

Article

Last Mile Urban Freight Distribution: A Modelling Framework to Estimate E-Cargo Bike Freight Attraction Demand Share

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Abstract: Urban freight transportation is facing significant challenges due to increasing demand, driven by globalization, e-commerce growth, and the adoption of just-in-time logistics. These trends have led to rising vehicle flows in urban areas, negatively impacting sustainability, economic efficiency, and road safety. In response, cities are exploring innovative last-mile delivery strategies that emphasize sustainability, flexibility, and cost efficiency. Among these strategies, cargo bikes—particularly electric cargo bikes (e-cargo bikes)—are emerging as promising low-emission solutions for urban freight distribution. However, despite their potential, a generalized methodology for estimating their demand share in urban contexts remains underdeveloped. This study proposes a comprehensive modelling framework to evaluate the freight demand share that can be addressed by e-cargo bikes, integrating quantity, restocking service, modal, and delivery sub-models, calibrated using data from a case study in Italy. The results demonstrate that e-cargo bikes could fulfil up to 20% of urban freight demand, depending on the category of goods transported, and underscore the feasibility of integrating e-cargo bikes into urban logistics systems. However, critical challenges related to scalability and cost-effectiveness persist, highlighting the need for further research and reliable cost data to support broader implementation.

Keywords: e-cargo-bikes; freight demand model; last-mile urban delivery



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1. Introduction

More than half of the population nowadays lives in urban areas, and this percentage will increase in the coming years, expected to reach 66% by 2050 [1], leading to an always-growing demand for freight, especially in urban areas. The ongoing process of globalization is witnessing a significant transformation where the movement of people and goods is rapidly expanding. This transformative phenomenon is leading the logistic distribution into new directions, creating a dynamic landscape. The rapid expansion of urban freight transportation, driven by fast changes in the supply chain such as just-in-time logistics and home deliveries, has led to a significant increase in deliveries and light-duty vehicle flow in residential areas. This trend, amplified by the development of e-commerce and the resulting affects on delivery characteristics as well as the lengths and durations of delivery roundtrips, poses substantial challenges to city sustainability and livability [2–5]. The rising presence of goods vehicles in urban spaces undermines sustainability across several key dimensions [6]. First, the environment is affected by increased congestion, as well as global and local emissions [7–9]. The economy, which effects logistic costs [10], and society, with an increase in road accident risk due to the increased flow of freight vehicles and

related effects of their interferences with other flows in urban contexts [11,12] are threatened and compromised.

Recognizing the challenges associated with urban freight transportation, many cities are beginning to implement targeted actions and policies within the framework of sustainable urban mobility plans (SUMP) and broader strategies for regional or city-level transportation. However, comprehensive approaches that specifically address last-mile delivery in urban areas and city centres are often lacking. To tackle the challenges of last-mile urban freight distribution, stakeholders—including shipping companies, integrators, logistics operators, and carriers—are increasingly driven to design and develop innovative models that address multiple dimensions. These include cost-efficiency, responsiveness to customer expectations, flexibility, resilience, and sustainability.

The strategies adopted for last-mile delivery typically depend on several key factors: the type and location of logistics facilities; the nature of the freight being transported; the size and type of vehicles used for deliveries; and the structure of distribution schemes. Examples of such schemes include the use of intermediate transshipment hubs, such as urban consolidation centres or micro-hubs. Moreover, effective last-mile distribution strategies must account for local contextual factors. These include the unique demand characteristics and dynamics of the area, specific customer expectations and requirements, regulatory conditions, and the physical features of urban road networks. By addressing these considerations, stakeholders can contribute to more sustainable, efficient, and adaptable urban freight delivery systems.

The use of innovative vehicles in last-mile urban freight distribution is a concept widely disseminated in the literature. Several studies have explored the challenges associated with adopting electric vehicles (EVs) in last-mile delivery operations. Some authors [13,14] highlighted key obstacles, including operational barriers such as limited driving range, battery-related issues like long charging times, and financial challenges such as high upfront costs, emphasizing the infrastructural and financial complexities of transitioning to a more sustainable vehicle fleet, citing the need for charging stations and the significant investment required for fleet acquisition. However, other authors challenged the limited driving range concern, concluding that EV battery capacities are sufficient for most last-mile operations [15–17]. Cargo bikes especially feature prominently in the literature as an alternative mode of transport in last-mile logistics, since they can potentially reduce congestion, noise, and air pollution, but require suitable infrastructures, acceptance, and adaptation to customers' expectations [18,19]. Most research focuses on the feasibility of freight cycling, considering factors like freight capacity limits [20], delivery type, and the density of commercial or residential areas [21,22]. The financial sustainability of urban last-mile freight distribution schemes based on the use of cargo bikes is one of the major concerns in the literature and some authors found that the existence and persistence of a suitable freight transport demand [23], alongside the adoption of mobile depot, micro-hubs or urban consolidation centres [24] are extremely beneficial conditions for the financial sustainability of a distribution model based on the use of such vehicles. Although the attraction and generation of freight demand in urban areas have been extensively studied through the development of systems of random utility models [25,26] and based on new sources of data [27,28], there is a lack of studies aimed at developing a generalized, quantitative methodology to evaluate the potential demand share for e-cargo bikes in an urban context.

This study seeks to bridge this gap by tackling the increasing challenges of last-mile urban freight distribution through an in-depth evaluation of the feasibility and potential demand share of electric cargo bikes (e-cargo bikes) as a sustainable and efficient transport solution. To this end, our study develops a comprehensive modelling framework that integrates multiple sub-models, including quantity, restocking service, modal choice, and

delivery, to estimate the proportion of urban freight that can be efficiently handled by e-cargo bikes. The model is calibrated using real-world data from a case study in Ravenna, Italy, enabling a detailed analysis of key influencing factors such as shipment size, delivery frequency, urban constraints (e.g., pedestrian areas and low-emission zones), and the nature of commercial activities. The paper is organized as follows: after a background literature review (Section 2) highlighting the advances proposed by the study, a methodological framework to estimate the potential demand share for e-cargo bike last-mile freight delivery is proposed (Section 3) and applied (Section 4) to a test case. Finally, some conclusions and roads ahead are drawn in Section 5.

2. Background

The concept of last-mile delivery has multiple definitions, but it is commonly understood as encompassing all logistics activities involved in distributing shipments to private households or commercial activities in urban areas [29]. Under this definition, last-mile delivery begins when a shipment arrives at an urban starting point, such as an urban consolidation centre, following long-haul transportation, and ends when the shipment reaches the customer's destination. Some definitions and perspectives on last-mile logistics can be found in [30,31]. The last mile is the most impacting and the least efficient stage of the logistic chain since it is characterized by short routes, low average speeds, low load factors of vehicles, and frequent start and stops, leading to a high cost/km ratio—up to 28% of total delivery cost [32]—and to remarkable environmental emissions. Several empirical investigations have pointed out that last-mile logistics account for up to 20% of energy consumption and up to 25% and more of emissions [33,34]. In Paris, for example, freight transport emissions represent 26% of total CO₂ emissions, while at the same time, the share of freight movements in vehicle-km is 13% [35], while a study recently published by AMAT [36] highlights that over 94% of freight daily attracted in the inner city of Milan (Italy) consists of B2B deliveries to commercial activities, and only the remaining 6% are B2C e-commerce deliveries. The impacts of freight transport are related to the geographical position, being influenced by many local factors such as congestion, technologies, and infrastructures [37]. From an environmental point of view, freight deliveries performed with traditional vehicles produce local and global emissions. Alongside the most relevant air pollutants emitted in urban areas, freight vehicles also compete for the usage of the road network and parking space capacity, increasing congestion and worsening road safety [38]. Moreover, economic impacts consist of time losses and unreliable deliveries due to congestion, use of resources, and cost of governmental regulation and planning [39,40].

An efficient urban logistics system can facilitate the flow of freight at low transport costs, reducing at the same time the environmental impacts produced, and keeping the shippers' ability to ensure delivery in the expected quantity, at the right place and time, and in accordance with customer expectations. The achievement of these goals can be obtained through the implementation of various types of city logistic measures and strategies, aimed at balancing the use of urban spaces and economic interests, synthesized as follows [41,42]:

- *Infrastructure measures*, mainly related to the development of new infrastructures to optimize freight vehicles' flow and deliveries. For example, parking areas for duty vehicles; Urban Consolidation Centers (UCC), Micro Consolidation Centers (MCC), Micro Hubs (MH), small transshipment, and storage infrastructure to support the implementation of last-mile distribution strategies based on low-impact duty vehicles with optimized capacity utilization; pick-up hub for e-commerce (e.g., lockers).
- *Measures based on Information and Communication Technologies (ICT), Intelligent Transport Systems (ITS), Internet of Things (IoT), and Artificial Intelligence (AI)*. Within this category falls a wide range of measures based on data collection and communication technolo-

gies, from apps and web-based services to book delivery bay, to control the access to limited traffic zones, to plan and manage delivery tours by means of an integrated platform, to improve traffic flow of specific freight vehicle categories (e.g., intelligent traffic lights or transit management systems), up to the use of innovative vehicles as Connected and Autonomous Vehicles (CAV) or Unmanned Aerial Vehicles (UAV).

- *Mandatory regulation measures*, to promote more responsible behaviours by the implementation of mandatory regulations. For example, time-window limited access (Limited Traffic Zones LTZ); access allowed only in compliance with environmental restrictions (Low Emission Zones LEZ or Zero Emission Zones ZEZ to promote the use of low- or zero-emission vehicles); vehicle-dimension access constraints.

Access restriction schemes are widely implemented across Europe to enhance environmental quality and mitigate road congestion effects in city centres. Some regulations exclude access to certain categories of vehicles, while others permit access contingent upon the payment of fees, often differentiated according to Euro emission classification standards [43]. Restrictions may also be imposed based on specific time frames, such as certain hours of the day, particular days or months, or distinguishing between working days and holidays [44,45].

New technologies are developing in a competitive scenario and in recent years have gained popularity in logistics systems by connecting a vast network of production sites, shippers, distribution centres, and freight vehicles, enabling the collection of extensive data on urban freight transport systems through networks based on Intelligent Transportation Systems (ITS), Information and Communication Technology (ICT), and IoT. Some of the ICT applications involve decision support tools in transportation planning, like freight vehicle routing and scheduling, supply chain execution applications [46], and field force automation applications [47]. Major areas of ITS utilization in urban contexts are Freight Management, Incident and Emergency Management Systems, and Transit Management Systems [48]. The impact of big data on urban freight transport has been explored, highlighting its potential to enhance load sharing and optimization in smart cities, improving transport efficiency and reducing externalities [49,50]. In the context of city logistics, such applications emphasize the importance of collaborative urban freight operations, such as sharing vehicle capacity, distribution centres, and information systems within the framework of the sharing economy, addressing strategic, tactical, and operational planning horizons, while supporting varying levels of information exchange [51].

Among the infrastructural measures, UCCs, MCCs, and MHs are key facilities designed to consolidate and enhance the efficiency of freight delivery operations in densely and highly congested urban areas. These facilities act as depots, with last-mile delivery performed using environmentally friendly, light-duty vehicles [52,53]. The fleet of light-duty vehicles usually operating in UCCs, MCCs, and MHs typically consists of clean vehicles powered by green fuels such as biofuels, natural gas, electricity, or hybrid technology. E-cargo bikes, in particular, are gaining popularity in these operations for delivering goods directly to the final recipients, allowing for shorter delivery routes by accessing areas restricted to motorized traffic and being less affected by traffic congestion, further improving delivery efficiency [54,55]. This delivery chain generally involves the use of conventional duty vehicles (such as trucks and vans) to transport goods from the producer or remote warehouses to UCCs, MCCs, or MHs located near city centres, while the final leg of delivery in congested or restricted areas is handled by e-cargo bikes or e-vans, potentially reducing delivery times and costs without hampering cities livability.

Suitable locations for these transshipment points include large parking lots or existing infrastructure such as loading docks. MCCs are smaller than UCCs and serve more limited and localized zones within a city [56]. UCCs and MCCs can be implemented together in a

coordinated system; e-vans can transport freight from UCCs to MCCs, while e-cargo bikes handle the last-mile delivery from MCCs to final recipients. In certain cases, MCCs can be replaced by mobile depots, such as trailers, which can be strategically relocated to different zones within the city. The literature on UCCs is wide and fragmented and addresses various aspects of this topic: design and management of the distribution structure [57,58], modelling and simulation [59–61], stakeholders involved, and business models [62–64].

E-cargo bikes are designed for delivering small parcels and light load freight in urban areas, with zero local pollutant emissions and low energy consumption. Additionally, they provide remarkable flexibility, operating efficiently in pedestrian zones, cycling paths, and conventional road infrastructures [56]. E-cargo bikes are particularly effective in city centres, where they can operate on narrow and congested streets with ease. They outperform traditional delivery vehicles for short-distance trips in dense urban areas, especially when transporting smaller deliveries [65], although the effects on vehicle flow and congestion resulting from the replacement of traditional freight vehicles with cargo bikes are subject to debate, some authors [66] suggest that the impact on traffic flow in terms of travel time and average speed is not always beneficial, particularly depending on the number of cargo bikes present, while the positive effect on space occupancy when parking for deliveries is more recognized [67]. Different types of cargo bikes are available, depending on the dimension, loading capacity, electric assistance, and position of cargo compartment [68]. Among the two-wheeled cargo bikes, there are the “longtails”, which place the cargo behind the rider, and the “frontlanders”, which feature a cargo box situated between the front wheel and the rider. These models can typically carry up to 80–100 kg of goods, while the most advanced electric pedal-assisted quadricycles can handle significantly larger loads, with capacities reaching up to 500 kg [18,68,69]. According to some studies [56], the adoption of e-cargo bikes is influenced by various factors across multiple domains, including vehicle performance (range, price, speed, etc.), operations (load capacity, type of goods, delivery scheme, etc.), infrastructure (road network characteristics, charging facilities availability, depots location, etc.), workforce, management scheme, and operating business model.

Inspired by the potential of e-cargo bikes as a viable alternative to conventional transport solutions for urban deliveries, as highlighted in the synthetic literature review presented above, it becomes essential to develop methods and models for evaluating their benefits in urban logistics. Therefore, this paper proposes a methodology to estimate the share of freight demand that can feasibly be delivered by cargo bikes within an urban context.

3. The Proposed Methodological Approach

3.1. Urban Freight Demand Model Characteristics and Requirements

Accurate and effective freight demand modelling is crucial for decision-makers to understand and plan the structure of urban freight systems [26]. Traditionally, freight demand is modelled as Freight Generation (FG), measured in tons, or Freight Trip Generation (FTG), referring to the number of freight trips within a given study area.

Freight Generation includes two components: Freight Attraction (FA), which represents the volume of freight delivered to commercial or production establishments, and Freight Production (FP), which denotes the quantity of freight or materials generated by activities within the study area. FG is primarily influenced by the intrinsic characteristics and intensity of economic activities; conversely, FTG not only depends on the variety of supplies required for economic activities but is also closely linked to the structure of the adopted restocking system [70].

At the urban scale, most studies utilize aggregate models to estimate FG [71]. Russo and Comi [72] introduced an aggregate approach to estimate FA, defining it as a quantity

influenced by the number of families and retailers located within the study area. Urban FG studies predominantly rely on predictors such as employment and area. For instance, Sánchez-Díaz [26] incorporated establishment categories and employment within those categories. Commonly employed methods include spatial linear regression models, generalized linear models, and ordered Probit/Logit models [73–75]. Furthermore, multiple correspondence analysis has been explored as an alternative methodological approach for FG estimation [76].

As shown in Figure 1, the logistics chain connects producers to end consumers through various pathways. Freight can either be delivered directly to the end consumer via trucks or vans, or the transport chain can be segmented into multiple legs involving transshipments, different stakeholders, and different transport modes. In cases where freight is stored in suburban hubs or warehouses, the first leg of the transport chain is typically carried out using ships, trains, or trucks. Subsequent stages of the logistic chain are usually performed by road, employing big vans or trucks for delivery.

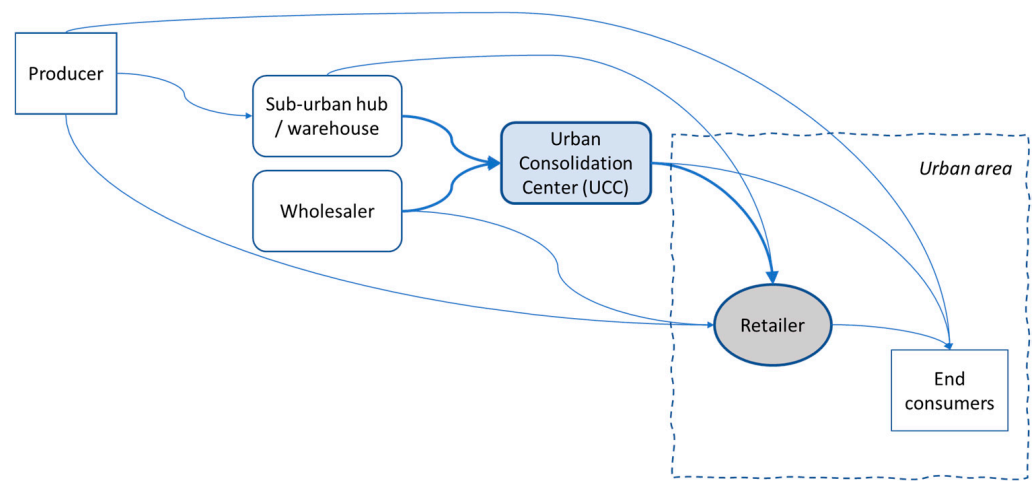


Figure 1. Structure of urban freight distribution.

Goods can be shipped by wholesalers instead of producers and delivered either to retailers (e.g., shops) or directly to end customers. In this frame, delivery schemes based on UCCs can be employed, where freight is unloaded and stored in the proximity of the city centre, after which small, environmentally friendly vehicles are dispatched to perform the deliveries to retailers or end customers.

As illustrated in Figure 2, the last mile of delivery is usually performed using small, often electric, vans and/or cargo bikes, aimed at improving the efficiency of freight distribution by consolidating shipments, optimizing the load factor of vehicles, and by shortening the kilometres travelled. In this context, the following section proposes a methodological approach to estimate the volume of freight that can be attracted and delivered using e-cargo bike distribution schemes within urban areas. The methodology considers key factors, including the characteristics of the urban areas to be served, the nature of the goods to be delivered, and the adopted restocking schemes.

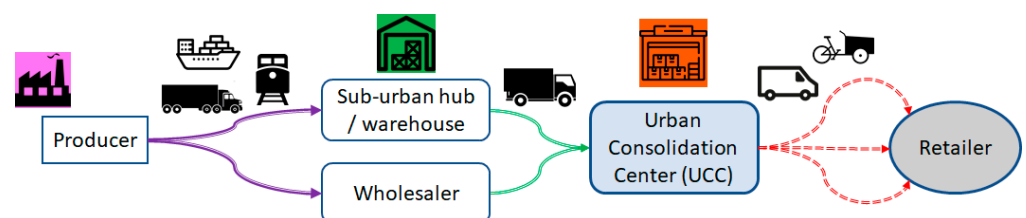


Figure 2. Urban freight distribution scheme with legs of delivery chain and transport modes involved.

3.2. Methodological Approach

The implementation of city logistics measures can benefit from planning and design tools that simulate the effects of specific scenarios using a “what-if” approach. Since transport system models play a critical role in these tools, the proposed framework employs a sequential demand modelling system. This system captures the actions of various stakeholders in urban freight transport while considering key dimensions such as the quantity and type of freight, delivery frequency, restocking service type, and transport mode [77,78]. The model’s output estimates the volume of generated freight demand that can be served in urban areas using cargo bikes, factoring vehicle capacity and range constraints.

The proposed modelling system (Figure 3) can be divided into four sub-models: quantity → service type → modal → delivery model.

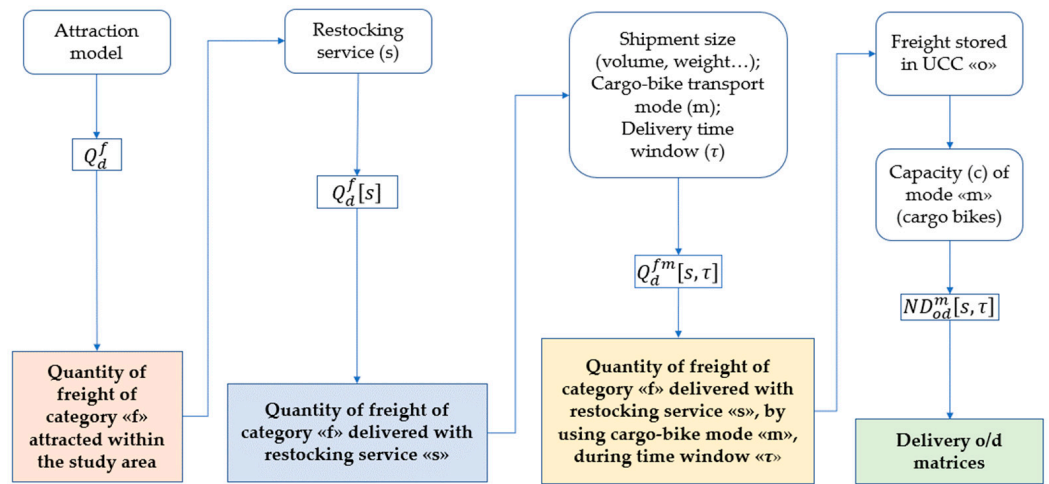


Figure 3. Proposed methodological approach.

The study area is divided into zones within which are located the commercial activities, and recipients of goods shipments. The quantities of attracted freight are estimated based on the characteristics of retailers and businesses within each zone, and the service type is modelled by considering the features of the logistical restocking process, while the probability of adopting cargo bike transport is determined using specific parameters.

3.2.1. Quantity and Restocking Sub-Model

The amount of freight attracted from every zone “d” located in the study area, for freight category “f”, and type of restocking service “s”, is given by the attraction and restocking sub-model (orange and blue boxes in Figure 4):

$$Q_d^f[s] = Q_d \cdot p[s/d] \tag{1}$$

where Q_d is the average quantity of freight attracted by zone “d” within the study area and is the result of the attraction model and $p[s/d]$ is the use probability of transport restocking service s. The restocking service type “s” can be on own account or operated by a third-party logistic service provider.

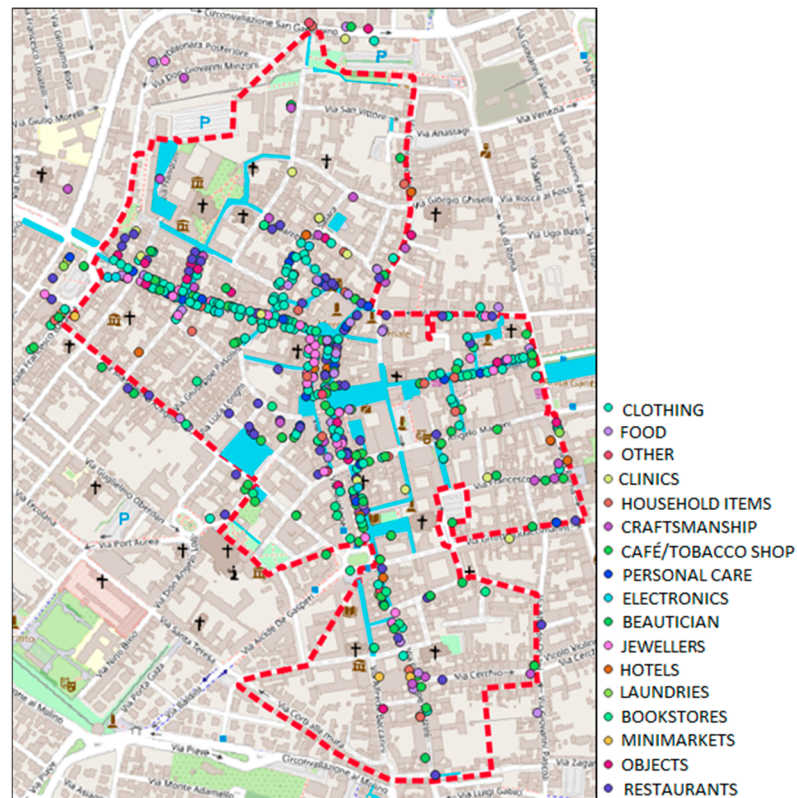


Figure 4. Location of the commercial activities in the study area, classified by category.

3.2.2. Modal Sub-Model

The modal sub-model provides the estimation of the amount of freight attracted from every zone “*d*”, of category “*f*”, during delivery time interval “*τ*”, restocked with service type “*s*” (output of the previous models) and by using the cargo bike transport mode “*m*” (yellow box in Figure 4):

$$Q_d^{fm}[s, \tau] = Q_d^f[s] \cdot p[\tau/sd] \cdot p[m/\tau sd] \tag{2}$$

where $p[\tau/sd]$ is the probability of having deliveries to zone “*d*”, for freight type “*f*” and with restocking service “*s*”, during delivery time interval “*τ*” and $p[m/\tau sd]$ is the probability that deliveries to zone “*d*”, for freight type “*f*”, with restocking service “*s*” during delivery time interval “*τ*” are performed with mode “*m*” (cargo bikes).

$Q_d^{fm}[s, \tau]$ is, finally, the amount of attracted freight stored in one or more Urban Consolidation Centre (UCC)—representing the origin node “*o*” of the last-mile delivery sub-model—delivered to the retailers located in each zone “*d*” of the study area during the reference period of analysis by using cargo bikes.

3.2.3. Delivery Sub-Model

The delivery sub-model defines the number of deliveries $ND_{od}^{fm}[s, \tau]$ to zone “*d*” from UCC “*o*”, performed with restocking service “*s*”, for freight type “*f*”, during delivery time interval “*τ*”, by using transport mode “*m*” (cargo bikes) with load capacity “*v*” and average shipment size $q(m|v)$ (green box in Figure 4):

$$ND_{od}^{fm}[s, \tau] = \frac{Q_{od}^{fm}[s, \tau]}{q(m|v)} \tag{3}$$

The final output of the system model is the delivery o-d matrix, containing the number of deliveries performed from a given origin “*o*” (an UCC) to every destination zone “*d*” within the study area.

4. Application of the Proposed Methodology

4.1. Case Study and Dataset

The model presented in the previous section has been applied to the case study of Ravenna, Italy, a city with a population of approximately 156,000 covering a surface of about 654 km². The historic city centre, characterized by narrow streets and historical buildings, with a surface of 21.15 km² and a population of almost 38,000, includes a Limited Traffic Zone (LTZ) covering 0.52 km², of which 37,704 m² are designated as pedestrian areas.

Access for traditional motorized vehicles is restricted by time windows: entry to the pedestrian zone is permitted only between 3:00 AM and 10:00 AM, while access to the LTZ is extended from 2:00 PM to 4:00 PM. These restrictions make accessing the city centre challenging for motorized delivery vehicles, requiring compliance with the specified time windows. The proposed methodological approach has been implemented within the LTZ of Ravenna’s city centre, where commercial activities have been classified into 17 different categories. The spatial distribution of the 487 commercial activities within the study area is illustrated in Figure 4.

A questionnaire was administered to a sample of retailers within the study area to identify the key characteristics of freight deliveries in the city centre. A total of 126 activities over 480 (sampling rate 26%) have been selected to be included in the sample set based on their category and location and all the invited retailers answered the survey (Table 1).

Table 1. Number of activities located in the study area and surveyed, for some of the considered freight categories.

Activity Category	Activities in the Study Area	Activities in the Sample
Food	35	8
Clothing	127	39
Household and personal care	44	12
Other goods	274	67

Stakeholders were surveyed regarding the type of freight they receive, the restocking method used (own account or third-party logistics providers), delivery frequency, and the quantity of freight received per delivery in terms of volume, weight, and packaging type. Additionally, retailers were asked about their willingness to accept deliveries via e-cargo bikes, after being presented with the characteristics and details of a distribution scheme utilizing these vehicles in a real-world urban context. The UCC is strategically located near the Limited Traffic Zone, ensuring seamless integration with the road network. Its proximity to delivery destinations, with connecting paths ranging from 700 m to 2.5 km, facilitates efficient last-mile distribution. The characteristics and capacity of the UCC are expected to be shaped by the estimated daily freight volume for all the considered categories, operating under the assumption that it will be restocked daily from warehouses situated outside the urban area.

The study area has a heterogeneous land use (residential, commercial, and touristic) which is mainly interested in attracting freight demand flows and the location of each sampled activity with special regard to road network accessibility has also been considered (i.e., location within a pedestrian zone). The data collected highlights freight attracted within the study area amounting to about 2200 tons per week. In terms of freight segmentation,

30% consists of foodstuffs (about 17% is delivered to restaurants and cafes, and 23% to retailers), 21% are dispatched to hotels, 47% consists of other end-consumer products (e.g., household, clothes, personal care, and health products), and the remaining 2% are goods related to services.

The system of models was implemented by adopting easy to understand and capture variables, especially for forecasting purposes. These variables include level-of-service attributes, restocking characteristics, and aggregate socio-economic factors, such as the number of employees. The models shown in the following paragraphs are the result of specification and calibration processes, during which various combinations of attributes have been tested. Calibration was performed using Ordinary Least Squares (OLS), Generalized Least Squares (GLS) or Maximum Likelihood (ML) estimators, depending on data availability, statistical modelling structures, and reliability.

4.2. Calibration of Quantity Sub-Model

Based on the aforementioned general framework, the first model is the quantity sub-model. Following an approach widely established in the literature [25,79], freight attraction models follow a parametric approach, ranging from ordinary least squares (OLS) regression to more advanced analytical structure such as generalized linear model (GLM), robust regression (RR), ordered Logit/Probit, and negative binomial regression. These models are typically specified by adopting a set of explanatory (independent) variables such as the number of employees, gross floor area, industry categories, and commodity type [26,80,81]. After testing various combinations of variables and model specifications, in this study, the average quantity of freight type “f” attracted by zone “d” in a week is expressed in the form of the following linear regression model:

$$Q_d^f = \beta_{EMP} \cdot EMP_d^f (kg/week) \tag{4}$$

where EMP_d^f is the number of employees for freight category f in zone “d” and β_{EMP} is a parameter to be calibrated.

The models have been calibrated by applying the GLS method, by minimizing the square of the differences between observed \hat{Q}_d^f and predicted Q_d^f quantities. The values of the coefficient of determination R^2 confirm the capability of the model to reproduce the quantities observed by means of direct survey for every freight category considered (Table 2). The signs of the calibrated coefficients are correct, and their statistical significance is confirmed by the t -standard values. These results, in line with the literature, confirm the relevant role played by the number of employees in the estimation of attracted freight.

Table 2. Calibration results of quantity sub-models.

Freight Category	Attribute	Parameter (t-Value; Sig.)
Food ($R^2 = 0.44$)	EMP	$\beta_{EMP} = 97.78$ (2.49; 0.037)
Clothing ($R^2 = 0.72$)	EMP	$\beta_{EMP} = 25.23$ (3.57; 0.016)
Household and personal care ($R^2 = 0.70$)	EMP	$\beta_{EMP} = 134.95$ (3.76; 0.009)
Other goods ($R^2 = 0.52$)	EMP	$\beta_{EMP} = 66.82$ (2.57; 0.042)

The total amount of freight Q_d attracted in the study area is then the sum of the sub-quantities of freight of all the “h” categories:

$$Q_d = \sum_{f=1}^h Q_d^f \tag{5}$$

The calibrated model has been applied to the LTZ of Ravenna, to test the model’s capability to reproduce the revealed quantity of attracted freight.

The comparison between estimated and revealed freight demand flows is represented in Figure 5, along with the percent root mean square error (RMSE%), given by the ratio between the square root of the mean square error and the average estimated demand. The results are quite scattered; however, the model shows a good performance in reproducing attracted flows of freight within the study area.

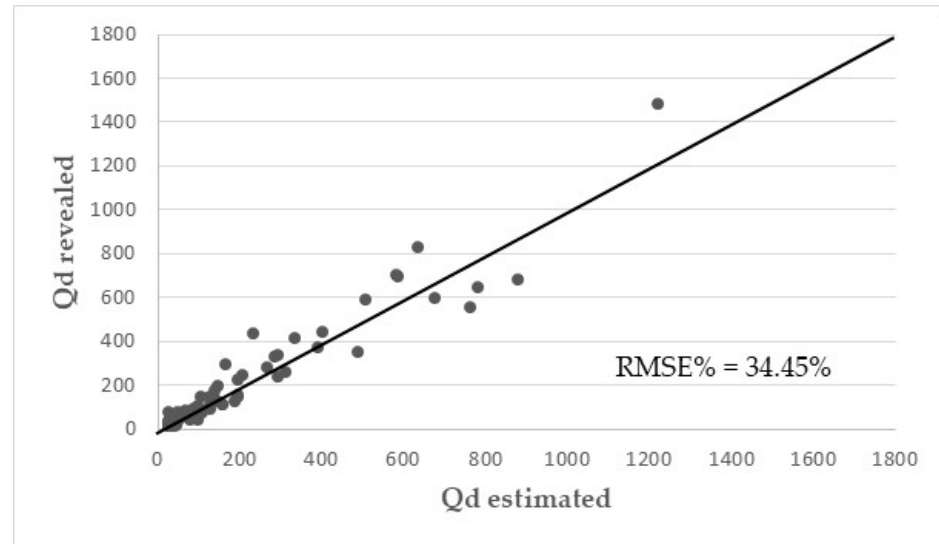


Figure 5. Revealed versus estimated attracted freight flows.

4.3. Calibration of Restocking the Service Sub-Model

The restocking service sub-model is obtained from direct retailer surveys by calibrating a logistic regression model. In the survey, the restocking service chosen by the retailer (own account or third-party logistic operator) and several other characteristics and data concerning the restocking process were collected.

Logistic regression is a particular case of generalized linear models (GLM) and is used when the dependent variable assumes only a binary value (0 or 1). Named $p(x)$ the probability to observe the outcome $y = 1$ given the values of x , β_0 and β , where x is the vector of independent variables, β_0 is the constant term of the model, and β is the vector of parameters, the logistic regression model formally applies the logit transformation to the dependent variable:

$$\ln \frac{p(x)}{1 - p(x)} = \beta_0 + x \cdot \beta \tag{6}$$

As shown above, the logit is the natural logarithm of odds of y , and odds are ratios of probabilities p of $y = 1$ to probabilities $(1 - p)$ of $y = 0$. By solving for $p(x)$ can be performed as follows:

$$p(x) = \frac{e^{\beta_0 + \beta x}}{1 + e^{\beta_0 + \beta x}} \tag{7}$$

The variables included in the model are summarized in Table 3. In detail, the dependent dichotomous variable is the restocking service (TP) chosen by the retailers (0 if the service is own account and 1 otherwise), and the independent variables, dichotomous or continuous, involve other dimensions of the restocking process (i.e., the restocking from the producer PROD, the average shipment weight q , the frequency of the deliveries FR and the delivery of goods in the food category, FOOD).

Table 3. Description of restocking service sub-model variables.

Variable	Codes/Values	Abbreviation
Third party provider	0 = own account 1 = third party	TP
Producer	0 = not from producer 1 = from producer	PROD
Avg. shipment weight	kg/shipment	q
Food	0 = no food and beverages 1 = food and beverages	FOOD
Frequency	deliveries/week	FR

The model was calibrated by applying the maximum likelihood method and the results are reported in Table 4.

Table 4. Coefficients of the restocking service sub-model.

Predictor	β	S.E.	Wald χ^2	Sign.	Exp(β)
Constant	0.031	0.475	0.004	0.948	1.031
PROD	2.008	0.812	6.123	0.013	7.451
q	−0.04	0.05	1.156	0.282	0.996
FOOD	−2.479	0.862	8.263	0.004	0.084
FR	0.248	0.109	3.944	0.046	1.281

Nagelkerke pseudo- $R^2 = 0.34$.

The individual effects of the selected variables on the restocking service probability can be assessed by using odds ratios (i.e., exponent of the regression coefficient, e^β). Odds ratios below 1 indicate that the probability of choosing third-party providers to perform restocking will decrease with an increasing value of a given driving factor, and vice versa.

As revealed by the calibrated coefficients, the probability of being restocked by a third-party logistic provider increased remarkably if the freight comes directly from the producer (odds ratio = 7.451); this indicates that while keeping all other driving factors unchanged, the direct restocking from the producer will increase the likelihood of the third-party logistic service providers by around 7.5 times. Also, the probability increases with the frequency of deliveries (odds ratio = 1.281) and the average shipment size does not seem to have an influence on the type of restocking service. Moreover, for food-and-drink retailers, the probability of restocking on own account is higher than other commercial activities (odds ratio = $0.084 \div 1 \approx 1 \div 11.9$).

4.4. Calibration of Modal Sub-Model

The modal sub-model is obtained from direct retailer surveys by calibrating a logistic regression model. The variables included in the model are summarized in Table 5. In detail, the dependent dichotomous variable is the vehicle type (VT) chosen by the retailers (1 if the service is provided by using cargo bikes and 0 otherwise), and the independent variables involve aspects related to retail characteristics, shipment size and restocking process (i.e., the presence of a warehouse in the retail shop W, the average shipment weight q, the location of the commercial activity in a pedestrian road PED, and the frequency of the deliveries FR).

The calibration highlights the strongly positive role played by the location of the commercial activity in a pedestrian area (PED) on the probability of choosing a restocking service based on cargo bikes (odds ratio = 2.637). As reasonably expected, frequency (FR) also exerts a positive effect on the choice of cargo bike mode of transport

(odds ratio = 1.43). On the other hand, the presence of a warehouse (W) in the commercial activity is not a positive driver toward the use of cargo bike transport mode (odds ratio = $0.230 \div 1 \approx 1 \div 4.350$ meaning that the presence of a warehouse in a commercial activity decreases by about 4.35 times the probability of being restocked by e-cargo bikes), but this is somewhat logical since the availability of space to store goods privileges restocking based on larger volumes per unit, typically carried out with high-capacity vehicles. Finally, the average shipment weight (q) again is not statistically significant.

Table 5. Description of modal sub-model variables.

Variable	Codes/Values	Abbreviation
Vehicle type	0 = other vehicles 1 = cargo bikes	VT
Warehouse	0 = no 1 = yes	W
Avg. shipment weight	kg/shipment	q
Pedestrian	0 = no location in pedestrian area 1 = location in pedestrian area	PED
Frequency	deliveries/week	FR

The results of the calibration are reported in Table 6.

Table 6. Coefficients of the modal sub-model.

Predictor	β	S.E.	Wald χ^2	Sign.	Exp(β)
Constant	-0.229	0.710	0.104	0.749	0.796
W	-1.470	0.583	6.357	0.012	0.230
q	-0.007	0.005	2.420	0.120	0.993
PED	0.970	0.198	4.089	0.041	2.637
FR	0.358	0.148	5.834	0.016	1.430

Nagelkerke pseudo-R² = 0.42.

4.5. Application of Calibrated Models to the Test Case

The system of models has been applied to the test scenario, to quantify the attracted freight demand within the study area—LTZ of Ravenna, Italy—potentially deliverable with e-cargo bikes, Q_d^{fm} , by applying the quantity, restocking service, and modal sub-models to the categories of recipients considered as follows:

$$Q_d^{fm} = \beta_{EMP} \times EMP_d^f \times \frac{e^{0.031+2.008PROD-2.479FOOD+0.248FR}}{1 + e^{0.031+2.008PROD-2.479FOOD+0.248FR}} \times \frac{e^{-0.229-1.47W+0.97PED+0.358FR}}{1 + e^{-0.229-1.47W+0.97PED+0.358FR}} \tag{8}$$

The results, in terms of the total attracted freight within the study area Q_d^f (for every freight category f considered) and e-cargo bike share of attracted freight demand are reported in Table 7.

The data in Table 6 shows the amount of attracted freight that can be delivered in the study area using cargo bikes ranging from just over 9% (“food” category) to over 26% (“other goods” category). For the “clothing” and “household and personal care” freight categories, the average is around 20%.

The average number of deliveries ND_d^{fm} to be performed by e-cargo bikes within the study area in the considered time window (one week) is finally provided by applying the delivery sub model, given the average size of the delivery $q(f)$ for every freight category considered:

$$ND_d^{fm} [s, \tau] = \frac{Q_{od}^{fm} [s, \tau]}{q(f)} \tag{9}$$

Table 7. Application of the system of models to the test case—estimation of attracted freight.

Freight Category	Attracted Freight Q_d^f [kg/week]	E-Cargo Bikes Attracted Freight Q_d^{fm} [kg/week]
Food	46,980	4300 (9.15%)
Clothing	8249	1709 (20.7%)
Household and personal care	3260	635 (19.5%)
Other goods	12,110	3223 (26.6%)

The results are reported in Table 8.

Table 8. Application of the system of models to the test case—estimation of number of deliveries.

Freight Category	Average Delivery Size $q(f)$ [kg/del]	Estimated Number of Deliveries ND_d^{fm} [del/week]
Food	86.8	50
Clothing	55.8	31
Household and personal care	41.9	15
Other goods	58.2	55

As shown in Table 8, the average delivery size is less than 100 kg, which is lower than the usual capacity limits of e-cargo bikes and in line with other results in the literature (for example Robichet et al. [24] find in Paris an average delivery weight of 91 kg). The average number of weekly deliveries is highest for “food” and “other goods” category activities (above 50 deliveries/week on average), while it is lowest for “household and personal care”.

5. Discussion and Conclusions

The use of cargo bikes for last-mile deliveries in urban centres is a promising logistics solution to reduce the impacts of road freight transport and enhance delivery efficiency. However, as with the design of any transportation system, the implementation of freight distribution schemes in urban areas based on consolidation centres and last-mile deliveries made with reduced/no-impact vehicles requires a robust estimation of the share of attracted demand that can feasibly be met using this transport mode. Although there are a number of studies in the literature addressing the estimation of freight demand flows in an urban area through Freight Generation and Freight Trip Generation models, there is a shortage of contributions focused on quantifying the proportion of demand that can be actually served by last-mile delivery solutions based on the use of small, zero-local-impact vehicles, such as cargo bikes. This is particularly relevant in light of the increasing restrictions and limitations imposed in congested urban areas. In this paper, a modelling system to evaluate the share of attracted freight demand deliverable to commercial activities located in an urban area by adopting a distribution scheme based on e-cargo bikes has been described. The system of models has been calibrated using the data collected in a real case study, the city centre of Ravenna, in Italy. The models were specified and implemented by following a sequential approach integrating the quantity of attracted freight, restocking services, delivery, and vehicle characteristics. The quantity sub-model describes the underlying aspects of freight transport demand generation, while the restocking sub-model aims to capture the factors that drive the choice of restocking type (own account or third-party logistic providers) by commercial activities. On the other hand, the modal choice sub-model highlights the operational attributes and context features of the commercial activities that steer toward the use of e-cargo bikes, and the delivery sub-model is necessary to implement delivery tour design and simulation models. The proposed modelling framework enables the assessment

of the effects of various factors influencing freight delivery in urban centres, including the economic characteristics of a traffic zone on the volume of attracted freight, the location of freight hubs (e.g., UCC) and commercial activities (e.g., within a pedestrian area) on the generated freight traffic for each zone, and the attributes of commercial activities, along with shipment size, on the selection of restocking service type and on the probability of adopting a delivery service based on e-cargo bikes transport mode. Additionally, the model accounts for an average number of deliveries based on freight type, and the capacity of vehicles.

The calibrated models show good statistical performance, and the modal sub-model confirmed that the location of the business served in a pedestrian area plays a significant role in the potential choice of e-cargo bike-based delivery mode, along with the higher required frequency of deliveries. The results obtained are of considerable importance in planning a last-mile freight distribution service in urban areas based on e-cargo bikes since, as pointed out by several authors in the literature, although it is theoretically possible to deliver significant quantities of goods using this system, it is difficult to make it cost-effective unless subsidies are applied [22,24], because the transport demand that can actually be steadily steered toward a restocking system with these characteristics is not of immediate and certain quantification. This is particularly significant in light of the rise in generalized logistics costs due to the increasing difficulties in dispatching duty vehicles to commercial activities located in pedestrian areas, widely complained about by business owners. The availability of a delivery option that enables a trade-off between efficiency and the cost of supply services in such a context is a crucial factor that can significantly influence the gain of a stable share of attracted freight demand, necessary to ensure the economic viability of a freight delivery service.

In detail, the application of the calibrated modelling system to the case study revealed that the share of freight demand attracted in a medium-sized urban centre, approximately 20% of the attracted freight demand can potentially be delivered using e-cargo bike-based distribution schemes. This percentage is notably lower for the “food” category (around 9%), primarily because e-cargo bikes are generally less suitable for transporting perishable goods. The frequency of deliveries plays a positive role in encouraging retailers to adopt both third-party restocking services and e-cargo bike-based solutions. Notably, the average shipment size does not appear to pose a significant barrier to the adoption of this system. This finding suggests that the availability of e-cargo bikes with substantial load capacities—some models on the market can carry up to 500 kg—has the potential to further increase the share of freight demand that can be met by this delivery method.

The proposed model has several potential applications for policymakers, logistics operators, and urban planners, addressing last-mile logistics optimization strategies and informing transportation policies with data-driven insights. It can also assist in investment decisions regarding UCCs, MHs, and CBs infrastructure, as well as enhance operational efficiency for logistics providers by pinpointing areas where e-cargo bikes are both economically and logistically viable. By offering an estimation of concrete data on the benefits and constraints of e-cargo bike integration, the model facilitates engagement between stakeholders, including retailers, delivery companies, and municipal authorities, enabling informed decision-making for sustainable and integrated urban freight operations.

Although the results obtained in this study are promising, some limitations should be acknowledged. First, the analysis was conducted within the context of a medium-sized city, where both quantitative and qualitative delivery differ significantly from those of larger urban centres. To address this, further applications on a larger scale are necessary to evaluate the effects of increased freight volumes, average delivery sizes, a greater diversity of goods categories, and the added complexity and constraints of more extensive road

networks. Another limitation lies in the fact that the modal sub-model did not include shipping costs due to the difficulty of obtaining reliable data on deliveries made by e-cargo bikes (the few companies providing such services offered very uncertain and heterogeneous values, often influenced by the provision of incentives). Investigations are ongoing to obtain reliable data and include them in subsequent model specifications. Finally, even if the goodness of the proposed general model architecture has been confirmed by the calibration performances, other model specifications and/or distribution of random residuals (e.g., Nested Logit, Probit) for restocking and modal sub-models are under evaluation.

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