

Article

BRT in the Middle Mile: A Potential Urban Logistics Platform

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Abstract

The growth of e-commerce has imposed new challenges on urban supply chains, especially in the middle mile, which still lacks structured, sustainable and scalable logistics solutions. This study investigates the feasibility of using the Bus Rapid Transit (BRT) system, widely present in cities of emerging economies, as an urban logistics platform for the transport of light and traceable goods. This research adopts a qualitative approach, with analysis of international experiences and development of a methodological framework based on three main components: technical, economic and governance. The results reveal that the use of idle operating windows, load compatibility and institutional articulation are key factors for the implementation of the system. The proposal represents a logistical innovation aligned with the new paradigms of urban resilience and the multifunctionality of public infrastructure. This study suggests that BRT could serve as a potential logistics platform for the middle mile, under specific operational and governance conditions.

Keywords: urban logistics; middle mile; public transport; Bus Rapid Transit (BRT); new logistics paradigms



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1. Introduction

The accelerated growth of e-commerce has reshaped urban supply chains, rendering traditional models—large logistics centers and intensive truck use—increasingly inefficient in dense metropolitan areas. The COVID-19 pandemic further exposed vulnerabilities and accelerated the demand for resilient, digitally integrated logistics. Recent studies emphasize operational flexibility and digital platforms [1], digital twins for resilience [2], and the role of Urban Logistics as a Service (ULaaS) in aligning mobility with logistics [3]. In this context, resilience becomes a design principle rather than a reactive measure. Within this transformation, the middle mile—linking consolidation centers to local distribution hubs—emerges as a critical yet underdeveloped stage. Unlike the last mile, supported by micromobility and direct-to-consumer delivery, the middle mile still lacks structured and scalable alternatives. ULaaS depends on its reliability [3], while major reports identify it as a systemic bottleneck: Ref. [4] highlights limits on speed and reliability, and ref. [5] calls for scalable solutions aligned with circular economy principles.

At the same time, cities in emerging economies such as Brazil have high-capacity public transport systems, particularly Bus Rapid Transit (BRT) corridors. Currently, BRT systems are in operation in several Brazilian capitals, such as Rio de Janeiro, Brasília, Belo Horizonte, Curitiba, Recife and Goiânia. These corridors usually cover medium and long

distances within the urban space, ranging between 15 and 40 km, and have specific characteristics that differentiate them from conventional public transport: segregated exclusive lanes, advance payment of the fare, level boarding and high-capacity articulated vehicles. Such attributes make BRT a relevant candidate for multifunctional uses, including cargo transportation in off-peak periods. These systems operate with segregated infrastructure and include idle operational windows—especially during off-peak hours—that could be strategically leveraged for logistics purposes. Ref. [6] highlight the feasibility of integrating public transport and logistics platforms through crowdshipping and shared-use initiatives. Ref. [3] reinforce that multifunctional infrastructure is a central guideline for smart and sustainable cities when combined with digital logistics models. Ref. [7] demonstrate, through simulation studies in Munich, that optimizing existing passenger transport capacity can significantly improve urban logistics efficiency.

International experiences show that the use of public transport for the movement of goods is technically feasible, provided that loads are compatible, operational planning is adequate, and institutional coordination is effective. Ref. [8] documents the operationalization of freight on the Madrid Metro as an emerging solution for last- and middle-mile delivery. Ref. [7] simulate the use of metro systems to replace part of freight transport in congested cities, reinforcing the potential of existing infrastructure. Ref. [3] systematize the digital integration required for these initiatives. However, structured studies that specifically evaluate the feasibility of using urban BRT systems for freight, without large investments in new infrastructure or vehicles, remain rare.

Given this scenario, this study seeks to answer the following question: is it feasible to use the infrastructure and medium-capacity vehicles of the BRT system as an urban logistics platform for the transport of light goods in the middle mile? To this end, a methodological framework based on three fundamental components—technical, economic, and governance—is proposed, anchored in the analysis of international cases and in the systematization of key variables involved in its application in different cities.

The originality of the proposal lies in the use of existing vehicles and infrastructure, without the need for significant structural adaptations, by exploiting the idle capacity of the BRT system to transport fractional, light, and traceable cargo. Compared to other methodologies, the proposed methodological framework demonstrates greater robustness because it leverages segregated BRT corridors already operating in many cities, reducing both costs and implementation risks. Unlike freight tram initiatives, which depend on vehicle adaptations and dedicated infrastructure (e.g., Zurich, Dresden, Amsterdam), or crowdshipping models that face challenges of security and user acceptance (e.g., Brescia, Rome), the BRT-based approach minimizes operational barriers and ensures scalability in contexts of emerging economies. Its robustness lies in the possibility of rapid deployment, lower financial requirements, and greater replication potential. In line with this rationale, ref. [1] underscores that resilient supply chains depend on adaptable models that make use of existing assets, while ref. [2] highlight the need to incorporate risk-oriented design to ensure operational feasibility. Building on these perspectives, ref. [3] argue that multifunctional public transport can serve as a logistics platform for marketplaces, offering digital integration with urban mobility systems. Complementing these views, ref. [5] stresses that optimizing idle urban assets is consistent with global priorities of resilience, digitalization, and sustainability. Together, these contributions reinforce the conceptual and empirical foundation of the methodological proposal advanced in this article.

2. Methodology

This study adopts a qualitative, exploratory, and descriptive approach, suitable for investigating the innovative and still incipient use of BRT systems as middle-mile logistics platforms for light goods in urban centers. The choice of this strategy is justified by the lack of consolidated quantitative data and the need to interpret emerging, complex phenomena through international experiences and contextual variables. Seminal contributions support this approach: Ref. [9] established resilience as a core concept in supply chains; Ref. [1] emphasized adaptable models that optimize existing assets; and ref. [2] highlighted risk-oriented design for operational feasibility.

Data collection relied on secondary sources such as peer-reviewed articles, technical reports from public and multilateral agencies, regulatory documents, and logistics/mobility portals. International cases across buses, BRT, metro, train, and tram systems were reviewed according to three criteria: modal diversity, operational relevance, and replicability in emerging economies.

A methodological framework was then developed (Figure 1), structured in three components—technical, economic, and governance—and three cross-cutting dimensions: (i) fundamental requirements, (ii) operational/strategic challenges, and (iii) institutional/legal barriers. It enables systematic evaluation and comparability, organizing heterogeneous evidence into a structured and replicable scheme adaptable to Brazilian contexts. These three components will be further detailed in Section 4.

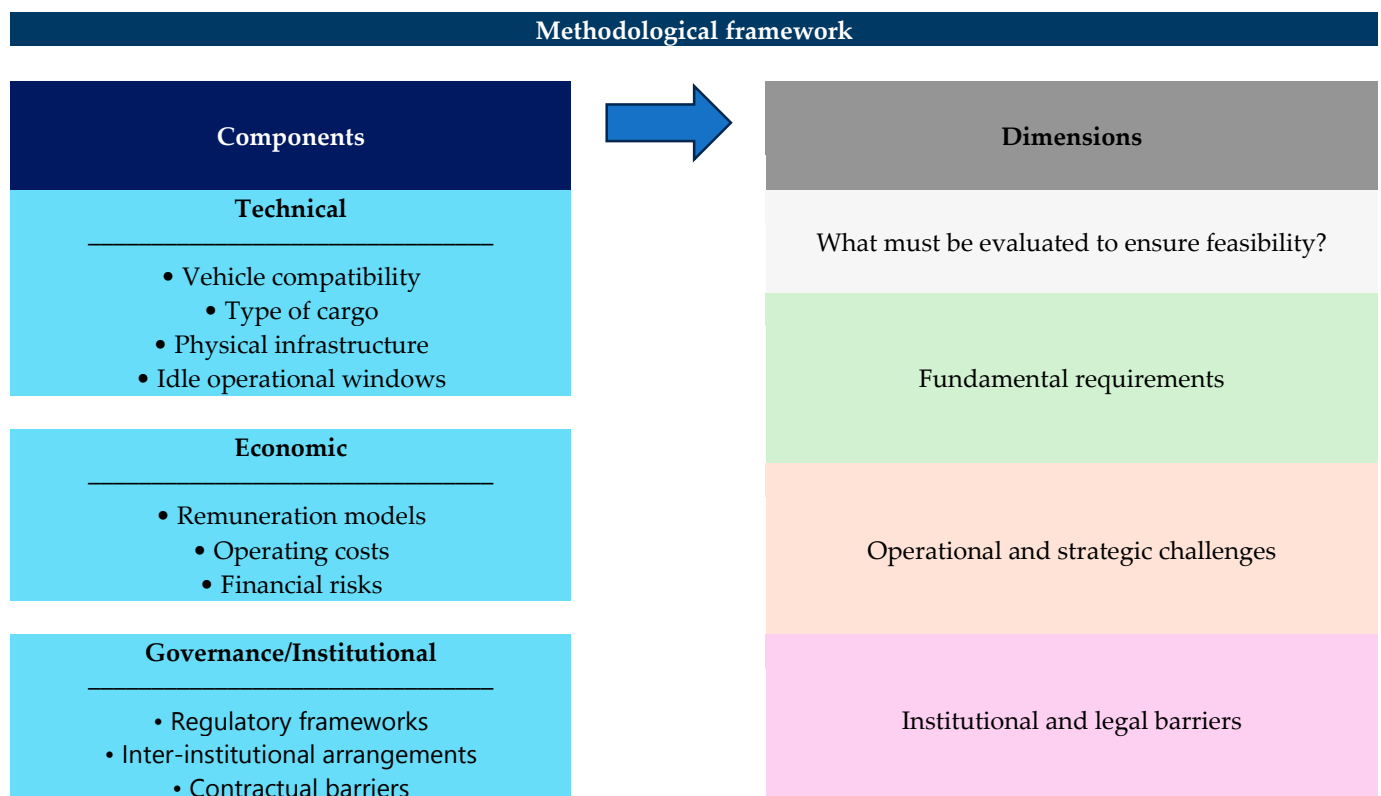


Figure 1. Proposed methodological framework.

In Brazil, the intermediate mile is carried out almost exclusively by *Veículos Urbanos de Carga* (VUC, Urban Cargo Vehicles—UCV), which connect airports, ports and large distribution centers to smaller hubs. These operations rely entirely on mixed, often congested tracks, which leads to high costs, delays and increased CO₂ emissions. No BRT corridor in the country is currently used for cargo transportation, which reinforces the innovative and exploratory character of this research.

Thus, the proposed methodology does not seek to test formal hypotheses, but rather to systematize evidence to support academic and practical recommendations. The methodology offers a structure adaptable to different urban contexts and will be illustrated in the Transcarioca corridor (Rio de Janeiro), which connects Tom Jobim International Airport (Galeão) to BarraShopping, using conservative assumptions and operating costs. The construction of the methodology was based on reflections about urban logistics challenges, particularly those related to transportation in the middle-mile segment.

In addition, the methodological proposal seeks to respond to a gap identified in the literature: although there are several studies on the use of public transport for cargo in subways, trains and trams, there are practically no structured investigations on the application of this logic to BRT. This choice is strategic because BRT corridors are widely present in emerging economies, especially in Latin America, operating over medium distances (15–40 km) and with high-capacity articulated vehicles. By systematizing technical, economic, and governance requirements in a replicable methodological framework, this study offers a practical basis for assessing the feasibility of integrating logistics functions into existing infrastructure, contributing to both academic literature and public policymaking.

These operations rely entirely on mixed, often congested tracks, which leads to high costs, delays and increased CO₂ emissions. No BRT corridor in the country is currently used for cargo, which reinforces the original and exploratory character of this research.

The comparative analysis of international experiences provides empirical and conceptual subsidies to assess the originality and feasibility of the proposal, considering both the specificities of the BRT system and the requirements of a more resilient, integrated and a more resilient, integrated, and sustainable urban logistics model, understood here as one that reduces truck flows in dense areas, mitigates CO₂ emissions, and optimizes the use of existing public transport infrastructure. The use of exploratory analytical approaches is consistent with the study's objective of proposing a structured methodological framework that is adaptable to real urban contexts, as suggested by [6], who examined crowdshipping integrated with public transport.

Thus, the method employed here does not aim to test formal hypotheses, but to organize and interpret empirical evidence in order to support practical and academic recommendations for the logistics integration of BRT systems, aligning with the new logic of urban logistics based on resilience, efficiency and operational intelligence.

Operational Framework—Generic Procedure for the Middle Mile via BRT

To assess the feasibility of logistics integration in Bus Rapid Transit (BRT) systems, a decision-oriented procedure is proposed, which can be applied in different cities that have this type of infrastructure. The method is composed of four sequential stages, each one functioning as a decision gate to be validated before moving forward:

Stage 1—Preliminary conditions (Gate G1). Verify: (i) the existence of a BRT corridor in operation with segregated lanes; (ii) the presence of relevant logistics demand in the area of influence; and (iii) the occurrence of recurrent congestion on alternative routes in mixed traffic. The process should only move forward if all three requirements are met.

Stage 2—Operational and physical evaluation (Gate G2). Identify fleet idle windows (via utilization histograms), estimate the useful volume of buses for transporting fractional loads and calculate the daily logistics capacity of the system. In this stage, the equivalence in VUC is also calculated, to allow direct comparisons with road alternatives.

Stage 3—Preliminary cost comparison (Gate G3). Compare the cost per cubic meter transported by BRT with urban transport benchmarks in VUC. The calculation must consider variable costs per kilometer, available volume, distance of the stretch and market

scenarios (low, medium, high). If the cost of BRT is within the competitive range, the Gate is approved.

Stage 4—Governance and pricing models (Gate G4). Evaluate regulatory and contractual permissions, the articulation between operators, public authorities and logistics companies, in addition to the definition of pricing models. Alternatives include marginal cost per $\text{m}^3 \cdot \text{km}$, volume contracts or public–private partnerships (PPP). Other managerial aspects may also be observed according to the specific characteristics of each situation.

The result is synthesized in a decision-making matrix, classifying technical, economic, and governance feasibility into High, Medium, or Low levels. The final recommendation is that pilot projects be initiated only when at least two dimensions present Medium/High viability, ensuring a balance between operational capacity, economic competitiveness and institutional legitimacy.

3. Literature Review

This literature review examines the transition from traditional logistics paradigms to a logic oriented towards resilience, digitalization and sustainability. It seeks to contextualize the strategic role of the middle mile and to support the multifunctional use of urban infrastructure, especially in public transport, as an emerging logistics solution.

3.1. Paradigm Hift: From Classic Logistics to Resilient Logistics

In recent decades, global logistics chains have undergone a profound transformation. The classic models, based on the search for operational efficiency, just-in-time logic, inventory centralization, and the globalization of production, have proven to be vulnerable in the face of systemic disruptions, such as the COVID-19 pandemic, the semiconductor crisis, geopolitical conflicts, and port logistics bottlenecks.

As a response to these shocks, what some authors call a new logistical logic has been consolidated, marked by resilience, adaptability, digitalization, and sustainability. This paradigm shift involves not only the adoption of new practices, but also a transformation in the mindset that guides the design and operation of supply chains (Table 1), as discussed by [1–3,5,9]. In this context, the role of digital transformation, through IoT, artificial intelligence, and blockchain, as an enabler of urban logistics platforms that are more resilient and responsive to the demands of e-commerce stands out [3].

Table 1. Comparison between logistics paradigms.

Thematic Axis	Pre-Pandemic Paradigm	New Post-Pandemic Paradigm
Central Objective	Operational efficiency	Resilience and agility in the chain
Chain Focus	Supply-driven	Demand-driven, customer at the center
Inventory Management	Just-in-time (minimum stocks)	Just-in-case (strategic and diversified stocks)
Globalization	Long, cost-based global chains	Nearshoring, regionalization, less geopolitical dependence
Technology	Point information systems (ERP, WMS)	Digital Integration: AI, IoT, Blockchain, Digital Twins
Innovation	Incremental, efficiency-driven	Disruptive, focused on adaptability and experimentation
Risk Management	Little emphasis, rarely structured	Central to decision-making and business strategy
Sustainability	Marginal activity or marketing	Circular economy as an operational imperative

In addition, marketplaces illustrate, in practice, this new paradigm. Rather than following the classic precepts of logistics, their operating models are built on agile, customer-centric, and digitally integrated networks that transform the middle mile into a competitive advantage. On these platforms, intermediate transport becomes a key lever to balance cost, time, and sustainability, as highlighted by [3]. These insights are consistent with the analyses of [10], who emphasizes the growing role of e-commerce platforms in reshaping urban freight flows, and ref. [11], who points to city logistics as an essential enabler to meet the operational demands of digital marketplaces.

The emergence of this new logistics school therefore implies the need for innovative solutions, new platforms and alternative ways of taking advantage of existing urban infrastructure. It is in this context that the proposal of this article is inserted: to use the BRT system as an urban logistics platform for the middle mile. Table 1 presents a systematization elaborated by the authors, based on the conceptual contributions of [1,3].

In the face of this new paradigm, urban logistics models need to be rebuilt based on three fundamental axes: (i) adaptability to uncertainties; (ii) incorporation of digital technologies; and (iii) multifunctional use of public infrastructure. The middle mile, previously invisible in the urban logistics agenda, emerges as a strategic component of this new arrangement. It is therefore necessary to rethink cities not only as delivery spaces, but as active logistics platforms.

In addition to the technical and economic dimensions, part of the recent literature already discusses environmental and social risks associated with the use of public transport for cargo. Refs. [10,11] highlight the importance of monitoring impacts on emissions, noise, and quality of service. Refs. [5,7] reinforce that environmental and social metrics must be incorporated from the pilot phase to ensure legitimacy and social acceptance. This research takes up such warnings and integrates them into the methodological proposal, broadening the view beyond the strictly operational feasibility.

3.2. Urban Freight Experiences in Public Transport

The use of public transport to move goods has been tested in several cities around the world. Although still poorly systematized, these experiences offer valuable lessons about feasibility, operational constraints, operating strategies, and institutional articulations.

The selected cases were organized into four main modes of transport—bus/BRT, subway, train and trams—based on the available documentation and their logistical relevance. The analysis was structured to highlight the motivations of the initiatives, the types of cargo involved, the operating hours, the logistics models adopted, the necessary physical adaptations and the applicability of these solutions to the urban middle mile of marketplaces. The selection of international cases considered three criteria: modal diversity (bus, BRT, subway, train, and tram), operational relevance (only implemented projects or structured pilots), and replicability in emerging economies (initiatives with limited adaptations and potential for transfer to contexts such as Brazil).

Based on these criteria, initiatives such as the Cargo Tram in Zurich and Frankfurt were included, for the long-term operational evidence; La Rochelle and Paris, for the innovative use of passenger services at off-peak times; and Miyazaki (Japan), for the integration between logistics and rural bus lines. On the other hand, purely experimental or short-term projects without proven impacts were excluded, as they do not provide consistent methodological inputs for generalization.

3.2.1. Bus and BRT Experiences

Several cities around the world have already used urban or intercity buses to transport goods. Cases such as the Greyhound Courier Express in the United States [12,13] exemplify continuous operations with exclusive or combined use of the luggage racks. In the North American case, the service was terminated in 2022, with an official announcement of the end of Greyhound Package Express operations as of 30 September 2022 [12].

The MULI Buslorry initiative, also in Sweden [14], and the KombiBus in the Uckermark region of Germany [15], integrate passenger and freight transport in rural areas, using hybrid vehicles or with trailers. The MULI project sought to combine the two types of transport to ensure cost efficiency and maintenance of services in regions with low population density. Similarly, the KombiBus was designed to enable deliveries in remote regions in an efficient and environmentally responsible manner.

The experience of the city of Miyazaki, Japan, highlights the partnership between the public operator and the private company Yamato Transport, promoting deliveries on the same regular buses in areas with an aging population [16]. In these areas, characterized by limited resources and population decline, logistical integration with public transportation generates significant efficiency gains.

The French cities of Paris and La Rochelle have also implemented pilot projects to integrate light cargo and passengers on urban routes, prioritizing night operation and sustainable delivery. In Paris, the strategy consisted of taking advantage of off-peak public vehicles for urban last-mile deliveries [17], while La Rochelle adopted sustainable practices with the use of clean vehicles and optimized routes [18].

The case of Cali, Colombia, highlights the typical challenges faced in Latin American cities: lack of regulation, conflicts with informal commerce, and lack of integration between the BRT system and urban logistics. The example demonstrates the institutional barriers that limit the articulation between public transport and efficient logistics solutions [19].

From these experiences, a general and comparative view of the operations that used buses to transport goods is constructed, with emphasis on the logistics models adopted, the main challenges faced and the current situation of each initiative (Table 2).

Table 2. Overview of Bus Experiences.

City/Country	Type of Use	Observation	Hours of Operation	Challenges Faced	Year of Commencement	Current Status
Greyhound—EUA	Charge only	Intercity with dedicated luggage compartment	Diurnal	Integration of the mode with parcel services.	1914	Closed (2022)
Bussgods—Sweden	Charge only	Parcels, packages, bicycles, musical instruments	According to regular bus schedules	Logistics integration, coordination between operators, terminal infrastructure.	~1992	In operation
MULI—Sweden	Cargo + Passengers	Rural areas with adapted vehicles	According to regular bus schedules	Vehicle adaptation, regulation, economic viability.	1998	In operation
Uckermark—Germany	Cargo + Passengers	Buses with trailer (KombiBus)	Diurnal	Rural integration, sustainable business model.	2015	In operation
Miyazaki—Japan	Cargo + Passengers	Partnership with Yamato, remote areas	Diurnal	Logistical integration, public acceptance, regulation.	2017	In operation
La Rochelle—França	Cargo + Passengers	Urban pilot project	Diurnal	Operational coordination, infrastructure.	2018	In experimental operation
Paris—França	Cargo + Passengers	Electric vehicles	Nocturne	Vehicle adaptation, coordination between operators, investments in urban infrastructure.	2019	Expanding
Cali—Colombia	Charge only	Informal cargo in the center, without integration with the BRT	Diurnal	Lack of regulation, presence of informal commerce, absence of integration with public transport.	No integrated operation started	On plan Diagnosis

After analyzing the cases presented, it is observed that the transportation of cargo by bus has been shown to be viable, especially in regions of low population density, where there is greater logistical flexibility. In general, the cargo transported is light, traceable and compatible with joint operation with passengers.

Key lessons learned from the bus experiences include:

- Compatible loads are mostly small, fractional and traceable;
- The use of idle operational windows—such as night periods or between peaks—is recurrent;
- Most initiatives require logistical coordination, but require low physical adaptation of vehicles;
- Only Paris used vehicles dedicated exclusively to the transport of light loads, operating during the night;
- None of the cases analyzed used the idle capacity of segregated urban BRT systems for the middle mile of marketplaces.

These initiatives demonstrate operational feasibility with a low degree of vehicle adaptation and intelligent use of idle hours. However, none of them applied the logic of the commercial middle mile using urban BRT in segregated corridors, which reinforces the originality of the proposal presented in this article.

Although punctual, these experiences point to trends aligned with the logic of resilient logistics: optimized use of urban assets, operational flexibility, and adoption of sustainable models in contexts of resource constraints. However, they remain short of a fully digital, resilient and scalable approach, such as that required by contemporary urban marketplaces.

Experiences with buses show feasibility for light and traceable loads, with low need for physical adaptation and recurrent use of idle windows (interpeak/night). The main barriers are logistical coordination, local rules, and economic sustainability outside specific niches. The gap is that there is no systematic use of segregated BRT corridors for the middle mile in dense urban contexts.

3.2.2. Experiences with Metro

Among the initiatives aimed at the use of the subway for urban freight transport, six relevant cases stand out, ranging from implemented operations, technical feasibility studies and computer simulations: São Paulo, Brescia, Madrid, Paris, Newcastle and Munich.

In São Paulo, in 2020, a feasibility study was developed focusing on the use of trains from Line 1-Blue of the subway for the transport of light packages during the night period. The proposal, conducted by the *Secretaria dos Transportes Metropolitanos de São Paulo* (STM-SP, São Paulo State Department of Metropolitan Transportation—DMT- SP), aimed to reduce the circulation of light commercial vehicles in the expanded center of the city. However, the project was not implemented due to regulatory and operational barriers [20].

In the Italian city of Brescia, a crowdshipping proposal was tested using computer models, simulating situations in which passengers themselves would transport small packages. The study pointed out challenges related to cargo security, user acceptance, and economic viability of the model [21].

The most recent case with effective operation is that of Madrid. Since 2024, Metro de Madrid, in partnership with the logistics operator GLS, has implemented the last mile project, using exclusive wagons during the night on Line 12 (MetroSur), with the final stage of delivery carried out by bicycles and sustainable modes [8].

In the UK, the City of Newcastle conducted a detailed technical study on the feasibility of using the Tyne & Wear Metro system for light trucking. The proposal provided for minimal operational and structural modifications to the wagons, as well as a cost-benefit analysis, although it was not implemented [22]. More recently, in Munich, a computer

study evaluated the potential of the metro to replace a significant part of urban freight transport, focusing on reducing emissions and optimizing existing logistics capacity [7].

Table 3 presents a synthesis of these experiences, highlighting the types of cargo transported, the main challenges faced and the current status of each operation.

Table 3. Overview of Metro Experiences.

City—Country	Type of Use	Observation	Hours of Operation	Challenges Faced	Year of Commencement	Current Status
São Paulo—Brazil	Proposal for cargo only	Technical study with night use for light packages	Nocturne	Limited space, lack of regulation, logistical synchronization	2020	Not deployed
Brescia—Italy	Light cargo with passengers	Automated subway crowdshipping simulation	Diurnal	Cargo security, user acceptance, economic viability	2021	In the study phase
Madrid—Spain	Charge only	Unique light package wagons with sustainable delivery	Nocturne	Loading and unloading logistics, regulation, capacity expansion	2024	Expanding
Newcastle—United Kingdom	Study for light load	Technical evaluation of the use of Tyne & Wear Metro for logistics	Nocturne	Technical feasibility, minimal adaptation requirement, cost-effectiveness	2017	Not deployed
Munich—Germany	Light load simulation	Computational model of subway uses for urban logistics	Nocturne	CO ₂ reduction, capacity optimization, integration with hubs	2024	In the simulation phase

The analysis shows that all initiatives used night hours, when there is less passenger circulation. The types of cargo transported are predominantly light packages and e-commerce goods. Although Madrid and Paris have concrete operational experiences, both have required significant physical and operational adaptations.

Key lessons from the subway experiences include:

- The initiatives predominantly use night periods, with low passenger demand;
- The transported cargo is, in general, light packages associated with e-commerce;
- There is high regulatory complexity and high adaptation costs for full logistics integration;
- Madrid has the closest application to a sustainable urban middle mile, although with a high degree of adaptation and focus on the last mile;
- To the best of our knowledge, none of the documented cases systematically proposes the use of idle windows with existing vehicles and without physical adaptations, as suggested in this research.

In addition to these experiences, other European cities have been the subject of studies and tests on the shared use of subways or light wagons for transporting cargo. Ref. [6] analyzed historical cases and pilots in Amsterdam, Dresden, and Zurich, proving the existence of real rail logistics initiatives at off-peak times. The same study also presented simulations for the Rome and Newcastle metros, highlighting the technical feasibility of these operations.

Despite the relevance of these initiatives, to the best of our knowledge no systematic proposal explicitly focuses on the use of idle operating windows with existing vehicles and without the need for physical adaptations, as advocated in this article.

Although they advance in technological and operational aspects, such experiences lack an integrated approach that combines smart urban logistics, strategic use of idle windows, and models based on digital platforms. These elements become central to the logic of resilient logistics, especially in the context of integration between urban mobility and e-commerce.

Subway operations tend to take place at night, with a focus on small parcels and require operational/physical adaptations and greater regulatory effort. There are potential gains (reliability, reduction in the number of trucks), but the costs and institutional complexity are high. The gap is that there is little emphasis on the intermediate mile and rarity of models without adaptations.

3.2.3. Experiences with Urban Trains

The use of commuter trains or suburban railways for freight transportation has been explored in some cities, often with a focus on specific cargo and dedicated operations.

In Mumbai (India), the traditional dabbawala system stands out, which uses the suburban railway network to distribute lunch boxes between the stations of the metropolitan region and the financial center of the city. The operation takes place even during peak passenger hours and is notable for its logistical precision, based on manual organization, without the support of automation or digital tracking [22].

In Paris (France), the supermarket chain Monoprix implemented, between 2007 and 2017, a rail supply system from its distribution center in Combs-la-Ville to the Gare de Bercy station, on the outskirts of the capital. From there, the cargo was transferred to light and electric vehicles, responsible for the final stage of deliveries to the stores. The model was discontinued after a decade, due to cost limitations and the complexity of the intermodal logistics involved [10].

In New York (USA), rail freight transport is used exclusively for the movement of solid waste, driven by freight trains operating from transfer stations located outside the dense urban core. The strategy aims to reduce the circulation of heavy trucks on the city's internal roads but does not involve urban transport of light loads or integration with the passenger system [23].

More recently, in Tokyo (Japan), the company JR East, in partnership with Yamato Transport, carried out tests with the use of urban passenger trains during the night for the transport of light packages. The initiative aimed to meet the growing demand for e-commerce by taking advantage of the idle operating windows of urban railways to avoid congestion and reduce emissions associated with deliveries. Although still in the experimental phase, it is a promising proposal for the insertion of light rail in the context of the urban middle mile [24].

Table 4 presents these railroad experiences, highlighting the main operational challenges and the specific purpose of each initiative. Experiences with urban or suburban trains for the transport of goods reveal models aimed at specific loads—such as food, waste or parcels—and characterized by dedicated operations. None of the initiatives analyzed uses the light passenger rail infrastructure, in idle hours, for logistical purposes aimed at the light urban middle mile, as proposed in this research.

Main aspects observed:

- The models analyzed focus on the transport of heavy loads (waste or industrial supplies) or on social food logistics initiatives;
- Rely on dedicated infrastructure and require complex intermodal integration;

- Neither operation directly applies to the logic of e-commerce or the short-distance urban middle mile.

In addition to these experiences, the case of Osaka, Japan, stands out, where the Hanshin Electric Railway company started, in 2023, the transport of light parcels on passenger trains, using dedicated compartments in the last car during idle hours [25]. Practices like this have become common in several cities around the world.

Table 4. Overview of Train Experiences.

City—Country	Type of Use	Observation	Hours of Operation	Challenges Faced	Year of Commencement	Current Status
Mumbai—India	Ready-to-eat foods	Dabbawala system with suburban trains	Diurnal	Manual screening, no tracking	1890	In operation
Paris—France	Charge only	Monoprix products, with urban distribution	Diurnal	High cost, complex intermodal logistics	2007	Closed (2017)
New York—USA	Charge only	Rail transport of solid waste	Diurnal	Limitations of urban access and segregation	2010	In operation
Tokyo—Japan	Charge only	Light orders (test with JR East/Yamato)	Nocturne	Economic viability, operational scale	2020 (pilot)	In testing

Although relevant, these experiences involve a high degree of infrastructural complexity and present models that are not compatible with the logic of e-commerce in dense urban areas. Thus, the innovative character of the methodological proposal of this study is reinforced, which is based on the use of existing urban public transport vehicles, in idle operational windows, to enable light and sustainable logistics in the middle mile.

Train experiences reflect a classic view of freight transport, centered on fixed routes and dedicated operations. These initiatives lack elements such as modularity, digital interoperability and operational flexibility, essential characteristics of the new logistics paradigm, driven by data and the multifunctionality of urban infrastructure.

Cases on suburban trains serve specific loads (e.g., food, waste) with dedicated operations and heavy reliance on infrastructure and transshipments. They are useful as a reference, but not very applicable to the intermediate mile of e-commerce in dense areas and do not take advantage of idle windows in a light way.

3.2.4. Experiences with Trams

Cities such as Zurich, Dresden, Amsterdam, Saint-Étienne and Frankfurt have tested the use of trams for urban deliveries, each with distinct operational characteristics and varying results.

In Zurich (Switzerland), the Cargo Tram has operated for over a decade collecting bulky waste across the city, while the complementary E-Tram project has demonstrated the feasibility of transporting larger consignments and recyclable materials. These initiatives show that freight integration is not limited to small, fractional and traceable goods, but can also accommodate heavier or bulkier shipments under specific operational arrangements. The initiative contributes to the reduction in truck circulation in the central area of the city [26].

In Dresden, CarGoTram was used for just-in-time transport of automotive parts between logistics centers and the Volkswagen plant. The operation used adapted trams and dedicated railway infrastructure, and was discontinued in 2020 [27].

In Amsterdam, the CityCargo pilot project sought to integrate light urban deliveries by trams, but was interrupted due to financial and operational challenges, including high costs and the requirement for specific infrastructure [28].

In the French city of Saint-Étienne, the TramFret project promoted the combined transport of passengers and light cargo, operating between 2017 and 2019. However, operational limitations and high costs led to the suspension of the initiative [29].

More recently, Frankfurt started the LogistikTram pilot project in 2019, aimed at exclusive night deliveries via adapted trams. The proposal is still in the experimental phase and focuses on the development of sustainable solutions for urban logistics [30].

Table 5 presents a comparative overview of these experiences with trams, showing the types of cargo transported, the operational models adopted, and the main obstacles faced in each case. Initiatives with trams focus on specific uses, mainly aimed at transporting waste or industrial supplies. The main lessons drawn from these experiences are:

- Trams are used for specific cargo or waste, not for light commercial logistics;
- Most cases require vehicle adaptations and investments in urban infrastructure;
- The proposal of this article is leaner, with a logistical focus directed to the middle mile and does not require the acquisition of new vehicles.

Table 5. Overview of Tram Experiences.

City—Country	Type of Use	Observation	Hours of Operation	Challenges Faced	Year of Commencement	Current Status
Zurich—Switzerland	Charge only	bulky waste	Day and night	Regulation, adaptation of vehicles	2003	In operation
Dresden—Germany	Charge only	Automotive Parts	Diurnal	Financial maintenance, infrastructure adaptation	2001	Closed in 2020
Amsterdam—Netherlands	Charge only	Urban goods	Day and night	High operating cost, insufficient government support	2007	Closed in 2009
Saint-Étienne—France	Cargo + Passengers	Supermarket products	Nocturne	High operating costs, logistical challenges	2017	Suspended in 2019
Frankfurt—Germany	Charge only	Urban goods	Nocturne	Terminal infrastructure, modal integration	2019	Pilot project

All the cases analyzed required some degree of vehicle adaptation or the use of new equipment, in addition to a high level of institutional articulation. The proposal presented in this study differs precisely because it anticipates a leaner solution, which dispenses with new vehicles and physical modifications, by proposing the use of the technical idleness of the BRT system as an urban logistics platform.

Although innovative in their respective contexts, these models represent niche solutions, with low scalability and limited digital integration. In contrast, the proposal of this study anticipates the principles of post-pandemic urban logistics: intensive use of data, efficient use of existing infrastructure, and minimal operational adaptation, as ways to ensure resilience and economic viability.

In addition, more recent initiatives include experiments in Strasbourg (France), where pilot projects evaluated the use of freight trams in central areas [14]; and in cities in Central

Europe, such as Prague (Czech Republic) and Poznań (Poland), which have been testing hybrid tram-freight models aimed at sustainable urban logistics [15]. Across Europe, similar practices have been observed in Zurich and Frankfurt, where tram projects range from bulky waste collection to night-time retail deliveries, almost always requiring vehicle and terminal adaptations and operating over limited ranges [10,15,18]. These initiatives illustrate the growing integration of freight into public transport systems across European cities, as highlighted by Dablanc and Buldeo Rai (2020) [10]. However, none of these experiences explicitly address the intermediate mile through the piggyback use of idle capacity.

3.2.5. Key Insights from International Cases

International cases confirm that freight in public transport modes is technically feasible when loads are light and traceable and when idle windows (interpeak/night) are used to minimize conflicts with passengers. In all modes, the decisive factor has been less technology and more governance (clear rules, coordination between operators, public authority and logistics operators). On the other hand, physical adaptations (vehicles/terminals) and integration costs tend to increase complexity and limit scale.

None of the cases reviewed use segregated BRT corridors for the intermediate mile with piggyback use of idle capacity without structural adaptations, exactly the focus of this article. This gap is relevant in emerging economies that already have BRT networks and face congestion on mixed roads.

The implications for the proposed model are: (i) Prioritizing light and modularized loads; (ii) anchor the operation in idle windows and/or low-emission vehicles; (iii) reduce physical adaptations to a minimum; (iv) structure governance (authorizations, pricing per $\text{m}^3 \cdot \text{km}$, volume contracts, PPPs); and (v) monitor KPIs (cost/ m^3 , reliability, CO_2 , VUCs avoided) from the pilot. These elements maximize the replicability and cost-effectiveness of the logistical use of BRT.

4. Methodological Framework: BRT in the Middle Mile

The analysis of the experiences of using public transport for logistics purposes—involving buses, BRT, subway, train, and tram—revealed recurring patterns and applicable lessons that allow for the identification of the main critical elements for the adoption of this logistics model in new urban contexts, within the new logic of urban logistics that seeks to optimize existing infrastructure and reduce externalities, aiming for more sustainable and efficient solutions to contemporary logistics challenges.

Based on these observations, this article organizes the determining factors into three main methodological elements: technical, economic, and institutional/governmental. This structure aims to facilitate an integrated understanding of the operational requirements, practical challenges, and institutional barriers involved in the implementation of a logistics solution based on the use of BRT for the middle mile of a marketplace. Such elements were built from common elements identified in the initiatives studied, such as:

- the need for 100% idle operational windows, that is, the BRT will only be able to transport cargo;
- the compatibility between the type of cargo and the available infrastructure;
- the models of remuneration and public–private articulation and;
- the regulatory adjustments essential to the feasibility of the logistical use of a system originally aimed at passenger transport.

The intersection between the empirical cases and the technical, economic and governance requirements allow the formation of an analysis matrix to support the methodological proposition later applied to the BRT context.

Each element will be detailed below, always structured from three dimensions:

- fundamental requirements for the operation;
- operational and strategic challenges to be faced;
- institutional and legal barriers that can hinder its implementation.

4.1. Technical Element—Physical and Operational Conditions

The feasibility of using the BRT system as an urban logistics platform in the middle mile of a marketplace depends fundamentally on technical conditions that ensure its compatibility with cargo flows and the operational requirements of the logistics sector. The analysis of the relevant experiences revealed that, although public transport was not originally designed for freight transport, there is a possibility to adapt it for this function provided that certain technical requirements are present or can be made possible with light and low-cost interventions.

These conditions mainly concern the existence of an idle operational window, the physical infrastructure available at the terminals, the configuration of the vehicles, the adequacy of the type of cargo, and the ability to integrate with the other links in the urban logistics chain. In this sense, the logic of resilient and digital logistics guides the adoption of technological solutions to ensure the traceability, safety, and adequacy of light loads transported in systems originally designed for passengers. Other management-related aspects, not addressed in this article, should also be considered individually according to the specific characteristics of each context. The following are the main requirements, challenges and technical barriers observed:

4.1.1. Requirements

The first of them is the existence of idle vehicles with an availability window for the use of goods transport. A gear diagram is able to show the possible schedules and volumes of available vehicles and their duration (e.g., trough time, early evening, early morning). This is a *sine qua* condition for the use of vehicles.

Another requirement is strategic urban insertion. This means identifying relevant origin and destination points in terms of cargo volume, between which the BRT service should operate in the middle mile. The distance between the points of origin and destination is also an important requirement and must be large enough to compensate for the loss of time resulting from any additional transshipment. In other words, time savings are expected compared to the operation in general road circulation.

Another key requirement is the use of segregated corridors, which provide time savings and predictability compared to conventional cargo vehicles in mixed traffic. Equally important is the adequacy—or the possibility of adapting—transshipment facilities at origin and destination points. Finally, cargo compatibility must be considered: fractional, light, non-perishable, and traceable goods are the most suitable for integration with BRT vehicles.

Finally, the existence, or possibility of adjusting the minimum infrastructure for sorting, loading and unloading at the points of origin and destination is also another condition for this model to make sense. Complementing all these requirements, it is important to bring a detailed comparison of the logistics stages from the first mile onwards in both the proposed model and the traditional model (Table 6).

The traditional model of a middle-mile operation depends on the existence of a Distribution Center, which receives cargo from various origins (medium and long distance) and reorganizes them with a view to the destination, for loading into trucks or vans that travel on conventional, often congested routes.

The proposed model assumes that this Sorting Center is in the first mile and no longer in the middle mile, since the arrival of goods must be strategically designed for boarding the BRT bus. This, in turn, must be close to a Logistics Integration Center (CIL), that is, the place

where the goods will dock for the modal shift—it can be an airport, a railway terminal, a bus station and even, on a larger scale, a port. In this case, the common destination loads are placed in the BRT vehicles based on their compartmentalization and the planned distribution routes.

Table 6. Detailed comparison of the logistical stages between the traditional model and the proposed one.

Stage	Traditional Model (Trucks/Vans)	Proposed Model with BRT in the Middle Mile
1. Mode offloading	Cargo removed from the hold by conveyors or platforms.	Cargo removed from the interior in the same way as in the traditional model.
2. Internal transport to the CIL (Logistics Integration Center)	Towed carts (dollies) transport the cargo to the CIL.	Same transport with dollies to the CIL.
3. Receiving and inspection at CIL	Conference, inspection (X-rays, Federal Revenue, etc.).	Identical: mandatory checking and inspections.
4. Temporary storage and operational sorting	Sorting, consolidating and repacking according to destination.	Early screening done at origin (first mile). Only final conference.
5. Embark on integration mode	Embark in a truck or van, via general circulation.	Board an adapted BRT vehicle, through a dock near the terminal (e.g., Airport Terminal).
6. Transport to the urban hub (middle mile)	Transport on public roads, subject to traffic and restrictions.	Transportation via segregated BRT corridor, with predictable time and route.
7. Disembarking at the hub and preparing for the last mile	Landing at CD or urban micro-hub with new sorting.	Direct disembarkation at an urban hub connected to the BRT, with cargo already organized for the last mile.

This operational logic reduces the permanence time of CIL cargo, allows direct boarding on adapted buses through logistics docks, and enables transport in segregated corridors with greater predictability and less urban impact. This is a relevant and positive disruption in the urban logistics chain, with direct benefits on efficiency, sustainability, and modal integration.

4.1.2. Challenges

To make cargo transport compatible with that of passengers even if each one uses 100% of the available vehicle. Although idle vehicles are fully available in certain periods, it is necessary to ensure that the transport of goods does not interfere with the next schedules of use for passengers, requiring strict technical criteria for the definition of schedules and vehicles used, respecting the premises of safety, comfort and accessibility of public transport.

Ensure the safety of goods during the journey. It is valid to ensure the integrity of the goods throughout the journey, preventing damage due to sudden movements, internal collisions, weather variations and even theft or violation attempts. This requires proper compartmentalization, locking systems and, eventually, on-board monitoring by sensors or cameras.

Ensure cycle time compatible with delivery contracts. The proposed transport model needs to meet the operational windows of logistics contracts, especially in the marketplace, which require predictability and compliance with delivery deadlines. This implies detailed planning of loading, moving and unloading time, with well-synchronized routines.

4.1.3. Barriers

Public transport operators unfamiliar with logistical demands. Professionals and companies involved in the operation of urban public transport generally do not have previous expertise in cargo logistics. This limitation can affect the efficiency of the service,

requiring specific training, changes in organizational culture, and the development of new operational routines.

Lack of technical standardization for cargo compartments in vehicles designed for public transport. The lack of regulatory standards on compartmentalization, safety, weight and volume limits, among others, represents a relevant obstacle. This gap can generate legal and operational uncertainty, making it difficult to adopt the model at scale and replicability in other urban contexts.

4.2. Economic Element—Settlement and Remuneration Model

The economic viability of using the BRT system as a logistics platform in the middle mile depends directly on its ability to generate value compared to traditional urban cargo transport models. This includes not only the reduction in final operating costs, but also the creation of sustainable remuneration mechanisms that contemplate the different actors involved: BRT operators, logistics companies, and the government.

The experiences of Zurich (Cargo Tram), La Rochelle (night-time freight trams), and Tokyo (subway freight pilot) indicate that integrating freight into public transport can represent an economically interesting alternative. These cases documented not only reductions in congestion and pollutant emissions, but also more rational use of urban infrastructure [10,11].

However, these advantages only materialize when there is a clear financial arrangement that balances costs, risks, and returns between the parties. The main requirements, challenges and economic barriers observed are presented below.

4.2.1. Requirements

Resulting cost is lower. The proposed model must demonstrate a better cost inclination in relation to traditional alternatives, presenting an overall cost lower than that of the conventional logistics operation. This implies evaluating everything from fuel and maintenance expenses to possible savings with tolls, parking and delivery time.

Estimate of the initial investment amount. The adoption of the proposed model requires prior measurement of the investments necessary to enable the logistics operation in the BRT system. These investments may include light adaptations in terminals (such as the installation of logistics docks), internal compartmentalization of vehicles, monitoring and on-board security systems, as well as eventual technological integrations with the logistics sorting and control centers. Although these are interventions with low structural impact, their quantification is essential to assess the financial attractiveness of the proposal and estimate the period of return on invested capital. Transparency in this calculation makes it possible to make feasibility decisions, foster the confidence of logistics operators and subsidize the negotiation of public-private partnerships or public financing instruments.

4.2.2. Challenges

Raise a pricing model that is attractive to operators and viable for logistics companies. Bring pricing means that make the service interesting for both BRT operators and logistics companies, ensuring a margin of financial sustainability for both sides.

Indicate possible financial gains between BRT operators, logistics operators and Public Authorities representing public transport users. The proposal must demonstrate how the BRT, the logistics operator and the public authorities can obtain direct or indirect financial benefits, such as increased revenue, better use of existing infrastructure or reductions in urban externalities.

Risk analysis (insurance, merchandise control). The model must consider costs with insurance, monitoring, tracking and control of loss or damage to goods, since such aspects directly impact the competitiveness and reliability of the service.

4.2.3. Barriers

Absence of contractual provision for the operation of cargo in the BRT system. The logistics operation within the BRT system may not be provided for in the current concession contracts, requiring regulatory revisions, contractual amendments or legislative changes that involve political and legal procedures.

Initial investment risk to adapt infrastructure with no guarantee of return. Although the physical adaptations planned for the logistics operation in the BRT system are, for the most part, of low cost and impact—such as vehicle compartmentalization or operational adjustments in terminals—the fact that they require prior investment still represents a considerable risk. This risk intensifies in the absence of contracts signed with logistics companies, which can result in low adherence and compromised financial return. In scenarios of uncertainty, even small interventions can trigger resistance from operators, especially when remuneration or compensation mechanisms are not clearly defined.

4.3. Element of Governance—Regulation, Articulation and Institutionalality

Governance is one of the central pillars to enable the use of public transport as an urban logistics solution. The proposal to use the BRT system in the middle mile requires a favorable institutional environment, with clear regulatory frameworks, effective interinstitutional arrangements and mechanisms for articulation between public and private actors.

The experiences analyzed demonstrate that the successful initiatives involved, for the most part, a tripartite governance composed of: strategic action of the local government, operational commitment of transport operators and direct engagement of the companies demanding the logistics service. This institutional triad proved to be essential to ensure technical feasibility, legal certainty, and scalability conditions for the pilot projects. Moreover, the absence of a clear governance structure proved to be one of the main impediments to the continuity or expansion of initiatives, especially when there were no formal mechanisms for intersectoral coordination, contractual clarity or precise definition of responsibilities between the entities involved. The main requirements, challenges and institutional barriers observed are presented below.

4.3.1. Requirements

Need to review concession contracts to allow cargo transportation. The concession contracts of the BRT system must be adjusted to formally contemplate the possibility of transporting goods in a complementary character to the transport of passengers, with clear legal and operational guarantees. Need for a Regulatory Framework that defines:

- Public purpose of mixed use with evidence of gains for urban mobility and logistics;
- Liability rules (insurance, claims, losses);
- Standards of coexistence between passenger and freight transport with a focus on safety, non-interference and technical standardization.
- Alignment between the following actors:
 1. The regulatory public entity, responsible for planning, authorizing and inducing integrated mobility and urban logistics policies;
 2. The operator of the BRT system, responsible for the infrastructure and technical operation of vehicles and terminals;
 3. The operator of the origin logistics infrastructure, such as intermodal terminals, distribution centers or logistics processing zones;
 4. The company requesting the logistics service, usually linked to marketplaces, urban logistics operators or retail chains;
 5. The strategic urban transshipment point, such as shopping centers, business hubs or consolidation hubs for the last mile.

4.3.2. Challenges

Possibility of logistics consortia or multi-party operational agreements. The viability of the model depends on the ability to establish public–private partnerships or operational agreements between different actors with different interests and institutional languages, which requires high legal and political articulation.

Implementation of a shared governance model. The project requires the creation of a governance body with representation of public and private entities, clear definition of roles, goals, responsibilities, and monitoring and transparency mechanisms.

Campaign of public acceptance and political articulation. The introduction of cargo in traditional passenger vehicles can generate social and political resistance, requiring communication strategies, transparency and involvement of civil society and the media.

4.3.3. Barriers

Fragmentation of institutional competencies (transportation, finance, infrastructure). Urban governance in Brazil is usually segmented between different departments and agencies (transport, finance, urbanism, infrastructure), making it difficult to have a systemic and agile articulation to implement innovative projects like this.

Bureaucracy and resistance to innovation in transport contracts. Public transport contracts are, in general, rigid and not very adaptable to new logistical demands, requiring significant legal and administrative efforts to implement changes.

Absence of specific public policies for the urban middle mile. The gap in structured policies for the transport of goods in the intermediate stage of the urban logistics chain—even in resilient and digital logistics—makes it difficult to raise funds, incentives and government support for the proposal.

5. Case Evaluation

To illustrate the generalizable procedure, the method is applied to the Transcarioca BRT corridor (38 km), connecting the Tom Jobim International Airport (Galeão) to BarraShopping, in Barra da Tijuca. The calculations use conservative assumptions and public data on BRT operation [31,32].

5.1. Stage 1—Preliminary Conditions (Gate G1)

The Transcarioca has been in operation since 2014, has segregated lanes and a fleet of articulated vehicles. At the ends of the stretch, there are relevant logistics hubs: Galeão as a gateway for express cargo and BarraShopping as a consumption hub. Alternative routes in mixed traffic (Red Line, Yellow Line and Av. das Américas) are congested. → Gate approved.

5.2. Stage 2—Operational and Physical Evaluation (Gate G2)

The fleet utilization histogram (Figure 2, [32]) shows significant idle windows between 10 a.m. and 4 p.m. In fact, around 30 vehicles gradually become idle starting at 8 a.m., making them available to begin middle-mile operations. Considering 20 idle articulated buses in this interval, each with 3 possible trips and an estimated useful volume of 15 m³:

The internal dimensions of the articulated buses used (29.5 m × 2.0 m × 2.5 m) [31] in this section reach approximately 100 m³. The internal layout with seats, stanchions, and handrails reduces the effective space available for goods, lowering the usable cargo capacity to around 70 m³ when no passengers are on board. Under a conservative approach, a capacity of 50 m³ can be adopted. It is worth noting that [1] reports a capacity of 15 m³ for articulated buses operating jointly with passenger services.

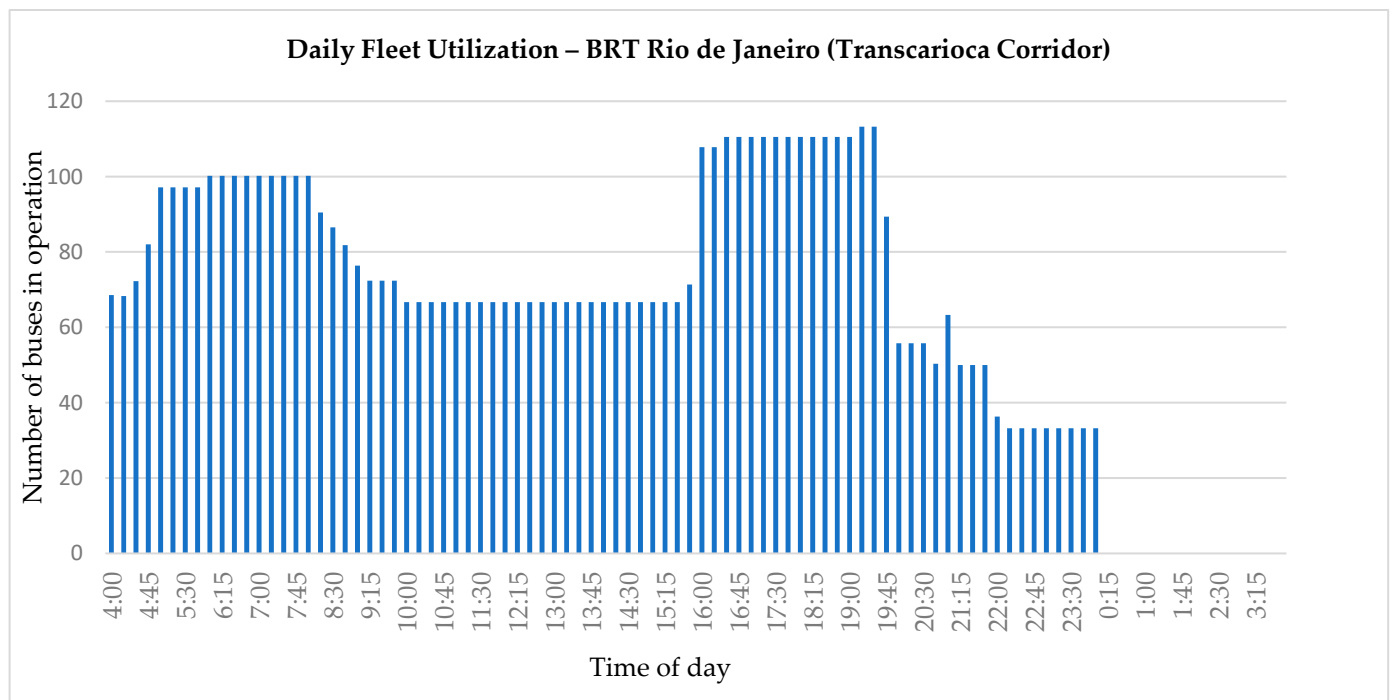


Figure 2. Daily fleet utilization in the Transcarioca BRT corridor.

For the selected route (78 km round trip), the cycle time—including travel time and loading/unloading operations—was estimated at 140 min during peak hours and 90 min during off-peak periods. Thus, within the idle window, it would be possible to use at least 20 vehicles to perform three complete round trips in middle-mile service.

In VUC with a 15 m³ capacity was selected for comparison with the BRT middle-mile scenario, as it represents the highest capacity among urban vans and therefore is expected to have the lowest unit operating cost (R\$/m³).

$$\text{Capacity per bus/day} = 70 \times 3 = 210 \text{ m}^3 \quad (1)$$

$$\text{Total fleet capacity/day} = 210 \times 20 = 4200 \text{ m}^3 \quad (2)$$

$$\text{Equivalence in VUC (15 m}^3 \text{ each)} = 280 \text{ VUC/day} \quad (3)$$

→ Gate approved.

5.3. Stage 3—Preliminary Cost Comparison (Gate G3)

$$\text{BRT variable cost: R\$ 3.60/km (articulated bus)} \quad (4)$$

$$\text{Distance (round trip): 78 km} \rightarrow \text{cost per trip} = \text{R\$ 280.80} \quad (5)$$

$$\text{BRT unit cost} = \text{R\$ 4.01/m}^3 \quad (6)$$

$$\text{VUC unit cost} = \text{R\$ 8.90/m}^3 \quad (7)$$

The cost per cubic meter of the BRT is significantly lower than that of the VUC. Additional advantages of the BRT system include higher reliability, due to its operation on segregated lanes, and direct access to the retail hub, which reduces the need for transshipment. To reinforce the cost analysis, three sensitivity scenarios were considered to examine the resilience of the proposed system under lower vehicle occupancy. Comparative table of scenarios: the methodological framework analysis shows competitiveness even under conservative conditions. Table 7 presents the comparative results for each scenario.

Table 7. Comparative feasibility scenarios BRT vs. VUC.

Scenario	BRT Load Factor	BRT Cost (R\$/m ³)	VUC Load Factor	VUC Cost (R\$/m ³)	Tendency
A	100%	4.01	100%	8.90	Highly favorable
B	75%	5.35	100%	8.90	Favorable
C	50%	8.02	100%	8.90	Marginal

The results demonstrate that, even under conservative conditions, the BRT methodology remains cost-competitive when compared to VUC-based operations. At 75% utilization, costs become balanced and the BRT achieves economic competitiveness, while at full utilization (100%) it becomes clearly favorable. Combined with the advantages of segregated infrastructure, higher reliability, and direct access to retail and consumption hubs, these findings reinforce the positive potential of adopting the BRT as a middle-mile logistics alternative. The replacement of approximately 280 VUCs per day corresponds to about 17.3 tCO₂ avoided daily (back-of-the-envelope estimate), considering an average distance of 78 km per vehicle. If operated in piggyback mode—taking advantage of existing trips during idle windows—the environmental performance becomes even more positive. → Gate approved.

5.4. Stage 4—Governance and Pricing Models (Gate G4)

Implementation requires contractual reviews, municipal authorization, inter-institutional coordination (SMTR, operators, marketplaces, and shopping malls), and a transparent pricing model. Feasibility is rated as Medium, but feasible in pilot.

Summary—Decision matrix.

Technical = High (proven operational capacity, equivalent to 280 VUCs/day).

Economical = (BRT cost = R\$ 4.01/m³, less than half of the VUC cost = R\$ 8.90/m³)

Governance = Medium (dependent on institutional adjustments).

The Transcarioca corridor shows a positive trend of viability for logistics use in the middle mile. A pilot project can adopt 3 daily trips in the off-peak, use BarraShopping as a redistribution hub, and monitor essential KPIs: cost per m³, reliability of deliveries, CO₂ avoided, and number of VUC replaced.

6. Discussion

The results of this research align with international experiences demonstrating the feasibility of freight integration into public transport systems under certain conditions. Tram-based initiatives in Zurich and Frankfurt, and metro-based pilots in Paris and Munich, confirmed that light and traceable cargo can be accommodated during idle operational windows, generating indirect benefits such as reduced truck traffic and lower emissions [5,7]. These outcomes are consistent with the arguments of [2,3], who emphasize multifunctional infrastructure and digital integration as enablers of resilient supply chains.

Despite these alignments, the BRT-based model diverges significantly from previous cases. Tram and metro initiatives frequently required costly infrastructure adaptations or dedicated wagons, while the BRT leverages existing segregated corridors and articulated vehicles with minimal modifications. Crowdshipping experiments in Brescia and Rome, although innovative, encountered barriers of social acceptance, liability, and safety. Furthermore, the majority of prior studies focused on the last mile, whereas this work addresses the middle mile, an underexplored but critical link in supply chains [4]. Importantly, no previous project has explicitly targeted the needs of digital marketplaces, which increasingly dominate e-commerce and require agile, cost-efficient intermediate transport.

Another contribution of this study is to highlight environmental and social dimensions often underdeveloped in the literature. By substituting part of van or truck flows with BRT vehicles, there is potential for significant CO₂ reduction, fewer urban freight trips, and decreased congestion in dense areas. These benefits align with global sustainability agendas [5]. However, trade-offs must be acknowledged: night-time operations, while efficient, may raise concerns about safety and labor conditions; daytime use could affect passenger comfort if not carefully managed. Thus, operational design must balance logistical gains with the quality of passenger services and broader social acceptance.

The integration of freight into BRT systems can reduce truck and van flows, cutting CO₂ emissions, congestion, and competition for road space, while promoting more rational use of existing infrastructure. However, risks must also be considered: extending vehicle use beyond regular hours may increase energy demand and maintenance costs; packaging and handling procedures can generate additional waste; and passenger discomfort or resistance may arise if logistics interfere with service quality. These trade-offs reinforce the need for controlled pilot projects, including systematic monitoring of emissions, safety protocols, and proactive communication with passengers and civil society to ensure social acceptance and a positive net balance.

Methodologically, this research advances beyond previous conceptual approaches by proposing a structured tri-dimensional framework—technical, economic, and governance—that enables systematic evaluation of BRT-based freight. Unlike earlier descriptive studies, this framework can guide both academic research and applied pilot projects. It also offers a replicable tool for assessing the feasibility of multifunctional transport systems in emerging economies, where resources for new infrastructure are limited but BRT networks are consolidated.

Finally, the discussion must consider governance and regulatory implications. As emphasized by [21], fragmented authority and rigid concession contracts are frequent obstacles to integrating logistics into public transport. The proposed methodological framework requires inter-institutional coordination involving transit agencies, logistics operators, and municipal regulators. Beyond technical feasibility, the creation of legal frameworks and incentive structures will be decisive for scaling pilots into stable operations. In this sense, the BRT methodological framework contributes not only a logistical alternative but also a governance challenge that calls for innovative contractual and institutional arrangements [33].

Compared to European and Asian cases, the Brazilian context faces more rigid institutional barriers. Current BRT concession contracts in Rio de Janeiro were designed exclusively for passenger transport and do not include provisions for freight integration. Any pilot project would require formal authorization and contract revisions by the *Secretaria Municipal de Transportes* (SMTR, Municipal Secretariat of Transport—MSTR), which acts as the main regulatory authority. In addition, institutional fragmentation between municipal, state, and federal levels reduces coordination capacity and increases transaction costs. Unlike Zurich or La Rochelle, where municipalities enjoy greater regulatory autonomy, Brazilian cities must overcome legal rigidity and overlapping mandates. Nevertheless, adaptive arrangements are possible, such as inserting experimental clauses into concession contracts or creating public–private consortia coordinated by SMTR, which could enable controlled pilot projects in the Transcarioca corridor.

Unlike previous studies that have mostly provided descriptive syntheses of freight-on-public-transport initiatives, this paper advances the debate by proposing a replicable tri-dimensional framework—technical, economic, and governance—that can be systematically applied to assess the feasibility of BRT-based freight operations. By integrating insights from diverse international experiences with the specific context of emerging economies,

the study goes beyond conceptual notes and offers an operationalizable tool that highlights both opportunities and constraints. This contribution fills a critical gap in the literature, positioning BRT as a distinct and underexplored alternative for middle-mile logistics in dense metropolitan areas.

7. Conclusions and Limitations

This study aimed to evaluate the feasibility of using BRT systems as a logistics platform for the middle mile, based on a three-dimensional framework—technical, economic and governance. The findings suggest that BRT can become a strategic and viable alternative, provided that specific operational and institutional conditions are observed.

From a technical point of view, real idle capacity was identified in off-peak windows, with relevant logistical potential for light and traceable cargo. Compatibility with this commodity profile reduces the need for structural adaptations, but scalability still depends on the standardization of solutions and the use of digital and IoT technologies to ensure traceability, security, and reliability.

In the economic dimension, the model shows competitiveness in medium and long urban stretches marked by congestion, generating indirect benefits such as lower emission of pollutants, more rational use of urban space and reduction in truck trips in dense areas. However, its financial viability requires clarity in remuneration models, coordination between operators, and specific incentives—such as PPPs, cross-subsidies, or public policies aimed at green logistics.

From the perspective of governance, the biggest challenge lies in the absence of a legal framework that formally allows cargo–passenger integration. Overcoming this barrier requires contractual adjustments, specific regulation, and strong articulation between concessionaires, municipal authorities, logistics companies, marketplaces, and consumption centers. Social acceptance and transparent communication are also critical conditions for pilots to evolve to regular operations.

In practical terms, this study recommends the development of pilot projects in corridors with a favorable profile, under public–private coordination, with monitoring of technical, economic, environmental, and social KPIs. Table 8 summarizes the main recommendations and indicators proposed. In addition, the detailed Pilot Blueprint for the Transcarioca corridor provides an initial application roadmap, including operational windows, redeployment hubs, and minimum performance metrics.

Despite its contributions, the research has limitations: it is an exploratory study, supported by secondary sources and international cases; no empirical pilots were conducted; and there was no detailed operational modeling of costs, downtimes, or capacity. In addition, the results are more applicable to cities that already have segregated BRT corridors and cannot be automatically generalized to other public transport contexts.

Table 8. Summary of recommendations and suggested KPIs for BRT-based freight integration.

Dimension	Recommendations	Suggested KPIs
Technical	Conduct quantitative modeling and simulations; define idle windows; test modular units.	Vehicle occupancy rate (%), logistics capacity (m ³ /day), delivery time (h), service reliability (%)
Economic	Develop comparative cost models vs. vans; assess financial risks; explore PPPs.	Unit cost (R\$/m ³ ·km), total logistics cost (R\$/day), cost savings vs. baseline (%), break-even volume (m ³)
Governance/Institutional	Revise concession contracts; establish multi-actor committees; define protocols.	Regulatory changes enacted, stakeholder participation, compliance rate (%)
Environmental	Monitor CO ₂ savings and congestion reduction; assess packaging impacts.	CO ₂ avoided (t/day), truck trips replaced (VUC/day), energy variation (%)
Social/Acceptance	Ensure passenger comfort; adopt safety protocols; engage users.	Passenger satisfaction index, number of incidents, acceptance rate (%)

Future research should move forward with quantitative simulations, cost–benefit analyses, financial feasibility studies under different compensation arrangements, and investigations into contractual innovation and collaborative governance mechanisms. The integration of emerging technologies—such as artificial intelligence, IoT, and real-time monitoring—should also be explored as a means of increasing efficiency, security, and social acceptance.

Therefore, the integration between passenger and cargo transport—when planned and regulated properly—can promote efficiency, sustainability, and resilience gains for urban logistics. This proposal contributes to smarter and more intermodal cities, capable of using their public infrastructure in a multifunctional and innovative way, aligning with the contemporary challenges of mobility and logistics in metropolitan regions.

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Abbreviations

The following abbreviations are used in this manuscript:

ADEME	French Environment and Energy Management Agency (France)
AI	Artificial Intelligence
AVL	Automatic Vehicle Location
BMVI	Federal Ministry of Transport and Digital Infrastructure (Germany)
BRT	Bus Rapid Transit
CAPES	Coordination for the Improvement of Higher Education Personnel (Brazil)
CEFET/RJ	Federal Center for Technological Education Celso Suckow da Fonseca (Brazil)
CD	Distribution Center
CIL	Logistics Integration Center
CNPq	National Council for Scientific and Technological Development (Brazil)
CO ₂	Carbon Dioxide
CSCMP	Council of Supply Chain Management Professionals
DSNY (NYC DSNY)	New York City Department of Sanitation (United States)
EF	Emission Factor
ERP	Enterprise Resource Planning
GLS	General Logistics Systems (Spain)
IoT	Internet of Things
JR East	East Japan Railway Company (Japan)
KPI(s)	Key Performance Indicator(s)
LET	Laboratoire d'Économie des Transports (France)
MLIT	Ministry of Land, Infrastructure, Transport and Tourism (Japan)
PPP	Public–Private Partnership
SMTR	Municipal Secretariat of Transport of Rio de Janeiro (Brazil)
STM-SP	São Paulo State Department of Metropolitan Transportation (Brazil)
tCO ₂	metric ton of CO ₂
UFRJ	Federal University of Rio de Janeiro (Brazil)
ULaaS	Urban Logistics as a Service
VUC	Veículo Urbano de Carga (small/medium urban cargo truck used in Brazilian cities)
VGF	Verkehrsgesellschaft Frankfurt (Frankfurt Transport Company, Germany)
WEF	World Economic Forum
WMS	Warehouse Management System
AI	Artificial Intelligence

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