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Linking Ecological and Logistics KPIs in Zero-Emission Logistics Zones: A Conceptual Framework

Nilesh Anand[ab*], Hervé Brisson[b], Ron van Duin[b,c,]

[a]*Rotterdam Business School, Kralingse Zoom 91, Rotterdam, 3063 ND, The Netherlands*
[b]*Rotterdam University of Applied Sciences, CoEHRTech, RDM-kade 59, Rotterdam, 3089 JR, The Netherlands*
[c]*Delft University of Technolog, Jaffalaan 5, Delft 2628BX, The Netherlands*

Abstract

Urban freight transport plays a crucial role in supporting economic activity in cities but also contributes significantly to congestion, energy consumption, and greenhouse gas emissions. In response, many cities are introducing Zero-Emission Logistics Zones (ZELZ) aimed at reducing the environmental impact of urban freight transport through regulatory and technological interventions. However, evaluating the effectiveness of such policies remains challenging because logistics performance indicators and ecological performance indicators are often analyzed separately in both research and practice. This study addresses this gap by developing a conceptual framework that links logistics key performance indicators (KPIs) with ecological KPIs within the context of Zero-Emission Logistics Zones. The framework is derived from a structured review of literature on urban logistics operations, logistics performance measurement, and environmental sustainability assessment. The review highlights that operational logistics decisions, such as routing strategies, fleet composition, delivery consolidation, and network design, directly influence environmental outcomes including emissions and energy consumption. Building on these insights, the study proposes an integrated framework that connects policy drivers, logistics operations, logistics KPIs, and ecological KPIs. The framework also illustrates the strength of relationships between operational indicators and environmental outcomes identified in the literature. The proposed framework provides a structured perspective that can support policymakers, logistics operators, and researchers in evaluating the sustainability of urban freight systems and designing more effective zero-emission logistics policies.
Keywords: Urban freight transport; Zero-emission logistics zones; Logistics KPIs; Environmental performance indicators; Sustainable city logistics

1 Introduction and motivation

Urban freight transport is an essential component of modern cities, enabling the distribution of goods to businesses, service providers, and households. However, the growth of e-commerce, increasing urbanization, and rising demand for rapid delivery have intensified freight activity in urban areas. As a result, urban logistics has become a significant contributor to traffic congestion, energy consumption, and greenhouse gas emissions in cities. Studies consistently highlight that freight transport is responsible for a considerable share of urban transport emissions and environmental externalities, including air pollution, noise, and increased road congestion (Sahu et al., 2022; Toktaş et al., 2024)

In response to these challenges, cities and policymakers have begun introducing regulatory and operational measures aimed at reducing the environmental impacts of urban freight systems. One increasingly adopted approach is the creation of *Zero-Emission Logistics Zones (ZELZ)* or similar low-emission urban freight zones. These zones typically restrict the access of high-emission vehicles to certain urban areas while promoting cleaner technologies, electrified fleets, consolidation centers, and innovative delivery solutions. Such policies aim to reduce emissions and environmental externalities while maintaining efficient goods distribution within cities (de Bok et al., 2021; Steimer & Kothari, 2022)

While the concept of zero-emission logistics zones is gaining attention, evaluating their effectiveness remains most challenging. Urban logistics systems are typically assessed using *logistics performance indicators (KPIs)* that measure operational efficiency, such as delivery time, vehicle utilization, route efficiency, and logistics costs. At the same time, environmental sustainability is evaluated through *ecological KPIs*, including CO_2 emission, energy consumption, air pollution, and environmental externalities. However, these two groups of indicators are often treated separately in the literature and in practice. Logistics KPIs are primarily designed to optimize operational efficiency, whereas ecological KPIs focus on environmental impacts. As a result, the relationship between operational logistics performance and ecological outcomes is rarely analyzed in a systematic way (Ferraro et al., 2023)

Understanding the interaction between logistics performance and environmental outcomes is particularly important in the context of ZELZ policies. Changes in routing strategies, vehicle technologies, consolidation practices, and delivery networks can simultaneously influence both logistics efficiency and ecological performance. For example, improved routing efficiency or higher vehicle utilization can reduce vehicle-kilometers traveled and consequently lead to lower emissions. Conversely, certain policy interventions may reduce emissions while increasing logistics complexity or operational costs. This indicates that the relationship between logistics KPIs and ecological KPIs is complex and requires a structured analytical approach.

Therefore, there is a need for a framework that systematically connects *logistics performance indicators with ecological performance* indicators within the context of zero-emission logistics zones. Such a framework can help clarify how operational logistics decisions influence environmental outcomes and support the design, evaluation, and monitoring of sustainable urban freight systems. From a theoretical perspective, this study contributes to the literature on sustainable urban logistics by integrating operational performance measurement and environmental sustainability assessment into a unified conceptual framework.

The objective of this study is to *develop a conceptual framework that links ecological KPIs with logistics KPIs in the context of Zero-Emission Logistics Zones*. The framework is derived from a structured review of the literature on urban logistics performance measurement, environmental sustainability indicators, and policy interventions aimed at decarbonizing urban freight systems.

The proposed framework is intended to support multiple stakeholders involved in urban logistics and sustainability planning. *City authorities and policymakers* can use the framework to evaluate the environmental impacts of logistics policies and design effective ZELZ strategies. *Logistics service providers and transport operators* can use it to better understand how operational decisions affect environmental performance. Additionally, *researchers and urban planners* can use the framework to analyze the interactions between logistics operations, performance indicators, and sustainability outcomes in urban freight systems.

By linking logistics KPIs with ecological KPIs within a unified conceptual structure, this study contributes to the development of more integrated approaches to evaluating and managing sustainable urban logistics systems. The framework also provides a foundation for future empirical studies and decision-support tools aimed at improving the environmental performance of urban freight transport.

This study contributes to the emerging research on sustainable urban logistics and zero-emission freight systems in several ways. First, the paper synthesizes existing literature on logistics performance indicators and ecological performance indicators in urban freight systems, highlighting how these two groups of indicators are currently treated separately in many studies. Second, the study identifies key relationships between logistics KPIs and ecological KPIs, demonstrating how operational logistics decisions—such as routing strategies, fleet composition, and consolidation practices—can influence environmental outcomes including emissions and energy consumption. Third, the paper proposes a conceptual framework that links ecological KPIs with logistics KPIs within the context of Zero-Emission Logistics Zones (ZELZ). This framework provides a structured perspective for analyzing the interactions between logistics operations, performance indicators, and environmental outcomes. Together, these contributions aim to support researchers, policymakers, and logistics practitioners in developing more integrated approaches for evaluating and managing sustainable urban freight systems.

The remainder of the paper is organized as follows. Section 2 presents the conceptual structure guiding the literature review. Section 3 synthesizes findings from the literature on logistics performance indicators, ecological indicators, and their interactions in urban freight systems. Section 4 develops a conceptual framework linking logistics KPIs and ecological KPIs within Zero-Emission Logistics Zones. Finally, Section 5 discusses conclusions and directions for future research.

2 Conceptual Framework for the Review

The objective of this section is to define the *conceptual structure guiding the literature review* and clarify how the different streams of research relevant to this study are organized. The literature on sustainable urban logistics spans multiple research domains, including logistics operations, performance measurement, environmental sustainability, and urban transport policy. Because these domains are often studied separately, it is necessary to establish a conceptual structure that integrates them and provides a coherent basis for the review.

This section introduces the key concepts that structure the analysis of the literature and explains how they relate to each other. These concepts include *logistics operations, logistics performance indicators (KPIs), ecological outcomes, ecological KPIs, and the policy environment of Zero-Emission Logistics Zones (ZELZ)*. By clarifying these relationships, the section establishes the analytical foundation for the subsequent literature review and supports the development of a conceptual framework linking logistics and ecological performance indicators.

2.1 Conceptual Structure of the Review

Urban freight systems consist of a set of logistics operations that enable the distribution of goods within cities. These operations typically include activities such as routing, fleet management, delivery scheduling, consolidation, and the organization of distribution networks. In the literature, the performance of these logistics operations is commonly evaluated using logistics key performance indicators (KPIs), which measure operational efficiency and service quality. Typical examples include delivery time, vehicle utilization, route efficiency, and vehicle-kilometers traveled.

At the same time, logistics operations generate a range of environmental impacts, including greenhouse gas emissions, energy consumption, local air pollution, and other environmental externalities. These impacts can be evaluated through ecological performance indicators, such as CO_2 emission, energy use, pollutant emissions, and environmental costs. These indicators are increasingly used to assess the sustainability of urban freight systems and to support the design of environmentally responsible logistics policies.

In recent years, cities have begun introducing policy interventions aimed at reducing the environmental impacts of urban freight transport. One such intervention is the implementation of Zero-Emission Logistics Zones (ZELZ), which restrict access for high-emission vehicles and encourage the adoption of low- or zero-emission delivery solutions. These policies can influence logistics operations by promoting electrified fleets, consolidation infrastructure, and alternative delivery models. As a result, ZELZ policies can indirectly affect both logistics performance and ecological outcomes.

Despite these developments, the literature often treats logistics key performance indicators and ecological indicators as separate analytical dimensions. Logistics KPIs are frequently used to optimize operational efficiency, while ecological KPIs are used to evaluate environmental impacts. However, operational decisions such as routing strategies, vehicle utilization, and fleet composition can simultaneously influence both types of performance indicators. Understanding these interactions is therefore essential for evaluating the effectiveness of sustainability policies such as ZELZ.

To structure the review and highlight these relationships, this study adopts a conceptual perspective that links logistics operations, logistics KPIs, ecological outcomes, and ecological KPIs within the policy context of Zero-Emission Logistics Zones. This conceptual structure is illustrated in Figure 1.

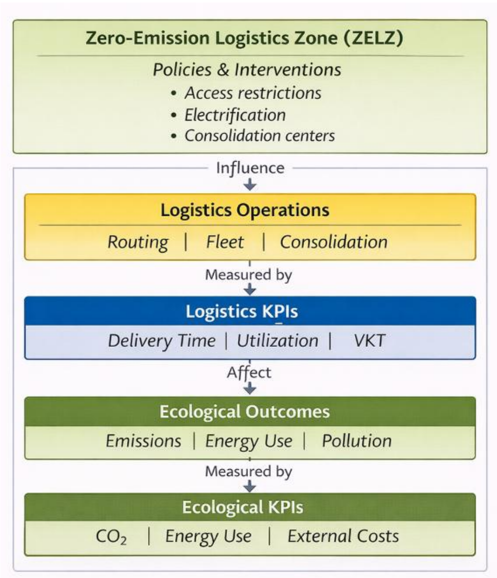

Fig. 1. Conceptual framework for the review

2.2 Conceptual Domain of the Literature Review

Figure 1 illustrates the conceptual domain guiding the literature review in this study. The figure highlights the main elements of the urban logistics system and the relationships between operational activities, performance indicators, environmental outcomes, and policy interventions. At the operational level, logistics activities such as routing, fleet management, and delivery consolidation determine the structure and efficiency of urban freight distribution systems. These activities are evaluated through logistics performance indicators, which capture operational characteristics such as delivery time, vehicle utilization, and vehicle-kilometers traveled (VKT). Logistics operations also generate environmental impacts, which are represented in the framework as ecological outcomes, including emissions, energy consumption, and environmental pollution. These impacts can be measured through ecological KPIs such as CO_2 emissions, energy use, and environmental externalities.

The figure also highlights the role of Zero-Emission Logistics Zones as a policy environment that influences logistics operations. By restricting high-emission vehicles and encouraging cleaner technologies and alternative delivery models, ZELZ policies can reshape logistics operations and thereby affect both logistics and ecological performance indicators. Overall, the conceptual structure presented in Figure 1 provides the analytical basis for the literature review conducted in this study. It enables the identification of relevant research streams and helps organize the analysis of how logistics performance indicators and ecological performance indicators are related in the context of sustainable urban freight systems.

3 Findings from the Literature Review

A structured literature search was conducted using databases such as Scopus, Web of Science, and Google Scholar. Keywords included urban freight, city logistics, logistics KPIs, environmental indicators, sustainable logistics, and zero-emission zones. These terms were combined to identify relevant studies on logistics performance and ecological impacts in urban systems.

3.1 Logistics operations and logistics KPIs in urban freight systems

Research on urban freight logistics has traditionally focused on how operational decisions shape the efficiency and performance of distribution systems in cities. Early conceptual work by Behrends (2013) emphasizes that urban freight sustainability cannot be evaluated without understanding the operational design of logistics systems, particularly routing strategies, vehicle fleets, and the spatial organization of delivery networks. Similarly, Perboli et al. (2018) demonstrate through simulation–optimization models that routing efficiency and distribution network structure significantly influence logistics performance indicators such as vehicle-kilometers traveled, delivery time, and fleet utilization. While these studies emphasize the importance of operational efficiency, they differ in how logistics performance metrics should be interpreted. For example, Nathanail et al. (2016) highlight the role of logistics terminals and consolidation centers in improving service reliability and network efficiency, whereas Giret et al. (2018) argue that operational metrics should be evaluated together with environmental considerations when comparing alternative delivery strategies. Despite these differences, most studies continue to prioritize operational indicators such as routing efficiency, delivery time, and vehicle utilization. Consequently, logistics KPI frameworks remain largely rooted in efficiency-oriented performance evaluation rather than sustainability-oriented system assessment.

A second line of research highlights how changing demand patterns reshape logistics operations and influence the interpretation of logistics KPIs. Trapp et al. (2021) show that individualized last-mile delivery services driven by e-commerce demand can reduce delivery density and vehicle utilization, thereby lowering operational efficiency despite improving service responsiveness. In contrast, Aziz et al. (2022) demonstrate that certain e-grocery logistics models can increase efficiency when deliveries are consolidated effectively and routes are optimized through centralized planning. These contrasting findings illustrate that logistics KPIs such as vehicle utilization and delivery density are highly sensitive to consumer behavior and service design. At the same time, Ferraro et al. (2023) argue that conventional performance measurement systems in logistics still focus primarily on productivity indicators, often neglecting environmental consequences. Similarly, Bartuška et al. (2023) observe that sustainability indicators are frequently introduced only as supplementary measures rather than as core elements of logistics performance frameworks. Taken together, these studies indicate that although logistics KPIs are widely used to evaluate urban freight systems, they are rarely structured in ways that explicitly capture the environmental implications of operational decisions.

A third stream of research emphasizes the role of technological innovation and digitalization in shaping logistics performance measurement. Demir et al. (2022) highlight how emerging technologies such as data-driven routing systems, automation, and advanced analytics are transforming last-mile logistics operations and enabling more precise measurement of operational indicators. Similarly, Gutiérrez-Franco et al. (2021) demonstrate that data-driven decision-support tools can improve logistics performance by optimizing routing and fleet allocation in real time. However, these technological developments also expose limitations in existing KPI frameworks. While advanced logistics systems can generate detailed operational data, the indicators used to evaluate these systems still tend to focus on operational efficiency rather than broader sustainability outcomes. This discrepancy suggests that the evolution of logistics technology has outpaced the development of integrated performance measurement frameworks capable of linking operational efficiency with environmental performance.

3.2 Ecological outcomes and ecological KPIs in sustainable urban logistics

Parallel to the operational literature, a growing body of research has examined the environmental impacts of urban freight transport and the indicators used to measure them. Mucowska (2021) identifies freight transport as a significant contributor to urban environmental externalities, including greenhouse gas emissions, air pollution, and noise. Similarly, Sahu et al. (2022) show that inefficient logistics operations often lead to increased energy consumption and higher emission levels in urban areas. These studies emphasize that urban freight sustainability cannot be evaluated solely through operational efficiency but must also consider environmental consequences. Consequently, researchers have increasingly focused on ecological KPIs such as CO_2 emission, energy consumption, and pollutant emissions to evaluate the environmental performance of logistics systems.

However, studies differ in how ecological indicators should be incorporated into logistics assessment frameworks. Nathanail and Papoutsis (2013) propose a structured approach in which environmental indicators are integrated into urban transport planning models, allowing policymakers to evaluate sustainability outcomes alongside operational performance. In contrast, Toktaş et al. (2024) emphasize the role of supply chain decarbonization strategies and argue that ecological KPIs should primarily guide strategic decision-making at the system level rather than operational logistics management. This distinction reflects two different perspectives in the literature: one that treats ecological indicators as operational evaluation tools and another that views them as strategic sustainability metrics.

Research on alternative delivery technologies further illustrates these differences. Melo and Baptista (2017) demonstrate that cargo bicycle deliveries can significantly reduce emissions compared with conventional van deliveries, particularly in dense urban environments. However, the authors also emphasize that these benefits depend on operational factors such as route length and delivery density. Similarly, Lemardelé et al. (2021) analyze drone-based and autonomous delivery systems and conclude that their environmental performance varies depending on energy sources, operational scale, and routing efficiency. These findings indicate that ecological KPIs cannot be interpreted independently of the logistics operations. Instead, environmental outcomes are strongly influenced by operational variables that are traditionally captured through logistics performance indicators.

Recent research also highlights the growing importance of technological innovation in reducing environmental impacts. Ferreira and Esperança (2025) show that the integration of electric delivery vehicles with artificial intelligence–based routing systems can significantly reduce both energy consumption and emissions while maintaining delivery performance. Similarly, Giordano and Christidis (2025) find that electrification strategies in urban distribution systems can improve environmental performance, although their effectiveness depends heavily on logistics network design and infrastructure availability. These studies illustrate that ecological performance improvements are closely linked to operational changes, reinforcing the need to analyze environmental indicators in relation to logistics KPIs.

3.3 Linking logistics KPIs and ecological KPIs

Although logistics performance and environmental sustainability have often been studied separately, a growing number of studies highlight the interdependencies between operational logistics indicators and ecological outcomes. One of the most widely recognized relationships concerns routing efficiency and environmental performance. Perboli et al. (2018) demonstrate that optimized routing strategies reduce vehicle-kilometers traveled, thereby lowering fuel consumption and emissions. Similarly, Gutiérrez-Franco et al. (2021) show that data-driven routing optimization can simultaneously improve delivery efficiency and reduce environmental impacts. These findings suggest that improvements in logistics KPIs related to routing and travel distance can directly contribute to better ecological performance.

However, other studies reveal that the relationship between logistics and environmental indicators is not always straightforward. de Bok et al. (2021) analyze the implementation of a zero-emission logistics zone in Rotterdam and find that emissions within the zone decrease significantly, but the total distance traveled by delivery vehicles may increase due to changes in distribution network structures. This finding highlights a potential trade-off between environmental benefits and logistics efficiency. Similarly, Beck et al. (2025) argue that increasing delivery frequency to satisfy customer expectations can reduce vehicle utilization and consequently increase emissions per delivery, even if delivery times improve.

The literature also emphasizes the importance of vehicle utilization and consolidation strategies in shaping the relationship between logistics and ecological KPIs. Trapp et al. (2021) show that higher vehicle utilization can significantly reduce emissions per parcel, whereas fragmented delivery patterns tend to increase environmental impacts. In contrast, Ghazal and Narayanan (2025) demonstrate that implementing parcel lockers and consolidation points can simultaneously improve logistics efficiency and reduce emissions by minimizing repeated delivery attempts.

Technological innovation may also help reconcile the trade-offs between logistics and environmental performance. Ferreira and Esperança (2025) find that combining electric vehicles with intelligent routing systems improves delivery performance while reducing emissions and energy consumption. However, Giordano and Christidis (2025) caution that electrification alone cannot guarantee environmental benefits unless logistics operations are optimized accordingly. These differing perspectives indicate that the relationship between logistics KPIs and ecological KPIs is highly context-dependent and influenced by technological, operational, and policy factors.

Table 1. Key studies linking logistics KPIs and ecological KPIs

Authors	Main focus	Logistics KPIs emphasized	Ecological KPIs emphasized	Main contribution for this study
(Behrends, 2013)	Sustainable urban freight assessment framework	Routing, fleet characteristics, delivery structure	Emissions, broader sustainability effects	Establishes that urban freight sustainability must be assessed through the structure of logistics operations rather than only through isolated transport outcomes.
(Nathanail et al., 2016)	Urban freight terminals and multi-stakeholder KPI evaluation	Terminal performance, service reliability, operational efficiency	Indirect environmental implications	Shows that logistics infrastructure such as terminals and consolidation platforms shapes both service performance and sustainability assessment.
(Giret et al., 2018)	Green delivery plan evaluation	Delivery time, route efficiency, utilization	Sustainable delivery impacts	Suggests that delivery plans should be evaluated through combined operational and environmental criteria, supporting integrated KPI thinking.
(Perboli et al., 2018)	Simulation–optimization in city logistics	Vehicle-km, routing efficiency, network design	Emissions as downstream outcome	Provides strong evidence that routing and network structure act as direct operational drivers of environmental performance.
(Bruzzone et al., 2020)	Integrated passenger and freight first-last mile operations	Operational performance, travel distance	Environmental and social externalities	Demonstrates that urban freight evaluation increasingly requires a multi-dimensional KPI structure spanning operational and environmental domains.
(Trapp et al., 2021)	Individualized last-mile delivery and consumer behavior	Utilization, order volume, delivery performance	Emissions	Shows that customer-driven service models affect vehicle utilization and can either improve or worsen environmental performance depending on operating conditions.
(Melo & Baptista, 2017)	Cargo cycles in urban logistics	Mobility efficiency, operating cost, route suitability	CO_2, energy, external costs	Shows that alternative delivery modes can improve ecological performance, but benefits depend on spatial and operational conditions.
(Lemardelé et al., 2021)	Drones and autonomous delivery devices	Operating cost, service-region suitability	Externalities, environmental impacts	Reinforces that new delivery technologies do not have fixed environmental advantages; outcomes depend on operational design and urban context.
(Ferraro et al., 2023)	Limits of traditional transport effectiveness metrics	Vehicle effectiveness, utilization, transport performance	Carbon emissions	Critically shows that conventional logistics KPIs can overstate performance when ecological impacts are excluded from the assessment logic.
(de Bok et al., 2021)	Zero-emission zone impacts in Rotterdam	Vehicle-km, delivery network changes	Emissions reduction inside the zone	Provides direct ZELZ evidence and shows that ecological improvement may coexist with operational trade-offs such as longer travel distances.
(Steimer & Kothari, 2022)	Zero-emission delivery zone policy design	Indirectly through operational adaptation	Emissions, urban externalities	Positions zero-emission delivery zones as a governance mechanism that reshapes logistics systems and therefore KPI relationships.
(Ferreira & Esperança, 2025)	EVs and AI optimization in urban logistics	Delivery time, fleet utilization, service performance	Energy use, CO_2 emissions	Offers strong integrated evidence that operational optimization and cleaner fleet technology can improve both logistics and ecological KPIs simultaneously.

Table 1 presents a synthesis of representative studies which creates the base for framework development in this paper. The studies selected cover foundational urban freight assessment, logistics KPI design, ecological KPI evaluation, operational innovations, and policy-oriented zero-emission zone research. Together, they show that while logistics and ecological indicators are often discussed in separate streams, the literature increasingly points to direct and indirect linkages between them.

3.4 Synthesis of the Review

The literature review highlights several important insights regarding the relationship between logistics operations, logistics performance indicators, and ecological outcomes in urban freight systems. First, research on logistics operations consistently demonstrates the importance of operational efficiency indicators such as routing efficiency, delivery time, and vehicle utilization. Studies (Behrends, 2013; Nathanail et al., 2016; Perboli et al., 2018) show that these indicators are widely used to evaluate the performance of urban freight systems. However, most logistics KPI frameworks remain focused primarily on operational efficiency and do not systematically incorporate environmental considerations.

Second, the environmental literature emphasizes the importance of ecological indicators such as emissions, energy consumption, and environmental externalities in evaluating the sustainability of urban freight systems. Researchers (Mucowska, 2021; Toktaş et al., 2024) highlight the growing importance of these indicators for guiding urban sustainability policies. Nevertheless, ecological KPIs are often applied independently from logistics performance metrics, which limits their usefulness for operational decision-making.

Third, the literature indicates that operational logistics decisions strongly influence environmental outcomes. Studies on routing optimization, vehicle utilization, and fleet electrification demonstrate that improvements in logistics performance can lead to reductions in emissions and energy consumption. At the same time, research on zero-emission zones and last-mile delivery systems shows that certain policy interventions may introduce trade-offs between operational efficiency and environmental performance.

Overall, the literature suggests that logistics KPIs and ecological KPIs are closely interconnected but rarely analyzed within a unified analytical framework. This fragmentation highlights the need for an integrated conceptual framework that systematically links logistics performance indicators with ecological performance indicators, particularly in the context of Zero-Emission Logistics Zones. The following section therefore develops such a framework based on the insights derived from the literature review.

4 Conceptual Framework Linking Logistics and Ecological KPIs in ZELZ

4.1 Purpose of the Framework

The purpose of the framework proposed in this study is to provide a structured perspective that links logistics KPIs and ecological KPIs within the policy environment of Zero-Emission Logistics Zones (ZELZ). By integrating operational logistics variables, performance indicators, and environmental outcomes into a single conceptual structure, the framework clarifies how logistics decisions influence environmental impacts and how policy interventions can shape these relationships.

4.2 Explanation of the Framework

Figure 2 presents the conceptual framework linking to Zero-Emission Logistics Zone policies, logistics operations, logistics performance indicators, and ecological performance indicators. The framework is organized into four main layers that represent different components of the urban freight system. At the top of the framework are policy drivers, represented by Zero-Emission Logistics Zone policies. These policies include regulatory instruments such as vehicle access restrictions, incentives for electrified fleets, and the promotion of consolidation infrastructure. These policy mechanisms influence the structure and organization of urban logistics systems by encouraging or requiring changes in delivery technologies and operational practices. The second layer represents logistics operations, which include activities such as routing strategies, fleet composition, delivery scheduling, consolidation systems, and network design. These operational elements determine how goods are distributed within urban areas and form the basis for measuring logistics performance. The third layer includes logistics key performance indicators (KPIs), which measure operational performance in urban freight systems. Indicators such as vehicle-kilometers traveled, route efficiency, vehicle utilization, and delivery time are commonly used by logistics operators to evaluate service performance and operational efficiency. The final layer consists of ecological performance indicators, which measure the environmental impacts generated by logistics activities. These indicators include CO_2 emission, energy consumption, air pollutions (such as NO_x, PM_{10}, $PM_{2.5}$), and environmental externalities associated with urban freight transport.

The framework also illustrates the relationships between logistics KPIs and ecological KPIs. These relationships vary in strength depending on the level of empirical support found in literature. For example, the relationship between vehicle-kilometers traveled and CO_2 emission is widely supported in the literature and is

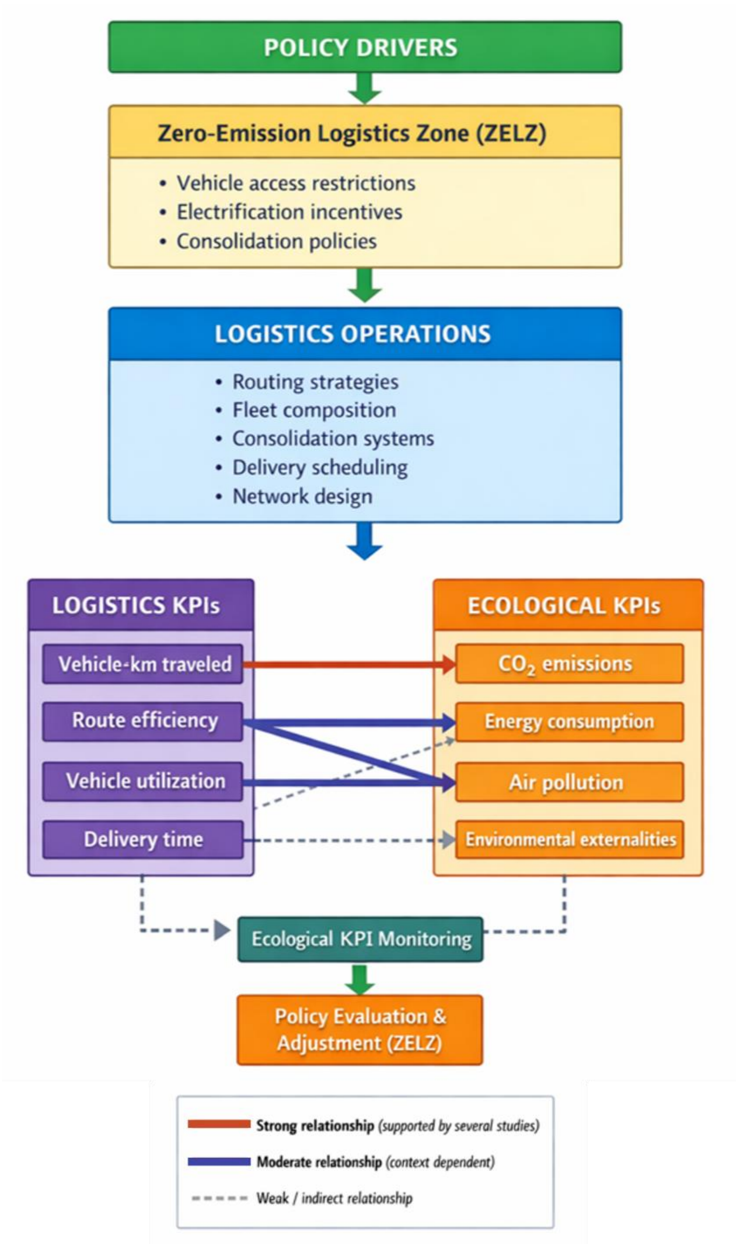

Figure 2. Framework Linking Logistics KPIs and Ecological KPIs in ZELZ

therefore represented as a strong relationship. Moderate relationships capture interactions that are supported by some empirical evidence but are context-dependent, such as the influence of vehicle utilization or route efficiency on emissions and air pollution. These relationships may vary depending on factors such as urban density, delivery patterns, and operational conditions. In contrast, indicators such as delivery time may influence environmental outcomes only indirectly through their effect on routing and operational decisions and are therefore represented as weaker relationships. By visually representing these relationships, the framework highlights how operational logistics decisions translate into environmental outcomes.

4.3 Application of the Framework for Stakeholders

The proposed framework can support decision-making for several stakeholders involved in urban freight systems, including policymakers, logistics operators, and researchers. For city authorities and policymakers, the framework can be used as a tool to evaluate the environmental impact of urban logistics policies such as Zero-Emission Logistics Zones. By understanding how logistics KPIs influence ecological KPIs, policymakers can identify which operational changes are most likely to reduce emissions or energy consumption. For example, a city implementing a ZELZ may use the framework to assess how restricting conventional delivery vehicles and encouraging consolidation centers could influence vehicle-kilometers traveled and ultimately reduce CO_2 emission within the city center. For logistics service providers and transport operators, the framework provides insights into how operational decisions affect environmental performance. Logistics companies can use the framework to identify operational strategies that simultaneously improve efficiency and reduce environmental impacts. For instance, improving route efficiency through advanced routing algorithms may reduce both delivery time and fuel consumption, thereby improving logistics KPIs while also reducing emissions.

The framework is also useful for researchers and urban planners studying sustainable freight systems. By explicitly linking operational indicators with environmental outcomes, the framework provides a structured basis for analyzing how new technologies, delivery models, or policy interventions affect the sustainability of urban logistics systems. Overall, the framework serves as a conceptual tool that connects operational logistics performance with environmental sustainability outcomes. This integrated perspective is particularly important for evaluating and designing Zero-Emission Logistics Zones, where both logistics efficiency and environmental performance must be considered simultaneously.

5 Conclusions and Future Research

This study aimed to develop a conceptual framework that links logistics performance indicators with ecological performance indicators in the context of Zero-Emission Logistics Zones. A structured review of the literature on urban logistics operations, logistics performance measurement, and environmental sustainability revealed that these two groups of indicators are often studied independently despite being strongly interconnected. Logistics KPIs are commonly used to evaluate operational efficiency, while ecological KPIs measure environmental outcomes such as emissions, energy consumption, and air pollution. However, operational logistics decisions (including routing strategies, fleet composition, and delivery consolidation) directly influence environmental impact. Based on these insights, this study proposed a conceptual framework that integrates policy drivers, logistics operations, logistics KPIs, and ecological KPIs into a unified analytical structure. The framework highlights how Zero-Emission Logistics Zone policies influence logistics operations and how operational performance indicators translate into environmental outcomes. From a policy perspective, the framework can assist city authorities in designing and evaluating ZELZ policies that reduce environmental impacts while maintaining efficient urban freight distribution. By identifying relationships between logistics and ecological indicators, the framework provides a structured approach for evaluating the sustainability of urban freight systems.

The study contributes to the literature in three main ways. First, it synthesizes existing research on logistics and environmental performance indicators in urban freight systems. Second, it identifies key relationships between logistics KPIs and ecological KPIs. Third, it proposes a conceptual framework that supports integrated evaluation of operational and environmental performance in Zero-Emission Logistics Zones. Several directions for future research emerge from this study. First, empirical studies are needed to validate the relationships proposed in the framework using real-world data from urban logistics systems. Second, future research could develop quantitative models that estimate the impact of specific logistics KPIs on ecological KPIs under different urban conditions. Third, case studies of cities implementing Zero-Emission Logistics Zones could provide valuable insights into how policy interventions reshape logistics operations and environmental performance. Finally, future research could expand the framework by incorporating social and economic indicators to provide a more comprehensive assessment of sustainable urban freight systems. Overall, developing integrated performance frameworks that link logistics efficiency with environmental sustainability will be essential for supporting the transition toward low/zero-emission urban logistics systems. Future research could extend the proposed framework by incorporating broader ecological indicators such as urban heat mitigation, biodiversity, water retention, and carbon capture, thereby linking urban logistics performance with wider urban sustainability outcomes.

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