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An Integrated Assessment of Battery and Hydrogen Electric Vehicles for Urban and Interurban Service Operations

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Abstract

Urban freight and service operations represent a critical challenge for cities, contributing to greenhouse gas emissions, congestion, and competition for curb space. In addition to parcel deliveries, many service trips combine transport with installation, maintenance, or packaging recovery, generating long vehicle dwell times and inefficient use of public space. This paper investigates alternative operational scenarios for such activities, evaluating technological and organizational options that can reduce their environmental and spatial impacts. The study compares a diesel LCV baseline with four zero-emission configurations: battery electric LCVs; battery electric LCVs integrated with micro-hubs and cargo e-bikes; hydrogen fuel cell LCVs for long-range operations, and hydrogen fuel cell LCVs combined with cargo e-bikes via micro-hubs. The methodological framework is based on a vehicle routing problem (VRP) formulation supported by empirical data from Rome. It integrates indicators of energy use, carbon emissions, and curb-side occupation, and it includes the spatial representation of routes on urban and inter-urban maps to highlight operational differences across the five scenarios. Results indicate that zero-emission vehicles can eliminate tailpipe emissions, while logistics reorganization through decoupling improves the use of public space and enables the recovery of packaging materials. Battery solutions appear best suited to short and medium distances, whereas hydrogen is advantageous for longer routes. Overall, the study shows that combining technological and organizational measures provides a robust pathway toward sustainable logistics and more efficient service operations in metropolitan contexts.

Keywords: city logistics; sustainable logistics; last-mile distribution; zero-emission vehicles; battery electric vehicles (BEVs); fuel cell electric vehicles (FCEVs); cargo e-bikes; micro-hubs; vehicle routing problem; curbside management

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1. Introduction

Urban freight transport represents one of the most complex and pressing dimensions of urban sustainable mobility. While essential for guaranteeing the continuous supply of goods and services to households, businesses, and institutions, freight operations generate significant externalities, including greenhouse gas emissions, local air pollutants, noise, congestion, and safety risks [1–3]. These impacts are disproportionately high compared to the share of freight vehicles in overall traffic, confirming the urgent need for policies and innovations that address logistics systems as a cornerstone of sustainable urban development, especially in the era of the on-demand economy [4,5].

At the policy level, the European Union has placed urban freight among its strategic priorities. The Sustainable and Smart Mobility Strategy sets targets for a 90 percent reduction in transport-related emissions by 2050 and requires zero-emission logistics in major urban centers by 2030 [6].

The academic literature, as shown in the following Section 2, confirms that freight cannot be treated as a homogeneous phenomenon. Instead, it involves a wide variety of demand patterns, vehicle types, and stakeholders, each with diverging objectives and perceptions of policy measures [1,2,7–9]. There is a range of conceptual and modeling approaches to understand and manage freight-related challenges. Taniguchi and Thompson [10] provide a structured framework for city logistics, showing how initiatives have evolved from basic access regulations to integrated strategies that combine technological, organizational, and governance measures. Several thematic areas have emerged as critical in shaping the sustainability of freight, including curbside management, packaging recovery, new operational models such as micro-hubs and cargo bikes, vehicle technologies such as battery electric vehicles (BEV) and fuel cell electric vehicles (FCEV), and digitalization and optimization.

In this context, the study aims to contribute to the literature by jointly addressing these five critical and interconnected thematic areas that are shaping the future of sustainable logistics. It evaluates the synergies and trade-offs that emerge when technological and organizational innovations are combined. In particular, it explores how the integration of zero-emission vehicle technologies with innovative operational models can contribute to the decarbonization and rationalization of urban and inter-urban freight. The study develops and compares multiple operational scenarios, ranging from conventional internal combustion vans to battery electric and hydrogen-powered light commercial vehicles (LCVs), both in stand-alone operation and in synergy with cargo bikes and micro-hubs.

The remainder of the paper is structured as follows. Section 2 reviews studies on the earlier recall thematic area of interest, while Section 3 describes the methodological approach used, including the modeling of operational flows and environmental assessment. Section 4 presents the definition of scenarios and their key performance indicators; Section 5 discusses the results of the comparative analysis, while Section 6 draws conclusions and highlights policy and research implications.

2. Background

The thematic areas, fundamental to shaping the sustainability of freight transport, which emerged from the state-of-the-art study, will be explored in the following subsections. First, the spatial organization of freight distribution is one of the most critical determinants of efficiency and sustainability in urban logistics [1,11,12]. Second, packaging waste has become one of the most visible and pressing externalities of modern freight distribution systems, requiring specific reverse logistics flows that are frequently neglected in planning [13]. Third, the evolution of city logistics is increasingly oriented toward innovative operational models such as micro-hubs and cargo bikes aimed at reducing the impact of traditional commercial vehicles, particularly in dense urban cores, and these innovations must be aligned with digital platforms and policy frameworks [14,15]. Fourth, the decarbonization of freight distribution is strongly linked to the technological evolution of vehicles; the shift toward battery electric and hydrogen fuel cell technologies is a key driver, but it requires careful assessment of energy infrastructures, operational constraints, and long-term sustainability [14,16]. Finally, digitalization is transforming urban freight logistics through advanced optimization and modeling tools that enhance planning and evaluation, supporting both public authorities and logistics operators in integrating vehicle routing, curbside management, and stakeholder needs [17].

2.1. Curbside Management

The management of curbside space is increasingly recognized as a bottleneck that determines the efficiency and equity of urban logistics [11,12,15]. In dense metropolitan areas, the limited availability of curbside space and its competing use for passenger vehicles, public transport, micromobility, and pedestrians often result in severe conflicts that directly affect the performance of freight operations [18]. Research has shown that curbside dynamics significantly influence travel times, emissions, and the cost structure of urban freight. The absence of available loading bays often forces delivery drivers to cruise in search of a parking spot, generating congestion and unnecessary emissions [19]. Operators usually consider the insufficient number of dedicated loading areas as the main obstacle to efficient urban logistics [20]. When legal curbside space is unavailable or too distant, carriers often internalize fines as a cost of doing business, perpetuating illegal parking practices [21]. Enforcement policies can reduce such behaviors, but their effectiveness depends on the balance between penalty levels, enforcement density, and delivery dwell times [22]. The challenge is further complicated by the coexistence of long-term land use dynamics and short-term operational requirements. As highlighted by Marsden et al., the curb is not only a physical boundary between road and sidewalk, but also a strategic urban resource that reflects power relations among different stakeholders and is continuously reshaped by new mobility services and technological innovations [20]. The intensification of demand caused by e-commerce, just-in-time delivery, and ride-hailing services has exacerbated existing tensions, requiring cities to reconsider how public space is allocated and regulated. Evidence suggests that more rational curbside allocation, combined with digital information services, can reduce cruising times, improve accessibility, and generate benefits not only for carriers but also for residents and local businesses [19,23]. In summary, the management of curbside and land use is central to the sustainability of urban freight. The challenge lies in balancing the competing demands of diverse stakeholders, ensuring efficient logistics while safeguarding urban quality of life. This balance requires a combination of planning instruments, regulatory innovation, enforcement, and digital tools, aligned with broader objectives of sustainable mobility and equitable use of public space. While models have explored driver behavior and enforcement policies, the direct impact of reorganizing logistics operations to fundamentally reduce curbside demand remains underexplored. This study explicitly quantifies the reduction in vehicle dwell time and public space occupation achieved through decoupled service models.

2.2. Packaging Recovery

The challenge of packaging and waste recovery has become increasingly relevant as cities move toward circular economy models, requiring specific reverse logistics flows that are frequently neglected in planning [13]. The European regulatory framework explicitly sets ambitious recycling targets, strengthens extended producer responsibility schemes, and calls for an increase in reusable packaging and reverse logistics flows to accelerate the transition toward a circular economy [24,25]. In the urban logistics context, the recovery of packaging waste is directly linked to the organization of service operations. Deliveries that involve the installation of goods, such as appliances or furniture, typically generate bulky packaging residues that are not always managed through conventional municipal waste systems. If these materials are not collected at the point of service, they often remain in the public space, contributing to the occupation of sidewalks, improper disposal, and social complaints. Conversely, integrating packaging recovery into delivery operations can mitigate these problems and create synergies between forward and reverse logistics. Recent case studies show the practical feasibility of integrating packaging recovery into innovative delivery models. Napoli et al. investigate a service pattern in Rome where electric LCVs are combined with cargo e-bikes dedicated to packaging collection. The results highlight that, compared to conventional models, this configuration can cut LCV parking times by more than 80 percent while enabling systematic collection of packaging waste at the customer site [26]. The introduction of micro-hubs not only facilitates these reverse flows but also enables the digital tracking of packaging recovery, aligning with broader urban sustainability objectives. At a strategic level, alternative consolidation practices, such as those identified by Verlinde et al., suggest that cooperative approaches to urban freight can also be extended to the reverse chain, reducing the number of vehicles required for waste recovery and optimizing vehicle load factors [27]. In essence, the management of packaging recovery in service operations is not merely a waste issue but a systemic component of sustainable logistics. It requires coherent regulatory frameworks, robust measurement tools, circular economy practices, and innovative service models. When adequately integrated, packaging recovery can reduce the environmental footprint of urban freight, alleviate pressure on public space, and generate added value for both logistics operators and urban communities. Our research integrates packaging recovery as a core component of the service cycle, evaluating its operational feasibility and contribution to circular-logistics objectives.

2.3. New Operational Models (Micro-Hubs and Cargo Bikes)

The evolution of city logistics is increasingly oriented toward innovative operational models aimed at reducing the impact of traditional commercial vehicles, particularly in dense urban cores. Micro-hubs, conceived as transfer and consolidation points, make it possible to decouple long-haul or interurban distribution from the last-mile delivery within city centers. By limiting the penetration of heavy or medium-duty vans into central areas, micro-hubs enable the final leg of distribution to be carried out with light electric vehicles or cargo bikes, achieving significant reductions in emissions, congestion, and road safety risks [28,29]. Several European and North American cities have already experimented with these solutions. In Rotterdam, simulation studies of alternative operational scenarios demonstrated that micro-hubs can substantially reduce vehicle-kilometers traveled and improve overall efficiency, provided that facilities are strategically located and embedded in integrated planning frameworks [30]. Similarly, in Seattle, a neighborhood-scale living lab tested the deployment of an e-cargo bike fleet operating from a micro-hub. Results showed significant reductions in van-kilometers traveled and associated CO_2 emissions, while also highlighting the importance of collaborative governance among logistics operators, municipalities, and local communities [31]. Cargo bikes represent one of the most promising instruments for short-range distribution. Studies conducted in Rome, Paris, and Lisbon showed that replacing motorized vans with cargo cycles can reduce local emissions, improve traffic fluidity, and enhance safety for vulnerable road users, albeit with clear limitations in payload capacity and operational autonomy [32–34]. In the Netherlands, the LEFV-LOGIC project provided empirical evidence that light electric freight vehicles and cargo bikes can be economically and environmentally competitive for specific flows, such as postal services, groceries, and convenience retail distribution [35]. Another key aspect concerns the optimal location of micro-hubs. Combining micro-hubs with cargo bikes and digitally supported routing platforms could underpin scalable distribution models, capable

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of addressing both environmental challenges and the equitable allocation of scarce urban space [36]. To sum up, while case studies have demonstrated their potential to reduce vehicle-kilometers and emissions, their application has largely been studied in the context of parcel delivery. This paper extends the analysis to more complex service trips and, critically, assesses the synergies of these models with a broader range of zero-emission vehicles, including hydrogen-powered LCVs.

2.4. Vehicle Technologies (BEV and FCEV)

The transition of vehicle technologies toward battery electric and hydrogen fuel cell solutions represents a fundamental driver of decarbonization, but requires careful evaluation of energy infrastructures, operational constraints, and long-term sustainability [14,16]. Battery electric vehicles (BEVs) have reached commercial maturity in the passenger segment and are increasingly penetrating LCV fleets, notwithstanding specific constraints related to range, charging times, and payload capacity [37,38]. Recent research on fuel cell bus deployment has further demonstrated the potential of hydrogen technologies in improving urban air quality and supporting large-scale zero-emission mobility transitions [39]. Experimental projects on small-scale electric vehicles for urban distribution have demonstrated their technical feasibility, while hybrid configurations combining fuel cells and batteries enable longer range and higher operational reliability, as confirmed by tests on PEM fuel cell–electric minibuses [40]. Infrastructure is a central element in the transition [41]. In the case of hydrogen refueling stations relying on onsite electrolysis, grid integration becomes a critical technical challenge. The coupling between renewable generation (e.g., photovoltaic or wind systems) and electrolyzers requires advanced power-flow management to address intermittency and voltage stability issues. Recent research highlights the role of self-coordinated voltage–power inverter systems as a viable solution to manage distributed renewable inputs while maintaining grid reliability. Such approaches are essential for ensuring that hydrogen infrastructure expansion aligns with broader energy-system stability objectives. The design of multi-purpose charging and refueling systems has been proposed to facilitate synergies between passenger and freight fleets, ensuring interoperability and efficient use of resources [42]. Empirical case studies conducted in Sicily show how electric LCVs can already perform urban and peri-urban deliveries when supported by adequate charging availability and route optimization, although challenges remain in terms of infrastructure density and integration with renewable energy sources [43,44]. More recent applications in Rome further highlight the potential of electric vans in decoupled delivery-service models, especially when combined with cargo bikes and reverse logistics flows [26,45]. The potential integration of BEVs with the electricity grid through vehicle-to-grid (V2G) services could further increase their attractiveness, allowing logistics operators to participate in energy markets while improving system flexibility [46,47]. Beyond the conceptual benefits, recent advances in power coordination and inverter control for distributed energy resources have demonstrated that voltage–power self-coordination mechanisms can enhance grid stability during bidirectional energy exchange. These control strategies are particularly relevant for fleet-based V2G aggregation, where simultaneous charging and discharging cycles require stable interaction with local distribution networks. Fuel cell electric vehicles (FCEVs) represent a complementary pathway for freight decarbonization, particularly suited for medium- and long-distance operations. Hydrogen-powered vans and trucks eliminate local emissions while maintaining short refueling times and operational ranges above 300 km, overcoming some of the main limitations of BEVs. Global assessments underline that hydrogen is expected to play a major role in transport decarbonization beyond 2030, with cost reductions in green hydrogen production and storage technologies progressively improving competitiveness [48]. Frameworks such as Dynamic Freight

Management emphasize that the effectiveness of vehicle technologies depends not only on technical parameters but also on their integration into broader logistics systems, including data-driven decision-making, dynamic curbside allocation, and energy optimization [49], requiring the use of advanced monitoring and predictive methods, including soft sensors, that can mitigate the limitations of small or incomplete datasets. In short, the technological transition of freight vehicles is not a linear substitution of diesel LCVs with BEVs or FCEVs, but rather a systemic transformation that requires infrastructure planning, integration with energy systems, and alignment with operational models. Only by combining these elements can urban freight logistics achieve a durable reduction in emissions while meeting the reliability and flexibility requirements of modern supply chains. Our study provides a nuanced comparison by embedding both BEVs and FCEVs within conventional and innovative (decoupled) logistics frameworks, thereby identifying their optimal use cases based on a combination of mission profile and organizational model.

2.5. Digitalization and Optimization

Digitalization and advanced modeling methods are transforming how logistics is planned and evaluated, offering new opportunities for integrating vehicle routing, curbside management, and stakeholder needs [17]. Digitalization has become a cornerstone of modern urban freight logistics, enabling advanced optimization techniques and new planning tools that support both public authorities and logistics operators. Decision-support tools have been developed to optimize freight routing and scheduling in urban contexts, demonstrating that well-structured simulation environments can significantly improve efficiency and reduce congestion [50]. A central area of development concerns the Vehicle Routing Problem (VRP) and its many variants, which remain at the core of freight optimization. Seminal algorithms, such as large neighborhood search heuristics [51] and open-source solvers [52], have expanded the applicability of VRP models to complex, real-world instances, including multi-depot, time-windowed, and dynamic demand settings. Extensions of the VRP to urban freight allow for the integration of service trips, parking constraints, and congestion effects, providing a more realistic representation of operational conditions [53]. Recent advances in computational science further enhance these optimization capabilities. Hybrid frameworks integrating artificial intelligence, heuristics, and exact methods have been tested in transport and logistics applications, showing the potential to solve large-scale problems in real time [54]. Integration between network design and routing is another field of innovation. This is particularly relevant in congested urban areas, where infrastructure capacity, signal regulation, and freight flows must be co-optimized [55]. Research on optimal micro-hub placement within multimodal logistics networks demonstrates how mathematical programming and approximation techniques can determine strategic facility locations, balancing operational costs and environmental objectives [56]. Moreover, methodological reviews emphasize that the adoption of advanced routing frameworks and decision-support systems is not purely a technical choice but also a governance issue, requiring collaboration across public and private actors to ensure effective implementation (RTBM accepted manuscript). To conclude, digitalization, optimization methods, and advanced computational frameworks are reshaping urban freight logistics. They enable the simulation, design, and operation of delivery systems that are simultaneously more efficient and more sustainable, thus supporting the transition toward integrated models of city logistics. This paper proposes a comprehensive VRP-based methodological framework to model and compare novel, multi-tier scenarios. This allows for a robust, quantitative assessment of complex systems that integrate different technologies, operational tiers, and performance indicators, including energy consumption, emissions, and curbside use.

2.6. Thematic Integration and Gap Identification

Urban freight transport constitutes a crucial yet complex component of contemporary city systems. On one hand, it plays an essential role in sustaining urban economies and ensuring the timely delivery of goods and services that support everyday life; on the other hand, it poses significant challenges, as it contributes to environmental pressures, competes for limited urban space, and often conflicts with broader goals of sustainable mobility and urban livability.

Both academic literature and policy frameworks emphasize the need for systemic approaches that integrate technological innovation, organizational change, and effective governance mechanisms. Such approaches are essential to align the diverse interests of stakeholders with the overarching objectives of building sustainable, efficient, and livable urban environments. Despite the extensive literature on city logistics, many studies address technological transitions, organizational measures, routing optimization, or spatial and curbside issues as largely independent dimensions. Conceptual frameworks such as those proposed in [10] provide a valuable systemic view, yet their empirical application often focuses on single interventions, limiting the ability to assess interactions and trade-offs across multiple dimensions. As a result, evidence on how different vehicle technologies and service organization models jointly affect energy use, emissions, routing efficiency, and curbside occupation remains fragmented [57–59].

This study advances the existing literature by adopting a cross-dimensional assessment framework that integrates vehicle technologies (BEV and FCEV), routing optimization, and alternative service organization models within a unified, scenario-based analysis. By grounding the comparison in empirical service-operation data and a consistent VRP formulation, the proposed approach enables a coherent evaluation of integrated solutions and clarifies the conditions under which coordinated technological and organizational innovations outperform isolated measures in urban and inter-urban service operations.

Table 1 summarizes the main thematic areas identified through the literature review, along with the related research gaps. Together, these elements provide an overview of the current state of knowledge and point to promising directions for future research.

Table 1. Summary of Thematic Areas and Research Gaps.

Thematic Area	Main Articles	Current State of Knowledge	Gaps Covered by the Current Paper
1. Curbside Management	[18,19,21,22]	Curbside space is a contested and critical bottleneck. Poor management leads to cruising for parking, double parking, congestion, and increased emissions.	Quantifies the significant reduction in LCV curbside occupation by decoupling delivery and service tasks through micro-hubs, offering a direct operational solution to space competition.
2. Packaging Recovery	[24–27]	Reverse logistics are essential for a circular economy, but are often neglected in urban freight planning. Service operations generate significant packaging waste.	Integrates packaging recovery directly into the daily operational model of decoupled scenarios and evaluates it as a key performance indicator, linking logistics efficiency with circular economy goals.
3. New Operational Models (Micro-hubs and Cargo Bikes)	[29,31,32,34,36]	Micro-hubs and cargo bikes are proven to be effective for last-mile delivery, reducing emissions and vehicle-kilometers traveled in dense urban areas.	Assesses the synergy of these models with both BEV and FCEV technologies, extending their applicability beyond standard parcel delivery to complex service trips and combined urban/inter-urban missions.
4. Vehicle Technologies (BEV and FCEV)	[27,52,54,55]	BEVs are efficient for short/medium-range urban routes, while FCEVs are advantageous for longer routes (>150 km) due to superior range and fast refueling.	Provides a comparative assessment of BEVs and FCEVs not just as standalone technologies, but within integrated, multi-tier logistics systems to identify their optimal operational niches and synergies.

Table 1. *Cont.*

Thematic Area	Main Articles	Current State of Knowledge	Gaps Covered by the Current Paper
5. Digitalization and Optimization	[13,41–43]	Vehicle Routing Problem (VRP) frameworks are the standard for optimizing freight routes to improve efficiency and reduce costs.	Applies a VRP-based framework to model and holistically compare novel and complex scenarios that combine different technologies (BEV/FCEV) and organizational structures (single vs. two-tier), using an integrated set of indicators.

3. Materials and Methods

The methodological framework adopted to assess the performance of alternative urban freight transport configurations is presented, including the study area and data sources, the definition of operational scenarios, the modeling approach for demand, routing, and scheduling, and indicators used for post-processing and evaluation.

3.1. Study Area and Data

The empirical application is set in the Metropolitan City of Rome, a polycentric urban region characterized by a dense historic core, extensive limited traffic zones (ZTL), and heterogeneous land uses that generate short delivery tours alongside service trips requiring prolonged curb occupation. In this context, freight demand interacts strongly with passenger mobility and with the regulated allocation of public space, which motivates the integration of freight into strategic mobility planning and freight-specific instruments [11,12,60].

Since comprehensive tracking datasets for freight vehicles were not available for this study, the demand layer was generated synthetically, but consistently with the spatial distribution of urban functions and the regulatory framework identified in municipal planning documents. In particular, the operational scenarios were developed in coherence with case studies provided by logistics operators active in the metropolitan area of Rome, whose practices and service patterns offered empirical evidence on vehicle types, delivery frequencies, spatial coverage, and dwell times. The reference missions were designed to represent three distinct spatial scales—dense urban core (within the GRA), suburban/peri-urban extensions, and regional interurban corridors—so as to capture heterogeneous operational contexts rather than focusing exclusively on the city center.

Although comprehensive GPS trajectory datasets were not available, the demand layer was generated synthetically and calibrated against operator-validated operational parameters and planning documents. The objective is therefore to ensure scenario realism and internal consistency across configurations, rather than to construct a statistically representative survey of the entire freight population. This approach supports comparative evaluation under controlled and transparent assumptions.

Synthetic delivery and service stops were located coherently with land use patterns and freight demand poles identified in municipal planning documents, with specific attention to activities that typically generate installation-related service trips and packaging recovery needs. Temporal attributes were assigned to reproduce typical peaks of retail, e-commerce, and service operations, while dwell times were drawn from distributions calibrated on existing literature and comparable case studies [61].

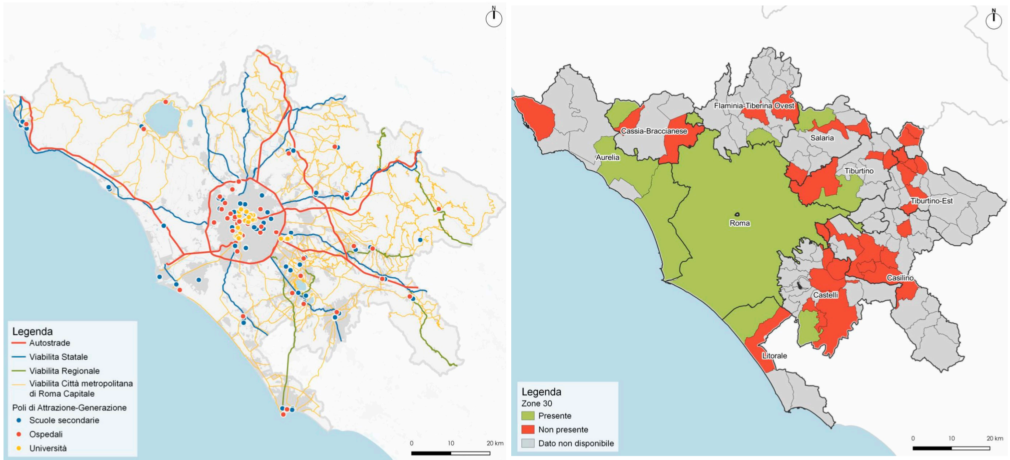
The transport network combines urban arterial and local streets with time-dependent speed profiles to capture recurrent congestion. The curbside layer includes authorized loading bays and their regulatory attributes, such as time windows and vehicle categories, complemented by assumptions on informal stopping practices where dedicated space is scarce. This allows us to explicitly represent the competition for curb space and the operational consequences of cruising for parking, double parking, and enforcement intensity [19,22,62–64].

Fleet characterization covers four vehicle classes aligned with the scenarios discussed in the Introduction, namely a conventional light commercial van, a battery electric van, a fuel cell electric van for extended range missions, and a cargo e-bike used in combination with a micro-hub for decoupled delivery service models. Technical parameters, such as energy consumption profiles, effective payload, and charging or refueling times, are specified at the scenario level based on established methodological contributions and recent applications in urban freight, deferring numerical calibration to the scenario section to keep the methodological description general and transferable [43,44,47,51,52,65–69].

To contextualize the study area, Figure 1a shows the main traffic generation and attraction poles of the Metropolitan City of Rome, overlaid on the road network. This representation highlights the concentration of freight demand inside the GRA (Grande Raccordo Anulare) and along the main arterial corridors, confirming the relevance of these locations for last-mile distribution and service trips. Complementarily, Figure 1b illustrates the distribution of traffic restricted zones (ZTL), which constitute one of the most binding regulatory constraints for freight operations, directly affecting vehicle accessibility and curbside availability [60]. Three representative service missions, labeled Route A, Route B, and Route C, were designed through Google My Maps and calibrated to Rome's operational context. The routes reproduce typical daily activities involving the delivery and installation of large household appliances, derived from [11,12,60]. They represent progressive spatial scales, Urban (within GRA) concentrated in the city core, Suburban (urban–peri-urban) extending across the outer ring toward nearby municipalities, and Inter-urban (regional) linking Rome with more distant regional destinations. Their schematic layout is shown in Figure 2. Each route served as a reference for testing five service patterns (SP1–SP5), combining different vehicle technologies and delivery configurations. A 30 min nominal dwell time per stop was assumed for LCVs, with an 8 h daily operating window and payload between 0.8 and 1.2 t. Energy-consumption factors were 0.20–0.23 kWh km^{-1} for BEVs and 0.011–0.012 kg H_2 km^{-1} for FCEVs [45,63], with maximum operational ranges of 150 km (BEV) and 450 km (FCEV). Within these limits, BEVs are feasible for Routes A and B, while FCEVs cover all three without mid-shift recharging or refueling. Field evidence confirms that many operators exceed authorized dwell times or double-park due to scarce loading bays, justifying decoupled service configurations (SP3 and SP5), where LCVs unload at micro-hubs and cargo e-bikes perform last-mile delivery and packaging recovery, substantially reducing curb occupation (≈85 min day^{-1} for the LCV) while maintaining service continuity. Quantitative inputs for the three routes are summarized in Table 2.

Data harmonization follows a common schema across layers. Each stop is linked to the nearest feasible curb segment and to a time window. The network graph is simplified to preserve turning penalties and access regulations, and the curb inventory is cleaned to remove duplicates and inactive bays. Quality checks include spatial consistency tests, basic descriptive statistics on stop density and dwell times, and face validation against planning documents. When empirical samples are small or partially incomplete, we complement observations with conservative priors and smoothing techniques inspired by applications that address limited datasets, to stabilize parameter estimation without overfitting [70].

This integrated dataset provides the inputs for the routing and scheduling model, for the curb allocation module, and for the energy and emissions assessment. The resulting framework supports a consistent comparison across operational scenarios while keeping the assumptions transparent and traceable to planning evidence, case study evidence from logistics operators, and peer-reviewed methods. The next subsection introduces the operational scenarios against which these data layers are applied.



(**a**) (**b**)

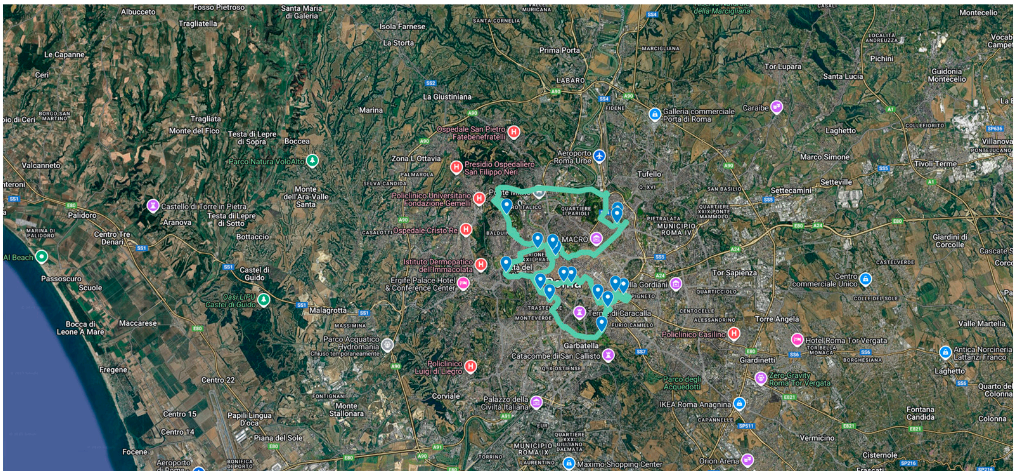
Figure 1. (**a**) Main traffic generation and attraction poles in the Metropolitan City of Rome. (**b**) Distribution of restricted traffic zones (ZTL) in the Metropolitan City of Rome.

3.2. Operational Scenarios

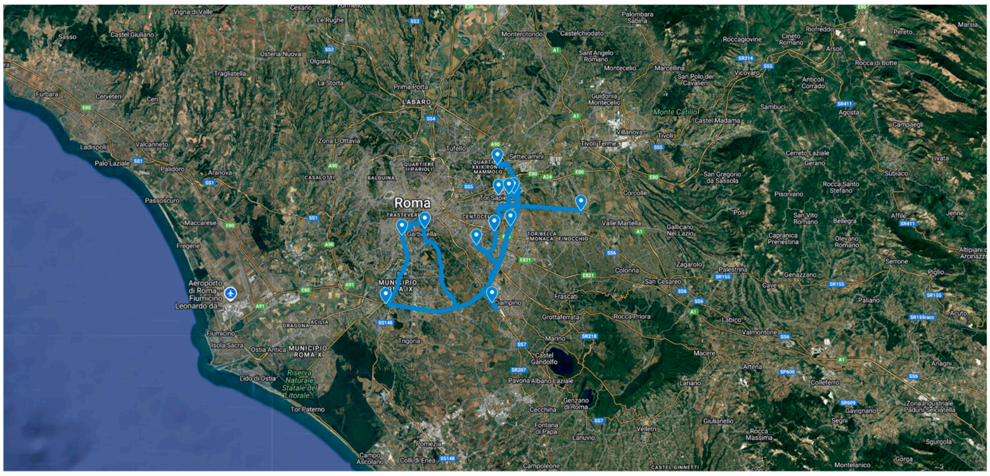
To evaluate the combined effects of vehicle technology and logistics configuration on service operations, five Scenario Patterns (SP) were defined, identified as SP1 to SP5. Each SP represents a distinct combination of propulsion system and organizational model, allowing a comparative analysis of technological and operational synergies. All configurations are assessed under consistent boundary conditions, assuming the same service demand, time constraints, and an eight-hour operational window representative of typical delivery and installation activities within the metropolitan area of Rome.

The scenarios can be summarized as follows:

- SP1 represents the current operational practice, where conventional LCVs perform the entire delivery and service cycle without intermediate trans-shipment; this configuration serves as the baseline for comparing subsequent innovations in technology and logistics [71];
- SP2 considers a full electrification of LCVs, maintaining the same single-tier service structure as SP1; battery electric LCVs are characterized by a realistic autonomy of 150 km per full charge, accounting for partial payload, stop-and-go conditions, and accessory use such as air conditioning or heating [45];
- SP3 introduces a decoupled configuration, where battery electric LCVs deliver goods to one or more micro-hubs from which cargo e-bikes complete the last-mile distribution and recover returnable packaging; this two-tier structure reduces LCV curbside occupation and enables a more flexible allocation of tasks between delivery and installation teams [72];
- SP4 includes hydrogen fuel cell LCVs operating in a single-tier structure without intermediate hubs; this scenario targets extended-range missions exceeding 150 km, where battery electric vehicles would require mid-shift recharging or face operational limitations; the configuration isolates the technological contribution of hydrogen propulsion to long-range zero-emission operations [73];
- SP5 combines hydrogen fuel cell LCVs with cargo e-bikes operating from micro-hubs; hydrogen vehicles perform trunk deliveries between the depot and peripheral or semi-central hubs, while e-bikes handle the local distribution and packaging recovery; this scenario explores the potential integration between hydrogen propulsion and decoupled service models, especially for missions combining regional travel with urban service operations [74].



(**A**)



(**B**)

(**C**)

Figure 2. Schematic representation of the three reference routes (Urban—(**A**), Suburban—(**B**), and Inter-urban—(**C**)) and corresponding service areas within the Rome metropolitan region. Map data © 2025 Google; imagery extracted from Google My Maps for illustrative purposes.

Table 2. Key parameters for the three reference routes.

Route	Spatial Scope	Total Distance (km)	Daily Stops (*n*)	Average Speed ($km\ h^{-1}$)	Representative Areas/Corridors
A—Urban	Within GRA	48	15	22	Historic core and semi-central districts (e.g., Prati, Testaccio, San Giovanni)
B—Suburban	Urban–peri-urban	99	12	40	Peripheral zones and municipalities outside GRA (e.g., Fiumicino, Pomezia)
C—Inter-urban	Regional	250	6	70	Regional corridors to Latina, Velletri, Viterbo, and beyond

Constant parameters: dwell time = 30 min per stop; operating window = 8 h day^{-1}; payload = 0.8–1.2 t; BEV range = 150 km; FCEV range = 450 km; energy consumption = 0.20–0.23 kWh km^{-1} (BEV) and 0.011–0.012 kg H_2 km^{-1} (FCEV).

Figure 3 illustrates the five Scenario Patterns by combining vehicle technology (horizontal axis) and service configuration (vertical axis). The matrix highlights the progressive transition from conventional to zero-emission technologies and from single-tier to decoupled logistics models.

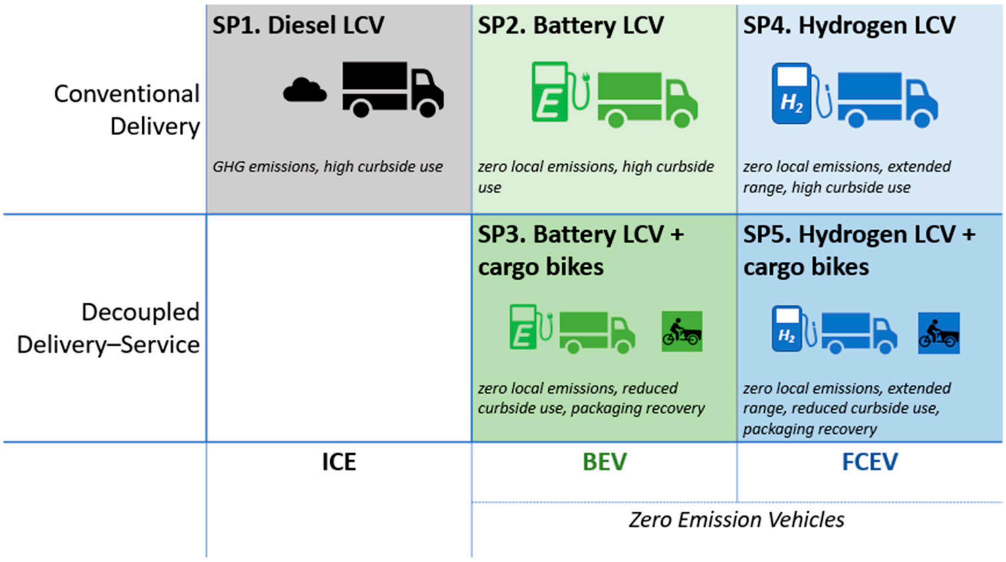


Figure 3. Matrix representation of the five Scenario Patterns (SP1–SP5) combining vehicle propulsion type and operational model.

The main assumptions for each configuration are summarized in Table 3. The table reports the type of main vehicle and auxiliary means, the energy carrier, range assumptions, required infrastructures, and the overall operational model. These parameters are harmonized to enable a consistent comparison among the scenarios and to support the analytical modeling presented in the following sections. For clarity, ECS refers to electric charging stations for battery electric vehicles, while HRS denotes hydrogen refueling stations used by fuel cell electric vehicles.

3.3. Modeling of Demand, Routing, and Scheduling

The methodological framework integrates a statistical-descriptive demand-generation module with a routing and scheduling engine designed to simulate daily freight and service operations under the five operational scenarios described in Section 3.2. The routing and schedule modeling approach follows the structure of the vehicle routing problem with time-windows (VRPTW), extended to capture the specific constraints of electric mobility, decoupled distribution schemes, and curbside occupation dynamics.

Table 3. Assumptions for the five operational scenarios.

Scenario	Main Vehicle	Auxiliary Means	Energy Carrier	Range Assumption	Infrastructure Needs	Operational Model
SP1	Diesel	None	Diesel	500 km	Conventional refueling stations	Conventional
SP2	Battery electric	None	Electricity	150 km	Depot and public charging points (ECS)	Conventional
SP3	Battery electric	Cargo e-bikes, micro-hubs	Electricity	150 km (LCV), 20–30 km (bike)	Depot and public charging points (ECS), micro-hubs	Decoupled
SP4	Fuel cell electric	None	Hydrogen	450 km	Depot and public charging points (HRS)	Conventional
SP5	Fuel cell electric	Cargo e-bikes, micro-hubs	Hydrogen	450 km (LCV), 20–30 km (bike)	Depot and public charging points (HRS), micro-hubs	Decoupled

The demand layer is composed of an empirical set of delivery and service stops representing typical daily operations of logistics and installation activities within the metropolitan and regional area of Rome.

The design of the statistic-descriptive demand was developed in collaboration with a major logistics operator active across the metropolitan and regional territory, ensuring that the assumed operational patterns, delivery frequencies, and service typologies are coherent with real business practices. This cooperation enabled the model to integrate representative values for vehicle load factors, delivery densities, and temporal profiles, thus improving the realism of the simulated operations. Each stop i is associated with a spatial coordinate, a quantity to deliver q_i, a service duration s_i, and a time window $[a_i, b_i]$.

The spatial distribution of stops is derived from the density of demand poles identified in municipal planning documents and refined using the operator's empirical insights regarding delivery hotspots and high-demand zones. The temporal distribution reproduces the morning and early-afternoon concentration typical of urban freight activities, in accordance with access restrictions and commercial opening times.

Three categories of stops are defined:

- parcel deliveries, with short service times (<10 min);
- bulky goods deliveries and installation services, requiring on-site work (20–60 min);
- packaging recovery tasks, representing reverse logistics operations, either independent or linked to installation visits.

Each vehicle is assigned a daily workload consistent with its operational range, capacity, and time constraints. The number of stops per tour and the total travel time are adjusted according to the energy system: battery electric LCVs are constrained by an effective range of up 150 km, while fuel cell electric LCVs (FCEVs) are introduced when mission distances exceed 150 km, assuming an operational range of approximately 450 km consistent with the assumptions reported in Table 2 or when operating conditions, such as payload, dwell time, or absence of charging opportunities, render BEVs impractical.

Let $G\ (N, A)$ be a directed graph where $N = \{0, 1, 2, \ldots, \mathrm{n}\}$ represents the set of nodes, with 0 denoting the depot (or micro-hub), and A the set of links connecting them. Each link (i, j) has an associated distance d_{ij} and travel time t_{ij} (the travel time is calculated considering the level of congestion).

The routing problem aims to minimize total travel time (t_{ij}) and service time (s_i) across all vehicles $k \in K$:

$$min\ Z = \sum_{k \in K} \sum_{i \in N} \sum_{j \in N} \left(t_{ij} + s_i\right) x_{ijk} \quad (1)$$

subject to:

$$\sum_{k \in K} \sum_{j \in N} x_{0jk} = |K| \qquad j \neq 0 \quad (2)$$

$$\sum_{i\in N} x_{iuk} - \sum_{j\in N} x_{ujk} = 0 \qquad \forall\, u \in N \setminus \{0\}, k \in K \tag{3}$$

$$\sum_{i\in N}\sum_{j\in N} q_i x_{ijk} \le Q_k \qquad \forall\, k \in K \tag{4}$$

$$a_i \le T_i \le b_i \qquad \forall\, i \in N \setminus \{0\} \tag{5}$$

$$\sum_{i\in N}\sum_{j\in N} d_{ij} x_{ijk} \le R_k \qquad \forall\, k \in K \tag{6}$$

$$x_{ijk} \in \{0,\ 1\} \qquad \forall\, i,\ j \in N, k \in K \tag{7}$$

where Q_k is the payload, $[a_i,\ b_i]$ is the time window for customer i, R_k = 150 km for BEVs, and R_k = 450 km for FCEVs, while T_{i} denotes the service start time at node i. The constraints ensure the logical consistency of each vehicle route: Equation (2) enforces vehicle departure from the depot, (3) guarantees flow conservation so that each visited node has one incoming and one outgoing link, (4) limits the total delivered quantity to the vehicle capacity, (5) constrains service start times within customer time-windows, (6) restricts the total traveled distance within the vehicle's range, and (7) defines binary decision variables.

The solution process applies a hybrid heuristic combining Clarke–Wright savings and nearest-neighbor sequencing under time-window and range constraints, following [52,75].

For the decoupled scenarios, a two-tier routing structure is applied to SP3 and SP5, representing upper-tier LCVs and lower-tier cargo e-bikes. LCVs deliver goods from the depot to micro-hubs $h \in H$, and e-bikes distribute them to customers. During the optimization procedure, vehicles starting from a micro-hub h serve a subset N_h (one subset for each micro-hub h) of customers. Under these assumptions, the problem can be formulated as in Equation (8).

$$min\ Z = \alpha \sum_{k\in K1}\sum_{i,j\in N} t_{i,j} x_{i,j,k} + \beta \sum_{m\in K2}\sum_{p,q\in Nh} t_{p,q} y_{p,q,m} \tag{8}$$

with flow conservation at hubs:

$$\sum_{i\in Nh} q_i = \sum_{k\in K1} q_h^k \qquad \forall\, h \in H \tag{9}$$

where $K1$ and $K2$ are the sets of upper-tier vans and lower-tier cargo e-bikes, α and β are the weights for time and energy costs across tiers, and $y_{p,q,m}$ is the problem variable.

Heuristic optimization combines Clarke and Wright savings with nearest-neighbor sequencing under time-window, capacity, and range constraints, with local search refinements to improve feasibility and tour compactness.

Each tour is scheduled within an 8 h operational window with a temporal granularity of 10 to 15 min, consistent with typical business opening times and access regulations. The cumulative tour duration for vehicle k is constrained by

$$\sum_{i\in N}\sum_{j\in N} (t_{ij} + s_i) x_{ijk} \ \le\ \Gamma \qquad \forall\, k \in K \tag{10}$$

with Γ set to 8 h. Depot and micro-hub operations are bounded by global time-windows $[\mathrm{A_{start}},\ \mathrm{A_{end}}]$ that constrain departure and return times of each route, so that $\mathrm{T_{0,k}} \in [\mathrm{A_{start}},\ \mathrm{A_{end}}]$ and $\mathrm{T_{return,k}} \le \mathrm{A_{end}}$.

Curbside allocation is modeled by assigning each stop to the nearest feasible curb segment within a fixed search radius. When no dedicated loading space is available, a penalty τ_p is added to the service duration s_i to represent search and maneuvering time. The cumulative value of $s_i + \tau_p$ across all tours provides the measure of total curbside occupation used later for scenario comparison.

For reproducibility purposes, the routing model adopts deterministic travel times derived from average congestion profiles associated with each route category (urban, suburban, inter-urban). Stochastic variability in traffic conditions is not explicitly simulated within the optimization procedure; instead, average speeds are calibrated ex ante based on empirical observations and planning documents. Sensitivity analysis on the maximum tour duration G partially captures the impact of operational variability.

Energy replenishment is modeled through range constraints rather than explicit charging or refueling functions. Battery electric vehicles are assumed to operate within a maximum daily range of 150 km without mid-shift charging, while fuel cell vehicles operate within a 450 km range without intermediate refueling. Charging and refueling times are therefore not optimized endogenously but implicitly incorporated through feasibility constraints.

Vehicle capacity constraints are enforced through the payload limit Q_k (0.8–1.2 t), and service times s_i are fixed at representative values derived from operator interviews and literature benchmarks. These assumptions ensure consistency and comparability across scenarios while maintaining computational tractability.

The model outputs include total distance and time, vehicle utilization, energy demand proxies, and aggregate curbside occupation per scenario. These quantities are intermediate variables that feed the environmental and operational indicators introduced in Section 3.4 and quantitatively analyzed in Section 4. To assess the robustness of the model with respect to operational time constraints, a sensitivity analysis will be performed in Section 4 by varying the maximum tour duration Γ within the interval {6 h, 8 h, 10 h}. This test aims to reflect possible seasonal peaks or extended shifts in real operations and to evaluate their impact on vehicle utilization, energy demand, and curbside occupation.

3.4. Definition of Indicators and Post-Processing Framework

The post-processing phase transforms routing and scheduling outputs into operational, environmental, and energy performance indicators suitable for comparing the five operational scenarios. Quantitative metrics derived from simulated vehicle movements are combined with energy conversion and emission factors consistent with European standards. For each vehicle k, the model provides total distance traveled D_k, travel time T_k, and curbside occupation S_k. Aggregated values, whose characteristics are shown in Table 3, are obtained as:

$$D_{tot} = \sum\nolimits_{k \in K} D_k \tag{11}$$

$$T_{tot} = \sum\nolimits_{k \in K} T_k \tag{12}$$

where T_k denotes the total travel and service time of vehicle k within the daily working horizon $\mathit{\Gamma}$.

The aggregate indicator for curbside occupation is:

$$S_{tot} = \sum\nolimits_{k \in K} S_k \tag{13}$$

Average distance per stop and average service time per operation are computed by dividing each total quantity by the number of stops n_s.

Vehicle utilization rate U_v represents the ratio between effective operating time and the 8 h daily window $\mathit{\Gamma}$:

$$U_v = \frac{T_k + S_k}{\Gamma} \tag{14}$$

Curbside occupation per operation, expressed in minutes per stop, is used as a proxy for public-space efficiency.

Energy demand for each vehicle is obtained from its specific consumption e_k (kWh/km for BEVs, kg H_2/km for FCEVs, L/km for ICE):

$$E_k = D_k * e_k \tag{15}$$

$$E_{tot} = \sum_{k \in K} E_k \quad (16)$$

Total equivalent CO_2 emissions are estimated as

$$co_{2,tot} = \sum_{k \in K} D_k * \rho_k \quad (17)$$

where ρ_k is the technology-specific emission factor (g CO_2/km), using well-to-wheel values for electricity and hydrogen. Two indicators summarize overall efficiency:

$$\eta_E = \frac{D_{tot}}{E_{tot}} \quad (18)$$

$$\eta_C = \frac{D_{tot}}{CO_{2,tot}} \quad (19)$$

η_E measures operational energy efficiency (km/kWh or km/kg H_2) and η_C emission efficiency (km/g CO_2). For scenarios involving micro-hubs and cargo e-bikes, packaging recovery rate and reduction in curbside occupation are introduced:

$$R_p = \frac{W_{rec}}{W_{del}} \quad (20)$$

$$\Delta S = \frac{S_{SP1} - S_{SPX}}{S_{SP1}} \cdot 100, \qquad x \in \{3, 5\} \quad (21)$$

For clarity, all variables used in the equations are consistently defined across the routing and post-processing framework. In particular, D_k, T_k, and S_k, respectively, denote the total distance traveled, total travel + service time, and curbside occupation of the vehicle k; H is the 8 h working horizon; e_k is the specific energy consumption (kWh km^{-1} for BEVs, kg H_2 km^{-1} for FCEVs, L km^{-1} for ICE LCVs); E_k is the total daily energy demand; and U_k represents the vehicle-utilization rate. η_E and η_C indicate energy- and emission-efficiency ratios, while P_{rec} and ΔS_x measure packaging-recovery performance and curb-time reduction for the decoupled patterns (SP3, SP5). All time-related quantities are expressed in hours unless otherwise stated.

A sensitivity analysis will be conducted on three parameters, namely the maximum tour duration Γ, the technology threshold between BEVs and FCEVs, and the electricity emission factor reflecting the renewable share of the Italian mix. This will test the robustness of the indicators under realistic operational fluctuations. To provide a unified view of the parameters and metrics derived from the routing and scheduling model, Table 4 reports the full set of performance indicators considered in this work, including their notation, units of measurement, and intended analytical use.

Table 4. Summary of performance indicators.

Category	Symbol	Indicator Description	Unit	Scope
Operational indicators	D_{tot}	Total distance traveled	km	Fleet productivity
	T_{tot}	Total travel time	h	Operational duration
	S_{tot}	Total curbside occupation	min	Space efficiency
	U_v	Vehicle utilization rate	-	Temporal efficiency
Energy and emission indicators	E_{tot}	Total energy demand	kWh/kg H_2/L	Energy performance
	$CO_{2,tot}$	Total equivalent CO_2 emissions	kg CO_2	Environmental impact
Comparative efficiency metrics	η_E	Energy efficiency (distance per energy unit)	km/kWh or km/kg H_2	Technology comparison
	η_C	Emission efficiency (distance per g CO_2)	km/g CO_2	Sustainability comparison

Table 4. *Cont.*

Category	Symbol	Indicator Description	Unit	Scope
Circular-logistics indicators	R_P	Recovered packaging	-	Circular-logistics performance
	ΔS	Reduction in curbside occupation vs. baseline	%	Public-space benefit

4. Results

The quantitative evaluation of the five service patterns (SP1–SP5) was performed for the three reference routes defined in Section 3.1. Each configuration was assessed in terms of total daily energy consumption, avoided CO_2 emissions, and curbside occupation. The results, summarized in Table 5, highlight how vehicle technology and delivery organization jointly affect environmental and operational performance.

Table 5. Summary of operational results for Routes A–C.

Route (Distance, Stops)	Service Pattern	Energy Consumption (kWh day^{-1}/kg H_2 day^{-1}/L Diesel)	CO_2 Avoided (kg day^{-1} vs. ICE)	LCV Curb Time (min day^{-1})	Curb Reduction vs. Baseline (%)	Packaging Recovery
A—Urban (48 km, 15)	SP1 (ICE baseline)	4.8 L → 12.5 kg CO_2 emitted	–	450	–	No
	SP2 (BEV)	9.6 kWh	≈12.5	450	0	No
	SP3 (BEV + cargo e-bikes)	9.6 kWh	≈12.5	85	81%	Yes
	SP4 (FCEV)	0.53 kg H_2	≈12.5	450	0	No
	SP5 (FCEV + cargo e-bikes)	0.53 kg H_2	≈12.5	85	81%	Yes
B—Suburban (99 km, 12)	SP1 (ICE baseline)	9.9 L → 25.8 kg CO_2 emitted	–	360	–	No
	SP2 (BEV)	20.8 kWh	≈25.8	360	0	No
	SP3 (BEV + cargo e-bikes)	20.8 kWh	≈25.8	85	76%	Yes
	SP4 (FCEV)	1.09 kg H_2	≈25.8	360	0	No
	SP5 (FCEV + cargo e-bikes)	1.09 kg H_2	≈25.8	85	76%	Yes
C—Inter-urban (250 km, 6)	SP1 (ICE baseline)	25 L → 65.3 kg CO_2 emitted	–	180	–	No
	SP2 (BEV)	N/A (range > 150 km)	–	N/A	N/A	–
	SP3 (BEV + cargo e-bikes)	N/A (range > 150 km)	–	N/A	N/A	–
	SP4 (FCEV)	3.00 kg H_2	≈65.3	180	0	No
	SP5 (FCEV + cargo e-bikes)	3.00 kg H_2	≈65.3	85	53%	Yes

Diesel baseline assumes 10 L 100 km^{-1} and 2.61 kg CO_2 L^{-1}. Dwell = 30 min per stop; decoupled patterns (SP3/SP5) set LCV curb time ≈ 85 min day^{-1}. "N/A" = not applicable (scenario infeasible due to range).

After presenting the quantitative results in Table 5, the analysis proceeds to a more detailed evaluation of the operational, energetic, and circular-logistics indicators defined in Table 3. These indicators were computed for each route and service pattern to provide a consistent comparison of vehicle technologies (BEV, FCEV) and organizational configurations (direct versus decoupled). The resulting values, summarized in Table 6, allow an integrated reading of energy demand, emission savings, curbside performance, and packaging-recovery effectiveness across all five patterns (SP1–SP5). The travel time reported in Table 6 corresponds to the primary route driving time, computed as the ratio between total route distance and average speed. As the reference route geometry and speed assumptions remain constant, this value does not vary across service patterns (SP1–SP5). In the decoupled configurations (SP3 and SP5), micro-hubs and cargo e-bikes affect curbside occupation and operational task allocation, while the trunk driving segment performed by the main vehicle remains unchanged. Service and dwell components are incorporated within the routing model and are reflected through the operational indicators presented in Table 6. In the present framework, micro-hub locations are exogenously defined rather than endogenously optimized. Their positioning reflects realistically available logistics spaces and planning-consistent intermediate nodes within the metropolitan structure. The model, therefore, evaluates routing and operational performance conditional on predefined hub locations, rather than solving a location-routing optimization problem. For the Urban route (A), BEVs can easily cover the 48 km daily distance with an energy demand below 10 kWh day^{-1}, completely eliminating local CO_2 emissions (≈12.5 kg day^{-1} avoided). The adoption of micro-hubs and cargo e-bikes (SP3) reduces LCV curb occupation from 450 to ≈85 min day^{-1}, an 81% reduction consistent with PMLS benchmarks for efficient curb-use management.

Table 6. Key performance indicators (KPI) for Routes A–C and Service Patterns SP1–SP5.

	KPI	Unit	SP1	SP2	SP3	SP4	SP5
Route A—Urban (48 km, 15 stops)	D_{tot}	km	48	48	48	48	48
	T_{tot}	h	2.18	2.18	2.18	2.18	2.18
	S_{tot}	min	450	450	85	450	85
	U_v	–	0.23	0.23	0.61	0.23	0.61
	E_{tot}	L/kWh/kg H_2	4.8 L	9.6 kWh	9.6 kWh	0.53 kg H_2	0.53 kg H_2
	$CO_{2,tot}$	kg	12.5	0	0	0	0
	η_E	km per unit energy	–	5.0	5.0	91	91
	η_C	km per g CO_2 (baseline)	3.83×10^{-3}	3.83×10^{-3}	3.83×10^{-3}	3.83×10^{-3}	3.83×10^{-3}
	R_P	%	0	0	100	0	100
	ΔS	%	–	0	−81	0	−81
Route B—Suburban (99 km, 12 stops)	D_{tot}	km	99	99	99	99	99
	T_{tot}	h	2.48	2.48	2.48	2.48	2.48
	S_{tot}	min	360	360	85	360	85
	U_v	–	0.29	0.29	0.64	0.29	0.64
	E_{tot}	L/kWh/kg H_2	9.9 L	20.8 kWh	20.8 kWh	1.09 kg H_2	1.09 kg H_2
	$CO_{2,tot}$	kg	25.8	0	0	0	0
	η_E	km per unit energy	–	4.8	4.8	91	91
	η_C	km per g CO_2 (baseline)	3.83×10^{-3}	3.83×10^{-3}	3.83×10^{-3}	3.83×10^{-3}	3.83×10^{-3}
	R_P	%	0	0	100	0	100
	ΔS	%	–	0	−76	0	−76
Route C—Inter-urban (250 km, 6 stops)	D_{tot}	km	250	250	250	250	250
	T_{tot}	h	3.57	3.57	3.57	3.57	3.57
	S_{tot}	min	180	N/A	N/A	180	85
	U_v	–	0.54	N/A	N/A	0.54	0.72
	E_{tot}	L/kWh/kg H_2	25 L	N/A	N/A	3.00 kg H_2	3.00 kg H_2
	$CO_{2,tot}$	kg	65.3	N/A	N/A	0	0
	η_E	km per unit energy	–	N/A	N/A	83	83
	η_C	km per g CO_2 (baseline)	3.83×10^{-3}	N/A	N/A	N/A	N/A
	R_P	%	0	N/A	N/A	0	100
	ΔS	%	–	N/A	N/A	0	−53

η_E is defined only for electric scenarios.

In the Suburban case (B), BEV operation remains feasible within the 150 km range limit, with an energy requirement of ≈21 kWh day^{-1} and a CO_2 reduction of ≈26 kg day^{-1} compared with diesel. The decoupled SP3 pattern yields a 76% curb-time reduction while maintaining service coverage through peri-urban micro-hubs.

For the Inter-urban mission (C), BEVs exceed their range constraint and require mid-shift charging interruptions; therefore, FCEVs become the only viable zero-emission solution. Their hydrogen use is ≈3 kg H_2 day^{-1} (0.012 kg km^{-1}), avoiding ≈65 kg CO_2 day^{-1} relative to diesel. The FCEV + cargo e-bike configuration (SP5) halves curb occupation, from 180 to ≈85 min day^{-1}. Across all routes, BEVs exhibit the lowest specific energy use, whereas FCEVs guarantee operational continuity for longer missions. Decoupled schemes (SP3, SP5) consistently achieve the greatest curb-time reductions and enable packaging recovery, confirming their potential as integrated measures for urban logistics decarbonization. The sensitivity test was implemented for G = 6 h, 8 h (baseline), and 10 h. As expected, reducing G to 6 h makes time feasibility more binding, especially for configurations operating close to their range limits, whereas increasing G to 10 h relaxes scheduling constraints and improves operational margins. The comparative ranking between BEV- and FCEV-based configurations remains consistent with the trends discussed above, particularly for long-distance missions approaching the BEV range threshold. To assess the robustness of this result, a distance-based sensitivity reasoning can be derived from the model assumptions. Under the reference daily operational range of 150 km, BEV feasibility becomes progressively constrained as route length approaches this threshold, particularly when fixed working-hour limits are enforced. Beyond this distance, intermediate charging or schedule adjustments would be required, potentially reducing operational efficiency. In contrast, FCEVs maintain operational feasibility within the assumed 450 km range without intermediate refueling, preserving route continuity.

These outcomes are also influenced by infrastructure density. Increased availability of fast-charging stations may partially mitigate BEV range limitations, while limited hydrogen refueling availability could introduce detour penalties for FCEVs. Therefore, the relative advantage of each technology depends jointly on route length and infrastructure configuration rather than on distance alone.

5. Discussion

The results presented in Section 4 confirm that integrating zero-emission vehicle technologies with innovative organizational models can substantially improve the sustainability of urban and inter-urban service operations. The methodological framework developed in this study combines routing optimization, energy assessment, and curbside-use indicators into a coherent decision-support tool. This structure allows the simultaneous evaluation of environmental and spatial impacts and provides quantitative evidence to guide planning instruments such as the [11,12,60].

While this study focuses primarily on operational feasibility, energy performance, and curbside impacts, a comprehensive Total Cost of Ownership (TCO) assessment would provide additional insights for fleet transition decisions. However, TCO outcomes depend strongly on context-specific parameters, including vehicle purchase costs, incentive schemes, energy prices, and infrastructure investment structures, which vary significantly across regions and time horizons. The present framework is designed to isolate structural operational differences between technological and organizational configurations under consistent boundary conditions. Future research may integrate detailed techno-economic modeling to complement the operational and environmental assessment developed here.

In addition, the economic feasibility of both BEV and FCEV scenarios is inherently sensitive to energy price volatility. Electricity tariffs and hydrogen production costs are subject to significant fluctuations driven by wholesale market dynamics, renewable penetration rates, and regulatory frameworks. In particular, hydrogen prices remain strongly dependent on production pathways and scale effects, while electricity prices may vary across time-of-use regimes. Although energy price modeling lies beyond the scope of this study, future extensions of the framework should incorporate dynamic price scenarios to assess the robustness of fleet transition strategies under variable market conditions.

From an energy and emission perspective, BEVs deliver the highest efficiency for short- and medium-range missions, with specific consumptions between 0.20 and 0.21 kWh km^{-1} and average energy efficiencies of ≈5 km kWh^{-1}. FCEVs extend zero-emission operation to longer routes, consuming 0.011–0.012 kg H_2 km^{-1} and ensuring full decarbonization beyond 150 km. The monotonic improvement observed from SP1 (diesel baseline) to SP5 (FCEV + cargo e-bikes) validates the technical feasibility of complete emission elimination across mixed fleets. These outcomes are consistent with the quantitative ranges reported in literature, confirming that current BEV and FCEV technologies already cover the operational envelope of service trips within metropolitan areas [48,76–78].

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Regarding spatial and temporal efficiency, the indicators S_{tot}, U_v, and ΔS highlight the decisive role of logistic decoupling. The introduction of micro-hubs and cargo e-bikes reduces curb occupation by 50–80%, raises vehicle utilization rates from $\approx$0.25 to > 0.60, and mitigates illegal parking practices caused by limited loading-bay availability. These gains translate into measurable improvements in public-space efficiency and delivery reliability, reinforcing the objectives of the PMLS measures that promote micro-hub networks and multimodal last-mile systems.

The circular-logistics dimension, represented by the recovered-packaging ratio R_P, adds a further level of sustainability. In the decoupled schemes (SP3 and SP5), the indicator reaches 100%, demonstrating that reverse logistics can be integrated within daily service routes without additional travel distance or time. This strengthens the link between urban freight decarbonization and the broader circular-economy agenda promoted by the European Green Deal.

The transferability of these findings should be interpreted in relation to urban form and spatial structure. The Rome case represents a dense European metropolitan context characterized by a compact historical core, moderate suburban expansion, and structured radial–ring mobility patterns. In highly compact, high-density cities (e.g., metropolitan areas with strong central concentration and limited curb availability), micro-hub and cargo-bike configurations may generate proportionally larger benefits in terms of curbside reduction. Conversely, in low-density, car-oriented metropolitan regions with dispersed demand patterns, longer average trip distances may amplify the relevance of high-range vehicle technologies, while reducing the operational viability of last-mile decoupling strategies.

According to internationally recognized urban classification frameworks, such as those developed by UN-Habitat, metropolitan systems differ significantly in density gradients, spatial continuity, and infrastructure provision. Therefore, the conclusions of this study are most directly applicable to medium-to-high density metropolitan regions with mixed urban–suburban service structures, and should be recalibrated when applied to substantially different spatial morphologies [79].

The operational feasibility of cargo-bike-based last-mile delivery should also be interpreted in relation to local environmental and topographical conditions. Adverse weather events, including heavy rainfall or extreme heat, may reduce rider efficiency and service reliability. Moreover, the hilly morphology of Rome, characterized by elevation gradients in several districts, can influence energy demand, delivery speed, and rider workload. While electric-assist cargo bikes mitigate part of these constraints, their performance remains more sensitive to terrain and climatic variability compared to motorized vans. These factors do not invalidate the structural benefits observed in the decoupled configurations, but they highlight the need for context-specific operational calibration when implementing micro-hub strategies.

Despite these positive results, several limitations must be acknowledged. The analysis assumes constant dwell times and average traffic conditions, omitting stochastic variability and congestion peaks that could affect operational times and energy demand. Economic parameters, such as total cost of ownership, energy-price volatility, and infrastructure availability, were not explicitly modeled. Future research should extend the framework to dynamic routing and stochastic dwell-time distributions, include cost and life-cycle-assessment dimensions, and validate the results through pilot implementations involving real logistics operators.

The use of scenario-based synthetic demand generation is a deliberate methodological choice, consistent with comparative urban freight modeling studies where controlled boundary conditions are required to isolate the effects of technological and organizational variables. The routing instances are calibrated using operator-validated operational parameters and planning documents, ensuring consistency with real-world service patterns. While large-scale GPS trajectory datasets may enhance empirical granularity, the objective of this study is not statistical inference over a freight population, but structured scenario comparison under transparent and replicable assumptions. Future research may extend this framework by integrating high-resolution empirical datasets to further strengthen external validation.

With specific reference to fuel cell electric vehicles, energy consumption in this study is estimated using average specific hydrogen consumption factors (kg H_2 km^{-1}), consistent with operational freight studies. The model does not explicitly represent electrochemical voltage dynamics or stack-level parameter calibration under variable load conditions. Future extensions could integrate advanced voltage modeling and high-precision parameter estimation techniques for proton exchange membrane fuel cells to refine energy consumption predictions, particularly under partial-load and highly dynamic operating conditions typical of interurban service missions.

Furthermore, while hydrogen FCEVs show advantages for long-range routes, their operational viability must account for degradation under real-world driving cycles. Recent studies demonstrate that voltage recovery phenomena and health state estimation models are critical for predicting lifetime costs [80].

The emission results presented in Section 4 refer primarily to operational (tank-to-wheel) performance. However, a comprehensive comparison between BEVs and FCEVs requires consideration of well-to-wheel emissions, which depend strongly on upstream energy pathways. For BEVs, lifecycle emissions are influenced by the electricity generation mix, whereas for FCEVs, the carbon intensity of hydrogen production is decisive. Green hydrogen produced via renewable electrolysis can significantly reduce lifecycle emissions, while gray hydrogen derived from steam methane reforming may substantially increase the overall carbon footprint compared to the operational zero-emission condition. Recent emission-factor databases and global hydrogen assessments indicate that lifecycle performance may therefore vary widely depending on national energy mixes and hydrogen production routes. Consequently, the suitability of FCEVs for long-distance logistics must be interpreted in relation to the decarbonization level of the hydrogen supply chain [81–95].

From a policy perspective, municipal authorities can play a pivotal role in enabling decoupled logistics models. First, zoning regulations and temporary-use permits can facilitate the allocation of strategically located micro-hub spaces within dense urban areas. Second, dedicated curbside loading zones and dynamic allocation systems can enhance the effectiveness of last-mile cargo-bike operations, reducing search time and illegal parking. Third, incentive schemes for zero-emission fleets, including access privileges, low-emission zone exemptions, and infrastructure co-financing mechanisms, can reduce transition barriers for logistics operators. Finally, coordination between urban freight planning (e.g., PUMS/SUMP frameworks) and energy infrastructure development is essential to ensure that charging and hydrogen refueling networks evolve consistently with fleet electrification strategies. Particular attention should also be devoted to the economic and spatial feasibility of hydrogen refueling infrastructure, as high capital costs, safety requirements, and land-use constraints may limit station deployment in dense urban districts, requiring coordinated and phased planning strategies.

Overall, the discussion confirms that combining BEV and FCEV deployment with decoupled, micro-hub-based logistics yields simultaneous benefits in carbon neutrality, energy efficiency, and spatial rationalization. The proposed analytical framework, therefore, offers a transferable methodology for assessing and designing sustainable logistics strategies in European metropolitan areas.

6. Conclusions

This study proposed and validated an integrated methodological framework to assess the decarbonization potential of service-trip operations through battery- and hydrogen-electric vehicles combined with innovative logistics schemes. The framework links vehicle performance data, spatial planning indicators, and operational parameters to quantify energy demand, emissions, and curbside impacts across heterogeneous mission profiles. Applied to the Rome metropolitan context, the model captures the multi-dimensional benefits of combining technological and organizational transitions.

From the operational analysis, BEVs were confirmed as the most efficient option for short- and medium-range missions, while FCEVs extend zero-emission operation to longer routes exceeding 150 km. Decoupled configurations, involving micro-hubs and cargo e-bikes, consistently reduce curb occupation by 50–80%, increase vehicle utilization, and enable full packaging recovery. These results demonstrate that vehicle electrification and logistic reorganization can produce complementary gains in energy efficiency, emission reduction, and urban-space optimization.

Methodologically, the work contributes a transferable set of performance indicators, covering energy, emissions, curbside use, and circular-logistics aspects, that can be replicated in other urban contexts using locally available data. The integration of these indicators with planning frameworks provides public authorities with a quantitative tool for monitoring the effectiveness of zero-emission strategies.

Future developments will address the inclusion of cost and life-cycle assessment indicators, the modeling of stochastic dwell times and congestion dynamics, and the validation of results through real-world pilot projects involving logistics operators. Extending the analysis to multi-day routing and energy-network interactions (charging and refueling infrastructures) will further consolidate the framework's applicability to urban-freight decarbonization and circular-economy planning.

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