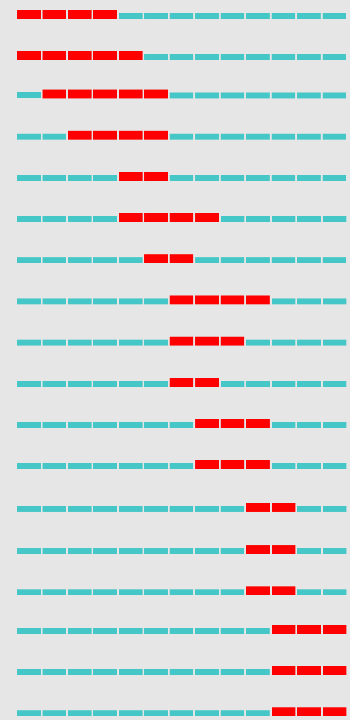
3.7.2. *Burst detection analysis*

According to studies, the significance of keywords depends not only on their frequency but also on how their density changes over time (Kleinberg, 2003). A keyword burst is when a keyword suddenly becomes popular in a certain stage of the research process. It can be utilized to discover cutting-edge research ideas and new research trends (Yue et al., 2020). CiteSpace uses burst detection analysis (BDA) to check the frequency variation and temporal distribution of keywords. The data is imported into the CiteSpace program, where the burst function is performed. The time span for this study is 2010–2023, with the period set to one year, suggesting that the interval time is a year. Finally, the results are shown in Table 9. According to the BDA, the keywords of TCEs from 2010 to 2023 can be divided into three periods.

The first stage (2010–2015). This is the initial stage of the research, and five keywords are obtained, including the keyword "CO_2 emissions" and its synonyms, which are the most common keywords during this period. The Copenhagen World Climate Conference in 2009 brought unprecedented attention to climate change and greenhouse gas emissions, and CO_2 emissions gradually became a new research hotspot

Table 9 – TOP18 keywords with the strongest citation bursts from 2010 to 2022.

Period	Keyword	Burst intensity	Temporal bar graph from 2010 to 2022
2010–2015	Carbon dioxide emissions	4.11	
	Carbon emissions	3.11	
	Greenhouse gas emissions	4.86	
	Energy	3.18	
	CO_2 emission	3.65	
2016–2019	Travel behavior	3.09	
	Fuel consumption	3.95	
	Strategy	3.84	
	Attitudes	3.60	
	Environmental impact	3.05	
	Hybrid	3.75	
	Industry	3.25	
2020–2022	Scenario analysis	3.47	
	Road	3.09	
	Data envelopment analysis	3.09	
	Decomposition analysis	3.52	
	Vehicle routing problem	3.20	
	Speed	3.17	



in the field of resource and environmental economics. Researchers started investigating and researching the connection between the transportation sector's CO_2 emissions and climate change at this time.

The second stage (2016–2019). During this time, the relationships between people's travel behavior and attitudes toward TCEs and the impact of TCEs on the environment have been highly valued, thus the use of the keyword "environmental impact" can be found to grow rapidly from 2016 to 2017. Reducing car travel and promoting green travel are often considered important solutions to reducing energy consumption and CO_2 emissions from the transportation sector. For example, Ding et al. (2014) proposed an approach to assess the impact of employer attitudes toward green commuting programs on employee commuting mode choice, empirically demonstrating that positive employer attitudes towards green commuting programs reduce employees' household car ownership. In addition, the transportation industry has become one of the most popular research areas in the TECs literature, with related research being categorized into two areas: supply and demand issues, and energy consumption. Studies related to transportation supply and demand include the analysis of passenger and freight transport, changes in supply and demand structure, adjustment and upgrading of transportation industrial structure, among other factors of influence. The studies on energy and pollution emissions mainly include measuring total energy consumption, identifying factors affecting energy consumption, examining changes in energy structure, and emission analysis.

The third stage (2020–2022). With the enhancement of people's awareness of environmental protection and the progress of technology, new energy vehicles gradually replace traditional fuel vehicles as the main mode of transportation. The green vehicle routing problem, especially the path optimization problem of hybrid vehicles, has emerged as a new field of research. For example, Zhen et al. (2019) studied the mode selection system of hybrid vehicles by building a mixed integer linear programming model to minimize the total energy cost. The particle swarm optimization algorithm (PSO) was designed and improved to effectively solve the model for optimal fuel use. In addition, the research of energy efficiency measurement based on DEA models has become more mature in recent years, and many improved DEA models and cross-over models are widely used in energy efficiency measurement.

The analysis of a low-carbon path can assist with the development of the transition to low-carbon energy use in the transportation sector. In order to set reasonable emission reduction targets, scenario analysis-based research on the transmission to a low-carbon path is being intensified. Scenario analysis helps to comprehensively assess the impact of different transportation policies on future transportation CO_2 emissions. Liu et al. (2021) used a real project-level asphalt pavement freeway in China with 15-year life span in China as a case to evaluate the CO_2 emissions and hotspots of road traffic. The scenario analysis results indicated that by 2035, implementing combined decarbonization measures with advanced automotive technology and construction supply chains can reduce 16.3% of total CO_2 emissions during the road life cycle. Scholars have used scenario analysis to predict traffic CO_2 emissions, and these studies involve the popularity of new energy vehicles (Vilchez and Jochem, 2020), emissions tax and subsidies (Chen and Wu, 2022), and carbon peak forecasts (Alamoush et al., 2022). The study of TCEs allows us to understand the current state of CO_2 emissions and assess the effectiveness of low-carbon emission reduction strategies within the transportation sector.

4. Conclusions and future work

4.1. Conclusions

In this study, 1185 articles extracted from the Web of Science (WOS) Core Collection were visualized and analyzed using the bibliometric visualization tools CiteSpace and VOSviewer. With the temporal and spatial distribution of the literature and research process as the main lines, the study used overall growth trend analysis, country/institution/journal analysis, co-citations analysis, keyword co-occurrence analysis, and burst detection analysis to systematically sort out the development history, research hotspots and research trends of TCEs. The following conclusions were drawn as followings.

(1) Statistics of bibliometric results

Since 1997, research on TCEs has gone through two distinct phases, including a period of slow growth from 1997 to 2009, followed by a period of dramatic growth from 2010 to 2022. The number of publications on related topics rises significantly to approximately 156 by 2022. A quantitative analysis of the countries, institutions, and journals most involved in the research on TCEs was performed. According to the country-region distribution of articles, 80 countries or regions are involved. China has the highest number of articles with 280. In terms of research institutions, the Helmholtz Association of Germany was the institution with the most published articles, with 24 (2.03%). In terms of journals, combining the number of publications and citations, Transportation Research Part D: Transport and Environment, Transportation Research Record, and Transportation Research Part A: Policy and Practice are among the leading journals in the field.

(2) Analysis results of document co-citation

By analyzing the cluster density mapping of reference co-citations, key references based on transportation CO_2 emission studies were visually analyzed, providing traceable literature results for subsequent researchers and presenting the results of TCEs studies in recent years. In terms of Citations, the more prominent co-cited references are mainly focused on the issues of the “green vehicle routing problem research”, “transportation and environment research”, “theoretical basis and green travel research”, “CO_2 emission reduction in aviation and shipping research”, which are some of the key concerns of TCEs research. Bektas T, Fontaras G, Chapman L, Corbett J, etc., are some of the important scholars who have made outstanding contributions to the field.

(3) Keyword co-occurrence cluster results

The keywords were extracted and the co-occurrence analyzed using the VOSviewer software. The research on TCEs was found to focus on four representative areas: “theory and methods”, “low carbon travel”, “green supply chain management” and “carbon emission drivers”. In addition, the keyword clustering timeline was plotted using Citespace software. It was found that the research conducted for each cluster was more concentrated around 2015, but the size and distribution of the nodes in each cluster were more even after 2015, indicating a trend of balanced development across the field of TCEs research.

(4) Keyword burst detection results

Keyword burst detection was performed on keywords using the CiteSpace tool. A total of 18 burst keywords were identified for the period 2010–2022. The research and development of TCEs was divided into three phases. The first phase (2010–2015) is the initial phase, and the research hotspots in this phase focus on the following keywords: CO_2 emission and its synonyms, greenhouse gases, and energy. The second phase (2015–2019) represented a period of explosive growth in TCEs research, during which time people's travel behaviors, attitudes, energy consumption issues, supply and demand issues in the transportation industry continue to become an increasingly important area of focus. In the third phase (2020–2022), the applications of methods such as scenario analysis, data envelopment analysis, and decomposition analysis increase dramatically. At the same time, the vehicle routing problem, which aims to reduce fuel consumption and CO_2 emissions, is receiving high attention. Keywords, such as CO_2 emissions, energy consumption, travel behavior, attitudes, scenario analysis, data envelopment analysis and vehicle routing optimization, reflect important topics in transportation CO_2 emissions research.

4.2. Discussions and outlook

CO2 emissions from the transportation industry account for a large proportion of global carbon emissions and have been researched extensively. Along with the progress of science and technology, future TCEs research will focus on the following aspects.

(1) Optimization of measurement and evaluation metrics for TCEs

Existing studies on the evaluation of TCEs are relatively abundant, but with the rapid development of the transportation sector, the measurement and evaluation indexes of TCEs need further improvement. The measurement methods mostly rely on carbon emission measurement factors, but the criteria for selecting indicators in existing studies are inconsistent or even significantly different, resulting in an inaccurate comparison of the total amount of different CO_2 emission factors. Therefore, it is necessary to establish a clear index system for CO_2 emissions involving the transportation sector. Currently, the accounting methods for TCEs can be summarized into five types. However, due to the complexity of the data required for the study, the accuracy of the calculation results is difficult to guarantee, and the measurement results under different methods often have errors. Researchers should improve the measurement methods for CO_2 emission estimation to improve the accuracy of such estimations. In addition, most studies only analyzed the total level of emissions and paid less attention to the spatial and temporal distribution patterns of emissions. The application of big data and mobile monitoring methods in measuring carbon emissions should be emphasized in future studies to obtain more detailed time-spatial inventories of pollution emissions. Further, a comprehensive assessment method system for TCEs that can reflect the spatial and temporal distribution patterns should be systematically proposed.

(2) Green logistics supply chain management under new technology

Firstly, through a range of science and technological developments and the improvement of transportation policies, the supply chain transportation methods and transportation costs are constantly evolving. Therefore, an optimal route should be explored that adheres to the new optimization objective. The development of intelligent logistics has led to changes in logistics coordination and the effective reduction of logistics costs. The research on green distribution paths, which considers factors such as transportation policies and transportation expenditures needs to be further explored. For example, the costs of additional transshipments and late arrivals can be further incorporated into the path optimization problem. Secondly, considering the CO_2 emissions of the green supply chain in the new scenario, existing studies have mainly considered various external factors that affect the efficiency of vehicle travel, such as vehicle load, temperature, road congestion and driver behavior. Future research can also be conducted in conjunction with big data and Internet of Things technologies. For example, big data technology can be used to process GPS data and build data-driven research models that analyze and optimize distribution routes, allowing them to be a better fit for any eventuality.

(3) Exploring low-carbon travel modes

Urbanization, technological development, flexible travel demands pose great challenges to urban transport systems, so there is an urgent need to explore new types of travel services that are more adaptable to today's urban developments. Many governments have promulgated environmentally oriented transportation policies to guide residents to shift their travel choices to urban public transportation and advocate low-carbon sharing travel. For example, policies enacted by California in 2018 to reduce ride-hailing services and encourage carpooling, and China's vehicle purchase tax reduction for new energy vehicles. Furthermore, it is necessary to evaluate the contribution of these policies to reducing CO_2 emissions and their impact on the environment in the future. In addition, the development of new fuel technologies and the search for new energy storage media that can replace fossil energy sources (e.g., power cells, hydrogen). In particular, exploring the possibility of its application in the civil aviation sector and shipping sector, where emissions are currently high, will be an important direction for reducing emissions in the transportation sector.

4.3. *Limitations*

This study has some research limitations. Firstly, the database was selected from the WOS Core Collection without considering some Chinese database sources, such as the China National Knowledge Infrastructure (CNKI), the Wanfang Database System, and the China Science and Technology Journal Database (CSTJ). In the future, relevant literature can be collected and organized by combining the WOS and Chinese database resources, so as to better understand and analyze the research status and developmental trend of TCEs. Secondly, due to the small number of articles that were published during the early years of TCEs in the WOS core collection, there are instances where clusters could not be formed in the relevant software. Therefore, the period of clustering failed to cover the whole process of TCEs development. In addition, only VOSviewer and CiteSpace were used to analyze the data in this study. Future research can also enhance data availability, while also exploring new visualization methods, such as combining more accurate text mining tools (Python, R language, etc.) to assist with the analysis.

Conflict of interest

The authors do not have any conflict of interest with other entities or researchers.

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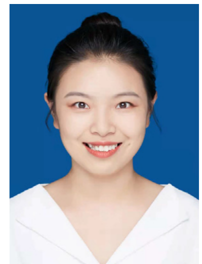

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