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Review

Carbon Emissions in Transportation: A Synthesis Framework

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Abstract: With the growing concern worldwide regarding greenhouse gas (GHG) emissions and their impacts on human health and the environment, transportation has become a central theme in their mitigation, responsible for 15% of anthropogenic GHG, 23% of global energy-related, and 8.7 Gt CO_2-eq emissions. This study's objective was to comprehensively review the current state of carbon mitigation in the transportation sector. This was conducted through a systematic literature review based on the multi-level perspective of socio-technical transition theory and structural contingency theory. In total, 30 review papers covering 3561 original articles were selected for full-text examination. The main findings were related to the fact that in order to build resilience against climate change, transportation services must adapt to the current scenario and act quickly to avert future changes. Enablers, barriers, benefits, disadvantages, and metrics in carbon emission reduction were identified. A comprehensive framework and a dynamic co-word analysis emphasised the interrelationships among the dimensions of sustainability transition in transportation. Important trade-offs among the transition dimensions are context-dependent and should be adapted to different countries and transport modes to succeed. The study sheds light on the need to investigate mitigation's often-neglected consequences and disadvantages.

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 the increased knowledge of its consequences for the environment, the economy, and humanity. As a result, reducing greenhouse gas (GHG) emissions, particularly CO_2, has become a common and inevitable goal to reduce the impacts of climate change [1,2].

When considering 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 (2022), 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 CO_2-eq that year, estimated to grow within the 16–50% range by 2050 [3] (pp. 1052–1053).

Transportation includes road, rail, air, and sea and may refer to the transport of passengers or freight. Seventy percent of direct transportation emissions come from road vehicles, followed by aviation (12%), shipping (11%), and rail (1%) [3] (p. 1052). 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, and vehicle, airplane, and ship manufacturing, maintenance and disposal, and operation [2]. The combined direct and indirect emissions from industry, buildings, and transportation totalled 66% of the total emissions in 2019 [2] (p. 66). Wei et al. [4] assessed the carbon emission effects of urbanisation and foreign investment in the Belt and Road Initiative (BRI), looking comprehensively at CO_2 emissions from fossil fuels, cement production, and natural gas combustion. The analysis comprised 74 countries in Asia, Europe, and North Africa, using the Open-Data Inventory for Anthropogenic Carbon Dioxide (ODIAC). The authors advocate for climate justice, compensating for carbon emissions from economic development and urbanisation with mitigation measures such as energy efficiency and innovation to address jobs lost due to energy transition and to satisfy aspirations for basic needs in BRI's low- and mid-income countries.

In 2019, GHG emissions chiefly came from the energy sector (20 $GtCO_2$-eq); industry (14 GtCO2-eq); agriculture, forestry, and other land uses (AFOLU—13 $GtCO_2$-eq); transport (8.7 $GtCO_2$-eq), and buildings (3.3 $GtCO_2$-eq). Despite a low decrease in emissions rates in 2010–2019 compared with the previous decade in the energy supply and industry, the emissions from transportation remained constant at approximately a 2% growth rate yearly [2] (p. 65). There is the expectation that transportation's contribution to GHG emissions will tend to rise due to travel demands, the use of heavier and low-efficiency vehicles, consumer behaviour that prefers car transportation to other displacement modes [5], population growth, an increase in GDP per capita in emerging countries, and the combined effects of transport with industry and buildings [1,3]. Some progress has been acknowledged, however, since the IPCC Fifth Assessment Report in 2014 and after the Paris Agreement in 2015, with the growing awareness of the need for demand management, growing electromobility, and emerging technologies involving biofuels for land use and hydrogen-based fuels in maritime and air transportation [1,3].

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 [6]. 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 [7]. Drawing on socio-technical transition theory, a multidisciplinary and holistic approach is needed to fully understand climate change, its impacts, and how to abate it [7,8]. Ferrer et al. [8] highlighted the interplay between the economy, society, and technology in solving sustainable urban infrastructure issues in a review of sustainable urban infrastructure. De Abreu et al. [9] performed a bibliometric analysis of the adaptation measures in road transportation infrastructure induced by climate change, retrieving 280 articles on the subject.

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

RQ1—What are the main barriers, enablers, benefits, and disadvantages of carbon emission reduction in transportation?

RQ2—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, metrics, benefits, and disadvantages of existing measures to reduce carbon emissions.

To attain this general objective, this study reviewed the extant literature against the backdrop of the multi-level perspective (MLP) of sustainability transition theory and contingency theory (CT) to offer an analytical synthesis framework. In addition, a tertiary review of carbon emission mitigation strategies in transportation was performed. The fulfilment of the objectives is expected to contribute to the theory and practice of carbon emissions strategies in the transportation sector.

The novelty and contributions of the manuscript are six-fold: (i) it addresses a gap and common criticism of the MLP literature in sustainability transitions—the lack of analysis of the consequences (i.e., outcomes and impact) of the transition process [10] (p. 189); (ii) it bridges MLP with auxiliary theories, such as the structural CT of organisations [11,12], addressing another gap in the MLP literature in sustainability transitions [13] (p. 34); (iii) it contributes to mid-range theory building in sustainability transitions; (iv) it offers a classification of enablers and barriers to sustainability transitions in transportation; (v) it proposes a framework relating barriers, enablers, and metrics in decarbonisation to the outcomes and impacts of the transition process; (vi) it provides a co-word analysis showing the dynamic interrelations among the dimensions of the sustainability transition in transportation, evidencing the strength of the links among dimensions.

The study is organised as follows. Section 1 is this Introduction. Section 2 provides a theoretical background regarding the sustainability transition landscape, introducing the MLP of socio-technical transitions and CT 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 the findings, deriving practical implications and directions for future research.

2. Theoretical Background

This research is ingrained in the MLP theory of socio-technical transitions and structural CT. The MLP was originally developed as a socio-technical approach to the analysis of technological transitions in transportation [14]. It brings a holistic approach, including analysing all stakeholders (international organisations, governments, policymakers, politicians, consumers, social institutions, NGOs, academia, engineers, firms), technologies, and regulations. It was later extended to sustainability transitions, emphasising that they depart from historical transitions because they are purposeful, relate to collective goods, use an ecological rather than economic view, and involve the major companies due to the high investments and sunk costs of the prevailing technologies [7]. The MLP encountered four criticisms that could be addressed with the aid of CT: (i) the MLP is too general (global models); (ii) the consequences of the transition are usually taken for granted and not analysed; (iii) the transition landscape, a major contextual variable in the MLP, is described in general and in vague terms; and (iv) the MLP does not resort to auxiliary theories [10]. CT complements the MLP with a focus on the notion of fit. In its simpler form, CT states that "organisations adapt their structures in order to maintain fit with changing contextual factors, so as to attain high performance" [12] (p. 698). The theory's applications imply that important contingency variables discriminate among contexts; contexts can be grouped based on contingency variables, and the most effective internal organisational designs should fit with the context to attain higher performance levels. This paper posits that sustainability transitions in transportation can have unintended consequences, and their outcomes and impacts should be analysed, which is consistent with the systems view of CT. Moreover, CT emphasises the context–structure fit. Doing so guides the analysis to identify technologies, processes, and systemic interactions among them. It also points to the relevance of describing major contextual variables, called the sustainability transition landscape. Furthermore, the use of theories auxiliary to the MLP was called for by Geels [13], among others. Finally, bridging the MLP and CT answers a recurrent call to contribute to theories in systematic literature reviews [15]. The sustainability landscape underlying the latest facts on carbon emissions is reviewed before introducing the theories.

2.1. Sustainability Transition Landscape

According to the MLP, landscapes are the wider context external to the transition. This "includes spatial structures (e.g., urban layouts), political ideologies, societal values, beliefs, concerns, the media landscape and macro-economic trends [and] (. . .) represents the greatest degree of structuration in the sense of being beyond the control of individual actors" [7] (p. 473).

The 2015 Paris Agreement pledges to keep the temperature increase below 2 °C above preindustrial levels and calls to advance measures to limit the rise in temperature to 1.5 °C by 2050 to "decrease the likelihood of climate change" (Articles 2.1 and 2.4). It urges countries to adopt nationally determined contributions (NDCs) to achieve these goals. However, the NDCs are off-track and uneven among countries [16,17]. In the more optimistic scenario, if all of the NDCs updated in 2022 are fully achieved, the temperature rise could reach, at best, 1.8 °C [18]. However, in all scenarios, the present level of emissions will be aggravated in 2050 by a population growth that will reach 9.7 billion [19], requiring 60% more food compared to 2006 levels [20] (p. 7) and an additional 26% of the total energy supply from 589.1 exajoules (EJ) in 2020 to 743.9 EJ according to stated policies [21] (p. 294).

Total CO_2 emissions were estimated in 2019 to be 39.32 gigatons (GT) from fossil fuels and land use change, with the large majority emanating from fossil fuels (35.26 GT), with three quarters from the energy sector [21,22]. The IEA [23] estimates that the total emissions from energy combustion and industrial processes were 36.8 GT in 2022, a growth of 0.9% or 321 Mt over the preceding year. The transportation sector accounted for 37% of CO_2 emissions from end-users in 2021, despite the downturn caused by the COVID-19 pandemic [21]. The emissions from transportation resumed their historical growth trend, increasing by 8% to nearly 7.7 Gt CO_2, and they are growing faster in emerging and developing economies [23]. If no actions are taken, domestic and international transportation's share of global GHG emissions could rise from a 20% level in 2021 to up to 60% by 2050 [24]. To reach a net zero scenario by 2030, the transport sector's emissions should fall by 20% [25]. Significant new commitments to efficiency and the use of low-carbon fuels are required to reach this target in all transportation modes. The global GHG emission targets can only be met if the transportation sector becomes carbon-neutral. Emissions in the sector include those from infrastructure (industry and buildings) related to road construction, motor efficiency, and the use of renewable fuels [26].

Therefore, the transportation sector and its supply chain are facing increased demands to intensify the use of renewable energies in its operations and transition towards a low-carbon society. The challenge ahead is a paradox combining several factors demanding orchestrated efforts. While the economic returns on investment in traditional fossil fuels are shrinking [27,28], the business opportunities arising from developing and adopting alternative renewable energies require large financial investments and innovation [29]. Innovation will be necessary to harness renewable and carbon-neutral resources (solar, wind, ocean, bio, hydrogen, nuclear, and geothermal energy and storage), agricultural food production, and carbon capture and use (carbon sinks in terrestrial and maritime ecosystems) [1]. Wang et al. [1] (p. 15) emphasised that "the extensive use of fossil fuels and deforestation to promote anthropogenic activities and urbanisation are entwined with global climate change". This landscape directly affects transportation. In addition, the preservation of economic growth and profitability faces a volatile scenario exacerbated by frequent SC disruptions, as recently evidenced by the COVID-19 pandemic and the Russian–Ukrainian war. The transportation sector is urged to contribute to lower carbon emissions in a volatile, uncertain, complex, and ambiguous (VUCA) world [30]. The main stakeholders (e.g., shareholders, governments, international agencies, and consumers) urge for a reduction in carbon emissions from the exploration and refining of fossil fuels and the transitioning of energy production and use to more sustainable operations and business models [31]. The pressure from stakeholders imposes an additional logical and moral burden on incumbent companies in the oil and gas sector to decarbonise their operations [32], affecting the transportation sector as a whole.

2.2. 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 [7]. 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" [7] (p. 471). They may take decades to develop gradually and are seen as co-evolutionary processes [7].

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 [8]. Socio-technical systems, however, are composed of multiple dimensions that constantly interplay with each other, suggesting that there is much to gain from exploring the "social" side as well [8].

With this in mind, the multi-level perspective (MLP) approach to socio-technical transitions seeks to provide a holistic understanding of the elements and actors involved in transportation systems and their interactions [7]. 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 [7].

Generally, three main levels are explored in the MLP [7]:

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

Figure 1 illustrates the dynamics involved among the three levels of the MLP. Changes and new ideas start in niches, typically emerging from experiments or innovation projects [7]. Continuous learning from niches challenges the regime, proposing a transformation or replacement of the existing regime, but it is mostly met with barriers formed by lock-in.

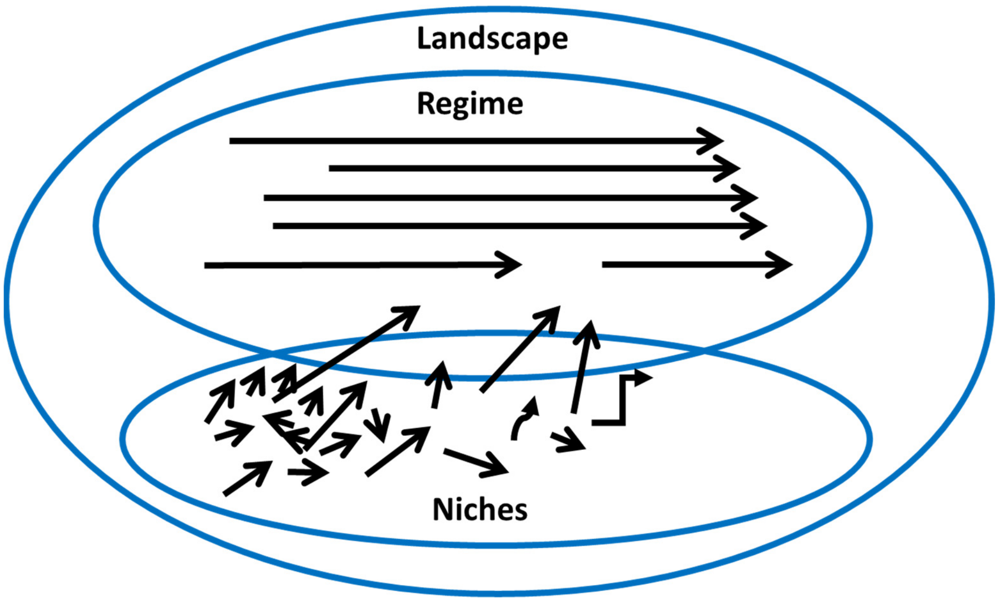

Figure 1. Levels of the multi-level perspective.

While the 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 MLP approach to socio-technical transitions in important ways and is briefly summarised next.

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

Structural CT 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 [11]. Conversely, there is a misfit when the environment and structure do not match, and this causes organisations to perform poorly [11].

The four basic postulates of CT [11], extended to the field of transportation carbon emissions, can be expressed as follows: (i) there is a mutually reinforcing effect between the landscape and the carbon emission mitigation initiatives; (ii) a high landscape–carbon emission fit causes effectiveness and a low fit causes ineffectiveness; (iii) there is no universal type of carbon emission initiative valid for all types of transportation modes and landscapes; and (iv) the outcomes of carbon emission mitigation strategies (i.e., their disadvantages and benefits) are measurable.

Applying the definition of operations management practice contingency research (OM-PCR) [12] to carbon emissions provides a powerful lens for the theoretical extension of SLR research. According to Drazin and Van de Ven [33], the analysis of environment–structure fit can be performed 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 the current research on carbon emissions in transportation. Under the selection approach, the fit between the environment (or landscape) and the structure (here, the emission mitigation initiatives) is assumed to produce the best outcomes. Therefore, under this perspective, the response variable (i.e., the outcome) is neither 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 the 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 effects on outcomes are jointly analysed, taking into consideration individual and interaction effects systemically (see [12], pp. 706–707, for a complete discussion of the typology).

Figure 2 illustrates the expected relationships between the environment, carbon emission initiatives, and their outcomes under the CT perspective in an attempt to answer RQ2 (describing the main dimensions utilised in the analysis). It assists in highlighting the general objective of contributing to the transition to a lower-carbon society by better understanding its dimensions. This framework is further extended in Section 4.6 "Synthesis Framework".

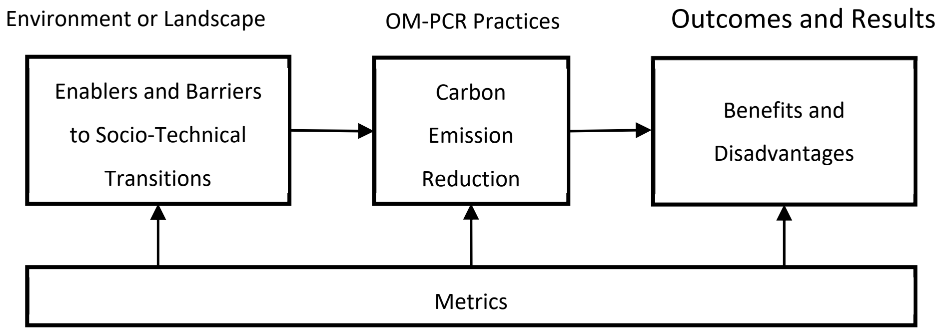

Figure 2. Effects of the operating environment (i.e., landscape) and carbon emission mitigation on outcomes.

The combination of the MLP approach with the socio-technical transition under the OM-PCR views provides the theoretical lens through which the SLR is undertaken. The high-level MLP 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 are paramount in searching for a typology of carbon emissions research, as described in Section 4. The OM-PCR pays direct attention to the measurement of the landscape, the carbon emission mitigation initiatives, their 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 the 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 [34]. Moreover, they can be powerful tools to elaborate and improve existing theories [15]. The use of theories in this literature review follows the guidelines provided by Seuring et al. [15] for the supply chain management field. Furthermore, they apply them to the analysis of carbon emissions in the transportation sector. According to Seuring et al. [15], 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" [15] (p. 5). This study adopts the fourth view of the role of theories in SLRs.

Different types of literature reviews are included in this tertiary review. They are classified into the broad categories proposed by Grant and Booth [35]: systematic, critical, literature, meta-analysis, and state-of-the-art reviews. Following Grant and Booth [35], 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 conducted extensive literature searches and critically evaluated them. A literature review is a generic term for the analysis of recent or current literature to 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.

Step-by-Step Approach for the Systematic Literature Review

The step-by-step approach devised by Thomé et al. [34] and based on Cooper [36] for systematic literature reviews was adopted for the tertiary research. It consists of eight main steps, as outlined in Figure 3.

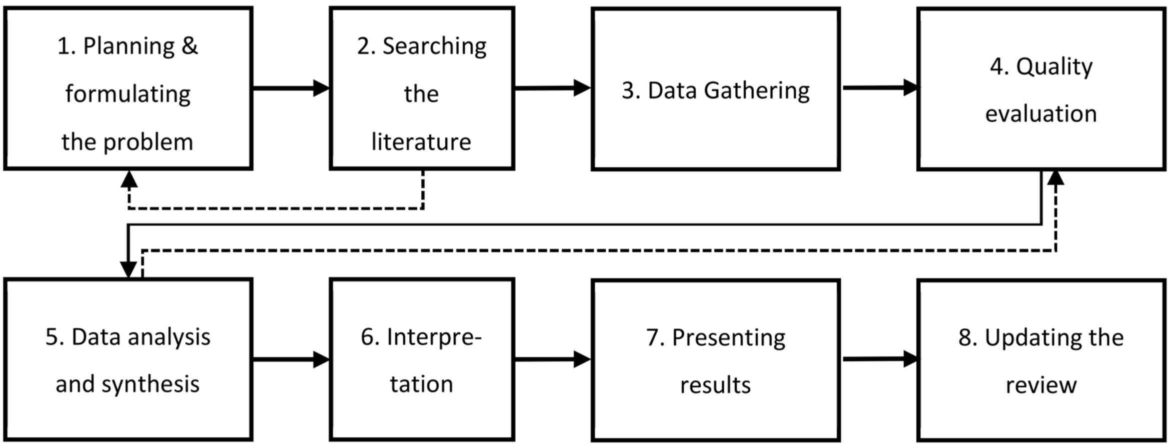

Figure 3. Step-by-step approach for the systematic literature review.

The dashed lines represent the recursive processes of consensus building among authors on the search and exclusion criteria and data analysis and synthesis. 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. The Scopus and Web of Science (WoS) databases were selected because of their extensive journal collections and relevance in the environment, engineering, and management domains [37].

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. The first set of keywords addressed the broad field of carbon emissions in transportation, directing the search to sustainability issues with the lenses of MLP and CT, looking at the dimensions of the transition and its effects or consequences, rather than to studies that would only report the measurement of emissions. In choosing the keywords, an attempt was made to use terms that were sufficiently general to cover the majority of studies in the field but, at the same time, sufficiently narrow to capture only relevant research related to the study's objective and research questions, consistent with Cooper [36] and Thomé et al. [34]. The second set of keywords restricted the search to the different types of literature reviews [34].

Table 1. Selected keywords and restrictions when 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 "CO_2" 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 (without 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 the tertiary research:		565
Total selected for the tertiary research (without duplicates):		411

Note: The wild character (*) following a word brings all subsequent letters (e.g. metric* will bring "metric" and "metrics").

First, the keywords related to the topic area, carbon emissions in transportation, were applied. Next, results were filtered based on the 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 the different definitions of literature reviews, as proposed by Verner et al. [38] and Thomé et al. [34], was applied to further filter the results. In all, 321 papers were retrieved from Scopus, and 244 were retrieved from WoS. After the 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—guidelines [39]. 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 [39]. Figure 4 presents a flow diagram of the studies selected and excluded from each level of this process.

The authors screened articles individually. After an initial round of screening, 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. After the screening, three hundred and twenty-four records were excluded, leaving eighty-seven papers for a full-text review.

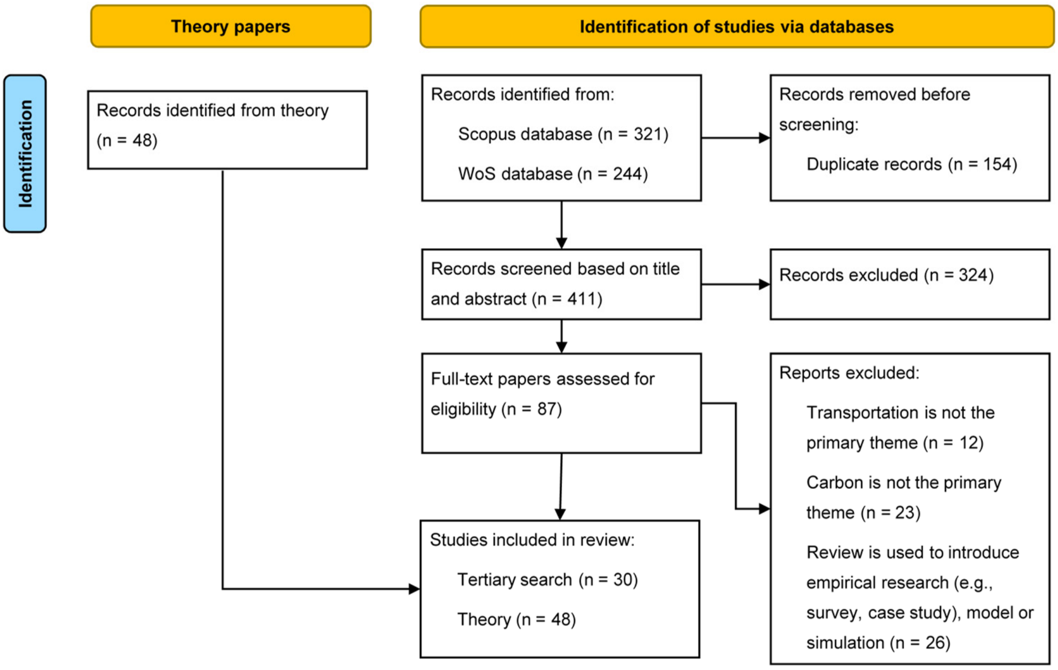

Figure 4. Flow diagram of the studies selected for the tertiary research, based on PRISMA [39].

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 and case study), model, or simulation. The third exclusion criterion followed Hedges and Cooper's [40] 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, 57 papers were excluded during this stage, yielding 30 papers for the tertiary research. This search was complemented by reference material for the theoretical basis of the SLR, resulting in an additional 48 theoretical papers on the MLP, contingency theory, and sustainability transitions. The search was updated on 15 May 2023.

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 [41] and complemented by quantitative co-word analyses. The inductive approach used the four steps proposed by Mayring [41]: (i) delimitation of the material (the selection process) and definition of the unit of analysis (the sustainability transition initiatives in transportation), (ii) background information on the material selected (descriptive bibliometric analysis), (iii) identification of the structural dimensions (analytical categories), and (iv) material evaluation leading to the description of the dimensions and its interrelationships (the framework offered in Section 4.6). In addition, a concept matrix [34] with the articles in lines and the dimensions in columns was formed and populated at this stage before drawing the framework. Finally, the co-occurrence of co-words was calculated and drawn using Bibliometrix [42], a software package programmed in R. According to Aria and Cuccurollo [42], "the aim of the co-word analysis is to map the conceptual structure of a framework using the word co-occurrences in a bibliographic collection". The co-word analysis is offered in Section 5 "Discussion".

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 this study's scope.

4. Results

This 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 summarising the main findings from the studies. The bibliometric review aims to identify the types of relevant work in the field and where they can be found. It is also meant to assist in refining the research questions and laying the ground for the identification of the dimensions of sustainability transition in transportation research. This is consistent with recommendations from Cooper [34].

4.1. Overview of Studies Selected for Tertiary Review

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

The 30 selected reviews in the Appendix A, combined, reviewed 3561 studies. Figure 5 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). The four papers from the 2023 update were excluded to avoid distorting the trend line with incomplete years. Out of the 30 selected reviews, 16 were published in the last three years, showing the growing relevance of the subject area. However, it is important to highlight that most of the research was conducted in the context of developed economies, with few studies addressing sustainability transition in transportation in emerging economies.

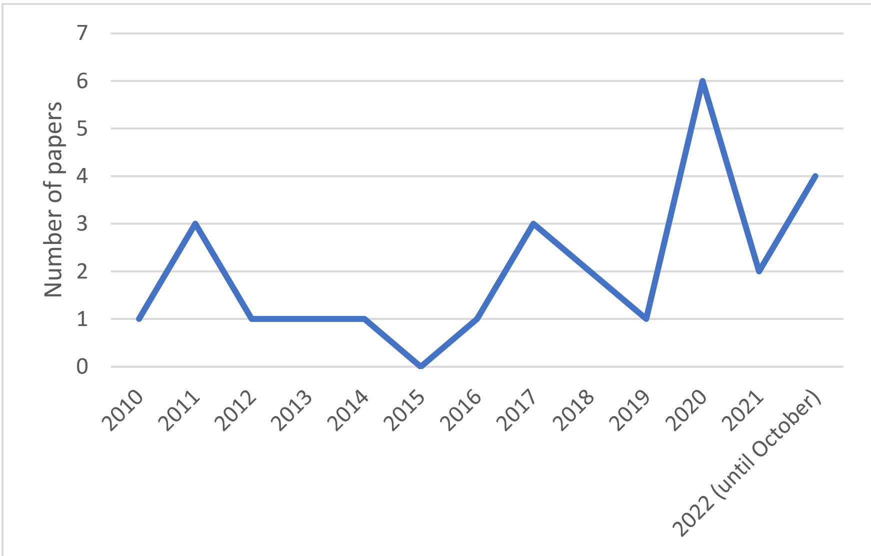

Figure 5. Number of studies selected for the tertiary review by publication date.

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 and Booth [35], as shown in Figure 5 and defined in Section 3 "Methodology".

Figure 6 displays the SLR methods. A systematic literature review was the most common methodology adopted [43–54], followed by narrative literature reviews [55–60], critical reviews [61–63], and, finally, meta-analyses [64,65] and state-of-the-art reviews [66,67]. 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.

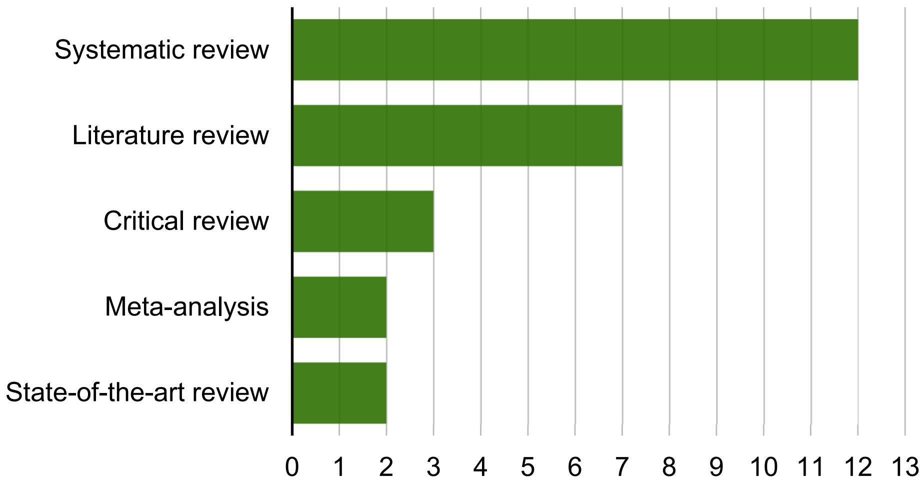

Figure 6. Methodology adopted in the reviews selected for the tertiary research.

Finally, Figure 7 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.

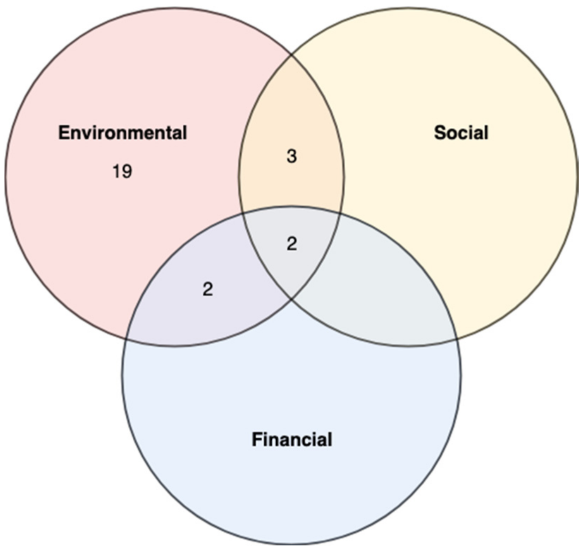

Figure 7. Sustainability dimensions included in the studies selected for the tertiary review.

4.2. Typology of Carbon Emissions Reduction in Transportation

Table 2 depicts a typology of carbon emissions reduction in transportation, composed 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 2. Typology of carbon emissions reduction in transportation.

Dimensions	Categories	Papers
Enablers and barriers	Technological innovations	[44,45,47,49–52,54,56,59,61–63,66]
	Operational measures	[44,45,49,52,54,59,62]
	Regulatory and economic measures	[45,52,55,58,59,61,67,68]
	Urban form and human behaviour	[46,51,53,61,63]
	Strategy and stakeholder pressure	[45,54]
Benefits and disadvantages	Climate change and other emissions	[43,47]
	Health	[43,47]
	Competitive advantage	[45]
	Cost impact	[45,68]
Metrics	Measurement and performance indicators	[43,45,49,57,60]
	Emissions modelling and inputs	[48,59,64–66]
	Life-cycle assessment	[45,49,56,60–62]

Sections 4.3–4.5 further detail the 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 the context. This is consistent with the context-dependent view of the theoretical lenses of CT [11].

4.3. Enablers and Barriers

This subsection explores the enablers and barriers to obtaining carbon emissions reduction, which are 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. [44] 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 using currently available technologies, such as hull design, economies of scale, reduced speed and fuel efficiency (e.g., biofuel, low-sulphur fuels, or natural gas), weather routing, and scheduling, could bring a reduction of 75% in carbon emissions in maritime freight transportation by 2050.

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 [63]. In a review of air transportation, Oguntona [59] finds that approaches linked to technological innovations have the highest long-term reduction potential in aircraft fleet emissions.

Electrification has proven to be a topic of great interest over the last few decades. Some studies compare the environmental impacts of diesel, hybrid, and electric vehicles [49,56]. For example, Hawkins et al. [56] 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-efficiency ICEVs regarding global warming potential [56]. This shows that EVs' environmental impact depends highly on the energy source mix used for charging. Garcia and Freire [62] 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 [62]. Behavioural aspects of the intention of using BEVs are equally important. Hoang et al. [69] review 45 studies on intention and behaviour using BEVs, concluding that most studies focus on intentions and fewer on actual behaviour. Moreover, most are perceptive measures rather than objective data on BEVs' adoption.

In the context of Nordic transportation, Salvucci et al. [63] 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. [63] 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 [61]. Li [61] also questions the sustainability of hydrogen energy since fossil fuels are still the primary source of hydrogen production in many countries.

Herold and Lee [45] identify speculations surrounding battery technology and energy source sustainability as major barriers to the adoption of electric vehicle technologies by top management in companies. Finally, Requia et al. [47] 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 CO_2 emissions [47].

While most studies recognise the mitigation potential of biofuels [44,59,62,63], it is also encountered with hesitation in developed and developing economies alike [44,61,63,66]. In a review of Nordic transportation, Salvucci et al. [63] observe considerable emissions reduction potential from adopting bioenergy. Nonetheless, they are sceptical about future scenarios that rely heavily on the importation of this energy source. As a global trend towards decarbonisation is observed, the bioenergy demand will likely grow, raising questions about its availability [63]. As an alternative, Salvucci et al. [63] recommend developing 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 [61] 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 [61].

In reviewing light-duty vehicle fleet emissions, Garcia and Freire [62] also find significant potential for reducing GHG emissions through biofuels. However, they classify this scenario as "optimistic" due to the studies reviewed not accounting for land use changes and biomass resource availability factors, thus suggesting that this initiative be combined with other mitigation measures, consistent with Bouman et al. [44].

In the maritime transportation scenario, Bouman et al. [44] review a series of CO_2 emissions reduction measures and identify the use of biofuels as the one with the largest potential. However, they point out that reduced CO_2 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 [44]. Bouman et al. [44] 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 [59] 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 and Freire [62] identify fuel consumption reduction as a fundamental approach to reducing light-duty vehicle fleet GHG emissions, particularly through weight reduction. They remark, however, that vehicle weight reduction should be coupled with other measures to reach its full potential.

Bouman et al. [44] find that improving a ship's hydrodynamic performance and minimising the water resistance by adjusting the hull's 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 [44]. Vidovic et al. [70] analyse five new technologies and their effects on decarbonising maritime transportation. They are alternative fuels, hybrid propulsion and hydrogen, digitalisation to increase vessel efficiency, hull drag reduction, and carbon capture and sequestration technologies. Regarding air transportation, Oguntona [59] explores next-generation aircraft models and retrofits to existing aircraft towards fuel efficiency. Finally, in a bibliometric review, Meyer [49] 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 [49,61,66]. 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. However, Meyer [49] calls for more real-world platooning applications to better understand this technology's impact. Faris et al. [66] 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 [66]. Faris et al. [66] find that ITS measures significantly impact vehicle emissions. However, since ITS commonly seeks to minimise transit times, emissions metrics are suboptimal, and, in many cases, the environmental impact might even be negative when the transit time increases. When optimising the transit time means opting for longer stop times or decreasing detour lengths, the optimisation will be environmentally beneficial. Nonetheless, the environmental impact will be suboptimal when the transit time optimisation suggests short stop times or longer detours [66]. Li [61] also briefly addresses ITS technologies, highlighting their potential to optimise traffic towards greater fluidity, thus reducing congestion, energy use, and GHG emissions.

From a comparative analysis of additive and conventional manufacturing, Pilz et al. [50] conclude that additive manufacturing reduces the distances and quantity of products transported, thus reducing energy consumption and CO_2 emissions. However, Pilz et al. [50] 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. Moreover, concerning technologies that indirectly impact transportation, Salvucci et al. [63] identify carbon capture and storage as a strategy.

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 [44]. However, as energy efficiency increases, some operational interventions will inevitably decrease their mitigation potential [62].

In the road freight transportation scenario, Meyer [49] identifies vehicle routing and the relationship between emissions reduction and cost as topics of great interest in academia. Miklautsch and Woschank [54] find that a significant emissions reduction can be obtained by shifting from road to rail transport. Local production, consolidation, container optimisation, shipping speed increases, pooling supply chains, truck sharing, carrier coordination, intermodal transportation, demand-side interventions, and vehicle selection are also identified as operational carbon mitigation measures [45,54,62].

In the air transportation scenario, Oguntona [59] 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. [44] 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 [61] 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 [61]. Herold and Lee [45] 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. [58] 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. [58] identify several MBMs for shipping in the literature that can be broken down into two main variants: fuel levies and emission trading systems (ETS). A 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 a sufficient incentive for companies to invest in sustainable technologies [58]. 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 for the importance of international ETSs in climate change mitigation, industry stakeholders raise concerns about regulation and administration's impact on competition and carbon leakage [58]. Schinas and Bergmann [68] review MBMs and emission trading systems (ETSs) in aviation and discuss how the lessons learned could be applied to the maritime sector. While they find that aviation research could largely assist the maritime industry, they identify that policy recommendations are still focused on single variables of ETSs and call for a more holistic understanding of ETSs' success.

O'Mahony [67] performed a state-of-the-art review of carbon taxes. While carbon taxes are commonly regarded as a leading solution to reduce emissions, O'Mahony's [67] findings show that carbon taxes are more effective as a support mechanism for other carbon reduction initiatives, rather than a standalone solution. Moreover, O'Mahony [67] identifies a gap in carbon tax implementation, mainly due to political and social barriers, which may be scaled down through more moderate taxes. Oguntona [59] identifies emissions trading, emission limit setting, fuel routes, and airport taxes as carbon mitigation measures in aircraft fleets. Camargo-Diaz et al. [71] review alternative economic incentives to decarbonise maritime and inland waterway transportation, classified into project financing, port tariffs, and onshore power service fees. Port tariffs are the most common incentive found in the review.

Carbon offsetting is the practice of paying third-party providers to generate GHG savings—through projects that either reduce or absorb CO_2—to compensate for emissions [55]. In a review of voluntary carbon offsets in tourism emissions reduction (i.e., non-mandatory carbon offsetting paid by the consumer), Eijgelaar [55] finds that this is not an efficient mitigation measure, currently compensating for less than 1% of all aviation emissions [55]. However, it is likely to remain a common practice due to the lack of awareness and pressure on the aviation and tourism industries to perform more structural changes [55]. Despite several tourism and aviation stakeholders agreeing that energy reduction should be the first-choice mitigation alternative, offsetting is still used to justify growth [55].

Alamoush et al. [52] 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 that these implementation schemes enable the employment of technical and operational measures to decarbonise ports and associated land transport and oceangoing vessels. Alamoush et al. [52] stress that, apart from regulations, 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

Regarding the urban dimension, Li [61] and Salvucci et al. [63] state that each urban area is particular in many ways, such as geography, demography, infrastructure, available resources, and socioeconomic characteristics, and, as a result, has specific transportation challenges. Therefore, modelling is only expected to treat it individually [63]. The urban form is decisive in shaping a city's energy consumption and the resulting GHG emissions [61]. Similarly, human behaviour and behavioural change policies also play a key role in shaping modal choices and the resulting CO_2 emissions in transportation [61,63]. However, as Salvucci et al. [63] pointed out, many energy–economy–environmental–engineering (E4) models still fail to consider this important dimension.

According to Li [61], 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 [61] predicts that metropolitan cities will be responsible for an increase in transportation energy demand in these economies. While transportation planning is often conducted independently of other urban services, Li [61] 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 [61]. Salvucci et al. [63] also observe that urban planning can significantly impact transportation and that varying granularity levels when assessing regions—evaluating the urban dimension and country dimension, for example—might provide valuable insights [63]. Wimbadi et al. [51] state that low-carbon mobility transitions are spatially constituted processes and identify cities as the birthplaces of testing and the subsequent implementation of urban decarbonisation experiments.

Salvucci et al. [63] identify income, GDP per capita, and fuel prices as determinants in modelling vehicle ownership and mileage. In addition, the travel time budget and transport infrastructure are key factors in shaping modal shifts [63]. If planned correctly, effective policies promoting modal shifts can reduce car ownership [63]. However, new mobility trends such as autonomous vehicles and mobility as a service (MaaS) have yet to be properly modelled regarding their impacts on car ownership, mileage, and congestion [63].

Another important aspect to consider in vehicle ownership is the phenomenon of urban sprawl. Li [61] 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 ownership. A similar trend can also be observed in developing countries in recent years [61]. Higher urban density, on the other hand, is associated with lower transportation-related emissions but with higher household energy demands [61]. In addition, in terms of urban density, Czepkiewicz et al. [46] find that people who reside in larger, denser, and more central neighbourhoods have a greater tendency to engage in long-distance leisure travel—particularly air and international travel—than people who live in suburban or rural areas. For example, Liu et al. [72] explore the effects of future climate uncertainties in the decision making in building retrofits in Hong Kong.

Li [61] also highlights the reinforcing loop dynamics between road infrastructure and car ownership. Road infrastructure is built in response to increased car ownership; better road infrastructure drives attractiveness in buying new vehicles [61]. In the case of developing economies, economic growth leading to greater per capita incomes will cause growing car ownership [61]. For Li [61], improving the quality and public perception and lowering public transportation costs and time are key to reducing private car ownership and the associated fuel consumption and carbon emissions.

Hu and Creutzig [53] performed a systematic review of 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 [53]. On the one hand, the flexibility of shared mobility can turn it into a major feeder of public transportation (thus supporting public transportation efforts) [53]. However, on the other hand, other characteristics (i.e., price, convenience, and quality) might lead to public transport's cannibalisation, causing a potential rebound effect on GHG emissions [53]. Hu and Creutzig [53] also draw attention to the association between shared mobility, digitalisation, and electrification, particularly in China.

4.3.5. Strategy and Stakeholder Pressure

Herold and Lee [45] 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 strategies and that improving sustainability performance can be key for differentiation. However, disclosure and communication with stakeholders are extremely important for carbon reduction to be a competitive advantage. Studies reviewed by Herold and Lee [45] also show that while stakeholder pressure is more powerful than governmental pressure, more is needed to motivate companies if carbon reduction is to align with a long-term strategy. Miklautsch and Woschank [54] also find that external pressure to reduce emissions has a weak impact on top management and that customer pressure needs to be more widely applied to the industrial sector.

Herold and Lee [45] also find that alignment between retailers and regulatory forces and the 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 usually questioned once their cost needs to be more meaningful to drive behavioural changes [45]. Finally, Herold and Lee [45] investigate carbon target setting and find that companies adopt many different carbon target-setting approaches and that, most of the time, targets are set at a corporate level, without a deeper understanding of reduction potential at an operational level. Moreover, regarding the relationship between emissions reduction and cost, Herold and Lee [45] identify that ambitious carbon reduction targets cannot be reached with limited investments.

4.4. Benefits and Disadvantages

Most studies focus 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 the 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 structural CT, takes for granted the outcomes of the landscape–mitigation fit [33].

While this review focuses on CO_2 emissions reduction, many carbon mitigation actions also reduce 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 [43]. Carbon monoxide, nitrogen oxides, sulphur dioxide (SO_2), and volatile organic components (VOC) are other air pollutants that might also be reduced through mass public transportation [43]. Electric vehicles, a technology commonly associated with GHG mitigation, may also exert a significant impact on gaseous pollutants—such as nitrogen oxides, VOC, and SO_2—and moderately reduce particulate matter emissions [47].

In a review focusing on EVs, Requia et al. [45] raise the debate on 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) [47]. Spatial distribution will be a key determinant of the health impact in these cases, reducing exposure in countries where most 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 [47]. Requia et al. [47] state that EVs must be coupled with clean energy sources to obtain a significant impact on health and emissions reduction.

In a review of ETSs in aviation, Schinas and Bergmann [68] 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. However, they also find that ETSs might lead to distorted competition between firms adhering and not adhering to the system, highlighting the importance of a universal approach to ETSs.

Herold and Lee [45] 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 activity [43].

Despite the advantages of decarbonising transport emissions, there are several impediments to the successful implementation of policies. Economic growth exerts pressure to increase transportation, raising barriers related to consumer choices of transportation modes and fairness [73]. Existing regulations, current infrastructure, and climate change also hinder the adaptation to mitigation policies [6]. Other factors delaying the sustainability transition in transportation are increased urbanisation and motorisation in emerging economies [59], poor public transportation, and a consumer preference for individual cars [43]. Furthermore, the continued future growth of maritime [44] and air transportation [55] poses an additional burden when decarbonising transportation, combined with the high costs and technological difficulties in developing renewable and non-fossil aviation and maritime fuels (e.g., hydrogen's costs) [1].

4.5. Metrics

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

Franco et al. [57] 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 condition techniques provide a more accurate reflection of reality but also have larger variability that must be considered. Noussan et al. [60] stress the importance of choosing the right emission factors and including variability when assessing the impact of mobility strategies for decarbonisation. Finally, Kwan and Hashim [43] highlight the importance of incorporating speed into emissions calculations since calculations based solely on distance might underestimate emissions—for example, by ignoring traffic congestion.

Herold and Lee [45] and Meyer [49] review several studies focusing on emissions quantification before and after implementing mitigation measures. Herold and Lee [45] also review studies investigating the trade-off between costs and emissions. Smit et al. [64] explore different types of traffic emission models and perform a meta-analysis of studies validating these. Finally, Oguntona [59] reviews nine approaches to modelling aircraft fleet development, comparing the long-term fleet-level emissions of different carbon mitigation measures.

When comparing different approaches to estimate transport's GHG emissions, Arioli et al. [48] find that most studies adopt a top-down approach (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 are 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 and Ciuffo [65] compare bottom-up and top-down methods in estimating air emissions from shipping. They remark on the high level of discrepancies in the 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 the results.

Faris et al. [66] 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 (i.e., bottom-up) and statistical (i.e., 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. [56] 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, responsible for 60–90% of the 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 [56].

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 [62]. With this in mind, Garcia and Freire [62] take the LCA further and adopt a fleet-based LCA capable of capturing these dynamics to review light-duty transportation. They find, however, that most of the reviewed studies fail to include the entire fleet life cycle, usually overlooking the production and disposal phases. Li [61] highlights the need for cost–benefit analyses using the LCA approach in urban transportation, as these allow for a holistic assessment of the costs incurred in private versus public transportation. Noussan et al. [60] 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. [60] point 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 and Lee [45] and Meyer [49] also review several studies incorporating LCAs. Noussan et al. [60] emphasise that the diversity of methodologies used to measure carbon emissions is a barrier in transportation because it neglects the interactions between transport modes and the emissions generated in other sectors, such as manufacturing, infrastructure construction and maintenance, the fuel supply chain, end-of-life emissions, and services required for the operation of transportation modes. For example, using fossil fuels to produce electricity for EVs is an important barrier to reducing emissions when only the tank-to-wheel emitted directly by the vehicle during its use is measured. The fact that LCA is not included in most research on emissions generated by transportation equally hinders comparisons between different transportation modes. The usefulness of the LCA approach in transportation could be further explored with methodologies applied to other sectors, such as Liu et al.'s [72] analysis of building retrofits in Hong Kong.

4.6. Synthesis Framework

Figure 8 populates the framework offered in Section 2.3 synthesising the results from the tertiary review and illustrating the interactions among the different key factors in carbon emissions reduction in transportation.

Focusing on the theme of carbon emission reductions in transportation, the first step in the framework's development was identifying 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 facilitating potential 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 that did not influence 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.

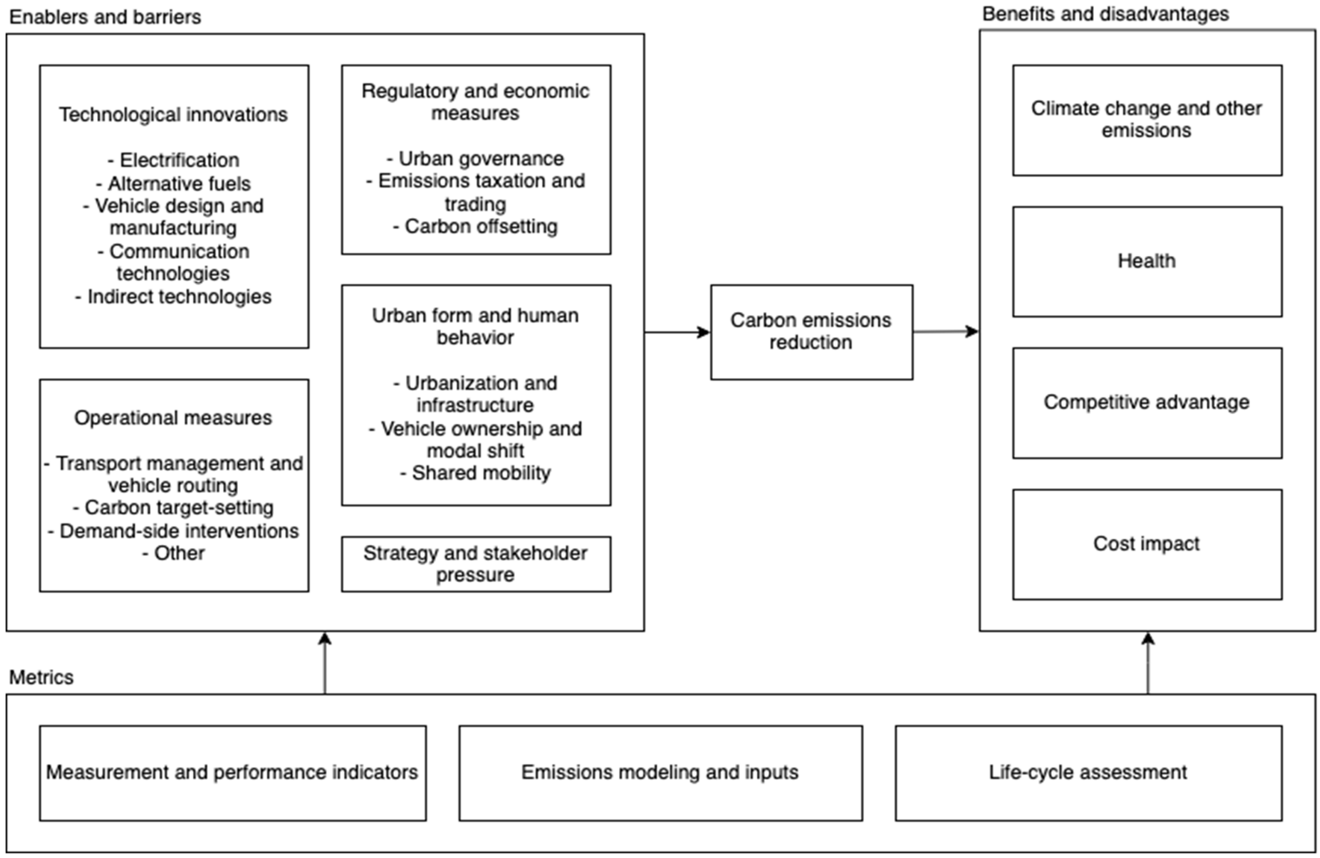

Figure 8. A synthesis framework for enablers, barriers, benefits, disadvantages, and metrics for carbon emissions reduction in transportation.

Figure 8 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

Viewed using the dual lenses of the MLP of socio-technical transitions and CT, the results outline the need to combine different approaches to policy mitigation in decarbonising the transportation sector. Regulations, technologies, consumer behaviour, and different stakeholders are at play in the transition. In addition, the need to contextualise mitigation policies according to the different transportation modes and countries is striking. It is worth noting that there is no "one-size-fits-all" policy or mitigation measure. It varies according to the contingencies of countries, innovation speed, technologies, and transportation modes.

The results also shed light on the difficulty of disentangling the benefits and disadvantages. Most outcomes could be seen as both a benefit and disadvantage and were not split into two separate groups. In answering RQ1, "what are the main barriers, enablers, benefits and disadvantages of carbon emission reduction in transportation?", the review identified a broad array of factors. Important technological innovations were reported in all transportation modes. However, there are challenges. For example, electric vehicles and the use of advanced biofuels in road, maritime, and aviation transport are still in their infancy, particularly in emerging economies. Moreover, the sector is capital-intensive, with costs, technologies, and business models locked in in the fossil fuel economy. The need for more advanced and less costly car battery cells and hydrogen-based transportation highlights two cases challenging innovation and technological development. However, overall, the technology appears as a necessary but insufficient condition for transitioning to a zero-emissions economy. Additionally, there are trade-offs among technologies. To point out only two elements of this quandary, there are trade-offs among sectors, with a need to balance, for example, biofuels, land use, and deforestation; the benefits and disadvantages of electric vehicles compared with the widespread use of biofuels are different in emerging and developed economies.

Operations in logistics seem more likely to produce immediate results when combined with new technologies. The review stresses the gains associated with platooning, ITS technologies, and vehicle selection and routing in freight transport. Early aircraft and ship retirement, associated with more efficient operations in navigation and landing in aviation, coupled with low maritime speeds, whether routing or scheduling, are also cases in point. The combined effect of technologies and operations can bring some benefits and disadvantages. Chiefly among them are reduced climate change and emissions, better public health, gains in competitive advantage for companies and their supply chains, and cost impact. Depending on contexts and timeframes, benefits can turn into disadvantages. For example, new technologies might reduce costs in the mid and long term but are more expensive than fossil fuel technologies in the near term.

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.

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?".

The proposed framework in Figure 8 partly answers RQ2, providing a static view of the relationships among the different dimensions of transport decarbonisation. Figure 9 depicts the relationships among carbon emissions dimensions in transportation. In addition, a dynamic view based on co-word analysis, depicted in Figure 9, shows another striking result: the unbalanced nature of the relationships among 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. Thicker edges mean more articles address both nodes.

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 only four papers analysed benefits and disadvantages. Most studies assumed that carbon emissions reductions are fundamentally beneficial and, as a result, failed to identify potential disadvantages or co-benefits. This finding is in line with one criticism of the multi-level perspective identified by Geels [10] (p. 189): "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 the systems logic of CT, however, it is possible to observe the importance of exploring the benefits and disadvantages of carbon emissions reduction initiatives. We observe that 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 that biofuels produce fewer tailpipe emissions than fossil fuels, their use might have backfiring effects depending on the context in which they are applied. While, in developing countries, biofuels might harm land use and food security, in developed countries, which rely on importations, energy security is the greatest risk. Moreover, the effects of different fuel technologies on city warming should be explored [74]. 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 mitigation strategies are only valid for some landscapes.

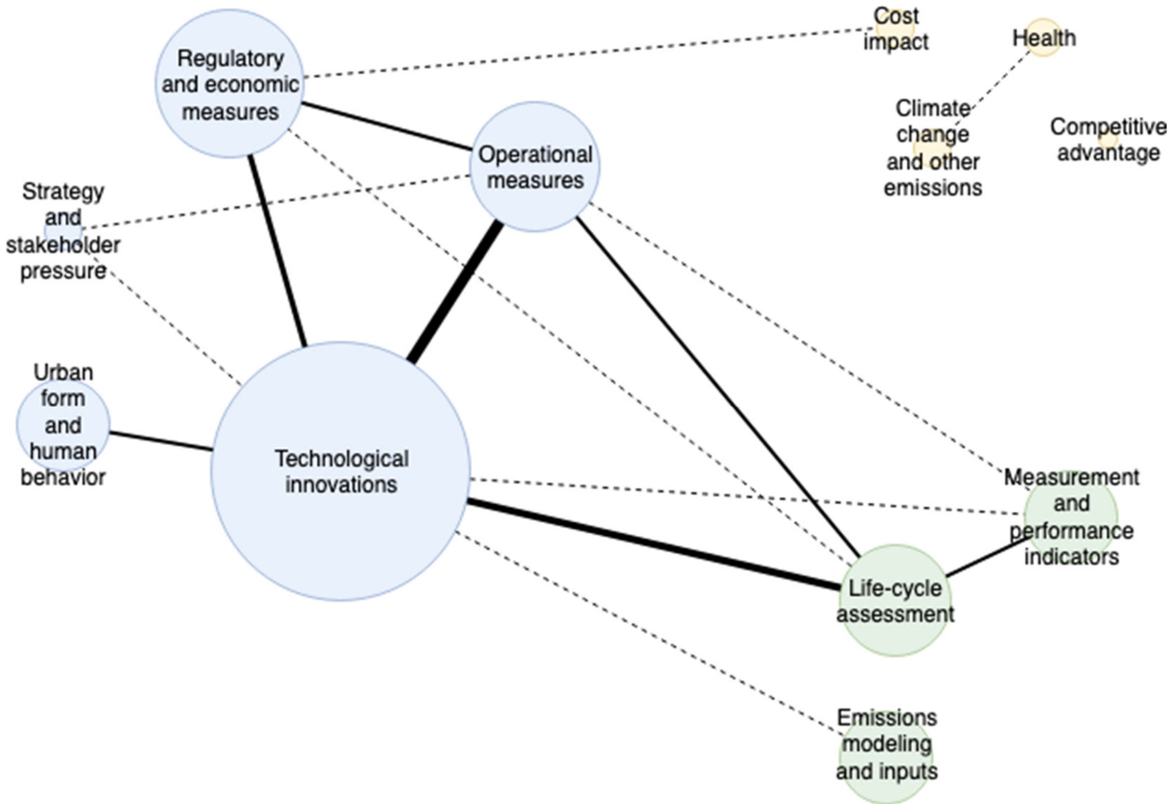

Figure 9. Relationships among enablers, barriers, benefits, disadvantages, and metrics in carbon emissions reduction.

Consistent with CT, Bouman et al. [44] also state that more than individual measures are needed to achieve significant GHG emissions mitigation. Regarding the fourth and last postulate of contingency theory (i.e., outcomes are measurables) applied to transportation carbon emissions, we see increasing interest from academia in measuring carbon emission reduction. Simulations of carbon emissions in inbound logistics operations and the use of alternative modes of transportation in emerging economies can be found, for example, in Muñoz-Villamizar et al. [75] for Mexico and the carbon emission impact of electric bike sharing in China [5]. However, the development of metrics to quantify outcomes other than emissions is still in its infancy.

The review also indicates that although all studies approached the environmental aspect of sustainability, the majority focused on this perspective only (see Appendix A). Few studies investigated sustainability's social or economic aspects or the triple bottom line. This lack of focus on outcomes is consistent with the MLP approach to socio-technical transitions. It indicates that we are at the beginning of a transition process, which could take decades to unfold completely. Currently, we observe multiple initiatives in transportation niches starting to enter the transportation regime. However, they still need more maturity to overcome the challenges and barriers and transform or replace existing regimes. Despite new initiatives focusing on reaching a carbonless energy matrix, the social and economic implications still need to be fully explored.

6. Conclusions

This study conducted a systematic literature review that selected and examined 30 review papers in the area of carbon emissions transportation, covering 3561 primary research papers. As a result, enablers, barriers, benefits, disadvantages, and metrics in carbon emissions reduction were identified, and a comprehensive framework was built. A dynamic view of the inter-relationships among different dimensions was also explored, providing indications for future research and theory building. Finally, the typology of carbon emissions reduction and the resulting synthesis framework provide a snapshot of the current dynamics of the social-technical transition in transportation.

There is progress reported in new technologies such as EVs and HVO, mainly in Europe and North America. Renewable fuels such as green hydrogen, ammonia, biomethane, natural gas, and synthetic methane are on the rise, but their pace of growth is lower than required to reach net zero by 2050 [25]. The 2021 updated NDCs could lead to global warming of 1.8 degrees Celsius by 2050 if implemented in full and on time, according to the most optimistic scenario [18]. However, the study also showed important technological and socio-technical gaps in carbon reduction in transportation. Advances in affordable new technologies, such as green hydrogen, are examples of technological gaps, particularly in maritime and air transportation. There is also a lack of new carbon transportation and capture technologies, which are required to expand alternative fuels such as synthetic methane and natural gas. The diversity of methodologies to measure carbon emissions and the different approaches for LCA hinder progress in reducing carbon emissions (i.e., measuring well-to-wheel versus tank-to-wheel emissions), making comparisons among emissions from different transport modes difficult. In addition, the concentration of studies measuring the direct emissions (from tank to wheel) fails to capture the interactions of carbon emissions from transportation with other sectors, such as transportation infrastructure, manufacturing, and buildings. This knowledge gap aggravates further the understanding of the unanticipated outcomes and impacts of the new technologies and policies for the reduction of carbon emissions. This review also shows the need to focus on the urban form and consumer behaviour. The preferences for the use of individual cars over shared mobility, public transportation, and less pollutant transport modes such as electric bikes still prevail, aggravated by urban mobility and the growth of urbanisation worldwide. It was also noted that the analysis of transportation emissions in emerging economies is less prevalent in the extant literature. This is noteworthy, chiefly because it is expected that with economic growth and more equitable access to the prevalent transport modes, developing countries' contributions to carbon emissions should rise. Practical implications from the review, limitations, and further directions for research can be found in this concluding section.

6.1. Practical Implications

This study combined the MLP of socio-technical transitions and CT for transportation carbon emissions. The result is a comprehensive overview of the current state of carbon emissions reduction initiatives in transportation, with a critical look at the outcomes from different environment–initiative relationships.

Identifying enablers, barriers, benefits, disadvantages, and metrics currently found in the literature provides practitioners with a better understanding of the current state-of-the-art in carbon reduction in the transportation sector, offering a "snapshot" of the current socio-technical transition state. In addition, the organisation of the dimensions of the carbonless transition in transportation into a typology and synthesis framework allows for 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 in different scenarios.

6.2. Study Limitations

This study has some limitations. They are mostly inherent to the research method. First, systematic literature reviews might result in different selections of papers due to the choice of keywords used for the search. The keywords chosen were apt to guide the research to address the research questions and objective of the paper. However, they were also a limitation because they restricted the research to one aspect of carbon emissions:

the analysis of the dimensions of enablers, barriers, metrics, and outcomes. Second, the bibliometric analysis was restricted by choice to the co-occurrence of keywords. This choice left important aspects of science mapping uncovered, such as the internationalisation of research networks, bibliographic coupling, and co-citation.

6.3. Future Research

There are four main directions for future research. First, the advantages and disadvantages of carbon emissions mitigation should be explored further, as most studies take the benefits for granted and need to analyse the trade-offs and the unanticipated results. Second, there is a need for more theory-based research on decarbonisation in transportation to guide empirical and analytical research in the field. Third, the research on carbon emissions in transportation and its mitigation should be investigated more in emerging and developing economies, where a rise in the use of traditional, fossil-fuel-based transportation might result from economic development, urbanisation, and more equitable access. Fourth, a complete bibliometric analysis of secondary sources on decarbonisation in transport could complement this research, partly addressing the limitations of the present study.

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

This study introduced the MLP of socio-technical transitions and CT as a backdrop to understanding carbon mitigation strategies in transportation. On the one hand, while socio-technical transitions provide a wider context for individual measures, they often focus on the transition itself and fail to capture the aftermath. On the other hand, the systems view of CT provides a more focused look at incorporating outcomes. The combination of both theories applied to sustainable transportation deserves further investigation.

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

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Appendix A

Table A1. 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. [64]	50	Meta-analysis	Road	Environmental [3]
Eijgelaar [55] [2]	80	Literature review	Air—Tourism	Environmental [3]
Li [61] [2]	98	Critical review	Multimodal—Urban	Environmental, social, and financial [3]
Miola and Ciuffo [65] [2]	49	Meta-analysis	Maritime	Environmental and social [3]
Hawkins et al. [56]	51	Literature review	Multimodal—Hybrid and electric vehicles	Environmental [3]
Franco et al. [57] [2]	190	Literature review	Road	Environmental [3]
Faris et al. [66] [2]	80	State-of-the-art review	Road—Intelligent Systems	Environmental [3]
Kwan and Hashim [43]	9	Systematic review	Multimodal—Mass public	Environmental and social [3]
Bouman et al. [44]	150	Systematic review	Maritime	Environmental [3]
Garcia and Freire [62]	69	Critical review	Road—Light-duty fleet vehicles	Environmental
Herold and Lee [45]	66	Systematic literature review	Multimodal—Logistics and freight	Environmental
Czepkiewicz et al. [46]	27	Systematic review	Multimodal—Long-distance leisure travel	Environmental [3]
Requia et al. [47]	65	Systematic review	Road—Electric mobility	Environmental and social
Salvucci et al. [63]	8	Critical review	Multimodal—European Nordic countries	Environmental [3]
Arioli et al. [48]	40	Systematic review	Multimodal—Urban	Environmental [3]
Lagouvardou et al. [58] [2]	78	Literature review	Maritime	Environmental
Meyer [49] [1]	715	Systematic quantitative review	Road freight	Environmental
O'Mahony [67] [2]	33	State-of-the-art review	Unspecified—Carbon taxes	Environmental and financial
Oguntona [59]	11	Literature review	Air	Environmental [3]
Pilz et al. [50]	18	Systematic review	Multimodal—Transport in manufacturing industry	Environmental
Schinas and Bergmann [68]	102	Integrative literature review	Multimodal—Aviation and maritime	Environmental and financial [3]
Wimbadi et al. [51]	41	Systematic literature review	Multimodal—Public transport	Environmental [3]
Alamoush et al. [52]	112	Systematic literature review	Multimodal—Marine ports (including land transport)	Environmental [3]
Hu and Creutzig [53]	687	Systematic review	Multimodal—Shared mobility	Environmental, social, and financial
Miklautsch and Woschank [54]	81	Systematic literature review	Multimodal—Freight	Environmental [3]
Noussan et al. [60] [2]	73	Literature review	Multimodal—Passenger transport	Environmental [3]
Hoang et al. [69]	45	Systematic Literature Review	Road	Environmental
de Abreu et al. [9] [1]	280	Systematic Literature Review	Road	Environmental
Camargo-Diaz et al. [71]	130	Literature Review	Maritime	Environmental
Vidovic et al. [70]	123	Literature Review	Maritime	Environmental

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

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