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Carbon Emissions in Transportation: A Synthesis Framework

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Posted Date: 2 February 2023

doi: 10.20944/preprints202302.0024.v1

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Carbon Emissions in Transportation: A Synthesis Framework

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Abstract: With a worldwide growing concern for greenhouse gas (GHG) emissions and their impact on human health and the environment, transportation has become a central theme in mitigation, responsible for 14% of human GHG emissions. To build endurance to climate change, transportation services must adapt to the current scenario and act quickly to avert future changes. Deeply rooted changes in socio-technical systems will be necessary to achieve significant CO2 reduction and secure the well-being of future generations. This study's objective is to comprehensively review the current state of carbon mitigation in the transportation sector. This is done through a systematic literature review engrained in the multi-level perspective of the socio-technical transition theory and the structural theory of contingency. Twenty-six review papers covering 2,983 original articles are selected for full-text examination concerning carbon emissions in transportation. Enablers, barriers, benefits, disadvantages and metrics in carbon emissions reduction are identified, and a comprehensive framework is built. Results provide a view of the current sustainability scenario in transportation and allow a better understanding of the factors influencing carbon emission initiatives in transportation and its outcomes.

Keywords: sustainability; socio-technical transitions; contingency theory

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1. Introduction

Over the last few decades, concerns over climate change have risen steeply due to increased knowledge of its consequences to the environment, economy and humanity. As a result, reducing greenhouse gas (GHG) emissions, particularly CO2, has become a common and inevitable goal to reduce the impacts of climate change.

When touching on the theme of GHG emissions and air pollution in general, transportation becomes inescapable due to the sector being one of the greatest contributors to global warming. According to the Intergovernmental Panel on Climate Change (2014), the transportation sector accounted for 15% of all anthropogenic and 23% of global energy-related GHG emissions in 2019. It was also responsible for 8.7 Gt of CO2 emissions that year, projected to double by 2050 [1] (98).

Transportation includes road, rail, air and sea and may refer to transporting passengers and freight. While it is common to focus on the emissions produced by exhaust gases during transportation operations, transportation generates environmental impacts at every step of its life cycle, including infrastructure construction and maintenance, vehicle, airplane and ship manufacturing, maintenance and disposal, and operation [2].

At the same time, transportation is affecting climate change; climate change is, in turn, also affecting transportation. Transportation is generally highly susceptible to weather conditions; while transportation systems and infrastructure are built to endure local weather conditions, continuous climate change creates vulnerabilities in such systems [3]. To build endurance to climate change, transportation services must adapt to the current scenario and act quickly to avert future changes.

Isolated carbon mitigation measures can only reduce emissions so far; deeply rooted changes in socio-technical systems will be necessary to achieve an 80% reduction in carbon emissions [4]. Drawing on socio-technical transitions theory, a multi-disciplinary and holistic approach is needed to fully understand climate change, its impacts, and how to abate it [4,5]. In a review of sustainable urban infrastructure, Ferrer et al. [6] highlight the existing interplay between economy, society and technology in solving urban infrastructure issues.

To achieve a comprehensive view of the current state of carbon mitigation in the transportation sector, the following research questions are put forward:

1. What are the main barriers, enablers, benefits and disadvantages of carbon emission reduction in transportation?
2. What are the main dimensions or categories utilised to describe the initiatives for carbon mitigation in the transportation sector?

In answering these research questions, this paper's general objective is to contribute to the transition to a lower carbon society by better understanding the dimensions, enablers, barriers, benefits and disadvantages of existing measures for reducing carbon emission.

To attain this general objective, this study will review the extant literature with the backdrop of multi-level sustainability transition theory and contingency theory to offer an analytical synthesis framework. In addition, a tertiary review of carbon emission mitigation strategies in transportation is performed. It is expected that the fulfilment of the objectives should contribute to the theory and practice of carbon emissions strategies in the transportation sector.

The study is organised as follows: Section 1 is this Introduction. Section 2 provides a theoretical background on socio-technical transitions and contingency theories subjacent to the analysis of the carbon emission strategies in the transportation sector. Section 3 describes the methodology adopted for the study. Section 4 presents results from the tertiary research. Finally, Sections 5 and 6 conclude the study with discussions of findings, deriving practical implications and directions for future research.

2. Theoretical Background

This research is ingrained in the multi-level theory of socio-technical transitions and the structural theory of contingency. It answers a recurrent call to contribute to theories with Systematic Literature Review methods [8].

2.1. Multi-Level Theory of Socio-Technical Transitions

Significant reductions in carbon emissions can only be achieved through fundamental changes in transportation systems or socio-technical transitions [4]. Socio-technical transitions are characterised as major shifts in socio-technical systems, which may include a variety of interacting components such as "technology, policy, markets, consumer practices, infrastructure, cultural meaning and scientific knowledge" [4] (471). They may take decades to develop gradually and are seen as co-evolutionary processes [4].

Most transportation research on climate change mitigation to date focuses on technological, economic and infrastructural elements — that is, the 'technical' side of socio-technical systems [5]. Socio-technical systems, however, are composed of multiple dimensions that constantly interplay with each other, suggesting there is much to gain from exploring the 'social' side as well [5].

With this in mind, the multi-level perspective (MLP) approach to socio-technical transitions seeks to provide a holistic understanding of elements and actors involved in transportation systems and their interactions [4]. Furthermore, it addresses the dynamics between stability and change and how new systems must surmount challenges to overcome the existing regime and establish a new normal [4].

Generally, three main levels are explored in the MLP [4]:

- *Niches*, small protected spaces where innovation takes place;
- *Socio-technical regimes,* the place of established practices, technologies and regulations; and
- *Socio-technical landscape,* the wider external context.

Figure 1 illustrates the dynamics involved between the three levels of MLP. Changes and new ideas start in niches, typically emerging from experiments or innovation projects [4]. Continuous

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learning from niches challenges the regime, proposing a transformation or replacement of the existing regime, but is mostly met with barriers formed by lock-in mechanisms [4,9].

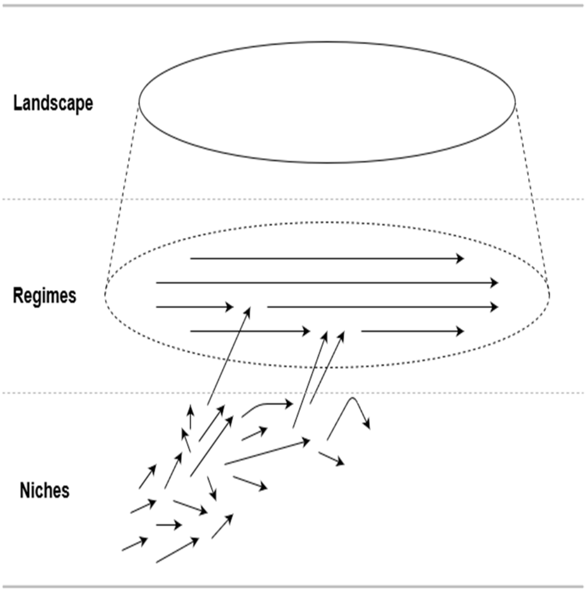

Figure 1. Levels of multi-level perspective. Source: Adapted from [4].

While MLP brings a high-level perspective to the analysis, it might need more fine-grained details to understand the *how*, *why* and *when* of specific carbon emission reduction initiatives and their outcomes in society and the environment. The contingency view in operation management research can complement the MLT approach to socio-technical transitions in important ways and is briefly summarised next.

2.2. Basic Elements of the Theory of Contingency in Strategy and Operations Management Research

The structural contingency theory posits that organisations perform well when there is a fit or adequacy between the environment in which it operates and the structural aspects of the organisation [10]. Conversely, there is a misfit when the environment and structure do not match, and this causes organisations to perform poorly [10]. Figure 2 illustrates the expected relationships between the environment, carbon emission initiatives and their outcomes under the contingency theory perspective.

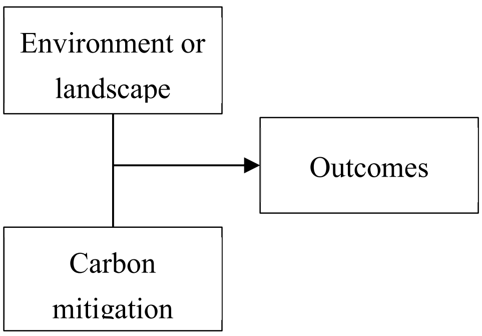

Figure 2. Effects of the operating environment (landscapes) and carbon emission mitigation on outcomes.

The four basic postulates of contingency theory [10], extended to the field of transportation carbon emissions, can be expressed as (i) there is a mutually reinforcing effect between the landscape and the carbon emissions mitigation initiatives; (ii) high landscape-carbon emission fit causes effectiveness and low fit causes ineffectiveness; (iii) there is no universal type of carbon emission initiatives valid for all types of transportation modes and landscapes; (iv) the outcomes of carbon emissions mitigation strategies (its advantages and benefits) are measurable.

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Applying the definition of operations management practice contingency research – OM-PCR [11] to carbon emissions brings a powerful lens for the theoretical extension of the SLR research. According to Drazin & Van de Ven [12], the analysis of environment-structure fit can be done in three different ways: using the logic of selection, interaction or systems. This distinction is important because it provides the elements needed to understand the variables included in current research on carbon emissions in transportation. Under the selection approach, the fit between the environment (or landscape) and the structure (here, the emissions mitigation initiatives) is assumed to produce the best outcomes. Therefore, under this perspective, the response variable (the outcomes) is not formally stated nor measured, and the environment-structure fit and its effect on the outcomes are taken as a given. Under the interaction perspective, individual relationships between environment and structural variables produce specific outcomes and are measured individually, variable by variable. Finally, under the systems approach, several environment and structural variables interact internally and among them, and their effect on outcomes are jointly analysed, taking into consideration individual and interaction effects systemically (see [11] (706-707) for a complete discussion of the typology).

The combination of the MLT approach with the socio-technical transition under the OM-PCR views provides the theoretical lenses through which the SLR is undertaken. The high-level MLT framework is an overarching analytical framework for transition research and provides a broad frame of reference to analyse carbon emission mitigation strategies and their constituent elements. Its lenses will be paramount to search for a typology of carbon emissions research described in Section 4. The OM-PCR lenses will direct attention to the measurement of the landscape, the carbon emission mitigation initiatives, its outcomes, and the relationships among them, leading to the synthesis framework proposed in Section 4.6.

3. Methodology

This section describes the methodology adopted to perform the SLR, including basic statistics from the review and methods applied in the tertiary research, a review of reviews. SLRs are scientific endeavours by their own merits and provide a reproducible and traceable synthesis of what is known about a given research subject [7]. Moreover, they can be powerful tools to elaborate and improve existing theories [8]. The use of theories in this literature review follows the guidelines provided by Seuring et al. [8] for the supply chain management field. It applies them to the analysis of carbon emissions in the transportation sector. According to Seuring et al. [8], SLRs can contribute to (i) theory building, mainly through inductive reasoning; (ii) theory modification through abductive reasoning; (iii) theory refinement through deductive logic; and (iv) theory extension, which "borrows theory from outside the field, thereby enriching the studied content and broadening the available theoretical repository" [8] (5). This study spouses the fourth view of the role of theories in SLRs.

Different types of literature reviews are included in this tertiary review. They will be classified into the broad categories proposed by Grant & Booth [45]: systematic, critical, literature, meta-analysis, and state-of-the-art reviews. Following Grant & Booth [45], the purpose of systematic reviews is to systematically search, appraise and synthesise research evidence, following pre-established guidelines. A critical review aims to demonstrate that the authors did extensive literature searches and critically evaluated them. A literature review is a generic term for analysing recent or current literature on varying degrees of completeness and comprehensiveness, including findings. Meta-analysis is a term reserved for the statistical analysis of quantitative studies. Finally, state-of-the-art reviews address more recent matters than reviews that combine retrospective and current approaches.

3.1. Step-by-Step Approach for the Systematic Literature Review

The step-by-step approach devised by Thomé et al. [7] and based on Cooper [13] for systematic literature reviews was adopted for the tertiary research. It consists of eight main steps: (i) planning and formulating the problem, (ii) searching the literature, (iii) data gathering, (iv) quality evaluation,

(v) data analysis and synthesis, (vi) interpretation, (vii) presenting results, and (viii) updating the review.

For the first step, *planning and formulating the problem*, the theme of carbon emissions in transportation was identified. Then, the authors extensively discussed and debated the topic and its gaps, formulating the research questions defined in the introduction.

The next step, *searching the literature*, involved selecting scientific databases, defining search keywords and queries, and defining exclusion criteria. Scopus and Web of Science (WoS) databases were selected due to their extensive journal collection and relevance in the environment, engineering and management domains [14].

Table 1 describes the keywords and restrictions used to search the databases. They were applied to the titles, abstracts and keywords with no limitations on dates.

Table 1. Selected keywords and restrictions for selecting papers for SLR.

Search keywords and restrictions	**No. of papers included**	
	Scopus	**WoS**
("transport*" OR "ship*") AND ("metric*" OR "measur*" OR "quanti*") AND ("green" OR "sustainab*" OR "environment*") AND ("climate change" OR "carbon" OR "CO2" OR "greenhouse effect")	16,437	11,375
Restricted to articles and reviews	13,458	10,420
English language only	12,949	10,315
Total selected from the topic area:	23,264	
Total selected from the topic area (w/o duplicates):	16,635	
("research synthesis" OR "systematic review" OR "evidence synthesis" OR "research review" OR "literature review" OR "meta-analysis" OR "meta-synthesis" OR "mixed-method synthesis" OR "narrative reviews" OR "realist synthesis" OR "meta-ethnography" OR "state-of-the-art" OR "rapid review" OR "critical review" OR "expert review" OR "conceptual review" OR "review of studies" OR "structured review" OR "systematic literature review" OR "literature analysis" OR "in-depth-survey" OR "literature survey" OR "analysis of research" OR "empirical body of knowledge" OR "overview of existing research" OR "body of published knowledge" OR "review of literature")	321	244
Total selected for tertiary research:	565	
Total selected for tertiary research (w/o duplicates):	411	

First, keywords related to the topic area, carbon emissions in transportation, were applied. Next, results were filtered based on document type (only articles, articles in press and reviews) and language (English language only). This search yielded 12,949 papers from Scopus and 10,315 papers from WoS, providing 16,635 papers in the topic area after removing duplicate papers. Finally, for the tertiary research, another set of keywords targeting different definitions of literature review proposed by Verner et al. [15] and Thomé et al. [7] was applied to further filter results. Three-hundred twenty-one papers were retrieved from Scopus and 244 from WoS. After duplicate papers were excluded, 411 papers were selected for abstract review.

For the third and fourth steps, *data gathering* and *quality evaluation*, a careful selection of articles followed the PRISMA— Preferred Reporting Items for Systematic Reviews and Meta-Analyses statement [16]. In addition, quality checks were strengthened by selecting only articles, articles in-press and reviews from peer-reviewed journals.

The selection of studies for the tertiary review was performed by the authors using PRISMA [16]. Figure 3 presents a flow diagram of studies selected and excluded at each level of this process.

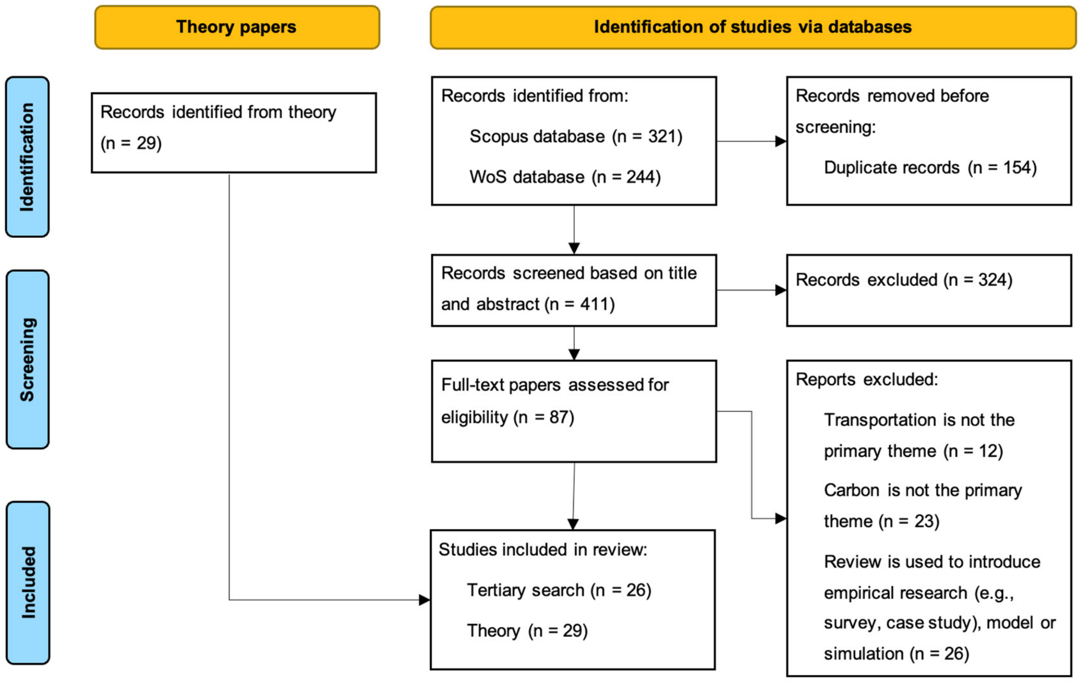

Figure 3. Flow diagram of studies selected for tertiary research, based on PRISMA [16].

The authors screened articles individually. After an initial round of screening, an 83.2% agreement was reached. However, the agreement rates were deemed low (Cohen's Kappa = 0.348; Krippendorff's Alpha= 0.342), prompting several discussions to resolve disputed choices. Fifty-one cases of disagreement were then debated until a consensus was reached between the authors. Three hundred twenty-four records were excluded after the screening, leaving 87 papers for full-text review.

During the full-text review, the following exclusion criteria were applied: (i) transportation is not the primary theme; (ii) carbon is not the primary theme; (iii) review is used to introduce empirical research (e.g., survey, case study), model or simulation. The third exclusion criterion followed Cooper & Hedges' [17] definition of research synthesis, which excludes narrowly focused reviews intended to introduce or produce new facts and findings from direct observation in empirical research or data modelling. As a result, 61 papers were excluded during this stage, yielding a final 26 papers for the tertiary research. This search was complemented with reference material for the theoretical basis of the SLR, resulting in an additional 29 theoretical papers on MLT, contingency theory, and sustainability transitions.

Sections 4 and 5 of this study compose the fifth and sixth steps in the SLR methodology, *data analysis, synthesis, and interpretation.* These steps were conducted qualitatively using an inductive approach [18] and complemented with quantitative co-citation and co-word analyses.

The seventh step, *presenting results*, can be attributed to the study and its following publication and distribution. Finally, the eighth and final SLR step, *updating the review*, is left as a suggestion for future research and lies beyond the study's scope.

4. Results

This results section presents an overview of the reviews selected for the tertiary research, followed by a typology of carbon emissions reduction in transportation and a framework that summarises the main findings from the studies.

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4.1. Overview of Studies Selected for Tertiary Review

The 26 literature reviews selected for the tertiary research are in Table 2, along with the number of studies included in each review and the methodology. Table 2 also includes the transportation sector each literature review focuses on and the sustainability dimensions addressed.

Table 2. Selected literature reviews with their respective number of studies, review methodology, transportation sector and sustainability dimension.

Literature reviews	No. of studies	Review methodology	Transportation modes	Sustainability dimensions
Smit et al. [19]	50	Meta-analysis	Road	Environmental[3]
Eijgelaar [20] [2]	80	Literature review	Air - Tourism	Environmental[3]
Li [21] [2]	98	Critical review	Multimodal - Urban	Environmental, social and financial[3]
Miola & Ciuffo [22] [2]	49	Meta-analysis	Maritime	Environmental and social[3]
Hawkins et al. [23]	51	Literature review	Multimodal - Hybrid and electric vehicles	Environmental[3]
Franco et al. [24] [2]	190	Literature review	Road	Environmental[3]
Faris et al. [25] [2]	80	State-of-the-art review	Road - Intelligent Systems	Environmental[3]
Kwan & Hashim [26]	9	Systematic review	Multimodal - Mass public	Environmental and social[3]
Bouman et al. [27]	150	Systematic review	Maritime	Environmental[3]
Garcia & Freire [28]	69	Critical review	Road - Light-duty fleet vehicles	Environmental
Herold & Lee [29]	66	Systematic literature review	Multimodal - Logistics and freight	Environmental
Czepkiewicz et al. [30]	27	Systematic review	Multimodal - Long-distance leisure travel	Environmental[3]
Requia et al. [31]	65	Systematic review	Road - Electric mobility	Environmental and social
Salvucci et al. [32]	8	Critical review	Multimodal - European Nordic countries	Environmental[3]
Arioli et al. [33]	40	Systematic review	Multimodal - Urban	Environmental[3]
Lagouvardou et al. [34] [2]	78	Literature review	Maritime	Environmental
Meyer [35] [1]	715	Systematic quantitative review	Road freight	Environmental
O'Mahony [36] [2]	33	State-of-the-art review	Unspecified - Carbon taxes	Environmental and financial
Oguntona [37]	11	Literature review	Air	Environmental[3]
Pilz et al. [38]	18	Systematic review	Multimodal - Transport in manufacturing industry	Environmental
Schinas & Bergmann [39]	102	Integrative literature review	Multimodal – Aviation and maritime	Environmental and financial[3]
Wimbadi et al. [40]	41	Systematic literature review	Multimodal - Public transport	Environmental[3]
Alamoush et al. [41]	112	Systematic literature review	Multimodal – Marine ports (including land transport)	Environmental[3]
Hu & Creutzig [42]	687	Systematic review	Multimodal - Shared mobility	Environmental, social and financial
Miklautsch & Woschank [43]	81	Systematic literature review	Multimodal - Freight	Environmental[3]
Noussan et al. [44] [2]	73	Literature review	Multimodal - Passenger transport	Environmental[3]

[1] Bibliometric review. [2] Total number not reported, inferred from reference lists. [3] Sustainability dimensions not reported, inferred by the authors.

The 26 selected reviews in Table 2, combined, reviewed 2,983 studies. Figure 4 illustrates the number of studies selected for the tertiary review by publication date. The reviews spanned 13 years of research on carbon emissions in transportation (i.e., from 2010 to 2022). Out of the 26 selected reviews, twelve were published in the last three years, showing the growing relevance of the subject

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area. However, it is important to highlight upfront that most research was done in the context of developed economies, with few studies addressing sustainability transition in transportation in emerging economies.

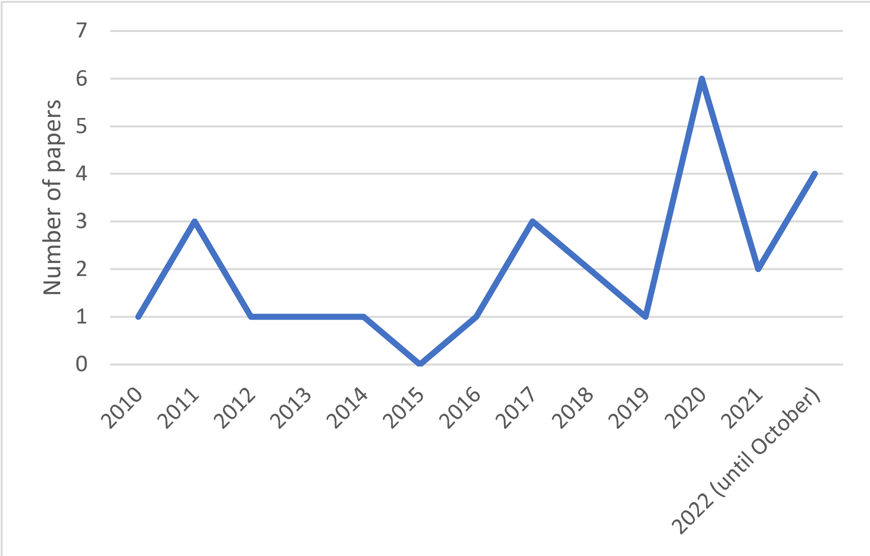

Figure 4. Number of studies selected for the tertiary review by publication date.

The review methodologies observed in Table 2 reflect each author's nomenclature to characterise their study. For a better understanding of the different methodologies adopted in the reviews, however, each study method was grouped into one of the following review types identified by Grant & Booth [45] in Figure 4 and defined in Section 3 – Methodology.

As illustrated in Figure 5, the systematic literature review was the most common methodology adopted [26,27,29–31,33,35,38,40–43], followed by narrative literature reviews [20,23,24,34,37,39,44], critical reviews [21,28,32], and, finally, meta-analyses [19,22] and state-of-the-art reviews [25,36]. Interestingly, even though the systematic review is the most popular review approach, all systematic reviews were concentrated in the last seven years (i.e., 2016 to 2022), showing an increasing trend towards more rigour in the academic review of the subject.

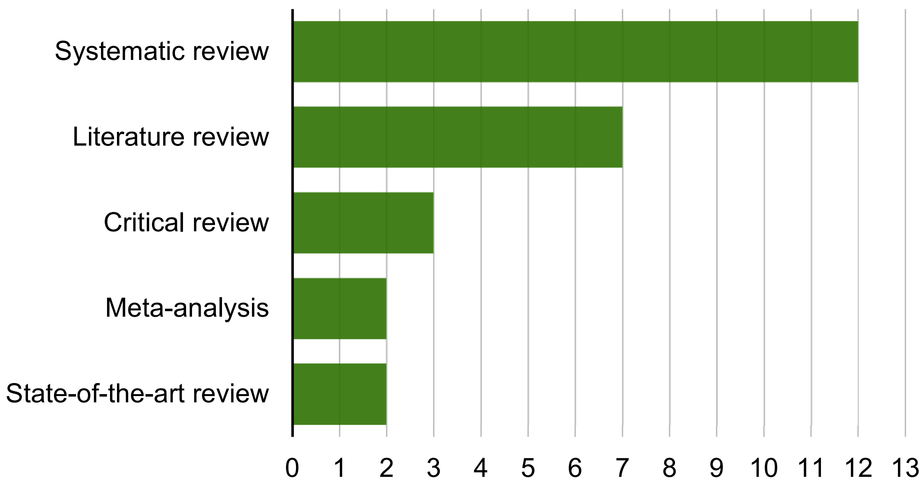

Figure 5. Methodology adopted in reviews selected for tertiary research.

Finally, Figure 6 illustrates the sustainability dimensions explored by each of the selected reviews. Over three-quarters of the studies focused exclusively on the environmental perspective of sustainability; three explored both the environmental and the social dimensions of sustainability; one addressed both environmental and financial sustainability; and only two investigated the full triple bottom line of sustainability.

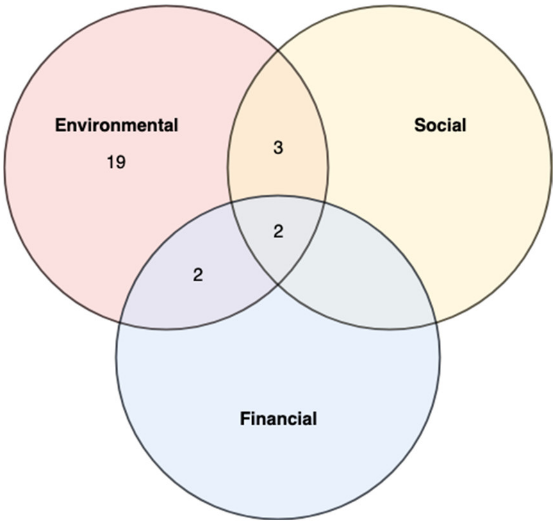

Figure 6. Sustainability dimensions included in studies selected for tertiary review.

4.2. Typology of Carbon Emissions Reduction in Transportation

Table 3 depicts a typology of carbon emissions reduction in transportation comprised of three main dimensions: *enablers and barriers*, *benefits and disadvantages*, and *metrics*. The majority of papers are concentrated on the dimension of *enablers and barriers* (20 papers), followed by *metrics* (14 papers), and finally, *benefits and disadvantages* (4 papers). Each dimension is also further subdivided into categories. Within *enablers and barriers*, *technological innovations* were by far the most popular topic (14 papers), followed in descending order by *regulatory and economic measures* (8 papers), *operational measures* (7 papers), *urban form (e.g., density, land-use mix, connectivity, and accessibility) and human behaviour* (5 papers) and *strategy and stakeholder pressure* (2 papers). Within *benefits and disadvantages*, *climate change and other emissions*, *health* and *cost impact* appeared in two papers each, while *competitive advantage* appeared in one paper only. Within *metrics*, the *life-cycle assessment* had six papers, and *emissions modelling and inputs* and *measurement and performance indicators* had five papers each.

Table 3. Typology of carbon emissions reduction in transportation.

Dimensions	Categories	Papers
Enablers and barriers	Technological innovations	[21,23,25,27–29,31,32,35,37,38,40,41,43]
	Operational measures	[27–29,35,37,41,43]
	Regulatory and economic measures	[20,21,29,34,36,37,39,41]
	Urban form and human behaviour	[21,30,32,40,42]
	Strategy and stakeholder pressure	[29,43]
Benefits and disadvantages	Climate change and other emissions	[26,31]
	Health	[26,31]
	Competitive advantage	[29]
	Cost impact	[29,39]
Metrics	Measurement and performance indicators	[24,26,29,35,44]
	Emissions modelling and inputs	[19,22,25,33,37]
	Life-cycle assessment	[21,23,28,29,35,44]

Sections 4.3–4.5 further detail findings from each dimension and their respective categories. It is worth noting that the same category can be either a barrier or an enabler depending on the context, explaining why enablers and barriers comprise a single dimension. The same applies to the categories of benefits and advantages, which vary depending on context. This is consistent with the context-dependent view of the theoretical lenses of the contingency theory [10].

 doi:10.20944/preprints202302.0024.v1

4.3. Enablers and Barriers

This subsection explores the enablers and barriers in obtaining carbon emissions reduction, which is identified in the literature and classified into five main categories: (i) technological innovations, (ii) operational measures, (iii) regulatory and economic measures, (iv) urban form and human behaviour, and (v) strategy and stakeholder pressure. Bouman et al. [27] stress that barriers can be mitigated in several ways and are more effective when mitigation measures are taken jointly rather than individually. For example, they suggest that the right combination of mitigation measures could bring a reduction of 75% in GHG emissions in freight transportation by 2050, using currently available technologies.

4.3.1. Technological Innovations

Technological innovations include electrification, alternative fuels, vehicle design and manufacturing, communication technologies, and other indirect technologies with carbon mitigation potential. Breakthrough technologies have experienced rapid and continuous growth in recent years [32]. In a review of air transportation, Oguntona [37] finds that approaches linked to technological innovations have the highest long-term reduction potential in aircraft fleet emissions.

Electrification has proven itself a hot topic over the last few decades. Some studies compare the environmental impacts of diesel, hybrid, and electric vehicles [23,35]. For example, Hawkins et al. [23] find that while battery electric vehicles (BEVs) powered by coal electricity tend to perform better than conventional internal combustion engine vehicles (ICEVs), the same is not true when comparing coal-powered BEVs to high-efficiency ICEVs. However, when electric vehicles (EVs) are powered by natural gas or low-carbon energy sources, they outperform even the most high-efficient ICEVs in terms of global warming potential [23]. This shows that EVs' environmental impact depends highly on the energy source mix used for charging. Garcia & Freire [28] also draw attention to electricity generation sources and find that these significantly impact light-duty vehicle fleet emissions, with renewable energy sources presenting great potential. Moreover, while the charging profile only slightly impacts GHG emissions, this scenario might change with an increase in battery size [28].

In the context of Nordic transportation, Salvucci et al. [32] identify electrified roads, fuel cell and battery electric vehicles, and electric ferries as the technological innovations with the highest potential in the region. Salvucci et al. [32] also highlight the importance of developing and analysing model scenarios that include these technologies so that the future demand for hydrogen and electricity can be accurately assessed. In the case of India and other developing countries, on the other hand, the high cost of hydrogen and fuel cell technology is a major obstacle to commercial rollout [21]. Li [21] also questions the sustainability of hydrogen energy since fossil fuels are still the primary source of hydrogen production in many countries.

Herold & Lee [29] identify speculations surrounding battery technology and energy source sustainability as major barriers to adopting electric vehicle technologies by top management in companies. Finally, Requia et al. [31] question how clean EVs are because they relocate emissions from roads to power plants, among other concerns. However, they conclude that, even in scenarios with a high share of coal-based electricity, EVs still lead to decreasing CO2 emissions [31].

While most studies recognise the mitigation potential of biofuels [27,28,32,37], it is also encountered with hesitation in developed and developing economies alike [21,27,28,32]. In a review of Nordic transportation, Salvucci et al. [32] observe considerable emissions reduction potential from the adoption of bioenergy but are sceptical about future scenarios that rely heavily on the importation of this energy source. As a global trend towards decarbonisation is observed, bioenergy demand will likely grow in the future, raising questions about its availability [32]. As an alternative, Salvucci et al. [32] recommend the development of a portfolio of domestic alternative fuel production chains, which will provide insights into domestic energy resources and storage capabilities. In the contrasting case of India, Li [21] points out that biofuels may play a role in reducing the country's dependence on imports but will have a small or neutral contribution to climate change mitigation. Moreover, using farmable land for biofuel crop cultivation raises pressing concerns about food security in developing countries such as India [21].

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In reviewing light-duty vehicle fleet emissions, Garcia & Freire [28] also find significant potential for reducing GHG emissions through biofuels. However, they classify this scenario as "optimistic" due to studies reviewed not accounting for land use changes and biomass resource availability factors, thus, suggesting this initiative be combined with other mitigation measures, consistent with Bouman et al. [27].

In the maritime transportation scenario, Bouman et al. [27] review a series of CO2 emissions reduction measures and identify the use of biofuels as the one with the largest potential. However, they point out that reduced CO2 emissions during combustion only partially represent the sustainability of biofuels. Agricultural factors, such as feedstock and crop rotation, as well as social and political concerns over land use, all impact the mitigation potential and complexity of the problem [27]. Bouman et al. [27] suggest that current energy sources can be either completely substituted or only complemented by biofuels and other alternative fuels and that these changes will reduce emissions not only in the use phase but also in the entire fuel life cycle. Finally, Oguntona [37] identifies promising future carbon reduction scenarios in air transportation with biofuels and suggests that policymakers and stakeholders in the industry should focus on securing the availability and sustainability of this resource.

Garcia & Freire [28] identify fuel consumption reduction as a fundamental approach to reducing light-duty vehicle fleet GHG emissions, particularly through vehicle weight reduction. They remark, however, that vehicle weight reduction should be coupled with other measures to reach its full potential.

Bouman et al. [27] find that improving ship hydrodynamic performance and minimising water resistance by adjusting hull dimensions, shape and weight in the maritime transportation sector is possible. They also identify several technological innovations that can increase power and propulsion and reduce emissions [27]. Regarding air transportation, Oguntona [37] explores next-generation aircraft models and retrofits to existing aircraft towards fuel efficiency. Finally, in a bibliometric review, Meyer [35] identifies after-treatment technologies as a strategy to reduce emissions.

Communication technologies — such as platooning and intelligent transportation systems — have been explored by several authors in recent years [21,25,35]. Platooning aims to reduce the aerodynamic drag of heavy-duty vehicles by using communication technologies to form closely-spaced groups of vehicles and, as a result, reduce carbon emissions, but Meyer [35] calls for more real-world applications of platooning to understand the impact of this technology better. Faris et al. [25] explore the environmental impact of Intelligent Transportation Systems (ITSs) on vehicle fuel consumption and emissions. ITSs use key evaluation metrics to assess performance and optimise vehicle routing based on information received through inter-vehicle communication [25]. Faris et al. [25] find that ITS measures significantly impact vehicle emissions. However, since ITS commonly optimises to minimise transit time, emissions metrics are suboptimal, and, in many cases, the environmental impact might even be negative when transit time increases. When optimising for transit time means opting for longer stop times or decreasing detour lengths, the optimisation will be environmentally beneficial. Still, environmental impact will be suboptimal when transit time optimisation suggests short stop times or longer detours [25]. Li [21] also briefly addresses ITS technologies, highlighting their potential to optimise traffic towards greater fluidity, thus reducing congestion, energy use and GHG emissions.

On a comparative analysis of additive and conventional manufacturing, Pilz et al. [38] conclude that additive manufacturing reduces the distances and quantity of products transported, thus reducing energy consumption and CO2 emissions. However, Pilz et al. [38] draw attention to the need for more studies in decentralised supply chains, particularly those based on the life cycle assessment (LCA) approach, for a more comprehensive understanding of the environmental impacts of additive manufacturing. Also, concerning technologies that indirectly impact transportation, Salvucci et al. [32] identify carbon capture and storage as a strategy.

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4.3.2. Operational Measures

While technical measures are sometimes limited by existing vehicles (i.e., some measures cannot be applied as a retrofit and need to be built-in in entirely new vehicles), operational measures do not have such limitations [27]. As energy efficiency increases, however, some operational interventions will inevitably decrease in mitigation potential [28].

On the road freight transportation scenario, Meyer [35] identifies vehicle routing and the relationship between emissions reduction and cost as topics of great interest in academia. Miklautsch & Woschank [43] find that significant emissions reduction can be obtained by shifting from road to rail transport. Local production, consolidation, container optimisation, shipping speed increase, pooling supply chains, truck-sharing, carrier coordination, intermodal transportation, demand-side interventions, and vehicle selection were also identified as operational carbon mitigation measures [28,29,43].

In the air transportation scenario, Oguntona [37] highlights consolidation, early aircraft retirement and air traffic management in navigation and landing as important measures to reduce emissions. Regarding maritime transport, Bouman et al. [27] identify economies of scale, speed in the hydrodynamic boundary, and weather routing and scheduling as measures that can significantly impact fuel consumption.

4.3.3. Regulatory and Economic Measures

Li [21] identifies governance as indispensable for urban development and climate change mitigation, particularly in developing economies. Effective policies should be thorough, including multiple aspects relevant to sustainable development and involving relevant stakeholders at every step [21]. Herold & Lee [29] find that government-imposed carbon policies are perceived as the greatest source of risk by managers in the transportation and logistics industry.

Lagouvardou et al. [34] perform a review of Market-Based Measures (MBMs) for decarbonisation in shipping. MBMs incentivise polluters to reduce emissions through financial means (such as market prices) based on the "polluter pays principle". Lagouvardou et al. [34] identify several MBMs for shipping in the literature that can be broken down into two main variants: fuel levy and emission trading system (ETS). Fuel levy, on the one hand, consists of a tax imposed on fuel, intending to induce speed and fuel consumption reductions in maritime transport; however, the level of the levy must be carefully designed since a low levy may not provide enough incentive for companies to invest in sustainable technologies [34]. ETSs, on the other hand, consist of a central authority setting caps on emissions and requiring polluters to hold permits to carry out polluting activities. While regulatory bodies advocate the importance of international ETSs in climate change mitigation, industry stakeholders raise concerns about regulation and administration's impact on competition and carbon leakage [34]. Schinas & Bergmann [39] review MBMs and ETSs in aviation and discuss how lessons learned could be applied to the maritime sector. While they find research in aviation could largely assist the maritime industry, they identify that policy recommendations are still focused on single variables of ETS and call out for a more holistic understanding of ETS success.

O'Mahony [36] performs a state-of-the-art review on carbon taxes. While carbon taxes are commonly regarded as a leading solution to reduce emissions, O'Mahony's [36] findings show that carbon taxes are more effective as a support mechanism to other carbon reduction initiatives rather than as a standalone solution. Moreover, O'Mahony [36] identifies a gap in carbon tax implementation, mainly due to political and social barriers, which may be scaled down through more moderate taxes. Oguntona [37] identifies emissions trading, emission limit setting, fuel route, and airport taxes as carbon mitigation measures in aircraft fleets.

Carbon offsetting is the practice of paying third-party providers to generate GHG savings — through projects that either reduce or absorb CO2 — to compensate for emissions [20]. In a review of voluntary carbon offsets in tourism emissions reduction (i.e., non-mandatory carbon offsetting paid by the consumer), Eijgelaar [20] finds that this is not an efficient mitigation measure, currently compensating for less than 1% of all aviation emissions [20]. However, it is likely to remain a common practice due to a lack of awareness and pressure on the aviation and tourism industries to perform

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more structural changes [20]. Despite several tourism and aviation stakeholders agreeing that energy reduction should be the first-choice mitigation alternative, offsetting is still used to justify growth [20].

Alamoush et al. [41] focus on ports and investigate implementation schemes utilised by port and public authorities (i.e., regulations and standards, economic incentives and disincentives, agreements, training and knowledge sharing and planning). They believe these implementation schemes enable the employment of technical and operational measures to decarbonise ports and associated land transport and oceangoing vessels. Alamoush et al. [41] stress that, apart from the regulation, which should be applied uniformly to avoid competitiveness, most other implementation schemes should be tailored to each case.

4.3.4. Urban Form and Human Behaviour

In the case of urban dimension, Li [21] and Salvucci et al. [32] state that each urban area is particular in many ways — geography, demography, infrastructure, available resources, socioeconomic characteristics, *etc.* — and, as a result, has specific transportation challenges. Therefore, modelling is only expected to treat it individually [32]. Urban form is decisive in shaping city energy consumption and resulting GHG emissions [21]. Similarly, human behaviour and behavioural change policies also play a key role in shaping modal choice and the resulting CO2 emissions in transportation [21,32]. However, as Salvucci et al. [32] pointed out, many energy-economy-environmental-engineering (E4) models still fail to consider this important dimension.

According to Li [21], urbanisation typically follows economic development and is essential for sustainable economic growth. In developing countries, cities are usually responsible for a high share of economic activities. Li [21] predicts that metropolitan cities will be responsible for an increase in transportation energy demand in these economies. While transportation planning is often done independently of other urban services, Li [21] states that integrated planning is extremely important for transportation development. For example, multiple synergies can occur between transportation and land use, and thus integrated planning could benefit both [21]. Salvucci et al. [32] also observe that urban planning can significantly impact transportation and that varying granularity levels when assessing regions — evaluating urban dimension and country dimension, for example — might provide valuable insights [32]. Wimbadi et al. [40] state that low-carbon mobility transitions are spatially-constituted processes and identify cities as the birthplace of testing and subsequent implementation of urban decarbonisation experiments.

Salvucci et al. [32] identify income, GDP per capita, and fuel prices as determinants in modelling vehicle ownership and mileage, and travel time budget and transport infrastructure as key factors in shaping modal shift [32]. Effective policies promoting modal shifts can reduce car ownership if planned correctly [32]. However, new mobility trends such as autonomous vehicles and mobility as a service (MaaS) have yet to be properly modelled regarding their impact on car ownership, mileage, and congestion [32].

Another important aspect to consider in vehicle ownership is the phenomenon of urban sprawl. Li [21] remarks that American and European cities have experienced a significant increase in area, disproportional to their low population growth, creating a need for private vehicle ownershi A similar trend can also be observed in developing countries in recent years [21]. Higher urban density, on the other hand, is associated with lower transportation-related emissions but with higher household energy demand [21]. Also, on urban density, Czepkiewicz et al. [30] find that people who reside in larger, denser and more central neighbourhoods have a greater tendency to go on long-distance leisure travel – particularly air and international travel – than people who live in suburban or rural areas.

Li [21] also highlights the reinforcing loop dynamics between road infrastructure and car ownershi Road infrastructure is built in response to increased car ownership; better road infrastructure drives attractiveness in buying new vehicles [21]. In the case of developing economies, economic growth leading to greater per capita incomes will cause growing car ownership [21]. For Li

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[21], improving the quality and public perception and lowering public transportation costs and time is key to reducing private car ownership and associated fuel consumption and carbon emissions.

Hu & Creutzig [42] perform a systematic review on shared mobility in China, including ride-hailing, car sharing and bike sharing. While shared mobility is intended to reduce car ownership and increase the use efficiency of vehicles, there is still much uncertainty surrounding its relationship with public transportation [42]. On the one hand, the flexibility of shared mobility can turn it into a major feeder of public transportation (thus, supporting public transportation efforts) [42]. However, on the other hand, other characteristics (i.e., price, convenience, and quality) might lead to public transport cannibalisation, causing a potential rebound effect in GHG emissions [42]. Hu & Creutzig [42] also draw attention to the association between shared mobility, digitalisation, and electrification, particularly in China.

4.3.5. Strategy and Stakeholder Pressure

Herold & Lee [29] identify competitive advantage as an emerging theme in the logistics and transportation carbon management literature. They find that efforts towards carbon reduction are strongly tied to business strategy and that improving sustainability performance can be key in differentiation. However, disclosure and communication with stakeholders are extremely important, so carbon reduction can effectively be a competitive advantage. Studies reviewed by Herold & Lee [29] also show that while stakeholder pressure is more powerful than governmental pressure, more is needed to motivate companies if carbon reduction needs to be in line with a long-term strategy. Miklautsch & Woschank [43] also find that external pressure to reduce emissions has a weak impact on top management and that customer pressure needs to be more widely on the industrial sector.

Herold & Lee [29] also find that alignment between retailers and regulatory forces and subsequent implementation of carbon policies present a great challenge that might impact the success of such policies. Moreover, the effectiveness of carbon pricing schemes is questioned once their cost usually needs to be more meaningful to drive behavioural changes [29]. Finally, Herold & Lee [29] investigate carbon target setting and find that companies adopt many different carbon target-setting approaches and that, most of the time, targets are set on a corporate level without a deeper understanding of reduction potentials at an operational level. Moreover, regarding the relationship between emissions reduction and cost, Herold & Lee [29] identify that ambitious carbon reduction targets cannot be reached with limited investments.

4.4. Benefits and Disadvantages

Most studies focused on the enablers, barriers and metrics dimensions of carbon emissions reduction. In most studies, carbon emissions reduction and climate change mitigation are identified as intrinsic benefits, and further co-benefits or disadvantages of emissions reduction are not explored. This indicates a gap in research concerning the post-implementation phase of carbon mitigation strategies and confirms the infancy of carbon concerns. It also partly reflects a dominant selection approach, which, according to the OM-PCR lenses of the structural contingency theory, takes for granted the outcomes of the landscape-mitigation fit [12].

While this review focused on CO2 emissions reduction, many carbon mitigation actions also reduced other emissions and air pollution. One example is the reduction of black carbon through implementing mass public transportation, which is harmful to climate change and the health implications of air pollution [26]. Carbon monoxide, nitrogen oxides, sulfur dioxide (SO2) and volatile organic components (VOC) are other air pollutants that might also be reduced through mass public transportation [26]. Electric vehicles, a technology commonly associated with GHG mitigation, may also cause a significant impact on gaseous pollutants — such as nitrogen oxides, VOC and SO2 — and moderately reduce particulate matter emissions [31].

In a review focused on EVs, Requia et al. [31] raise the debate on EVs shifting air pollution — rather than inherently reducing it — in countries mainly powered by fossil fuels. In such scenarios, it may be argued that emissions are transferred from vehicle tailpipes in roads (predominantly urban areas) to power plants (usually located in suburban or rural areas) [31]. Spatial distribution will be a

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key determinant of health impact in these cases, reducing exposure in countries where the majority of the population is concentrated in cities and only shifting it to countries with a more even population distribution; however, this might raise issues of fairness [31]. Requia et al. [31] state that EVs must be coupled with clean energy sources to obtain a significant impact on health and emissions reduction.

In Schinas & Bergmann's [39] review of ETSs in aviation, they find no significant impact of ETSs on firm economic performance or logistics and operations. On the other hand, higher efficiency and an impact on valuations are reported. They also find that ETSs might lead to distorted competition between firms adhering or not to the system, highlighting the importance of a universal approach to ETS.

Herold & Lee [29] identify competitive advantage as a benefit of corporate strategies that adopt carbon mitigation measures, stating that environmental sustainability can be an important differentiation strategy. In addition, specific mitigation measures, such as mass public transportation, might generate secondary benefits to carbon emissions reduction, such as fewer traffic injuries and increased physical activities [26].

4.5. Metrics

This section reviews indicators of measurement and performance indicators, emissions modelling and inputs, and life-cycle assessments.

Franco et al. [24] compare techniques for measuring road vehicle emissions and developing emission factors and find that controlled environment techniques are more mature, despite being more expensive. At the same time, real-world conditions techniques provide a more accurate reflection of reality but also have larger variability that must be accounted for. Noussan et al. [44] stress the importance of choosing the right emission factors and including variability when assessing the impact of mobility strategies for decarbonisation. Finally, Kwan & Hashim [26] highlight the importance of incorporating speed into emissions calculations since calculations based solely on distance might underestimate emissions, ignoring traffic congestion, for example.

Herold & Lee [29] and Meyer [35] review several studies that focus on emissions quantification before and after the implementation of mitigation measures, and Herold & Lee [29] also review studies that investigate the trade-off relationship between costs and emissions. Smit et al. [19] explore different types of traffic emission models and perform a meta-analysis of studies validating these. Finally, Oguntona [37] reviews nine approaches to modelling aircraft fleet development, comparing long-term fleet-level emissions of different carbon mitigation measures.

When comparing different approaches to estimate transport GHG emissions, Arioli et al. [33] find that most studies adopt a top-down approach (usually using national or municipal-level statistics), followed closely by a bottom-up approach (using large volumes of data from sometimes multiple datasets), and on-site measurements is the least common method. However, while bottom-up is the most accurate method, it can also be the most challenging regarding data availability. Therefore, data availability and the aim of the GHG inventory should be considered when choosing the best approach. Similarly, Miola & Ciuffo [22] compare bottom-up and top-down methods in estimating air emissions from shipping. They remark on the high level of discrepancies in results from both approaches — attributed mainly to information sources — and introduce the use of multiple data sources simultaneously as a workaround towards greater accuracy in results.

Faris et al. [25] review vehicle fuel consumption and emissions modelling combined with ITS. They explore the different modelling scales and find that microscopic models provide greater accuracy, but macroscopic models are indicated for aggregate emissions inventory estimations. They also classify empirical (bottom-up) and statistical (top-down) modelling approaches. Finally, they conclude that mesoscopic (between microscopic and macroscopic) and empirical models are the most indicated for ITS network optimisation and environmental impact assessment.

Hawkins et al. [23] utilise a life-cycle inventory (LCI) approach to compare the environmental impacts of electric vehicles and conventional internal combustion engine vehicles. They find that the GHG of electric vehicles is highly dependent on the use phase, which is responsible for 60-90% of the

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life cycle global warming potential for battery electric vehicles powered by fossil-based electricity sources. However, more comprehensive LCIs, including all phases of the electric vehicle life-cycle, are still needed to understand the full environmental impact of these vehicles [23].

LCAs are typically centred on the life cycle of a given product and fail to capture transient effects caused by the introduction or replacement of products and technologies [28]. With this in mind, Garcia & Freire [28] take LCA further and adopt a fleet-based LCA capable of capturing these dynamics to review light-duty transportation. They find, however, that most reviewed studies fail to include the entire fleet life-cycle, usually overlooking the production and disposal phases. Li [21] advocates the need for cost-benefit analyses using the LCA approach in urban transportation, as these allow for a holistic assessment of costs incurred in private versus public transportation. Noussan et al. [44] review LCAs and well-to-wheel (WTW) emissions. WTW differs from an LCA as it does not consider energy and emissions in building facilities and vehicles or end-of-life aspects. Noussan et al. [44] call out the difficulty in comparing different assessments due to the inclusion of different stages (*e.g.*, some studies include infrastructure and others do not) and advocate for a standardised evaluation framework. Herold & Lee [29] and Meyer [35] also review several studies incorporating LCAs.

4.6. Synthesis Framework

Figure 7 presents a framework synthesising the results from the tertiary review and illustrating the interactions between the different key factors in carbon emissions reduction in transportation.

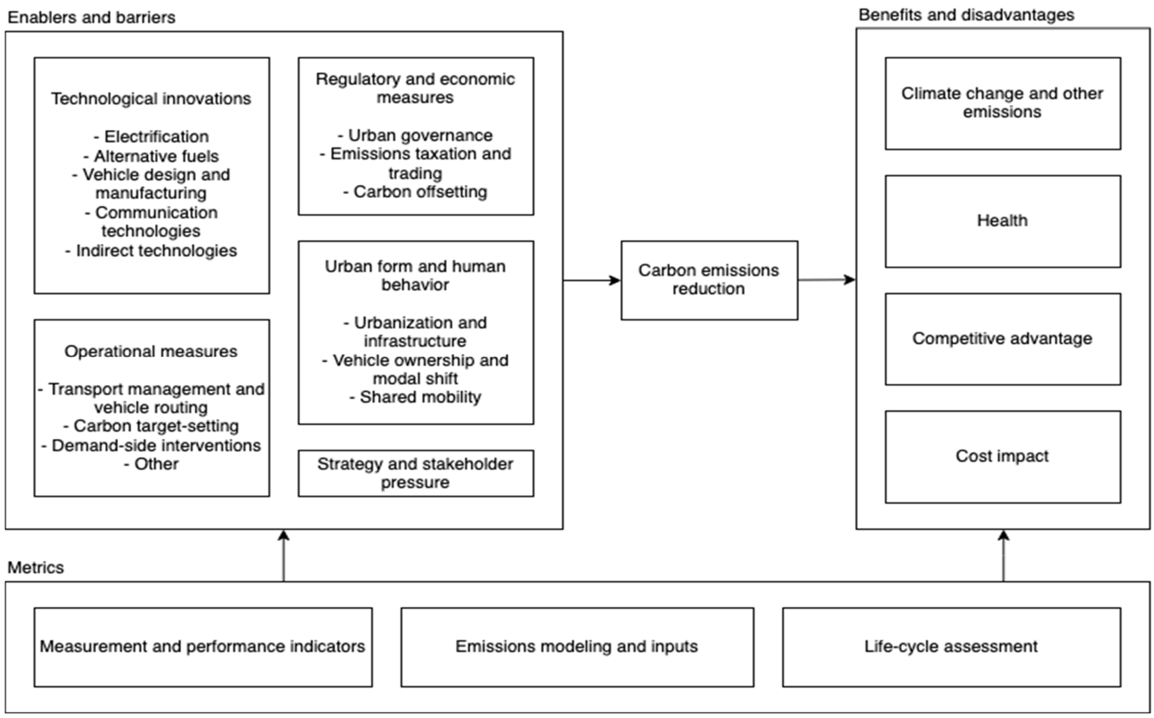

Figure 7. A synthesis framework for enablers, barriers, benefits, disadvantages and metrics for carbon emissions reduction in transportation.

Focusing on the theme of carbon emission reductions in transportation, the first step in the framework development was to identify key factors surrounding this topic in the reviewed literature. These factors were then classified into three major categories: enablers and barriers, benefits and disadvantages and metrics.

Factors that fell into the enablers and barriers category were any factors that influenced or determined carbon emissions reduction, either by acting as an enabler and potentialising mitigation or acting as a barrier and preventing reduction. Benefits and disadvantages were factors that were an outcome or consequence of emissions reduction, both positive and negative, but did not influence

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emissions reduction directly. Finally, metrics included any method or approach to measure or quantify carbon mitigation. These could be applied to either model the potential impact of factors influencing mitigation or measure a given strategy's real-life effects.

Figure 7 depicts the system's approach under OM-PCR: the interaction among enablers and barriers enhances or hinders carbon emissions reduction, leading to benefits or disadvantages. Enablers, barriers, emissions, benefits and disadvantages are objectively measurable.

5. Discussions

Enablers, barriers, benefits, disadvantages and metrics in carbon emissions reduction were identified, and a comprehensive framework was built. The main enablers and barriers identified were technological innovations, operational measures, regulatory and economic measures, urban form and human behaviour, strategy, and stakeholder pressure. It is worth noting that most of these factors can act as either enablers or barriers depending on the context, emphasising the relevance of a contingency view of carbon emission in transportation. There is no "one-size-fits-all" policy or mitigation measure; strategies, programs, and results vary depending on each country or region's development level, energy matrix, transportation modes and prevalent economic activities, among others. A similar phenomenon was observed in the benefits and disadvantages dimension: most outcomes could be seen as both a benefit or disadvantage and therefore were not split into two separate groups. The benefits and disadvantages identified were climate change and other emissions, health, competitive advantage and cost impact. Finally, measurement and performance indicators, emissions modelling and inputs and life-cycle assessment were classified as metrics and used to measure the carbon emissions reductions. Identifying such factors answers RQ1: "What are the main barriers, enablers, benefits and disadvantages of carbon emission reduction in transportation?". The development of a typology answers RQ2: "What are the main dimensions or categories utilised to describe the initiatives for carbon mitigation in the transportation sector?".

Another out-striking result was the unbalanced nature of the relationships among the categories—figure 8 attempts to illustrate the relationships between the categories identified in Section 4 - Results. The size of each node represents the number of articles addressing each theme, and the edges represent at least two articles addressing both the connected nodes. Dashed edges mean two articles only, and continuous edges mean three or more articles. Ticker edges mean more articles address both nodes.

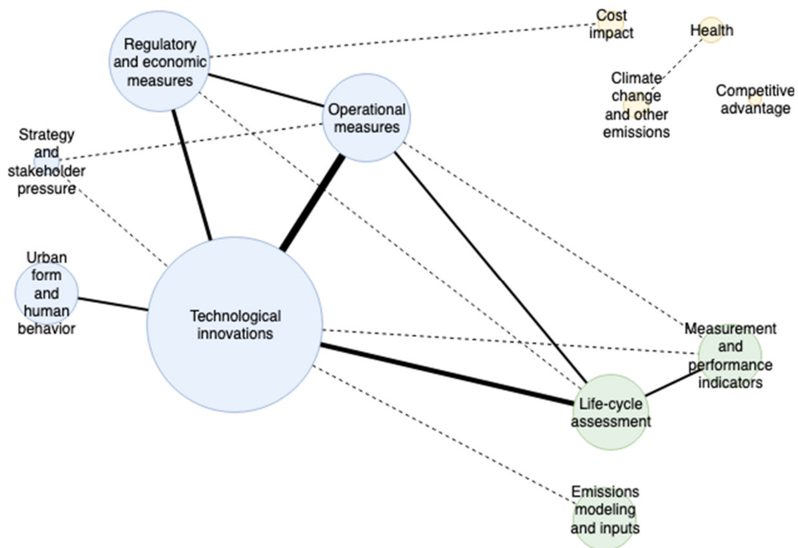

Figure 8. Relationship between enablers, barriers, benefits, disadvantages and metrics in carbon emissions reduction.

While enablers, barriers, benefits and disadvantages were all present in the literature, it was clear that they were all explored to different depths: 20 papers examined enablers and barriers, whilst

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only four papers analysed benefits and disadvantages. Most studies assume carbon emissions reductions are fundamentally beneficial and, as a result, fail to identify potential disadvantages or co-benefits. This finding is in line with one criticism of the Multi-Level Perspective identified by Geels [46]: "Assuming that 'green' innovations are intrinsically positive, they [transitions scholars] rarely address how much sustainability improvement they offer and if this would be sufficient to address persistent environmental problems at the speed required".

Under the lens of contingency theory, however, it is possible to observe the importance of exploring the benefits and disadvantages of carbon emissions reduction initiatives. We observe that both landscapes and mitigation initiatives are well explored, but there is still much to learn from the outcomes of these relationships. One interesting example is the case of biofuels. While experiments have shown biofuels produce fewer tailpipe emissions than fossil fuels, their use might have backfiring effects depending on the context they are applied to. While in developing countries, biofuels might harm land use and food security, in developed countries, which rely on importations, energy security is the biggest risk. This shows that understanding the outcomes of mitigation initiatives is necessary to understand their fit in different landscapes and, thus, gain valuable insights into their effectiveness and potential success. It also shows that universal mitigation strategies are only valid for some landscapes.

Consistent with contingency theory, Bouman et al. [27] also state that more than individual measures are needed to achieve significant GHG emissions mitigation. Considering this, exploring the relationship between different carbon reduction initiatives is also interesting in achieving meaningful results. Regarding the fourth and last postulate of contingency theory (i.e., outcomes are measurables) applied to transportation carbon emissions, we see increasing interest from the academy in measuring carbon emission reduction. Simulations of carbon emissions in inbound logistics operations in an emerging economy can be found, for example, in Muñoz-Villamizar et al. [47]. However, developing metrics to quantify outcomes other than emissions is still in its infancy.

Another interesting finding was that all reviewed studies approached the environmental aspect of sustainability, and the majority focused on this perspective only. Few studies investigated sustainability's social or financial aspects or the triple bottom line. This is consistent with the multi-level perspective approach to socio-technical transitions and indicates we are at the beginning of a transition process, which can still take decades to unfold completely. Currently, we observe multiple niches in transportation starting to appear, but they still need more maturity to overcome challenges and barriers and transform or replace the existing regimes. New initiatives focus on reaching an energy matrix with less carbon, but social and economic implications still need to be fully explored. The typology of carbon emissions reduction in transportation and the resulting synthesis framework provides a snapshot of the current state of sustainable transitions in transportation.

6. Conclusions

This study conducted a systematic literature review that selected and examined 26 review papers in the area of carbon emissions transportation, covering a total of 2,983 primary research papers. As a result, enablers, barriers, benefits, disadvantages and metrics in carbon emissions reduction were identified, and a comprehensive framework was built. Practical implications from the review and limitations and directions for future research can be found in this concluding section.

6.1. Practical Implications

This study combines socio-technical transitions theory and contingency theory in the field of transportation carbon emissions. The result is a comprehensive view of the current state of carbon emissions reduction initiatives in transportation with a critical view of the outcomes that result from different environment-initiative relationships.

Identifying enablers, barriers, benefits, disadvantages and metrics currently found in the literature provides researchers and practitioners with a better understanding of the current state-of-the-art in carbon reduction in the transportation sector, providing a "snapshot" of the socio-technical transition state we are in. In addition, the organisation of such into a typology and synthesis framework of carbon emissions reduction in transportation allows a better understanding of the different categories being explored in each dimension and uncovers the need for a greater focus on the benefits and disadvantages of mitigation initiatives applied to different scenarios.

6.2. Future Research

As shown by the contingency theory applied to carbon emissions in transportation, there needs to be more research on the outcomes of the carbon emissions reduction initiative. Therefore, investigating the benefits and disadvantages of initiatives in different scenarios is recommended for future research. Furthermore, going beyond contingency theory, an investigation on the synergies between different measures (i.e., initiative-initiative fit) would also be interesting and a valuable finding for companies and policy-makers to devise strategies.

This study introduces socio-technical transitions theory and contingency theory as a backdrop to understanding carbon mitigation strategies in transportation. On the one hand, while socio-technical transitions provide a wider context to individual measures, it often focuses on the transition itself and fails to capture the aftermath of such. Contingency theory, on the other hand, provides a more focused view that incorporates outcomes. The combination of both theories applied to sustainable transportation deserves further investigation.

Finally, the larger part of the existing literature on sustainability in transportation focuses on developed countries. To reach significant carbon reduction worldwide, devising strategies aimed at developing economies is as important as analysing the sustainability transition in developed economies.

Funding: This research was funded by the National Council for Scientific and Technological Development (CNPq), grant number 311862/2019-5; Coordination for the Improvement of Higher Education Personnel (CAPES), finance Code 001; and the Foundation for Support of Research in the State of Rio de Janeiro (FAPERJ), grant numbers E26-203.252/2017 e E26-201.251/12021.

Data Availability Statement: Not applicable.

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