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Carbon Emission Reduction in Urban Transport: A Comprehensive Review of Urban Transport Challenges

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Abstract: *Urban transportation systems are a major contributor to carbon emissions, intensified by traffic congestion and fast urbanization. Public transportation, sustainable roadway infrastructure, and alternative vehicle technology may mitigate emissions and ease urban congestion. Nonetheless, infrastructural constraints and expenses continue to pose substantial problems. The main objective of this study is to comprehensively review the published articles in the Scopus database related to the technology, policies, and infrastructure employed to sequester carbon emissions in urban transportation. MATLAB software was used to extract and analyze data from 119 research studies on sustainable urban transport systems. The findings underscore the necessity of aligning transportation techniques with sustainability goals, employing digital technology, Life Cycle Assessment, and enhancing public transit networks. The shift to electric vehicles offers prospects for sustainability; yet, difficulties in resource extraction and disposal methods persist. This study underscores the necessity for a supplementary strategy to address urban transportation issues. Significant research gaps in urban transportation were uncovered, particularly in the aspects of sustainable transit, including high-speed rail, real-time environmental navigation systems, and lifetime assessments of highway corridors. Challenges include limited ranges, insufficient charging infrastructure, and the need for renewable energy integration inside electric vehicles. The transition to electric and hydrogen-powered vehicles appears promising; yet, challenges such as infrastructure inadequacies, dependence on energy sources, and high costs remain. A holistic strategy is necessary to address these shortcomings, including economic feasibility, environmental sustainability, and technological progress. The imperative of transforming urban transportation systems into sustainable, low-carbon models is emphasized, enhancing urban resilience and quality of life.*

Keywords: Carbon emission, comprehensive review, energy consumption, sustainable urban transportation system, urban transport.

1. INTRODUCTION

Urban transport systems are a significant source of carbon emissions globally, which is further worsened by traffic congestion and rapid urbanization. The growing demand for transportation, driven by economic expansion and population growth, has led to increased vehicle usage, further intensifying carbon emissions and environmental degradation. In countries like Bangladesh, for example, tourism-related transport has heightened traffic congestion, showcasing the dual challenge of economic development and environmental sustainability. [1]. Globally, the transportation sector accounts for 27.6% of energy consumption and 22.7% of CO_2 emissions from fuel combustion, underscoring its substantial role in climate change [2] [3]. Recent studies highlight the complicated connection between energy consumption, economic development, and carbon emissions, particularly in developing countries such as Bangladesh, highlighting the necessity for proactive governmental measures to reduce future emissions [4]. Remote sensing technology has been employed in spatial mapping and estimating analyses to evaluate automobile emissions in the Caraga Region of the Philippines. The study, utilizing Sentinel-5P satellite imagery, offers essential insights into emission patterns and their correlation with urban transportation dynamics [5].

Traffic congestion not only increases emissions while idling and inefficient utilization of fuel, but also raises health concerns due to air pollution, as particulate matter and ozone are known killers and result in premature deaths [6]. The financial costs of congestion are just as mind-boggling, as pointed out by the combined $461 billion expenditure in transportation-related matters by the United States, the United Kingdom, and Germany in 2017 [7]. Still, amidst these challenges, there are opportunities such as the promotion of public transit, investment in sustainable road infrastructure, and adoption of alternative vehicle technologies. Public transport, which includes high-speed rail (HSR) and buses, has been proven to alleviate urban congestion and reduce emissions when properly managed [8].

Sustainable road infrastructure, including pavements and green spaces, further reduces the environmental impact of transportation by minimizing maintenance needs and mitigating urban heat island effects [9]. More importantly, electric vehicles and hydrogen fuel cell vehicles represent a vital pathway to lower emissions. Still, challenges in terms of infrastructure limitations and cost are very big hurdles ahead [10][11]. The effectiveness of congestion pricing and intelligent traffic management systems has been witnessed in cities such as London and Singapore, demonstrating the role of governance in reducing carbon emissions.

2. METHODOLOGY

The primary objective of a comprehensive literature review paper is to furnish a contemporary and systematically arranged summary of existing literature on a certain topic, therefore offering value to its readers [12]. This study followed the steps outlined by Tranfield et al. [13] To analyze the relationships between and among the selected published articles in this review.

Selecting the most reliable source database is the initial and important stage in establishing credibility in a literature review article. The Web of Science (WOS) and Scopus were regarded as the most superior, unbiased, and rigorous in their publication selection process and ongoing evaluation of journal integrity, consistency, and citation analysis capacity relative to other databases [14]. Nonetheless, the Scopus database is favored for its superior coverage and more expedited updates of its library of published materials [14][15]. Consequently, the Scopus database was utilized in this paper to collect published journal articles relevant to carbon emission reduction in urban transport for the last decade (2014-2024).

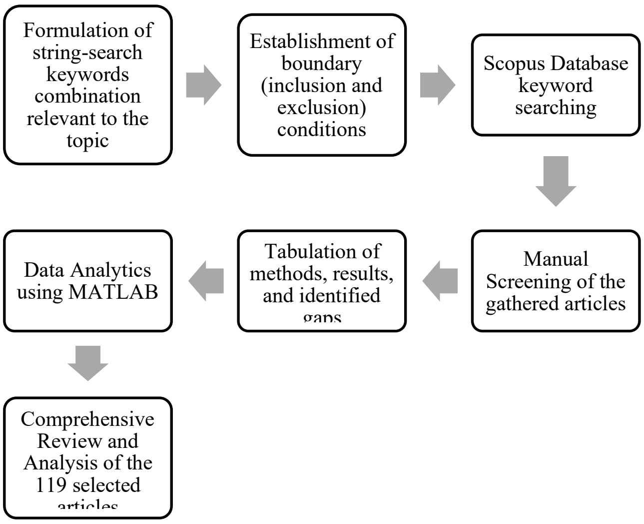
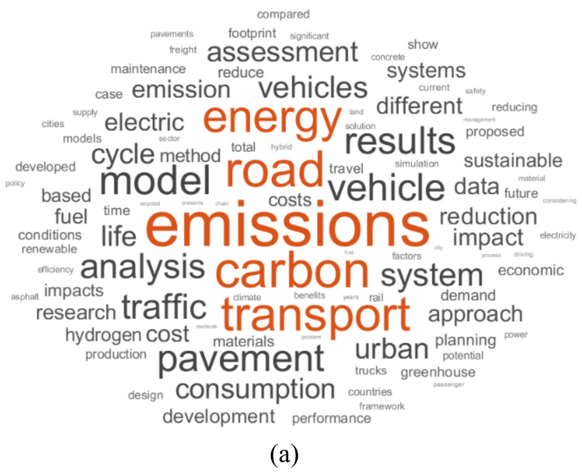


Fig. 1. Review Methodology Framework

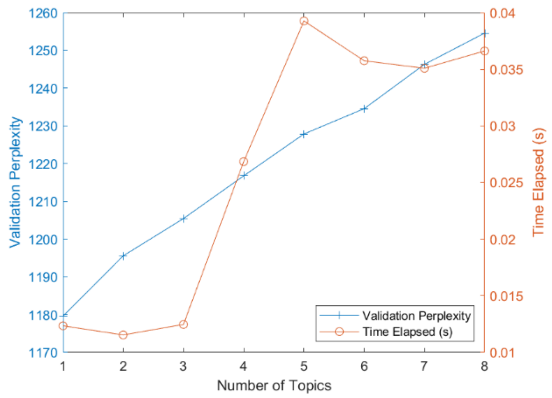
The string-search keywords combination, (TITLE-ABS-KEY (“urban”) AND TITLE-ABS-KEY (“transport” OR “transportation”) AND TITLE-ABS-KEY (“carbon emission”) AND TITLE-ABS-KEY (“technology” OR “policy” OR “policies” OR “infrastructure”)) AND PUBYEAR > 2013 AND PUBYEAR < 2025 AND (LIMIT-TO (DOCTYPE , “ar”)) AND (LIMIT-TO (PUBSTAGE , “final”)) AND (LIMIT-TO (SRCTYPE , “j”)) AND (LIMIT-TO (LANGUAGE , “English”)) AND (LIMIT-TO (OA , “all”)) was used to gather published articles in the Scopus Database related to the studies of carbon emissions in the urban transportation. The search query was further filtered to collect only the relevant and latest publications, including journal articles published between 2014 and 2024, written in English, and accessible to the researchers. The Scopus search was conducted in October 2024 and resulted in 233 articles. The articles were subjected to manual screening. The applied methodology, study findings, and gaps were concurrently detected and stored in a Microsoft Excel file. Those papers that merely connect to the main objective of this study, those for which only their abstract was available, and those that lacked information were excluded. The quality of each study was assessed to mitigate any errors and biases. Errors pertain to studies characterized by unreliable or inaccurate results. In contrast, biases involve the inclusion of subjective judgments by the authors, exemplified by publication bias, in which unfavorable findings are intentionally omitted to achieve a specific conclusion. [16]. After careful evaluation, only 119 articles passed the manual screening and were reviewed.

MATLAB software was used for data extraction, importing studies, and analyzing using the latent Dirichlet allocation (LDA) method for textual data analysis. LDA offers a generative probabilistic model for distributing words within a text associated with a particular topic [17].

Based on the gathered articles, a word cloud presented in Figure 2a provided a general overview of the reviewed topics. This word cloud verified the accuracy of the search keywords used, as the terms “carbon,” “emissions,” and “transport” were the most dominant words for this topic. A Validation perplexity was also employed to ascertain the number of topics to be examined in this investigation. The validation perplexity graph in Figure 2b indicates that a range of four to seven topics would suffice for the current study’s discussion. Nonetheless, the elapsed time indicated that four subjects were considered adequate for the examination, considering the themes and prominent characteristics of the 119 collected papers. Therefore, this study examined four topics. After establishing the number of topics, the LDA model was employed to uncover the latent themes within the articles. This approach is widely utilized to fit a topic model. It constitutes a three-level hierarchical Bayesian modeling procedure that categorizes a collection of elements into subjects delineated by words or phrases. [18]. Figure 3 displays the topic probabilities and mixes based on LDA Figure 3 displays the topic probabilities and mixes based on LDA. Figures 3 indicate that the four subjects were adequately dispersed throughout the 119 documents. The first topic has the dominant keywords “transport,” “system,” “urban,” “method,” “demand,” which were interpreted as “Sustainable Urban Transportation Systems.” It tackled the critical role of sustainable urban transportation systems in addressing global environmental and sustainability challenges. The second topic has the dominant keywords “model,” “vehicles,” “emission,” “different,” and “approach,” which were interpreted as “Different Approaches to Reducing Vehicle Emissions” and covered the different approaches to reducing vehicle emissions. The third topic has dominant keywords “emissions,” “carbon,” “road,” “pavement,” and “traffic,” which were interpreted as “Carbon Footprint of Different Road Transport Modes” and discussed the carbon footprint of varying road transport modes. The fourth topic has dominant keywords “energy,” “results,” “vehicle,” “consumption,” and “electric,” which were interpreted as “Analyzing the Energy Consumption Results of Autonomous Electric Vehicles (AEVs)” and analyzed the energy consumption results of autonomous electric vehicles (AEVs).



(a)



(b)

Fig 2. (a) Word Cloud and (b) Validation Perplexity and the Number of Topics generated from the 119 reviewed articles

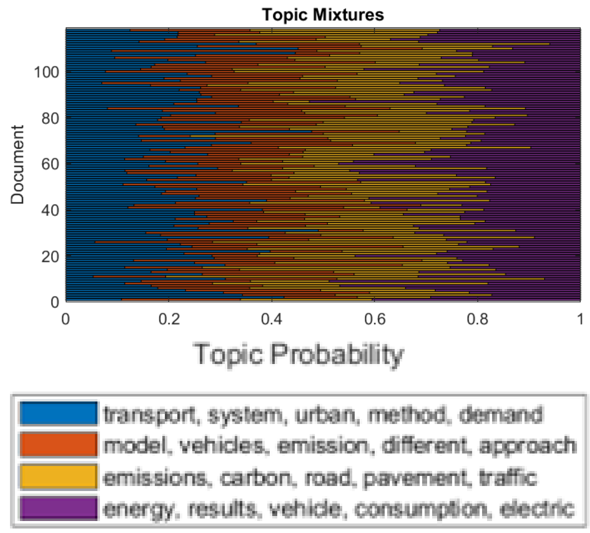


Fig 3. Topic Mixtures and Probability based on the 119 reviewed articles

3. RESULT AND DISCUSSION

3.1 Sustainable Urban Transportation Systems

Sustainable urban transportation systems are critical in addressing global environmental and sustainability challenges. Research emphasizes the need for balancing transportation modes with ecological goals [1]. Digital tools such as e-ticketing systems in countries like Bangladesh facilitate greener travel behaviors by automating services and optimizing resources. Life Cycle Assessment (LCA) is essential in the assessment of environmental impacts from transportation, covering direct emissions and the whole life cycle of vehicles and infrastructure, which can significantly reduce emissions with technological advancements and optimized operations [2].
Environmental impacts of transport projects could be mitigated through efforts such as EMA and EEA, the latter of emission reduction. [19]. Public transport systems, which also include HSR, are able to reduce urban emissions while enhancing economic activity and urbanization, though they are only sustainable in the long term if their associated carbon footprints are reduced and railway electrification is optimized [20]. Compact city models increase efficiency in energy, but sustainable public transport systems are a necessity to negate trade-offs [21].
Traffic optimization strategies, including enhanced traffic algorithms and ITS, improve urban mobility while minimizing environmental impacts [22-[24]. While transitioning to EVs offers opportunities for sustainability, there are challenges in the extraction and disposal processes of resources [10]. For managing the CO_2 emission, road transport policies are at the forefront by using tools such as Indicators for Transport Sustainability and regional sustainable development values [7][25]. Urban transport challenges can only be overcome when economic, environmental, and technological considerations are addressed from a complementary standpoint.

3.2 Different Approaches to Reducing Vehicle Emissions

Reducing vehicle emissions is a combination of technological, policy, and behavioral changes that include improving energy efficiency and using renewable energy in vehicles. This results in improved fuel economy and emissions reduction, with metrics showing sharp efficiency gains, [1]. LCA is considered an integrated tool for assessing construction and operation-based emissions, with attention to the use of materials such as low-carbon steel in infrastructure projects to mitigate environmental impacts [2].
Models for earthmoving operations also suggest optimizing hauling distances and material management to lower emissions during pre-construction phases [19]. Public transport systems, including high-speed rail and electrified transit, can reduce urban emissions, although increased travel demand may offset some gains [20]. Compact urban development further supports public transport interconnectivity, reducing reliance on private vehicles [21].
The electrification of vehicles will be another strategy. Replacing ICEVs with electric vehicles and utilizing alternative energy sources, such as renewable will significantly reduce the emissions [26]. Cargo bikes and blue hydrogen as an alternative fuel bring more scope in reducing emissions, despite the current price and infrastructure obstacles [27]. Long-term reductions also include policies that support low-carbon transport modes and sustainable tourism [28].
Innovative technologies, such as photovoltaic systems for hybrid buses, show considerable environmental advantages over traditional diesel fleets [10]. Models that analyze urban transit systems show how rail integration can change passenger behavior, reducing car use and associated emissions [8]. Regional differences in transportation carbon efficiencies must be evaluated to tailor effective strategies [29].
Policy interventions like fuel levies, limitations on engine sizes, and competition among manufacturers on emissions are crucial to reducing emissions [7]. Such measures, together with renewable energy adoption and developments in intelligent transport systems, would cover all facets of achieving sustainable urban transport and mitigation of climate change impacts.

3.3 Carbon Footprint of Different Road Transport Modes

The carbon footprint of the different road transport modes varies considerably with vehicle type, infrastructure, and energy source. Optimizing fleet management strategies, as presented by [1], can reduce carbon emissions by as much as 40% while simultaneously improving profitability and service quality. Road infrastructure also has a significant share, with asphalt roads requiring 23 TJ and concrete roads 27 TJ of energy per kilometer over a 40-year lifespan, highlighting the need to include the maintenance and operation phases in carbon footprint calculations [2].

In general, rail transportation has a relatively lower carbon footprint than road transport. However, its lifecycle emissions are highly dependent on the construction and maintenance phases. For example, the emission contribution of rail infrastructure is at 28% during construction and 48% during maintenance [2]. High-speed rail (HSR) is an alternative to short-haul flights with lower greenhouse gas emissions, and urban transit systems, such as subways, can decrease energy use and emissions depending on how effectively they replace private vehicles [20].

The carbon footprint of cargo transport by rail also depends heavily on electrification and operational circumstances, requiring case-specific analysis for accurate assessment [30]. Similarly, road transport contributes significantly to the emissions of food supply chains, with localized short chains attributing 79% of total emissions to transport, highlighting the importance of route and mode optimization [31].

Shifting from fossil-fueled vehicles toward electric vehicles decreases emissions significantly, should the electricity is derived from low-carbon sources. High dependence on high-carbon energy sources can undermine such environmental benefits coming from EVs. [32].

The carbon footprint of road transport is shaped by a combination of vehicle efficiency, infrastructure design, and energy source. Technological advancements and optimization strategies are important, but a holistic lifecycle approach is critical to effectively reducing emissions across the transport sector.

3.4 Analyzing the Energy Consumption Results of Autonomous Electric Vehicles (AEVs)

The energy consumption and environmental impact of AEVs depend on vehicle type, infrastructure, fuel sources, and operational contexts. Survey data from (Babri et al., 2023) highlights the current distribution of vehicle types and their emissions, emphasizing the role of traffic volume and vehicle characteristics in estimating environmental footprints. Emission calculations for AEVs require advanced models that incorporate road conditions and congestion scenarios, such as those integrated into the Norwegian Regional Transport Model.

LCA is vital in assessing the energy consumption and emissions of AEVs throughout their lifecycle, from production to disposal [31]. Although AEVs significantly reduce operational GHG emissions, the advantages can be nullified by non-renewable electricity sources [26]. Renewable energy integration in the charging of AEVs is therefore essential for environmental sustainability.

Urban logistics studies like [27] indicate that AEVs can have a significant impact on reducing emissions during last-mile deliveries. However, their limited range and infrastructure are seen as challenges. Studies on infrastructure and traffic indicate that 99% of GHG emissions and energy consumption happen in traffic operations, which shows the importance of efficient road design and optimized traffic management to avoid energy use [33].

Studies like [10] promote electric mobility as a means to balance economic development with environmental quality. However, full lifecycle impacts, including the production and disposal of batteries, are crucial considerations. Studies highlight that policies, such as financial incentives and renewable energy adoption, play an important role in decarbonizing the transportation sector and maximizing the benefits of AEVs[7].

4. RESEARCH GAPS

There are huge research gaps in sustainable transport that still need to be explored. High-speed rail, for instance, has been proven to affect urban carbon footprints and economic activities [20][30]. Other sustainable transport modes and real-time eco-navigation systems using dynamic traffic and carbon emission estimates are not well developed [23]. The lifecycle assessments of road corridors have shown no embedding in detailed traffic scenarios, uncertainty analyses, and climate change impacts on infrastructure safety and economic factors [33][34].

Table 1. Challenges of reducing carbon emissions in urban transport.

Challenges	References
Development of Sustainable Transport Modes	[20] [23] [30]
Lifecycle Assessments and Climate Change	[33][34]
Policy and Integrated Emission Reduction Strategies	[8] [28]
Electrification of Transport and Hybrid Technologies	[26] [29] [35]
Renewable Energy Integration and Fuel Cell Technologies	[11] [32]
Simulation Models for Urban Transport and Infrastructure	[36][37]

Further research is also considered in global infrastructure and legal frameworks for renewable hydrogen and methane fuels. Properly integrated policies can help achieve emission reduction together with technological adoption in maritime and land transport, as exemplified in Norway's case of tourism around Geiranger fjord [28]. Electrifying the transport sector, as spearheaded by the EU, would call for further studies into the optimal hybrid model, appropriate hybrid technology, and specific regional policies[29] [35] . Challenges in the implementation of electric vehicles in logistics include limited ranges and insufficient charging infrastructures; thus, other alternatives for fuel are needed along with strategic positioning of stations. In addition researchers will also be required to fine-tune renewable energy integration into electric vehicles, especially scaling fuel cell electric vehicles alongside battery electric vehicles, concentrating on hybrid models and efficient hydrogen production [32][11].

The DES models for transport and infrastructure need to be developed beyond highway projects, with alternative fuels and enhanced data accuracy in urban transport planning [36][37]. Pavement safety and longevity research highlights the need for photoluminescent materials to enhance nighttime visibility, abrasion-resistant glass beads for road markings, and multi-sensor data for structural assessments, while further exploration of geosynthetics in flexible pavements is essential for cost-effective solutions [6]. These gaps underscore the importance of a multidisciplinary approach to advancing sustainable transport, reducing emissions, and improving infrastructure.

5. CONCLUSION

The study stresses the complex inter-relationship between technological innovation, policy, and sustainable practices. Key findings capture that though public transit, intelligent traffic management and EVs hold considerable opportunities for cutting emissions, their impact will have to be backed by supporting infrastructure and governance frameworks [2][6]. Life Cycle Assessments (LCA) have been found to be instrumental in quantifying the environmental impacts of transport projects, which require holistic approaches that integrate upstream and downstream processes [3][25].

The transition to electric and hydrogen-powered vehicles is promising, but barriers such as infrastructure deficits, energy source dependencies, and high costs remain formidable [8][9]. For example, congestion pricing and compact urban development have proved to reduce emissions due to traffic. However, regional differences would need customized strategies, and hence, their application may be varied [19]. Renewable energy source integration in the transportation system, combined with technological upgradation of the vehicles, provides an attractive pathway to long-term sustainability [23].

However, major gaps in research are still left behind, such as the scalability of wireless charging technologies, lifecycle assessments specific to climatic impacts, and the optimization of hybrid transport models [30][24]. Multidisciplinary approaches to addressing these gaps include economic feasibility, environmental sustainability, and technological innovation. This review reaffirms the urgency of concerted global efforts to transform urban transport systems into sustainable, low-carbon ecosystems capable of combating climate change while enhancing urban resilience and quality of life.

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