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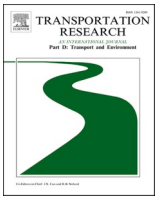

Missing the forest for the trees: what road freight decarbonisation research overlooks☆

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ABSTRACT

Decarbonising road freight transport is a critical priority for achieving global climate targets. This paper investigates how academic research conceptualises and addresses decarbonisation pathways in road freight transport. It applies a two-step literature review, combining aggregate and disaggregate search strategies, distinguishing between road freight transport and city logistics. Using the Avoid–Shift–Improve framework as an analytical benchmark, findings show that most studies focus on isolated technological solutions, while demand-reduction and modal-shift strategies receive comparatively less attention. Crucially, only a marginal subset of the literature explicitly adopts a structured, integrated, and multidimensional perspective; the majority conducts fragmented and narrowly scoped analyses, limiting the capacity to inform systemic and potentially effective policy strategies. This paper identifies this critical research gap and advocates for a paradigm shift in academic inquiry. Future studies should employ conceptual frameworks that capture the interdependencies among policy measures, thereby supporting the design and implementation of successful freight transport decarbonisation pathways.

1. Introduction

Freight transport accounts for about 30% of transport-related carbon emissions, resulting in 7% of worldwide global greenhouse gas (GHG) emissions (e.g., Miklautsch et al., 2022; Stojanović et al., 2021; Hammond et al., 2020). According to OECD-ITF (2020), global freight demand in 2050 will be three times higher than in 2015, with an estimated increase of its contribution to global emissions rising to 16%. Road freight generates 40% of global road transport emissions and represents the largest share of the total (e.g., de Saxe et al., 2023a,b; Teter et al., 2017).

Decarbonising road freight is a major challenge for logistics stakeholders. Achieving substantial carbon reductions requires coordinated efforts across the sector. Both private and public actors have access to a wide range of interventions to cut emissions from logistics operations. However, no single solution can deliver the scale of reductions needed on its own.

Conceptual frameworks help manage this complexity. They allow managers and policymakers to classify available options, build

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coherent strategies, and combine multiple decarbonisation levers. These frameworks support a structured and comprehensive approach, avoiding fragmented or isolated efforts. Briand et al. (2024) propose a pathway design framework integrating demand-side, modal, and technological levers for national freight decarbonisation. Similarly, Ghisolfi et al. (2022a) model freight decarbonisation using system dynamics across demand, mode, and fuel transitions, though they find that most studies remain narrowly scoped. McKinnon's five-lever "Green Logistics" is a prominent framework example (McKinnon, 2016; McKinnon, 2018), consisting of (1) reducing freight demand, (2) improving asset utilization, (3) shifting to lower-carbon modes, (4) improving energy efficiency, and (5) switching to low-carbon fuels. The ASIF framework (Schipper & Marie-Lilliu, 1999) suggests lowering overall transport *Activity*, shifting the *Structure* toward more sustainable modes, improving the *Intensity* by enhancing operational efficiency, and decreasing the carbon intensity of the *Fuel* used. Conceptually similar, the *Avoid–Shift–Improve* (ASI) framework (Dalkmann & Brannigan, 2007), though originally developed for passenger mobility and adopting a pragmatic perspective (Shah et al., 2021), has acquired increasing relevance for freight, especially among practitioners, since it provides a simple yet structured approach to emissions reduction. In particular, *Avoid* refers to reducing freight demand and trip length through measures like shipment consolidation, improved logistics planning, and empty-trip reduction; *Shift* promotes moving freight from road to low-carbon modes such as rail or inland waterways; and *Improve* focuses on cleaner technologies, including low-emission vehicles and alternative fuels (Koç et al., 2025; Pfoser, 2022; Turan et al., 2024). Recent scenario studies further demonstrate the need for coherent, system-wide strategies. Zhang and Hanaoka (2022), focusing on China, and Hoehne et al. (2023), concentrating on the United States, simulate long-term freight decarbonisation pathways. Both find that achieving substantial emissions reductions—up to 80% by 2050—requires combining rapid technological improvements (*Improve*) with demand reduction (*Avoid*) and modal shift (*Shift*).

Despite these valuable contributions, one might ask whether the prevailing literature often examines interventions in isolation rather than through a structured and integrated perspective that accounts for multiple dimensions and their interrelations. To investigate this possibility, one can consider the ASI framework as a useful benchmark for assessing the scope and comprehensiveness of the existing research panorama. In fact, the ASI framework has been widely applied, and given its straightforward three-dimensional structure, it offers a practical lens through which to identify systemic approaches in the literature. While it is by no means the only possible framework, it represents a suitable and transparent reference point for the purpose of our analysis.

The paper contributes to the literature by answering two main research questions:

RQ1: How comprehensively has academic research approached the development of decarbonisation strategies for road freight, in general, and city logistics, in particular?

RQ2: What research trends and policy measures are currently shaping the academic study of road freight decarbonisation?

These research questions are essential for a deep understanding of how decarbonisation strategies are conceptualized and investigated, assessing whether the scientific literature in this domain predominantly addresses stand-alone measures or acknowledges their limited effectiveness in isolation, thereby emphasizing the importance of synergetic approaches to meet long-term climate objectives. This allows the identification of potential research gaps that academia can fruitfully address. Moreover, they offer actionable insights for policymakers by identifying the most promising measures within an integrated conceptual framework aimed at freight decarbonisation.

The paper performs a systematic literature review. It employs a large and multidisciplinary database of peer-reviewed items published in scientific journals, enumerates the keywords used, specifies the timeframe of the papers analysed, states the inclusion/exclusion criteria adopted, and justifies all methodological choices taken. To enhance the search's completeness and better capture the conceptual alignment of freight decarbonisation research with ASI principles, research experts in the field provided a comprehensive list of keywords linked to all three ASI dimensions. The paper subsequently used these keywords for the final search.

The remainder of the paper is organized as follows. Section 2 illustrates the literature review methodology. Section 3 outlines the results of the bibliographic search, with a focus on road freight and city logistics. Section 4 identifies the dominant trends in the research literature on freight transport decarbonisation. Section 5 discusses findings, while section 6 concludes the paper.

2. Methodology

This paper adopts a two-step procedure with the aim of investigating both road freight and city logistic decarbonisation strategies, as Fig. 1 illustrates. Although "road freight" encompasses both long-haul and short-haul transportation, city logistics deserves an ad-hoc investigation due to its specific relevance and to examine whether urban and non-urban freight follow distinct decarbonisation pathways. Although urban freight covers far fewer kilometres than extra-urban transport, and heavy-duty trucks used for long-distance haulage consume more energy than the vans typically used in city logistics, the impact of the latter remains considerable because their operations take place in close proximity to large numbers of people.

The systematic literature search begins with the identification of keywords, which are then combined into search strings. The search uses the Scopus database and matches terms in article title, abstract, or keywords. After defining the general theme-related keywords, namely "road freight", on the one hand, and "city logistics" OR "urban freight" OR "urban logistics" OR "last mile logistics", on the other, the paper performs an aggregate and a disaggregate investigation.

The first step (aggregate) uses the search string "decarbon*"[1] OR "low carbon" OR "zero carbon" OR "carbon neutral", since decarbonisation is the most used and inclusive keyword reflecting the process/strategies to cut CO2 emissions, followed by low carbon

[1] The asterisk (*) acts as a truncation symbol to include words with common root and different stems: decarbonise-ze, decarbonisation-zation and decarbonising-zing.

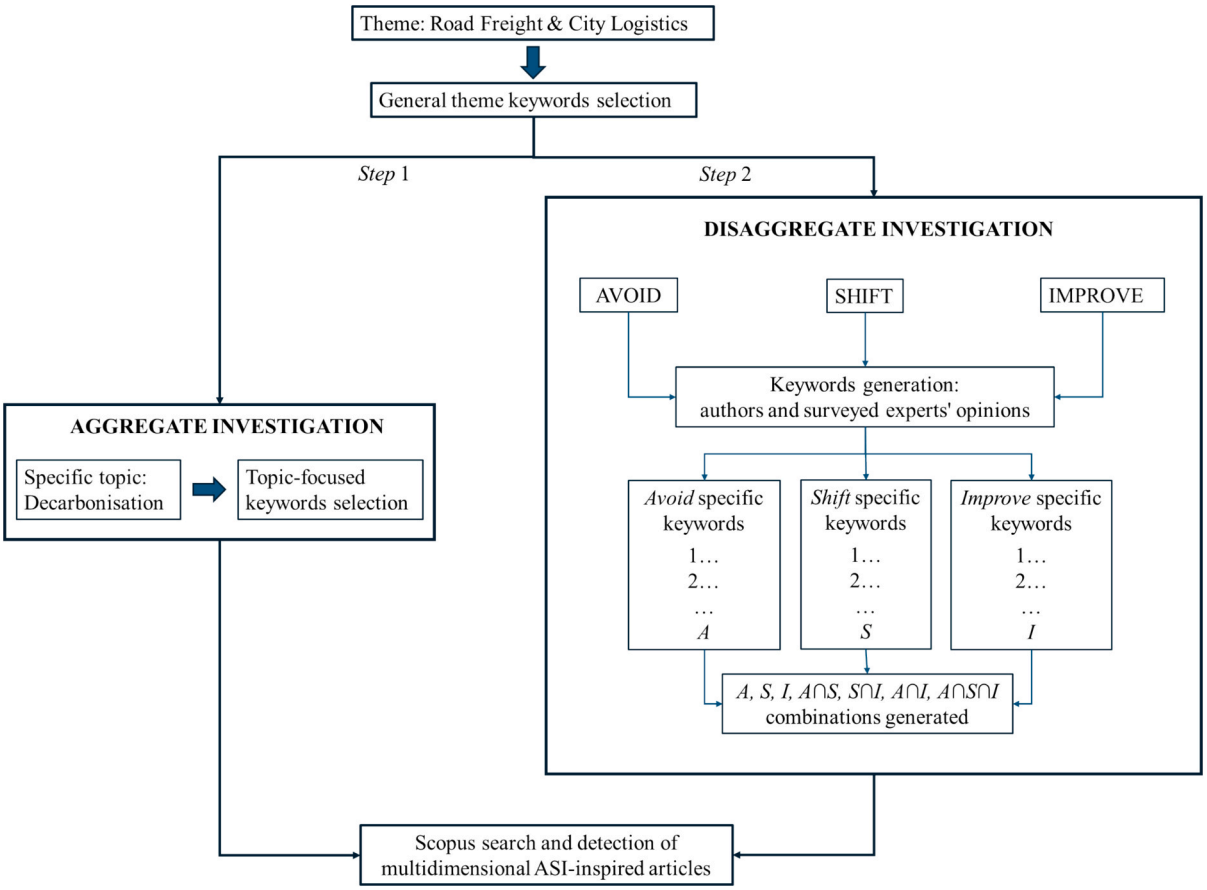

Fig. 1. Search methodology.

(Wimbadi & Djalante, 2020). After obtaining the article corpus, one can search for multidimensional ASI-inspired items.

Since not all articles *implicitly* dealing with road freight or city logistics decarbonisation *explicitly* mention "decarbonisation" or equivalent words in article title, abstract or keywords, the second step (disaggregate) unpacks the search into single ASI-related keywords and their combinations. The keyword list for each component is based on an initial proposal by the Authors, further validated by expert opinions. In more detail, this process relies upon specific suggestions arising from an ad-hoc selected group of freight transport worldwide experts. A total of 53 people involved as contributors to the "Handbook on City Logistics and Urban Freight" (Marcucci et al., 2023a) was asked to validate and integrate an initial list of 30 keywords *via* a concise web-based questionnaire. This process resulted in the substitution of two original keywords and the addition of thirteen more to the initial list, helping to ensure comprehensive coverage of relevant strategies and avoid potential blind spots. The identified keywords (see Table 1) were combined to construct targeted search queries.

Adopting this two-step method, the review captures both the explicit and implicit ways the literature addresses freight transport decarbonisation with a multidimensional vision, while maintaining a clear analytical distinction between long-haul and urban freight contexts.

3. Results

This section aims to summarise the existing scientific literature on the subject in response to RQ1. In particular, it outlines the results of two potentially complementary searches: road freight (3.1) and urban logistics (3.2) decarbonisation.

3.1. Decarbonising road freight

The search produced 142 items, with 106 articles, 22 conference papers, 4 book chapters and 10 reviews (editorials, notes, *errata*,

Table 1
ASI-related keywords.

AVOID	SHIFT	IMPROVE
CIRCULAR ECONOMY	CARGO *CYCLE	ALTERNATIVE FUEL*
or	*or*	*or*
CONSOLIDATION	CARGO BIKE	BIODIESEL
or	*or*	*or*
DECOUPLING	CONTAINER	BIOFUEL
or	*or*	*or*
DEMAND MANAGEMENT	CROWD SOURCED	CATENARY
or	*or*	*or*
DEMAND REDUCTION	CROWDSHIPPING	ECO-DRIVE
or	*or*	*or*
HIGH PRODUCTIVITY	DRONE	E-FUEL
or	*or*	*or*
LAND USE PLANNING	INTERMODAL*	E-HIGHWAY
or	*or*	*or*
LOAD FACTOR	MICROMOBILITY	ELECTR*
or	*or*	*or*
OFF HOUR DELIVER*	MODE CHOICE	GREEN VEHICLE
or	*or*	*or*
OMNI CHANNEL	PUBLIC TRANSPORT*	HYDROGEN
or	*or*	*or*
OPTIMIZATION	RICKSHAW	TRUCK PLATOONING
or	*or*	
PARCEL LOCKER	ROAD TO MARITIME	
or	*or*	
ROUTING	ROAD TO RAIL	
or	*or*	
SHARING ECONOMY	ROAD TO WATER	
	or	
	ROBOT	
	or	
	SHORT SEA SHIPPING	

conference reviews, and articles not in English were not considered).[2] Fig. 2 shows the publication trend until the search date. It illustrates the increasing attention paid in the literature to road freight decarbonisation over time, with a marked increase in recent years.

The 10 review papers concentrate on the market adoption of different fuels and powertrains (Kluschke et al., 2019), use of biofuels in diesel engines (de Oliveira Gonçalves et al., 2025; Fernández-Rodríguez et al., 2021; Palander et al., 2018) and e-fuel production (João Roberto et al., 2025), electrification of long-haul freight transportation (Jha et al., 2023) shift from road to rail (Kaack et al., 2018), adoption of fuel cell powertrains for heavy-duty vehicles (Pardhi et al., 2022), role of packaging fill rate in vehicle utilisation efficiency (Ahmad et al., 2022). The review form Koç et al. (2025) focuses on planning model or decarbonizing road freight transportation, covering operational, tactical, and strategic advances. Finally, the quantitative review on road freight decarbonisation by Meyer (2020), not classified as a "review" in Scopus, relies on bibliometric and network analysis techniques to categorise the literature in three groups: technological innovation, last mile optimisation, economic measures.

Most of the papers solely address the impact of technological improvements, a finding that aligns with Meyer (2020), who similarly observed that road freight decarbonisation is often approached through technological innovations, including communication technologies, alternative fuels, and high-capacity vehicles. This emphasis reflects a tendency to prioritise technological solutions over measures aimed at reducing demand and fostering shifts to less energy intensive modes, while opportunities related to *Avoid* and *Shift* strategies are recognised, they remain comparatively understudied in this body of literature. Within the specific context of studies explicitly addressing road freight decarbonisation, technological solutions dominate with the ASI framework seldom used.

Across the 142 papers reviewed, 13 (around 9%) explicitly address road freight decarbonisation through a multidimensional perspective aligned with the Avoid–Shift–Improve (ASI) framework. In these studies, ASI is not always formalised as a modelling tool or used to quantify the combined effects of its three pillars; instead, it functions as a conceptual and strategic structure guiding the design of integrated decarbonisation pathways. What unites them is the recognition that emission reductions require simultaneous action on travel activity, modal structure, and vehicle technology.

Some of these papers adopt an analytical or modelling perspective, using ASI to structure quantitative scenarios or decision frameworks. Zhang et al. (2022), Kany et al. (2022), and Mulholland et al. (2018) apply the three-pillar approach to assess national or regional freight systems, showing that combining demand management (Avoid), modal reallocation (Shift), and technological improvement (Improve) can deliver more effective outcomes than focusing on any single measure. More recent contributions such as

[2] Please keep in mind, here as in the remainder of the paper, that this classification is the one Scopus provides. Therefore, it may happen that an article contains a literature review, but is not defined as a 'review' in Scopus.

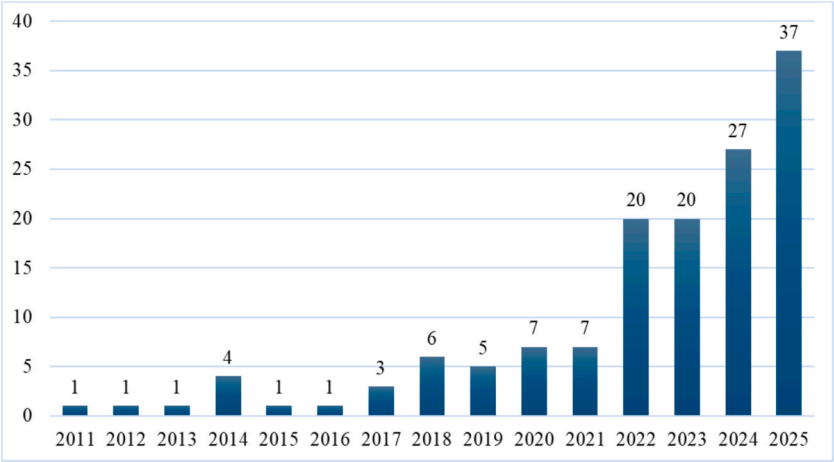

Fig. 2. Publication trend until 23 September 2025.

Henke et al. (2024), Briand et al. (2024), and Gao et al. (2024) follow a similar logic: they develop models and policy frameworks that integrate logistics efficiency, multimodality, and low-emission technologies under a common strategic framework. In these works, ASI serves as a reference structure for system-level transition analysis, even when its components are explored through different quantitative or qualitative methods.

Other studies interpret ASI from a strategic and governance-oriented perspective, focusing on how institutional coordination and policy design can operationalise multidimensional transitions. Churchman et al. (2025) present two complementary approaches: one centred on "decision pathways" that align technical, infrastructural, and regulatory choices, and another that develops a governance framework to enable purposive, incremental transition processes. Van Geelen et al. (2025) adopt a similar systemic lens, describing decarbonisation as the joint deployment of measures across the three ASI levers. Liu et al. (2025) and Nnene et al. (2025) extend the approach to regional and national contexts, analysing how the interaction of logistics optimisation, modal restructuring, and technological innovation can drive long-term carbon neutrality. Picone et al. (2025) apply ASI as an analytical taxonomy in a systematic review of emission assessment methods, identifying the imbalance of current research toward Improve strategies and calling for more integrated ASI-based approaches.

One could, in principle, group other articles into a broader set of multidimensional approaches, as they refer to or analyse measures that touch on more than one ASI component. However, according to the methodology this review adopts, it would not be appropriate to include them in the ASI-based subset. These studies do not structure their analysis around a multidimensional framework, nor do they aim to define national or regional decarbonisation pathways using ASI as a guiding tool. Instead, they pursue other research goals, such as behavioural analysis, expert forecasting, or thematic classification, without adopting an integrated approach to decarbonisation. Although they may reference measures that fall under *Avoid*, *Shift*, or *Improve*, these are treated in a fragmented way, without articulating how such measures interact or contribute collectively to a systemic transition. For this reason, these studies are placed in the broader A + S + I set, which includes works that refer to measures from across the ASI dimensions, but lack the intentionality, coherence, or integrative perspective that characterises an ASI-guided approach (Fig. 3).

In more detail, Wu et al. (2022) analyse the link between freight operators' low-carbon behaviour and regional GDP, implicitly addressing Avoid and Improve dynamics, but focus on socio-economic correlations rather than on how such measures interact. Liimatainen et al. (2014, 2015) and Liimatainen (2021) discuss logistics optimisation, fuel efficiency, and modal shift within Delphi surveys, touching all ASI dimensions, yet their results remain thematic and expert-based, not structured around an integrated decarbonisation logic. Churchman & Longhurst (2022) and Churchman et al. (2023) examine decarbonisation options through stakeholder perspectives and socio-technical classifications that overlap with ASI categories, but their aim is to understand governance processes rather than operationalise the framework. Finally, Falanga et al. (2025) maps EU directives and regulations linked to Avoid, Shift, and Improve measures, but its approach is descriptive and regulatory, discussing the coexistence of instruments rather than their coordinated or interactive effects.

Out of the 142 articles initially identified through the aggregate approach, 8 were excluded from further analysis because it was not possible to assign any of them to an ASI category, since they do not focus on the impact of decarbonisation measures to develop medium/long-term emissions reduction strategies for the road freight sector.

The documents retrieved with the aggregate approach can be grouped into overlapping sets representing the three ASI framework dimensions (Fig. 3).

To analyse the degree of multidimensionality in the literature, the documents retrieved through the disaggregated keyword search according to the ASI framework have been classified in a seven-class typology based on the presence of one (A, S, I), two (AS, AI, SI), or all three (ASI) dimensions (Table 2).

Among these, the ASI category – i.e., papers addressing all three components – represents a well-defined subset that can be identified with certainty via a dedicated query, and was therefore taken as a fixed starting point. Conversely, partial combinations (AS,

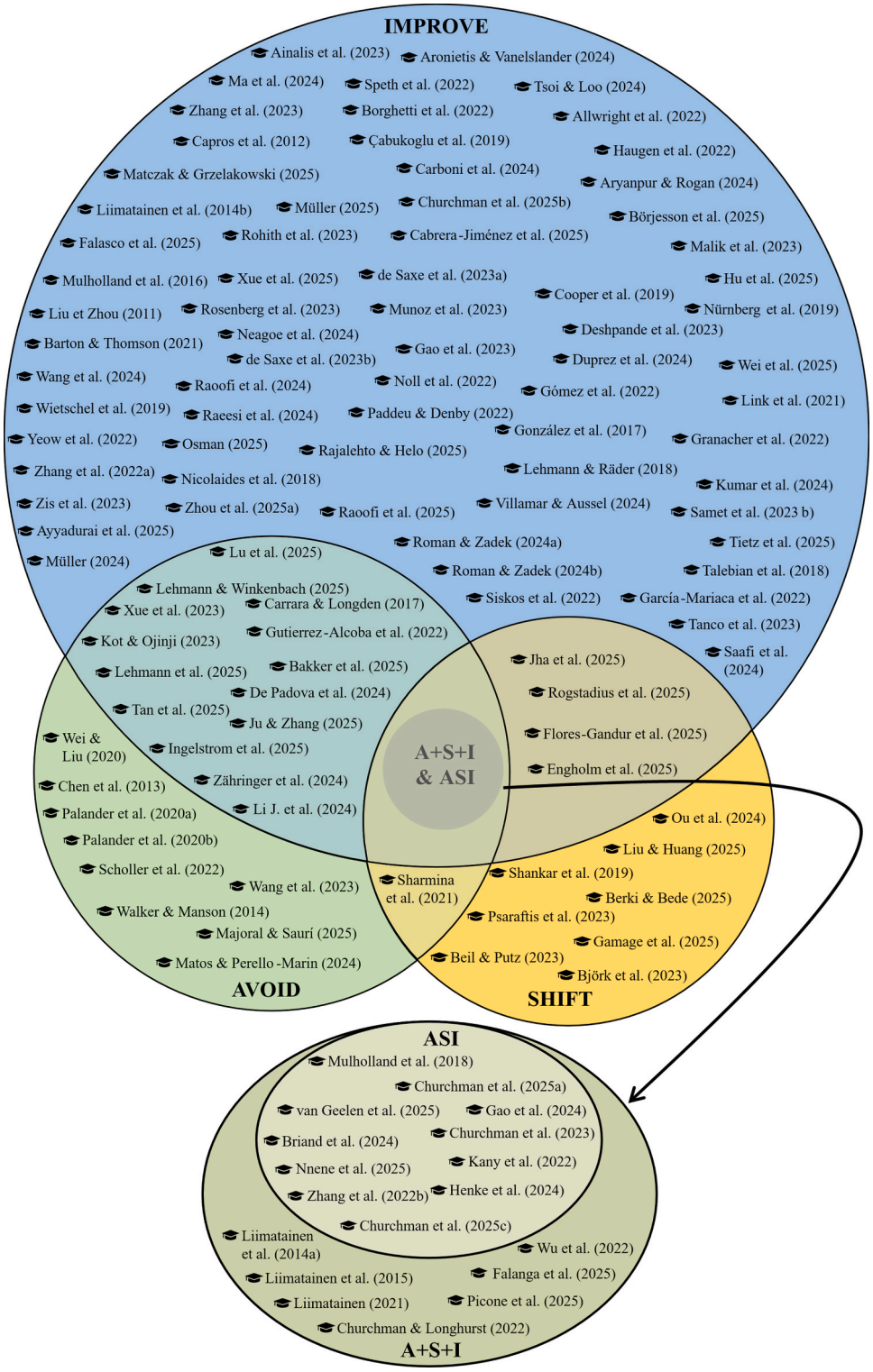

Fig. 3. Papers on road freight decarbonisation by ASI categories (articles cited in figure are listed in Appendix A).

Table 2
Scopus disaggregate search results for *road freight*.

	Papers	Reviews	Conference Papers	Book chapters	TOTAL
A (Avoid)	108	7	38	12	165
S (Shift)	63	3	28	5	99
I (Improve)	144	12	56	12	224
A I	33	3	13	2	51
A S	11	0	8	2	21
S I	11	2	2	1	16
A S I	0	1	0	0	1
TOTAL	370	28	145	34	577

AI, SI) may include overlapping papers also counted under ASI. To isolate the exclusive contribution of each two-dimensional class, we applied the following correction:

- $AS = AS_{total} - ASI$
- $AI = AI_{total} - ASI$
- $SI = SI_{total} - ASI$

where each X_{total} refers to the number of documents retrieved from Scopus for that specific combination of dimensions, without excluding potential overlaps with other subsets.

Once these values were obtained, the exclusive single-dimension subsets (A, S, I) were computed by subtracting all overlapping components involving that dimension, as follows:

- $A = A_{total} - AS - AI - ASI$
- $S = S_{total} - AS - SI - ASI$
- $I = I_{total} - AI - SI - ASI$

This approach ensures that each document is counted only once in the corresponding cell of Table 2, allowing a consistent estimation of the number of studies falling into each distinct level of ASI multidimensionality

The single-dimension search including title, abstract and keywords in Scopus yielded 165 papers for Avoid, 99 for Shift, and 224 for Improve. These results are reported in Table 2.

When combining the various components, one discovers that only a few items involve two dimensions and only the review by Rahman et al. (2025) the whole set, thus confirming the limited adoption of a structured and integrated approach in road freight decarbonisation by academic research. The review by Rahman et al. (2025) uses optimization methods and Industry 4.0 technologies

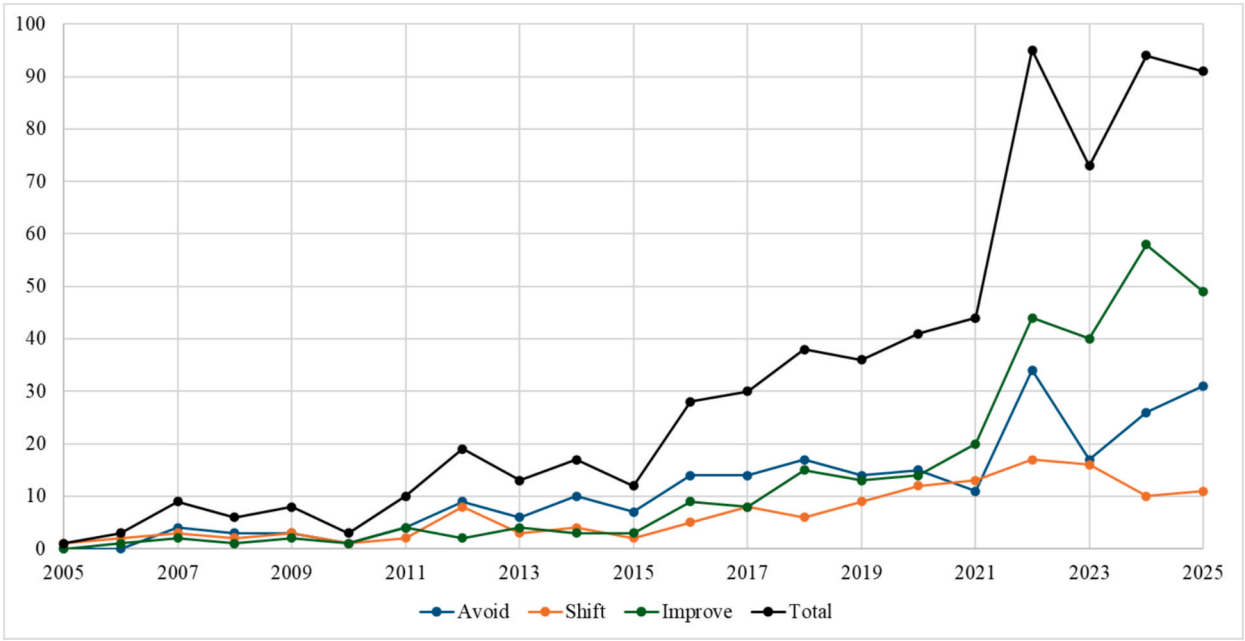

Fig. 4. Publication trend in road freight over the period 2005 – September 2025 by single ASI category.

as two applied perspectives to analyse how each has contributed to the different environmental, social, and economic sustainability factors in road freight transport. In contrast, our study moves beyond this technological and methodological focus by examining how the broader academic literature conceptualizes and integrates decarbonisation pathways, highlighting the lack of systemic, multidimensional approaches that connect diverse policy and operational levers within a coherent framework (ASI).

Fig. 4 illustrates the publication trends for each group since 2005, which is considered "year zero" by a revision of the Effort-Sharing Regulation that set a 40% reduction in GHG emissions by 2030 compared to 2005 for non-ETS sectors (European Parliament, 2023).

Fig. 5. Papers on urban freight decarbonisation by ASI categories (articles cited in figure are listed in Appendix B).

All the three categories are gaining momentum over the last few years – in particular after 2015 – one might conjecture as a consequence of the Paris Agreement on climate change (adopted on December 12th 2015 and entering into force on November 4th 2016). However, in 2023 there is an overall 26% decrease in papers published compared to 2022 (only the papers on the *Shift* dimension remains constant).

3.2. Decarbonising urban freight

The aggregate search generated 85 items including 53 articles, 21 conference papers, 8 book chapters, and 3 reviews published since 2014 (year of publication of the first contribution of the identified list) until the search date (September 2025).

Research articles addressing urban freight decarbonisation through the reduction of trips and vehicle kilometres travelled (Avoid) mainly focus on optimisation-based approaches that enhance the spatial and operational efficiency of delivery networks. The most common topics include multi-objective routing, facility location, vehicle scheduling, and load consolidation to minimise distances and improve network performance. Further contributions explore demand management and parcel allocation, the design of consolidation centres and micro-depots, and the integration of logistics into urban planning to reduce redundant movements and improve accessibility. Overall, Avoid studies adopt quantitative and modelling-oriented methods aimed at rationalising logistics operations, prioritising efficiency and spatial optimisation rather than broader systemic or behavioural shifts in freight demand.

In the Improve category, electrification continues to dominate as the central pathway toward low-carbon urban logistics. The literature concentrates on battery-electric vehicles, charging infrastructure optimisation, and the financial and environmental evaluation of clean vehicle adoption. Complementary topics include hydrogen and renewable energy applications, pricing and incentive mechanisms to promote low-emission fleets, and the effects of digitalisation on carbon efficiency. Common methodological approaches combine techno-economic analysis with optimisation and simulation models, focusing on improving vehicle performance and reducing well-to-wheel emissions while maintaining existing logistics structures.

The Shift dimension is represented by studies that explore modal and operational transitions in last-mile distribution. Most research focuses on the use of cargo bikes, e-cargo tricycles, and underground freight systems as alternatives to conventional road-based deliveries. These contributions examine performance, energy savings, and service quality under different urban configurations, frequently highlighting the need for supporting infrastructure, regulation, and land-use integration. While these approaches demonstrate potential for significant emission reductions, they remain context-specific and often framed as pilot-scale or scenario-based interventions rather than systemic modal transformations.

Ten papers adopt a bidimensional perspective, addressing two ASI levers in combination. Avoid + Improve is the most frequent pairing, where routing optimisation and low-emission vehicles are integrated to enhance both system efficiency and technological performance—these studies often apply AI-based scheduling or energy-aware routing models that minimise travel while improving fleet energy use. Shift + Improve combinations examine the complementarity between new transport modes (such as cargo bikes or underground logistics) and clean vehicle technologies, linking modal reallocation with electrification or renewable energy integration. Avoid + Shift approaches are fewer and typically explore how digital tools and land-use planning can simultaneously reduce delivery distances and promote alternative modes—for example, through the coordination of logistics hubs, digital twins, or physical internet concepts. Despite their methodological variety, these contributions share an emerging attention to multidimensionality, though they usually retain a technical rather than systemic focus.

A broader group of eleven papers can instead be classified as A + S + I, encompassing both previously reviewed and recent studies. These include Aditjandra, 2018, Campisi et al. (2022a,b), Demir et al. (2022), Kijewska & Iwan (2018), Melkonyan-Gottschalk & Palmié (2023), Tavasszy (2021), Yang & Gao (2015), Yang et al. (2016), as well as the more recent contributions by Pana Tronca & Rotaris (2024, 2025), Shardeo & Sarkar (2025), and Paddeu et al. (2024). All these works consider multiple ASI dimensions—addressing demand, modal, and technological measures—but treat them descriptively or in parallel, without formalising ASI as an analytical or operational framework. For instance, policy-oriented papers examine carbon pricing, regulatory coordination, or stakeholder engagement across different levers, while governance studies emphasise institutional capacity and multi-actor cooperation for urban freight decarbonisation. However, the three dimensions are discussed as interdependent themes rather than components of an integrated decarbonisation model. A total of 9 out of the 85 articles were out of topic, since no decarbonization actions or strategies were included or addressed.

The documents retrieved in the aggregate procedure can be grouped into overlapping sets representing the three ASI framework dimensions (Fig. 5).

Table 3
Scopus disaggregate search results for *urban freight*.

	Papers	Reviews	Conference Papers	Book chapters	TOTAL
A (Avoid)	715	27	410	62	**1214**
S (Shift)	155	6	93	25	**279**
I (Improve)	175	6	93	27	**301**
A I	181	3	76	11	**271**
A S	147	3	63	16	**229**
S I	52	7	27	8	**94**
A S I	52	4	16	13	**85**
TOTAL	**1477**	**56**	**778**	**162**	**2473**

The single-dimension search including title, abstract and keywords in Scopus yielded 1214 papers for *Avoid* (Operations Research studies are dominant in this case), 279 for *Shift*, and 301 for *Improve*. When combining the keywords, such that at least one keyword for each group (see Table 1) is contained within the title, abstract or keywords, 85 papers emerge: 52 articles, 4 reviews, 16 conference papers, 13 book chapters. Table 3 summarizes the results, while the publication trend over time is shown in Fig. 6.

None of them presents a multidimensional analysis to draw pathways for urban freight decarbonisation. The article by Andruetto et al. (2023), for instance, adopts a three-dimensional combination of keywords in urban freight, but it categorises the impacts of electrification, consolidation, cargo bikes, and automation in terms of key performance indicators (KPIs) only. The review paper by Cano et al. (2022) identifies the main topics and research trends related to sustainable logistics for e-commerce; it is not surprising that the article's abstract contains keywords that recall a multidimensional analysis, without addressing decarbonization scenarios. Finally, the three-volume book by Awasthi (2019) addresses key challenges in different fields in the area of sustainable city logistics planning. Even if the Authors analyse a variety of aspects that may cover the full ASI spectrum, the study does not focus on the adoption of an integrated strategy to decarbonize last mile logistics.

The research effort suggests that even though one can retrieve several studies by unpacking the ASI groups into the single keywords (see Table 1), few adopt a truly multidimensional approach. This finding is particularly significant suggesting that most studies are not primarily decarbonisation-focused, but rather innovation-driven, with technological or operational innovations occasionally addressing one or two ASI strategies without explicitly pursuing comprehensive emissions reduction objectives.

4. Research areas/trends on policy measures aimed at decarbonising road freight

This section overviews existing GHG reduction strategies emerging from the road freight sector literature analysis, to address RQ2. Table 4 summarizes the most relevant interventions conceived to foster a low-carbon transition. For each measure, the paper reports a selection of relevant, yet not exhaustive, references, barriers and opportunities for its development, and the most suitable application context.

The *Avoid* domain plays an important role, the greatest in last mile logistics decarbonisation research, according to vehicle routing studies that are frequently applied in the urban freight context. Reducing freight transport demand is also relevant and influenced by a variety of elements such as population growth, disposable income, GDP growth, and product prices, to name just the most relevant. The latter also incorporates transport costs, which can be affected by policy measures to ensure external cost internalization. If additional costs are transferred to the final consumers according to the user-pays principle, the impact on demand will depend on each product's price elasticity. Moreover, the internalization of external road freight costs could represent a key driver to promote the shift from road to rail and water, given the alteration of relative mode prices it generates. On the other hand, Ghisolfi et al. (2022b) observe that even if the sharing and circular economy concepts have yet to reach their maturity, they represent possible ways of decoupling GDP from freight transport demand.

Studies on electrification and low-carbon fuels are prominent in road freight research, and the measures they typically imply can be included in the *Improve* category. Nicolaides et al. (2017) indicate that electric trucks, including hybrid and fuel cell technologies, overhead catenary and inductive power transfer system are most promising to reduce road freight sector emissions. Although

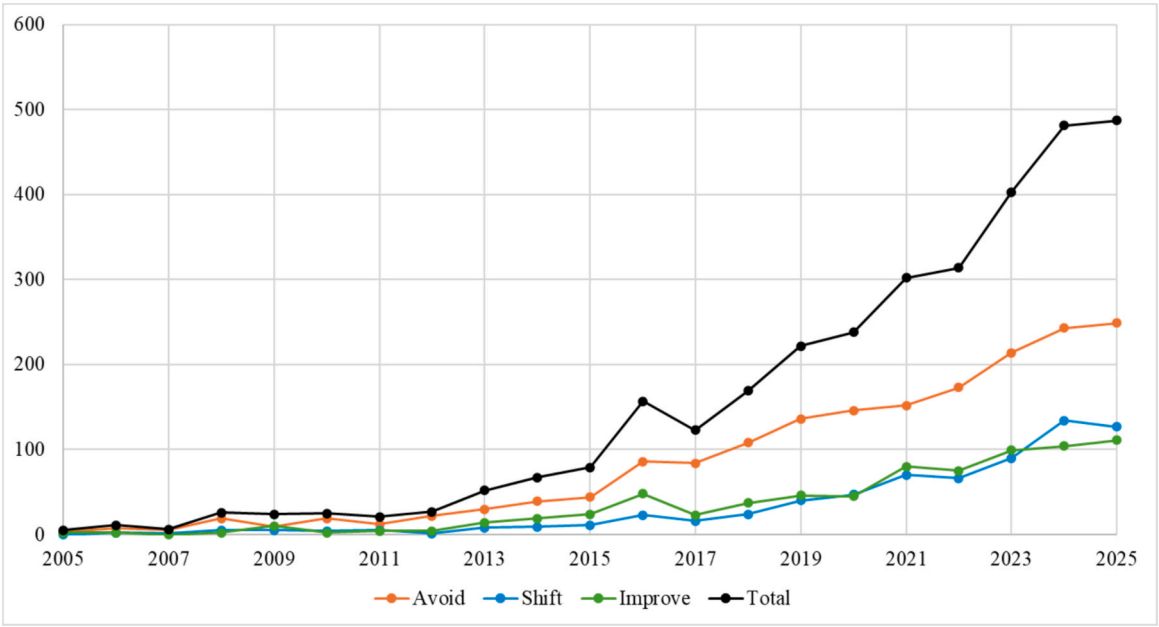

Fig. 6. Publication trend in last mile logistics over the period 2005 – September 2025 by single ASI category.

Table 4
Measures to reduce emissions from road freight.

Dimension	Intervention	Main references	Barriers	Opportunities	Application
Avoid	Optimization of vehicles use (routing, load factor)	Rizet et al. (2012); Ni & Wang (2021); Hao et al., 2025; Wei and Liu, 2020	Restricted transport flexibility; higher delivery time	Less drivers and vehicles required (less congestion)	Long-haul logistics and urban freight
Avoid	Off-hour/Off-peak deliver	Holguín-Veras et al., 2018; Kim et al., 2025; Sánchez-Díaz et al., 2017	Regulatory restrictions (i.e. noise disturbances in residential areas); retailers acceptance	Reduced traffic congestion; increased operational efficiency (travel time and unloading parking availability)	Urban freight
Avoid	Demand reduction (decoupling, circularity, land-use)	Wiedenhofer et al. (2020); Ghisolfi et al., 2024; Holguin-Veras et al., 2021	Consumer behaviour and awareness; complexity in supply chain adaptation	Resource efficiency and cost savings; extended product life cycles	Long-haul logistics and urban freight
Avoid/ Shift	Crowdshipping	Gajda et al., 2025; Gatta et al., 2018; Pourrahmani and Jaller, 2021; Punel et al., 2018	Incentives for general public engagement; reliance on occasional drivers/riders; trust, safety, and privacy concerns	High emission reduction potential (if performed with green modes); less traffic congestion	Urban freight
Avoid/ Shift	Robot and drone-assisted delivery	Cha et al., 2022; Choi et al., 2025; Kellermann et al., 2020; Plank et al., 2022; Rejeb et al., 2021	Organizational, safety-related, and regulatory issues	Route optimization and less kilometres travelled in urban environment	Urban freight
Shift	Shift from road to rail or maritime transport	Elbert and Seikowsky, 2017; Kaack et al., 2018; Takman and Gonzalez-Aregall, 2024; Yin et al., 2021	Transshipment costs; increased number of involved actors; complex coordination; longer travel time (without shuttle trains); Restricted transport flexibility	High emissions reduction potential; good reliability, punctuality and planning capability due to (train) schedule; less traffic congestion	Long-haul logistics and Urban freight
Improve	Full electrification (battery electric propulsion)	Bakker et al., 2025; Çabukoglu et al., 2018; Liimatainen et al., 2019; Nykvist and Olsson, 2021	Costs for fleet renewal; additional electric energy; insufficient battery range for long distances; investments for network of fast-charging stations	High emissions reduction potential	Heavy/light-duty vehicles. Better suited for LCV
Improve	Eco-drive	Ayyildiz et al., 2017; Gong et al., 2025; Pinchasik et al., 2021	Costs for drivers training; couriers and road users acceptance; limited emissions reduction potential (if performed with diesel-fuelled trucks)	No additional requirements for vehicles and infrastructure	Heavy/light-duty vehicles in highway context
Improve	Biofuels	Cabrera-Jimenez et al., 2025; Cao et al., 2020; Fernández-Rodríguez et al., 2021; Na et al., 2015	Currently more expensive than diesel; large amount of glycerine produced	Compatible with diesel engines, as well as blended (no additional costs for fleet renewal)	Heavy/light-duty vehicles. Better suited for HCV
Improve	E-highway (dynamic conductive charging with catenary systems)	Mareev and Sauer, 2018; Scherrer et al., 2020; Schöpp et al., 2024; Wietschel et al., 2019	High infrastructure investments; highway capacity reduction (dedicated lanes for trucks); costs for fleet renewal	High emissions reduction potential	Heavy-duty vehicles in highway context
Improve	Dynamic inductive charging	Abuajwa et al., 2025; Danese et al., 2021; Agostino et al., 2022	High infrastructure investments; costs for fleet renewal	High emissions reduction potential; also usable by passenger cars	Heavy/light-duty vehicles in highway context

electrification plays the lion's role within road freight decarbonisation literature, González Palencia et al. (2020) assert that even assuming higher penetration rates of all-electric vehicles, GHG emissions reduction will not be sufficient to achieve the ambitious targets energy transition policies pursue. They conclude that electrification alone is not sufficient to reach net zero emission targets by 2050, suggesting, once again, the need to foresee complementary measures to powertrain electrification within road freight decarbonisation pathways. However, more recent system-level analyses by Raoofi et al. (2024, 2025), offer a more dynamic and comprehensive perspective, highlighting how adoption patterns, charging infrastructure development, and policy interventions can significantly alter the potential for freight electrification to meet climate targets. Other technological advancements falling within the *Improve* category are catenary systems and truck platooning. The former can be operated with battery trolley trucks that are charged when connected to the overhead lines, and with diesel-hybrid trolley trucks, operating in electric mode on catenary equipped highways and in diesel mode on all other roads. A significant GHG emissions reduction could be obtained were electricity generated via renewable sources (Wietschel et al., 2019). However, financial issues associated with infrastructure equipment and acceptance barriers due to the involvement of multiple stakeholders (policy makers, truck producer and truck shipping companies) have yet to be overcome.

Modal *Shift* from road to rail or maritime is increasingly recognized as a key measure for decarbonising freight transport systems and alleviating congestion. Studies suggest that fostering such interventions requires coordinated accompanying measures, such as targeted subsidies to bridge cost gaps, infrastructure and service improvements to enhance reliability, and behavioural interventions to

address cognitive barriers in logistics decision-making (Yin, 2022; Kaack et al., 2018). Crowdshipping, literally implying shipping goods via the crowd (Marcucci et al., 2017a), can be also considered as a *Shift* measure. Passengers can act as couriers and perform deliveries either via non-dedicated or dedicated trips. A particularly sustainable form of this service is the public transport-based crowdshipping, also known as "green crowdshipping" (Gatta et al., 2017; 2018). While better suited for city logistics, a recent work by Akbar et al. (2024) proposes an adaptation of such a service for interurban freight transport.

5. Discussion

This study reveals a substantial gap in the current academic landscape surrounding the decarbonisation of freight transport, particularly concerning the adoption of integrated and systemic conceptual frameworks. While the academic community has widely acknowledged the urgency of reducing GHG emissions from the freight sector, our findings highlight a predominant tendency to address the challenge through fragmented and narrowly focused analyses.

The literature review shows that most studies concentrate on individual technological interventions (*Improve*), with significantly less attention devoted to demand-reduction strategies (*Avoid*) and modal shifts (*Shift*). More importantly, there is a marked lack of integrated approaches: only three articles dealing with road freight, in general, and one with city logistics, in particular, explicitly adopt a conceptual framework that jointly addresses all three ASI pillars. Recent work has begun to address this limitation. Churchman et al. (2025), for example, emphasise the need for decision sequencing and system-level coordination in road freight decarbonisation. Their approach, based on systems thinking and participatory modelling, highlights the interdependencies between technical, institutional, and governance factors, align with the findings of this review and reinforce the need for a structured framework that supports analysis across multiple dimensions of transition.

The limited use of structured and multidimensional perspectives stands in contrast with the inherent complexity of the freight system, where multiple factors interact and influence each other dynamically. A plausible explanation for this shortfall lies in the prevailing academic practice of dissecting problems into narrow, isolated questions. While this method allows for analytical precision and tractability, it also reinforces disciplinary silos, discourages systemic thinking, and overlooks interdependencies among measures thus providing an incomplete and potentially biased overall picture. Scholars often focus on specific technologies, behavioural aspects, or policy instruments without situating these within broader, integrative frameworks. As a consequence, research offers fragmented insights, reducing its capacity to inform actionable and synergistic decarbonisation strategies.

The limited number of papers adopting an integrated approach thus becomes not only a diagnosis of the literature's fragmentation but also a benchmark against which the contribution of this study should be assessed.

To advance effectively, future research must consequently transition to new paradigms. Academic inquiry into freight decarbonisation must evolve toward the design and evaluation of integrated strategies, capable of reflecting the interrelations between policy levers, technologies, behavioural patterns, and operational dynamics. Specifically, if the aim is to assess the impacts of decarbonisation strategies and to foster their deployment, researchers must adopt conceptual frameworks that simultaneously capture the effects of different, yet intertwined, interventions.

Interestingly, the potential for a more integrated research paradigm appears particularly promising in the field of city logistics, reflecting the complex and policy-intensive nature of urban freight systems, where spatial constraints, stakeholder diversity, and technological experimentation converge. As such, city logistics could serve as an incubator for more sophisticated and multidimensional analytical approaches, which could then be extended to the broader road freight domain.

Research trends suggest an over-reliance on technological aspects as opposed to behavioural ones, recognising that adoption dynamics, as also highlighted by Raoofi et al. (2024), are crucial, and that achieving a widespread cultural shift among stakeholders often requires significantly longer timeframes than the deployment of new technologies alone (Sunio et al., 2022). This is especially true in the light of the daunting challenges cities face today, particularly in terms of energy consumption and environmental impact, mainly consisting of the enormous increase in traffic flows linked to e-commerce and, more recently, due to the pandemic aftermath, to e-grocery (Aziz et al., 2022). This is also due to the huge difficulty of including all stakeholders in urban logistic planning decision-making processes (Marcucci et al., 2021; 2017b), even when adopting the most advanced methods to ensure their acceptability (Marcucci et al., 2023b; Le Pira et al., 2017;) and participation (Maltese et al., 2023; Gatta et al., 2017). Furthermore, actions inducing demand reduction are under-researched while they play a complementary role to technology improvements in modelling decarbonisation pathways (Sharmina et al., 2021; Kaack et al., 2018).

Unlike passenger transport, freight transport lacks a direct behavioural/organisational counterpart to measures such as teleworking. While actions such as taxation, awareness campaigns, or innovations in delivery models (e.g., home delivery or public transport-based crowdshipping using non-dedicated trips) may reduce vehicle-kilometres travelled by improving the efficiency with which existing demand is served, they do not diminish the underlying need for goods movement.

It is important to note that the paper focuses exclusively on studies explicitly framing their contribution in relation to decarbonisation goals, whereas other research streams (e.g., modal shift) do not necessarily adopt a decarbonisation-oriented vocabulary. This may represent a limitation when identifying research trends. However, what is crucial is not the individual measures themselves, but the adoption of an integrated approach within a comprehensive low-carbon transition framework. This recommendation should not be interpreted as a call to universalise ASI. This framework is just one among several useful tools that can guide multidimensional research. Other approaches can equally offer valid conceptual scaffolds, provided they encourage the comprehensive consideration of multiple interacting decarbonisation levers.

To sum up, this study calls for a deliberate shift in the academic approach to freight decarbonisation, from a fragmented to an integrated mindset. By embedding transport policy analyses within coherent conceptual frameworks, future research can better inform

effective and context-sensitive decarbonisation pathways, ultimately accelerating the transition to sustainable freight systems.

6. Conclusions

This paper provides a comprehensive review of the academic literature on road freight and city logistics decarbonisation, focusing on the extent to which existing research adopts integrated and multidimensional approaches (RQ1) and mapping the most relevant types of measures and policy trends (RQ2).

This study offers a complementary perspective compared to previous literature reviews, focusing not only on the thematic content of freight decarbonisation research but also on the multidimensionality of strategic approaches. For example, Meyer (2020) employs bibliometric methods to map thematic clusters in the field, identifying concentrations around vehicle technology, last-mile logistics, and economic instruments. However, such analyses primarily describe *what* is being studied rather than *how* coherently these elements integrate within broader decarbonisation strategies.

Using the ASI framework as a reference lens, the paper identifies conceptual coverage of its core components, both individually and in combination. The analysis reveals a predominant tendency toward fragmented investigations, with most studies focusing on isolated technological solutions, overlooking measure interconnections and failing to conceive them within a broad conceptual framework. Possible extensions of our study include using alternative frameworks for analysis and expanding the evidence base to include policy documents, industry reports, and other forms of grey literature.

Despite the growing recognition of freight transport's critical role in climate change mitigation, our findings underscore that only a marginal portion of academic contributions adopt a truly systemic and structured approach. Notably, only three publications explicitly frame their decarbonisation analysis within an integrated conceptual framework. This reflects a broader epistemological gap: current research remains largely shaped by siloed investigations into policy interventions, failing to fully address the complex nature of freight systems and the required synergies among decarbonisation measures within an integrated perspective.

This gap presents a twofold opportunity. First, it marks a significant limitation in the current state of knowledge that risks impairing policy relevance and implementation feasibility. Second, it positions this paper as an original and distinctive contribution, not only in mapping the field's limitations but also in proposing a concrete shift in how freight decarbonisation research is conducted.

To move forward, scholars are encouraged to adopt integrative frameworks that can capture the dynamic interplay of interventions. Research should aim to simultaneously address all major decarbonisation dimensions, examining how measures such as demand reduction, modal shift, and technological upgrades interact and co-evolve in real-world contexts. The transition to sustainable freight systems will require more than incremental innovation. It demands a conceptual reorientation in academic inquiry, recognising the multifaceted nature of decarbonisation to produce insights capable of informing robust, synergistic, and context-sensitive policy design. This study hopes to contribute meaningfully to that shift, inviting future research to move beyond isolated perspectives and toward a more comprehensive, system-aware understanding of the role freight transport plays in the low-carbon transition.

CRediT authorship contribution statement

Sergio Maria Patella: Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization. **Filippo Carrese:** Writing – review & editing, Writing – original draft, Visualization, Resources, Investigation, Data curation. **Ila Maltese:** Writing – review & editing, Writing – original draft, Resources, Methodology, Investigation. **Valerio Gatta:** Writing – review & editing, Writing – original draft, Methodology, Investigation. **Edoardo Marcucci:** Writing – review & editing, Writing – original draft, Supervision, Methodology.

Declaration of competing interest

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

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.trd.2025.105207.

Data availability

Data will be made available on request.

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