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Decarbonizing Transport Systems: Freight and Logistic Policy Pathways toward the EU "Fit for 55"

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ABSTRACT

Logistics and freight transport play a critical role in national economies but also represent one of the most challenging sectors to decarbonization, due to its operational complexity, fragmented structure, and strong dependence on fossil fuels. In Italy, despite progressive technological improvements, greenhouse gas (GHG) emissions from road freight remain significantly above the reduction trajectory required by the European Union's Fit for 55 targets. This paper investigates how logistics and operational strategies, framed within the Avoid–Shift–Improve (ASI) approach, can contribute to the decarbonization of the Italian road freight sector by 2030. A bottom-up analytical methodology is adopted to estimate current (2023) road freight mobility demand associated with the Tank-to-Wheel (TTW) emissions, disaggregated by vehicle class, Euro emission standard and road type. Starting from this baseline, a set of policy-driven scenarios is developed, including a Business-As-Usual and an optimistic ASI-oriented scenario, and an additional Logistics Rationalization Scenario (LRS) based on freight transport optimization and network restructuring measures. The Avoid dimension is explored through logistics optimization measures, such as load consolidation, reduction of empty trips, and efficiency improvements in last-mile distribution. The Shift dimension evaluates the impact of modal reallocation from road to rail and intermodal solutions for long-distance freight flows. The Improve dimension focuses on fleet renewal, electrification, diffusion of hydrogen trucks, and the adoption of low-carbon fuels such as HVO and biomethane. Results show that even under optimistic assumptions, technology alone is insufficient to meet EU climate objectives without significant logistics restructuring. The proposed LRS provides an additional contribution towards closing the remaining emission gap through freight consolidation, network optimization and reduction of empty trips. The paper concludes by discussing managerial and policy implications for logistics operators and decision-makers, emphasizing the need for coordinated operational and regulatory interventions to support the transition towards low-carbon freight systems. The paper also highlights the relevance of road network resilience assessment with particular reference to bridge infrastructure vulnerability and proactive risk management as a complementary infrastructure-side dimension of freight decarbonization strategies.

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Introduction

Road freight transport represents a critical backbone of modern logistics systems, enabling the functioning of national and international supply chains through the movement of raw materials, semi-finished goods, and final products. However, its central role in logistics operations is also associated with significant environmental externalities. In Europe, the transport sector accounts for approximately one quarter of total greenhouse gas (GHG) emissions, with road freight being one of the most carbon-intensive components due to its operational characteristics, energy intensity, and dependence on fossil fuels [1,2].

From a logistics and operations management perspective, road freight transport is a complex socio-technical system. It involves highly fragmented actors, tight delivery schedules, just-in-time production models, increasing demand volatility, and growing pressure to reduce costs while improving service performance. These structural features make road freight a "hard-to-abate" sector: interventions aimed solely at improving vehicle technology are often insufficient if not accompanied by changes in logistics organization, routing choices, modal allocation and network design [3-6].

The strategic relevance and decarbonization challenges of road freight have increasingly attracted attention at the international level. Several countries, including Japan, the United States, China and Australia, have recently introduced national strategies to accelerate the transition of freight transport, combining technological innovation with logistics restructuring [7-10]. In parallel, the European Union has set sector-specific climate objectives within the Green Deal and the Fit for 55 package, reinforcing the need to curb freight-related emissions [11,12]. This growing policy interest is accompanied by an expanding scientific literature emphasizing that effective decarbonization requires integrated approaches addressing both technological improvements and operational transformations across supply chains [13].

In Italy, road transport dominates freight movements, accounting for more than 85% of total inland freight volumes. Despite progressive improvements in vehicle efficiency and emission standards, national GHG emissions from the freight sector have not decreased at a pace consistent with the European Union's decarbonization goals [14]. This resistance to change is not only technological but also operational: many logistics chains are optimized for speed and flexibility rather than for environmental performance, and modal alternatives such as rail freight are still structurally underutilized. Furthermore, the physical condition and resilience of the road network infrastructure itself represents an often-overlooked dimension of freight decarbonization. In Italy, the exceptionally high density of bridges relative to national geographic extension a consequence of the country's complex orographic and morphological characteristics makes the transport network particularly vulnerable to structural degradation. Most Italian bridges were built between the 1950s and 1960s using design standards now considered obsolete, particularly with respect to seismic actions, and many are approaching the end of their design life. Any reduction in bridge performance due to deterioration or damage can generate significant disruptions to freight flows, forcing inefficient rerouting, increasing vehicle-kilometres and, consequently, raising GHG emissions. The resilience assessment of existing road networks must therefore be considered an integral dimension of sustainable freight transport planning.

Against this background, decarbonizing freight transport requires not only cleaner vehicles but also a transformation of logistics strategies and operational practices. This transition involves redesigning supply chain configurations, improving freight consolidation, reducing empty runs, enhancing intermodal integration and rethinking delivery patterns [15-18]. In this regard, the Avoid–Shift–Improve (ASI) framework represents a useful operational lens to address decarbonization from a logistics management perspective [19-21].

An additional but equally relevant dimension of this challenge concerns the structural resilience of the road transport network itself. Bridges, tunnels and other critical infrastructural elements constitute the physical backbone through which freight flows are routed; any impairment of their performance has direct consequences on the efficiency and carbon intensity of logistics operations. This connection between infrastructure resilience and decarbonization has gained increasing policy attention in Italy, where initiatives such as the DATAGRAM project a Decision Support System for "DATA and strateGies for Resilience AssessMent" are developing multidisciplinary methodologies to assess and manage road network resilience through the integration of structural engineering, transportation engineering and Geographic Information System (GIS) databases. By coupling resilience-based risk management with proactive maintenance planning, such approaches can help prevent the network disruptions that generate detours, increase vehicle-kilometres and, ultimately, undermine the decarbonization targets addressed in this paper. Incorporating resilience assessment into freight transport planning therefore represents a complementary, infrastructure-side lever to the demand-side and technology-side strategies examined within the ASI framework.

Within the ASI paradigm, avoid strategies target the reduction of unnecessary transport demand through better logistics planning, digitalization, and load optimization. Shift strategies support the transfer of freight flows towards more sustainable transport modes and intermodal solutions. Improve strategies focus on technological advancements of vehicles and fuels, combined with operational efficiency gains. Unlike purely technological approaches, the ASI framework emphasizes the interaction between transport demand, modal choice, and operational performance within supply chains [22,23].

In line with these considerations, this paper investigates the role of logistics and operational strategies in the decarbonization of road freight transport in Italy through the application of the Avoid–Shift–Improve framework. The study adopts a bottom-up quantitative approach to estimate freight transport demand and related greenhouse gas emissions for a baseline year (2023), with reference to 2005 as benchmark year for EU climate targets. Starting from this baseline, alternative scenarios up to 2030 are developed, reflecting both current policies and an optimistic implementation of ASI-oriented measures.

The main objective is twofold. First, the paper provides an operationally grounded assessment of the environmental impacts of current logistics patterns in Italian road freight transport. Second, it evaluates how different combinations of logistics strategies, such as freight consolidation, modal shift to rail, and accelerated fleet renewal, can contribute to reducing emissions while maintaining acceptable levels of logistical performance and service quality.

By bridging environmental assessment with logistics and operations management, this work contributes to the ongoing debate on sustainable freight transport by highlighting how decarbonization pathways must be embedded within real-world logistics constraints, economic trade-offs and operational decision-making processes. The findings aim to support logistics operators, infrastructure managers and policy makers in designing integrated strategies for a low-carbon transition of the freight transport system.

This work incorporates the ASI FOR FREIGHT research project – supported by Italy's National Recovery and Resilience Plan through the National Center for Sustainable Mobility (MOST), Spoke 10 as a practical case study to examine the real-world implementation of EU decarbonization policies.

Methodology and Data Sources

Methodological Approach Adopted

This study adopts a detailed analytical approach to estimate road mobility demand, energy consumption, and greenhouse gas (GHG) emissions. The main objective is to provide an accurate assessment of the environmental impact of road transport in Italy. A bottom-up analysis method is followed, which involves a detailed estimation of transport demand categorized by vehicle type (light and heavy commercial vehicles for freight transport), environmental category (Euro class), and road type. This approach, which builds estimates from individual data points to form a comprehensive assessment, enables a more precise evaluation of emissions by considering fuel consumption and vehicle characteristics.

The Methodology Follows Three Operational Steps:

- Estimation of freight mobility demand disaggregated by vehicle type, road type and emission class.
- Computation of Tank-to-Wheel energy consumption and GHG emissions using Joint Research Centre (JRC) and the European Environment Agency (EEA) emission factors.
- Validation through comparison with national fuel sales and energy statistics.

To enhance the accuracy of the analysis, the vehicle fleet is classified by: (i) vehicle type (LCVs, HDVs), (ii) Euro emission class, and (iii) fuel type (diesel, LNG, biofuels, hydrogen, electric).

The analysis also considers the expected fleet renewal by 2030, integrating assumptions about the penetration rate of electric and alternative-fuel trucks, based on EU regulatory targets and market trends.

The year 2005 is chosen as the reference point, as it represents the reference year for EU "Fit for 55" target, while the year 2023 is chosen as the base-line period. Following the ASI framework, an optimistic forecasting for 2030 is developed based on current policies and planned investments, including higher adoption of electric and hydrogen-powered trucks, a greater share of biofuels, and a stronger modal shift from road transport to rail one.

This scenario was designed to evaluate whether current strategies (in an optimistic perspective) are sufficient to achieve the European Union's emission reduction targets and to identify potential improvements.

The adopted method enables a detailed estimation of road mobility, energy consumption, and GHG emissions, providing a solid foundation for assessing the effectiveness of sustainability policies in the Italian transport sector.

Overview of Available Data Sources

Accurate data on freight transport demand are crucial for assessing current emission levels and evaluating the potential impact of decarbonization policies. In Italy, multiple official sources provide information on road transport activity. The analysis is based on official national and European datasets, including ISPRA emission inventories, ISTAT freight statistics, AISCAT motorway traffic data, MIT transport reports and EUROSTAT freight databases. Additional information on fleet composition and mobility trends was integrated from ACI, ACEA and Sustainable Urban Mobility Plan (SUMP) reports.

However, despite the availability of these sources, several limitations persist in the reconstruction of road freight transport demand.

Among the most relevant studies available to date, several critical issues and limitations can be identified:

- Some studies rely on overly optimistic assumptions, making the proposed scenarios unrealistic, for instance, regarding the market penetration of electric vehicles.
- The transition toward the desired low-emission future is often not structured into progressive, time-based milestones, making it difficult to track the feasibility of intermediate steps.
- Not all studies conclude that the "Fit for 55" targets will be achievable within the transport sector, raising concerns about the effectiveness of current policy frameworks.

Moreover, at the national level, there is still no comprehensive understanding of road freight transport demand. Current official data sources do not allow for a complete and consistent reconstruction of freight mobility across the Italian territory. Instead, they provide partial estimates, conflicting figures, or data derived from different calculation methodologies [24-27]. Additionally, none of these sources classify traffic by vehicle size or emission class, further limiting the accuracy of analyses. Given these gaps, a detailed estimation of freight transport demand, disaggregated by vehicle type (e.g., weight, Euro class) and road category (e.g., highways, extra-urban roads, urban roads), is both a critical challenge and an urgent necessity to support evidence-based policymaking and ensure an effective transition towards sustainable freight mobility.

The Avoid-Shift-Improve (ASI) Framework

Key Concepts and Applications to the Freight Transport Sector

The Avoid–Shift–Improve (ASI) framework provides a structured approach for reducing greenhouse gas (GHG) emissions in the transport sector. Applied to freight, the ASI paradigm recognizes the limitations of relying solely on technological improvements and emphasizes the importance of integrated strategies targeting demand, modal choice, and technological advancements [14]. Adopt the ASI framework to develop scenario-based analyses for the decarbonization of Italy's road freight transport by 2030, offering insight into the differentiated impact of policy actions across the avoid, shift, and improve dimensions.

The ASI approach is increasingly used in transport decarbonization scenario-building due to its comprehensiveness and adaptability. In the freight sector, this paradigm helps conceptualize three interconnected strategies: (1) Avoid strategies focus on reducing freight transport demand or avoiding unnecessary travel; (2) Shift strategies promote the use of more sustainable modes, such as rail and intermodal systems; and (3) Improve strategies enhance vehicle and fuel efficiency. This framework supports the definition of a future scenario, highlighting the potential impacts of ASI-aligned policies on emissions and energy consumption for the Italian freight transport context.

Avoid Strategies: Reducing Transport Demand and Improving Logistics Efficiency

Avoid strategies in the freight sector aim to reduce overall vehicle-kilometres travelled by increasing logistical efficiency and minimizing unnecessary freight movements.

In the 2030 scenario, avoid measures reduce vehicle-kilometres through load consolidation, reduction of empty runs and improved urban logistics efficiency.

Shift Strategies: Modal Shift towards Rail and Intermodal Transport

Shift strategies in the freight sector aim to reduce greenhouse gas emissions by encouraging a modal reallocation from road to more sustainable transport modes, such as rail and short-sea shipping. In the proposed 2030 scenario, modal shift policies are assumed to be strengthened through the continuation and enhancement of national incentives like Marebonus and Ferrobonus. These incentives, combined with infrastructure investments and regulatory support, are projected to increase the share of rail for long-distance freight movements (i.e., over 300 km), reaching the European Commission's target of 30% modal share by 2030. Shift strategies focus on long-distance freight flows (>300 km), leveraging intermodal transport and national incentives such as Ferrobonus and Marebonus.

Improve Strategies: Vehicle Technology Advancements and Operational Efficiency

Improve strategies focus on enhancing vehicle efficiency and reducing emissions through technological innovation, fleet renewal, and cleaner fuels. In the proposed 2030 scenario, aggressive assumptions are made regarding the renewal of the light and heavy commercial vehicle (LCV and HCV) fleets. These include higher annual replacement rates, accelerated penetration of battery electric vehicles (BEVs), and initial deployment of hydrogen-powered trucks. By 2030, BEVs are projected to reach a significant percentage of the LCV and HCV fleets, while a low fraction of the HCV will also be hydrogen-fuelled trucks.

In addition to electrification, the proposed scenario assumes a substantial use of second-generation biofuels, particularly Hydrotreated Vegetable Oil (HVO) and Compressed Bio-Methane (CBM), replacing fossil diesel and CNG in compatible fleets. These fuels, classified as part of the circular carbon cycle, allow for significant Well-to-Wheel (WtW) GHG reductions and complement the benefits of fleet electrification.

Results and Discussion

Estimated Demand for Road Freight Mobility in 2023

By applying the described methodology and integrating official statistical data with industry studies and research, the total road freight transport demand for the year 2023 has been estimated.

The resulting value amounts to more than 85,000 million vehicle-kilometres, representing the sum of the contributions from Light Commercial Vehicles (LCVs) and Heavy Commercial Vehicles (HCVs).

Specifically

- Approximately 65% of the total demand is attributable to LCVs, corresponding to over 55,000 million vehicle-kilometres.
- The remaining 35% is associated with HCVs, with an estimated value of about 30,000 million vehicle-kilometres.

The following table presents some of the estimated results.

Table I: % Distribution of LCVs and HCVs Road Mobility Demand by 2023, by Environmental Class Groups

		Euro 0-I-II	Euro III-IV	Euro V-VI	Total
LCVs	All	11%	32%	57%	100%
HCVs	< 14 tons	9%	22%	69%	100%
	14,1 - 20 tons	6%	22%	72%	100%
	20,1 - 28 tons	6%	17%	77%	100%
	> 28 tons	1%	11%	88%	100%

Estimated Greenhouse Gas Emissions Attributable to Road Freight Mobility in 2023

Subsequently, the tank-to-wheel (TTW) greenhouse gas emissions, expressed in tonnes of CO2 equivalent, related to road freight transport for the year 2023 were estimated.

The resulting total amounts to more than 30 million tonnes of CO2eq, representing the sum of emissions from Light Commercial Vehicles and Heavy Commercial Vehicles.

Specifically

- Approximately 40% of the total emissions are attributable to LCVs, with a total of about 12 million tonnes of CO2eq.
- The remaining 60% is attributable to HCVs, with an estimated value of more than 18 million tonnes of CO2eq.

The Effects of Trend Scenarios on Greenhouse Gas Emissions to 2030

Having consolidated the 2023 baseline estimates, the proposed optimistic 2030 scenario described in Section III were applied for the 2023-2030 horizon. The resulting TTW emission trajectories are shown in Figure 1.

The proposed 2030 scenario, built on optimistic (ambitious) assumptions for logistics optimization, accelerated modal shift incentives and rapid penetration of zero- and low-carbon technologies, achieves an about -25% reduction relative to 2005, showing a considerable gap with respect to the EU "Fit-for-55" milestone, highlighting how logistic reorganization is as critical as technological transition.

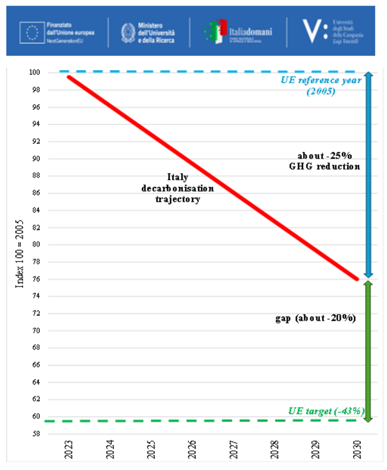

Figure 1: Road Freight Greenhouse Gas TTW Emissions (GHG) (index 100 = 2005), Decarbonization Trajectory 2023-2030

Possible Additional Logistic Strategies to Decarbonize Road Freight Transport in Italy

The previous sections demonstrated that technology-oriented Improve measures alone are not sufficient to achieve the European decarbonization targets for road freight transport by 2030. For this reason, an additional scenario is introduced, explicitly focused on logistics and operational rationalization strategies, designed to complement the ASI approach and close the remaining emission gap.

Logistic Rationalization Scenario (LRS)

The Logistic Rationalization Scenario (LRS) builds upon the optimistic ASI scenario by integrating structural logistics measures aimed at reducing transport demand and improving network efficiency through operational reorganization.

The scenario assumes the large-scale adoption of advanced logistics practices. The following measures are considered:

- Freight Consolidation and Load Factor Optimization, through shared urban distribution centres and collaborative logistics schemes, leading to a 10–15% reduction in vehicle-kilometres for urban and regional flows.
- Reduction of Empty Trips via digital freight marketplaces and real-time matching between demand and supply, resulting in an 8–10% decrease in empty truck-kilometres on medium and long-distance routes.
- Network Reconfiguration through hub-and-spoke optimization, reducing redundant flows and inefficient routing, with an estimated 5–7% reduction in total freight transport demand.
- Partial Re-Localization of Supply Chains, promoting shorter and more regional logistics networks in selected sectors, contributing to an additional 3–5% reduction in tonne-kilometres.

Contribution to Emission Reduction Targets

When combined with the optimistic ASI scenario, the LRS provides an additional 12–18% reduction in GHG emissions from road freight transport by 2030, allowing the overall decarbonization trajectory to converge towards the EU target of –43.7% compared to 2005 levels, in line with the Fit for 55 framework.

This result highlights that logistics and supply chain reorganization is not merely a support measure but a structural level of decarbonization. Without such operational transformation, even the widespread adoption of low-emission vehicles remains insufficient to achieve climate targets.

Managerial and Policy Implications

From an operations and logistics management perspective, the scenario implies that decarbonization requires:

- Investments in collaborative logistics platforms and digital freight systems.
- Development of urban consolidation centres and intermodal logistics hubs.sss
- Targeted policy incentives focused not only on vehicles but also on logistics efficiency and freight rationalization.

These findings reinforce the need to shift from a vehicle-centered decarbonization approach to a logistics-centered transition strategy.

Conclusions

This study aimed to assess the decarbonization trajectory of road freight transport in Italy within the framework of the Avoid-Shift-Improve (ASI) paradigm, with particular focus on its application in forecasting scenarios developed within the ASI FOR FREIGHT project, part of the National Centre for Sustainable Mobility (MOST, Spoke 10). The core objective was to quantify greenhouse gas (GHG) emissions from freight transport and to evaluate the potential of ASI strategies to reduce them under the 2030 optimistic (accelerated decarbonization) scenario.

The main findings show that technological improvements alone are insufficient to achieve the EU 2030 climate targets. The additional Logistic Rationalization Scenario demonstrates that freight transport optimization and supply chain reorganization can close a significant part of the remaining gap left by technology-driven policies. While "Improve" strategies such as the electrification of fleets and the deployment of low-carbon fuels play a crucial role, their impact remains limited if not accompanied by structural changes. Avoid and Shift strategies reduce demand and reallocate long-haul flows, but their effectiveness strongly depends on logistics system reorganization. In the estimated 2030 scenario, the integrated application of all ASI pillars leads to a significant reduction in vehicle-kilometers and associated emissions, demonstrating that an ambitious but realistic combination of policies could enable Italy to align with EU decarbonization trajectories.

As a contribution to the ASI FOR FREIGHT research initiative, this work provides insights into how national freight decarbonization policies can be structured and assessed. The ASI framework proves particularly suitable for identifying policy synergies and trade-offs across demand management, modal reallocation, and technological innovation.

Results highlight that deep decarbonization requires integrated logistics strategies combining demand management, modal shift and technological transition. From an operational perspective, logistics operators must invest in consolidation systems, fleet renewal and intermodal integration, while policy makers should focus on coordinated incentives and infrastructure support.

By utilizing the ASI framework, Italy has an opportunity to significantly reduce transport-related emissions, aligning with the broader climate goals for 2030 and 2050. Future research should focus on disaggregated freight behaviour models and the integration of Well-to-Wheel and life-cycle emissions to improve long-term scenario robustness. Additionally, future work should explore the integration of resilience assessment of existing road networks including the systematic evaluation of bridge vulnerability, maintenance prioritization and seismic risk into freight decarbonization modelling frameworks. Decision Support Systems oriented towards network resilience, such as those built on GIS-based multi-hazard data and resilience-based risk management methodologies, offer a promising avenue to account for infrastructure-side constraints and disruption risks when projecting long-term emission trajectories for the Italian road freight sector [24-27].

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