TRB Annual Meeting

Is Crowdshipping A Sustainable Last-Mile Delivery Solution? A Case Study of Rome

--Manuscript Draft--

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ABSTRACT

Last-mile delivery, one of the most polluting segments of the supply chain, is the focus of numerous studies. There are various innovative delivery methods aimed at mitigating its adverse effects. This study explores whether crowdshipping (CS) could serve as a sustainable urban logistics solution for Rome, assessing its environmental viability. It poses the question: Can Rome adopt CS, and if so, how sustainable would it be? Using real-world data, we employed the MASS-GT simulation tool to simulate parcel demand for various parcel companies in Rome's urban areas. Additionally, we considered real data on trips made by employees to offices within the study area and their modes of transport. The analyses include predicting parcel demand and forming parcel schedules, both with and without CS. We also assessed employees' willingness to make detours for parcel pickups. Our findings suggest that CS can reduce emissions depending on users' willingness to adjust travel routes, which can be incentivized through monetization. Furthermore, by considering the fleet composition of parcel companies, we quantified the potential emissions savings achievable through CS. The results indicate that CS is applicable in Rome and could significantly reduce emissions by approximately 1.3 tonnes of CO_2 per day, equivalent to 93 euros in the EU's Emissions Trading System. This approach aligns with European emissions plans and validates the feasibility of CS in Rome through practical research. It offers valuable insights for policymakers, emphasizing the importance of encouraging user participation and supporting CS platforms.

Keywords: Crowdshipping, Sustainable urban logistics, Urban freight simulation, Agent-based model, Sustainability

INTRODUCTION

In recent decades, delivery and e-commerce services have grown, offering innovative solutions in the last-mile logistics (LML) sector. However, due to the interface with final customers, it strongly relates to the satisfaction level of users. Moreover, it still has challenges and is often described as one of the supply chain's most expensive and polluting elements (*1*). With the growing e-commerce trend worldwide, intelligent solutions are needed to meet the increasing demand. For instance, Global e-commerce is projected to grow at a compound annual growth rate of 9% through 2027 (*2*), or the parcel delivery market in Italy has shown rapid expansion in Europe, boasting a compound annual growth rate of 8.5% over the last five years (*3*). One practical approach involves integrating passenger and freight transport systems to maximize the utilization of passenger transport capacity, which can be considered a form of CS. This approach enhances flexibility and optimizes resource utilization, and may improve delivery efficiency. CS became well-known in 2015 after its adoption by Amazon (*4*). Moreover, one of the recent studies addressing the problem of urban deliveries revolves around crowd logistics as well (*5*). One of the challenges in incorporating CS is matching supply and demand, a process that depends on the willingness of users to participate in the system (*6, 7*). However, integrating CS with innovative last-mile delivery solutions, for instance, parcel lockers, could minimize the extra distance traveled by crowdshippers, thereby lowering CO_2 emissions (*8*). Although some studies include CS as a sustainable delivery solution (*9*), some argue that the benefits of such a service are highly dependent on the CS business model. Some examples include peer-to-peer (*10*), retailer-oriented (*11*) and reverse logistics (*12*) CS. The literature on CS has primarily focused on survey-based stated preference experiments due to the lack of operational data, with limited emphasis on real data analysis, with the notable exception of (*13*). In this manuscript, we innovate an approach by employing a multi-agent-based simulator. This simulator not only calculates the available supply level—identifying potential CS drivers willing to join the system—but also efficiently matches parcel demand with the available supply. It also explores the potential for integrating CS into existing employee commuting patterns to enhance sustainability, including their chosen modes of transport, such as bicycles in Rome. Hence, CS services can reduce environmental impact by leveraging existing trips instead of creating dedicated ones. This approach minimizes drawbacks like longer travel times and higher fuel consumption typically associated with additional vehicle trips (*14*). However, this approach also has tradeoffs, such as potential labor impacts, increased workload for employees serving as CS drivers, and the need for proper incentivization. Despite its significant environmental benefits, addressing these challenges is crucial for developing a sustainable and equitable CS system. For instance, Li et al. (*15*) found a tradeoff between a taxi company's profit and the acceptance rate of parcels for delivery in taxi-based CS systems. The objective of this research is to investigate the potential environmental benefits of CS by considering real employee commuting pattern data. To do this, we used a simulation tool to investigate different CS scenarios. In contrast to previous studies focusing on public transport or non-employee crowdshippers in Rome (*11, 16, 17*), our approach emphasizes the utilization of real data and leads to behaviorally realistic findings. This distinction allows us to provide novel insights into the potential environmental impacts and market feasibility of CS in urban settings in Rome. The paper is organized as follows: Section 2 introduces the study's concept and objectives. Section 3 offers a detailed literature review on crowdshipping (CS). Section 4 outlines the methodology used in the study. Section 5 presents the findings and results of our analysis. Finally, Section 6 provides a discussion of the results and draws conclusions.

LITERATURE REVIEW

Several studies have investigated various aspects of LML, particularly crowdshipping (CS). These investigations have covered a wide range of topics, delving into the operational efficiency, cost-effectiveness, and environmental impacts of CS compared to traditional delivery methods. Researchers have further examined the social and economic benefits for involved participants. For instance, (*7*) focused on the logistics, demand, operational strategies, and management of CS services in freight transportation. Furthermore, (*18*) explored the feasibility and potential of CS in urban areas and investigated conditions under which individuals would be willing to participate, emphasizing the need for more qualitative and quantitative research with real-world data. (*19*) highlighted the need to explore the sustainability implications of CS, especially toward achieving zero-emission targets. Additionally, (*20*) focused on understanding factors influencing the implementation of crowd logistics, acknowledging the roles of credit risk for crowd workers and platform reliability, both crucial yet often overlooked elements. Moreover, (*21*) studied the integration of crowdsourcing options into existing last-mile delivery platforms using floating population data to optimize operations, noting a lack of research combining crowdsourcing with existing platforms, particularly regarding pricing strategies varying by geographic area. (*22*) developed a comprehensive CS mathematical optimization model for last-mile delivery services, aiming to balance profitability, delivery quality, and environmental sustainability. However, the study also highlighted gaps in integrating crowdsourcing with existing delivery platforms. Additionally, Tapia et al. (*13*) underscored the potential of CS in urban freight transport to reduce environmental pollution. The study revealed higher vehicle kilometers and CO_2 emissions for certain delivery types, suggesting the need for complex analyses considering various urban environments and delivery scenarios. Building on this foundation, our study introduces an innovative approach by analyzing employee commuting patterns to integrate CS. This novel method aims to further optimize environmental benefits by leveraging existing commuting trips, thereby reducing the need for additional vehicle journeys and enhancing the sustainability of urban freight transport. From an environmental perspective, leveraging trips already made by commuters prevents additional emissions associated with freight vehicles (*23, 24*). This benefit is amplified when CS is achieved by using environmentally friendly modes of transport such as bikes, contributing to emissions reduction. Furthermore, (*25*) found that CS will be environmentally beneficial if it primarily utilizes sustainable transport methods. Moreover, (*6, 26, 27*) proposed an innovative approach to last-mile delivery by integrating CS but highlighted a research gap in real-world data availability. On the one hand, studies focusing on occasional couriers' (OC) behavior are limited (*28*); on the other hand, recent research has shown that OCs are willing to travel longer distances depending on the compensation offered by CS services. Another behavioral study (*29*) demonstrated the commercial potential of bicycle CS, considering supply and demand dynamics. Miller et al. (*30*) found that the fundamental premise of minimizing driver detours forms the basis for CS participation. This means that an OC's decision to pick up a delivery depends on whether the location is convenient to their home, workplace, or other destinations. Beside, trust is also a crucial factor when using CS platforms; For instance, (*31*) highlighted the influence of trust, which is related to the reputation of the delivery company and affects the adoption of CS. Delivery time directly influences service choice but does not affect trust. Moreover, (*32*) examined the potential for CS to generate new trips rather than consolidating existing ones, revealing a higher probability of low-income individuals initiating delivery trips from their homes. According to the research by (*9*), providing users with the flexibility to schedule delivery dates and times could incentivize them to use CS services more frequently.

Beside that, wholesale shops are experimenting with having their employees deliver packages to nearby homes at the end of their workday (*33*). Furthermore, Bajec and Tuljak-Suban (*22*) found that existing CS optimization models do not specifically address the reduction of negative environmental impacts, whether considered alone or in conjunction with other objectives. In addition, (*34*) examined the emissions produced by delivery tasks with and without the involvement of crowdshippers. Despite this, their proposed CS model for allocating delivery tasks did not incorporate environmental considerations. Other studies evaluate the impacts of public transport-based CS platforms. For instance, (*17*) aimed to assess the economic, environmental, and social benefits of last-mile delivery solutions in Copenhagen using public transport-based CS. Similarly, (*11*) analyzed sustainable and economic impacts by studying demand levels, vehicle kilometers saved, and externality reductions. (*35*) evaluated the potential impacts of implementing CS services on traffic congestion and pollution in urban areas, specifically in Rome, modeling traditional delivery services and two alternative CS frameworks one car-oriented and one public-transit-oriented. Likewise, (*9*) argued that CS holds promise for reducing pollution from last-mile deliveries in urban areas by utilizing metro networks and smart lockers located inside or outside stations. Additionally, (*16*) examined the willingness of individuals, specifically students, to serve as crowdshippers for B2C e-commerce deliveries via public transportation systems in Rome. Their study, which did not use a simulator, considered a payment of 5–10 euros per delivery and a maximum detour distance of 2.4 km. Not all studies report positive outcomes regarding the potential impacts of CS. According to (*35*), CS is often described as a 'double-edged sword' when considering its effects on sustainable logistics operations. Major service providers like Uber and Lyft (*36*) view CS services as a potential extension to their business models, leveraging idle capacity and time, However, it's unclear if these services will result in more trips for people who can pick up and deliver items. Crowd logistics remains an emerging field with significant challenges, particularly in understanding the factors influencing business adoption. Previous research has not conclusively demonstrated whether a multi-channel delivery system offers improved efficiency and reduced emissions compared to a single-channel system. Our study utilizes a multi-agent-based simulator to examine these dynamics in detail. Compared to previous simulations with this simulator, (*13*), our innovation is to include observed commuting data from employees using bikes and personal cars from Rome in the analysis. Our data analysis reveals how different commuting modes impact efficiency and emissions. By providing insights into these factors, our study contributes to the empirical evidence of the likely impacts of CS and offers valuable guidance for businesses considering multi-channel logistics strategies.

METHODOLOGY

This section outlines the data sources, methodology, and model utilized in this study to assess the environmental and economic effects of implementing a CS platform. In this study, we explore through established modeling and simulation approaches, whether CS would be market-feasible in the municipality of Rome, as well as whether it could contribute to the city's emission reduction targets. The detailed methodology is illustrated in Figure 1, which provides an overview of the workflow. Each step is explained in detail below.

Data Collection

To ensure a comprehensive and robust analysis, we collected data from a diverse array of sources. These included primary sources such as industry publications, market research studies, and gov-

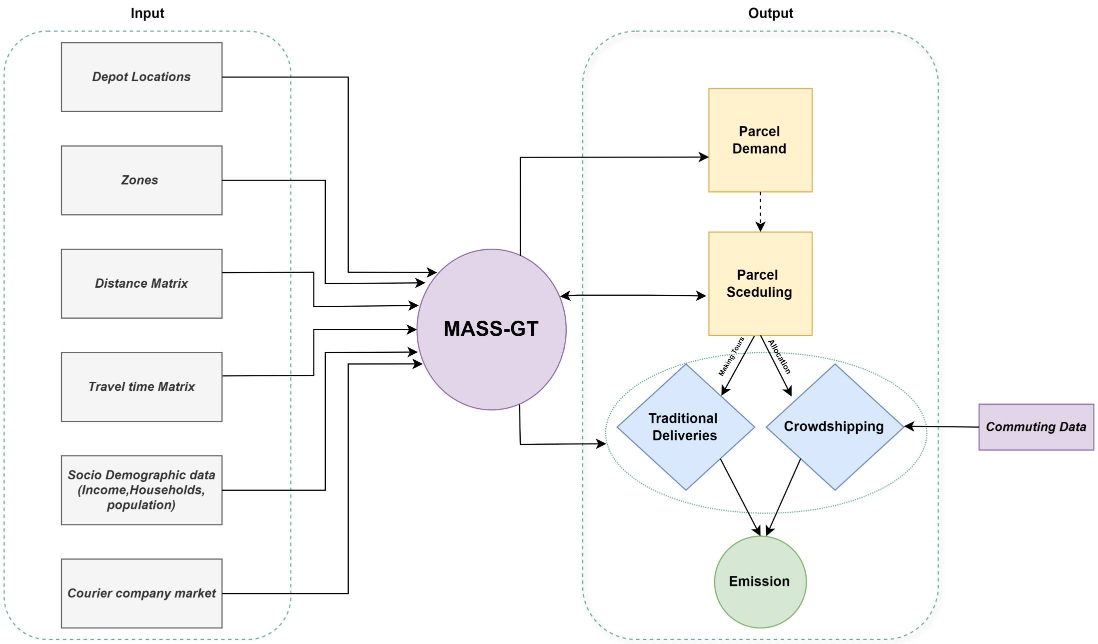

FIGURE 1 Methodology outline

ernment databases to enhance the accuracy, depth, and validity of our findings.

Depot Locations: These refer to the specific geographical sites within the city of Rome where parcel depots are established for the storage, sorting, and distribution of goods and packages within the logistics network. In this study, we identified and mapped the locations of the major courier companies' depots across Rome Using OpenStreetMap (*37*). This data was then integrated into our analysis to understand the spatial distribution of logistics operations.

Zones: Zones are introduced as smaller segments of the network. For the purpose of detailed analysis in our case study, we utilized the city geographic zones derived from the 2021 census data provided by the Italian Statistics Institute ISTAT (*38*). ISTAT provided the census data at the provincial level, which we then refined to focus solely on the urban areas of Rome. This process resulted in 8,658 cells. Each cell contains information such as region ID, population categorized by age and gender, and the number of households, among other Socio-Demographic variables. These divisions are based on a detailed cell structure within Rome, as illustrated in Figure 2.

Distance Matrix: To create the distance matrix, we used the centroids of each zone as starting points. Python and the OSMNX library (*39*) were employed to calculate road distances between these points, rather than using Euclidean distances. Due to the project's scale, we utilized the Blue Delft supercomputer server (*40*) to handle the computational demands of solving around 74 million instances of Dijkstra's algorithm, as implemented by OSMnx. This parallelized approach efficiently managed the calculations for our large 8658 x 8658 matrix.

Travel Time Matrix: To develop a travel time matrix, we used the centroids of each zone as reference points. By assigning travel speeds, specifically, an average free-flow speed of 50 km/h to the network edges, OSMNX (*39*) estimates travel times between these centroids, which represent each zone.

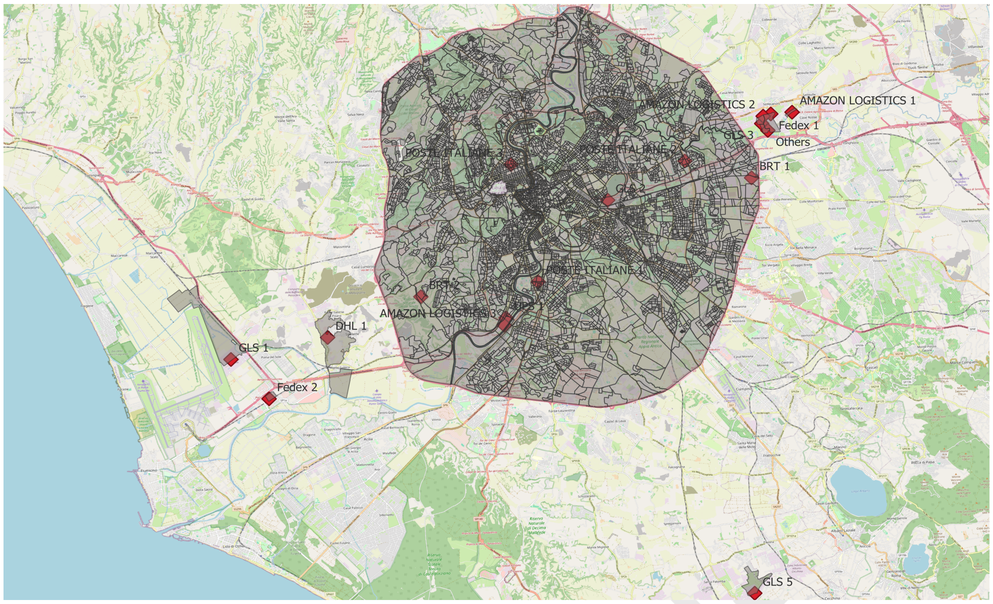

FIGURE 2 Study area with depot locations

Courier Market Shares: We obtained valuable insights from Statista (*41*) regarding the market shares of parcel delivery companies operating in Italy. According to the data, as of 2021, Poste Italiane held the largest market share at 17%. This information was critical in shaping our strategic considerations for a case study focused on parcel delivery logistics in Rome, as detailed in Figure 3.

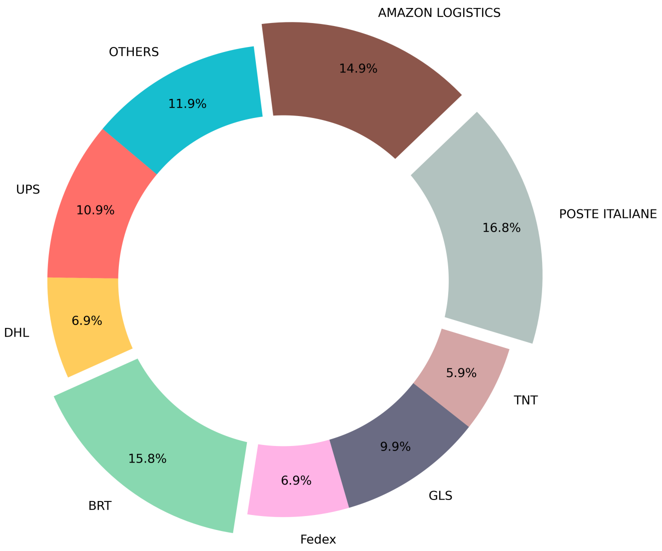

FIGURE 3 Market share of the leading parcel shipping providers in Italy 2021

The Home-Work Travel Plan Data:

The Home-Work Travel Plan, known as Piano Spostamento Casa Lavoro (PSCL) in Italian, is a strategic document that analyzes company mobility to promote sustainable transportation by reducing reliance on private vehicles. Utilizing PSCL data, we studied commuter trips within Rome, crucial for modeling CS scenarios, in collaboration with Movesion company (*42*). This rich dataset includes information on employees commuting to work across Italy, covering aspects such as trip modes, origin and destination coordinates, and modes of transport. We filtered this dataset to focus on the study area of Figure 2, specifically examining trips made via private vehicles and bikes (including scooters). Subsequently, we generated Table 1 to present detailed information on employees' trips to their workplaces; These commuting patterns were then matched with our designated zones, allowing us to determine the number of trips originating from each zone and their destinations within the city.

TABLE 1 PSCL data

Variables	PSCL data	This study
Mode	Bike, Private Car, public transport, walking	Car, bike
Offices	552	317 (car), 45 (bike)
Employees	50059	30652 (car), 4598 (bike)

Agent-Based Model Platform: MASS-GT

MASS-GT (Multi-Agent Simulation System for Goods Transport) is an agent-based modeling platform developed specifically for simulating a wide range of transportation and logistics scenarios. It leverages multi-agent systems to accurately model the behavior and interactions of individual entities such as vehicles, parcels, and infrastructure components within transportation networks (*43*). MASS-GT consists of three interconnected modules: the shipment synthesizer, the tour formation model, and the network model, as referenced in (*43*). Within the shipment synthesizer, the parcel demand module generates the demand for parcels, while the parcel scheduling module assigns parcels to vehicles and organizes delivery routes. Household data across various zones and the average parcel demand per household serve as inputs for the parcel demand module, resulting in a set of parcels with designated origins and destinations. These parcels are then processed by the scheduling module, which simulates the creation of distribution tours for parcel delivery. This scheduling module is essential for assessing the impact of conventional freight transport delivery methods. MASS-GT is set up to replicate real-world conditions. This includes defining agent behavior, setting operational constraints, and simulating scenarios to analyze and optimize delivery logistics. The MASS-GT platform has been utilized in various cities and projects (*13, 43–46*), confirming its practical applicability and robustness. Our study aims to leverage this model for practical analysis rather than focusing on the detailed verification of its methodology. In the model, the most suitable parcels are determined by the detour distance relative to the parcel trip distance. This detour should be minimized to ensure sustainable crowdshipping. The equation for this relative detour can be found in the equation below.

$$\text{relative detour } rd_{p,t}(-) = \frac{\text{traveler's detour (km) - parcel trip distance (km)}}{\text{parcel trip distance (km)}} \tag{1}$$

Specifically, we will use MASS-GT to analyze two distinct scenarios: the traditional delivery model by vans, as provided by MASS-GT according to parcel demand, and a scenario incorporating employee commuting data, which integrates this new mode into the Non-CS scenario. Our objective is to evaluate the environmental impact, particularly in terms of CO_2 emissions, based on the kilometers traveled in each scenario. When the model input is loaded, and processing begins, the 'crowd shipping' phase, as illustrated in Figure 1, initiates. In this phase, travelers input their trips into the platform, which then iterates over available transportation modes (car and bike) and their users. For each trip, the platform generates a list of potential parcels by applying several filters: parcels already claimed are excluded, parcels must have either the origin or destination within the same municipality as the traveler's route, and the parcel's trip must be at least half the length of the traveler's trip. These filters help reduce computation time and ensure that only relevant parcels are considered. For each remaining parcel, we calculate the relative detour using the given equation. Parcels with a relative detour below a threshold have their compensation calculated and are stored as potential options. After evaluating all parcels, the three with the lowest relative detours are selected and presented to the traveler. The traveler then calculates the utility of each offered parcel using equation **below** and selects the one with the highest utility. If this utility exceeds a predetermined threshold, the traveler chooses to carry the parcel, informs the platform of their decision, and becomes an occasional carrier. The platform records this match, and the process for this traveler concludes.

$$\text{utility}_{p,t}\left(\frac{€}{\text{h}}\right)=\frac{\text{provided compensation}_p(€)}{\text{detour time}_{p,t}(\text{h})+2\cdot\text{drop-off time}_t(\text{h})} \tag{2}$$

This procedure is repeated for all willing travelers. Ultimately, this results in some travelers choosing to ship parcels while others do not. The platform tracks these outcomes, and parcels that remain unclaimed are forwarded to conventional carriers for delivery.

Scenario Analysis

We analysed two main scenarios in this study:

Traditional Parcel Market: This scenario represents conventional parcel delivery methods without CS, using standard last-mile routes with company-owned or contracted vehicles. These vehicles follow predetermined routes, delivering parcels directly from depots to recipients. Our analysis focused on several key aspects: the number of delivery tours required to meet parcel demand efficiently, the total distance traveled by delivery vehicles, and the emissions produced. We also examined the distribution of tours among vans and calculated the total kilometers covered, aiming to optimize operations, ensure timely deliveries, and explore opportunities for emissions reduction.

CS Parcel Market: The process starts with the customer placing an order on the platform. The platform sets the strategy, collects orders, and calculates the best orders and compensations. Travelers share their trip details with the platform, which then offers them shipments. Once a traveler accepts an offer, they make the trip themselves or act as occasional carriers as detailed in Figure 4 from (*47*).

In this study, we consider each crowdshipper delivering a single package, with an average weight of 3 kg and a van capacity of 180 parcels. Since willingness drives CS participation and due to a lack of data for a similar case study, we assume a rough willingness percentage of

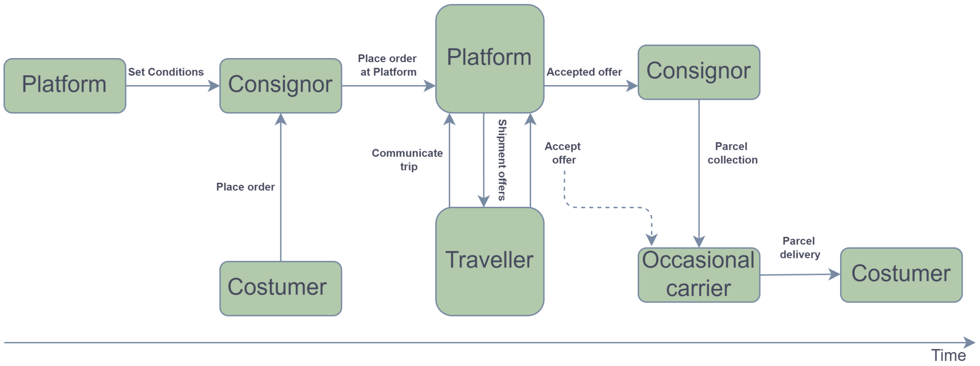

FIGURE 4 Overview of CS process

30%. This estimate accounts for the difference in willingness between employees and students, as evidenced by the 87% willingness rate reported for students in the same case study by public transport (*16*). The lower percentage for employees reflects their different motivations and constraints compared to students. Sensitivity analysis may further validate this assumption by examining the impact of varying willingness rates on our results. Travelers are expected to select parcels based on specific preferences, including pickup/drop-off times and a value-of-time (VOT) metric for detours compensated in euros. The Car VOT for Italy is estimated at 6 euros/h in (*48*), while a Bike VOT of 5.75 euros/h is assumed for bicycles, which is in line with other work in the literature (*47*). Moreover, the acceptance of travelers in CS platforms hinges significantly on the compensation offered. Higher pay tends to lead to more accepted orders from travelers. However, for CS to remain economically feasible, the payment to travelers must be less than what consignors pay for conventional delivery services. According to (*49*), the average cost of parcel delivery in the business-to-consumer market was 3.35 euros in 2020. To compete effectively with traditional delivery services, CS services should ideally set their maximum price at this level. Travelers are compensated based on the distance they travel to deliver parcels. The maximum compensation for the longest trip is set at 3.35 euros, aligning with the consignor's payment. For shorter trips, the compensation is structured to cover the traveler's time for pick-up and drop-off tasks. Despite a lack of specific research on the minimum desired compensation for travelers, a baseline of 1.50 euros has been established for this study, according to (*47*). To formulate the compensation structure, we design a mechanism that exhibits desirable properties such as generous compensation for shorter trips and diminishing returns for longer trips. To achieve this, we propose a simple logarithmic model, as shown in Equation 3. This approach ensures that shorter trip lengths are compensated more generously per kilometer to offset the time spent on pick-up and drop-off activities.

$$\log((\text{parcel distance})+5) \tag{3}$$

According to (*50*), drop-off times are estimated at 2 minutes per parcel for delivery vans, halved for bicycles primarily due to quicker parking. we assume that parcel pickup times are symmetric with respect to drop-off times. Table 2 summarizes our chosen model parameters.

TABLE 2 Specifications and numbers

Specification	Numbers
Number of zones	8658
Van max parcel capacity	180
Average parcel weight	3 kg
Bike max parcel load	1
Car max parcel load	1
Bike willingness to ship	30%
Car willingness to ship	30%
Bike VOT	5.75 €/h
Car VOT	6 €/h
Unloading Bike	0.016 h
Unloading Car	0.033 h
Unloading Van	0.033 h

Emission calculation In this section, we detail the methodology used to calculate emissions for both CS and non-CS scenarios. We specifically focus on tailpipe emissions, which are negligible for electric vehicles (EVs). Lifecycle emissions are beyond the scope of this analysis. We focused on Poste Italiane, the leading parcel delivery company in Italy (*41*), to base our assumptions on an electric fleet to calculate non-electric fleet emissions for our scenario. According to the operator's reported fleet composition data (*51*) , as shown in Table 3, we estimate that 60% of their fleet in 2022 consisted of traditional internal combustion engine (ICE) vehicles. We adopted this percentage as a proxy for other companies in the industry in our simulation analysis. For commuter vehicles in the CS case, we can assume a small proportion to be EV users. According to (*52*), 6% of individuals in Rome use electric cars, a figure we integrated into our calculations. These assumptions are necessary due to the lack of precise data on the percentage of electric vehicles used by each parcel company or the number of employees driving EVs in our PSCL data. While these are rough approximations, the substantial difference in EV penetration rates between freight and CS allows us to draw meaningful qualitative conclusions. We calculated emissions based on the distance traveled by vehicles in both scenarios. In the non-CS scenario, emissions are computed considering the kilometers traveled by vans alone. In the CS scenario, emissions are calculated from the combined distance traveled by both vans and private cars, including eventual detours. The calculations follow Equation 4:

$$\text{Total emission} = (\beta \times \mathrm{KM}_{\mathrm{van}} \times \mathrm{EF}_{\mathrm{van}}) + (\gamma \times \mathrm{KM}_{\mathrm{car}} \times \mathrm{EF}_{\mathrm{car}}) \tag{4}$$

Where:

$\beta = 0.6$ (non-electric van fleet ratio),

$\gamma = 0.94$ (non-electric car ratio),

$\mathrm{KM}_{\mathrm{van}}$ = kilometers traveled by van,

$\mathrm{KM}_{\mathrm{car}}$ = kilometers traveled by car,

EF = emission factor for each type.

This linear relationship assumes that emissions increase proportionally with distance traveled, which simplifies the model and allows for more robust and faster computations. Although there are emission models in the literature that are typically nonlinear, we opted for a linear model to enhance computational efficiency.

TABLE 3 Corporate fleet data of Poste Italiane

	2020	**2021**	**2022**
Total vehicles	32,791	31,645	30,850
of which:			
traditional vehicles	28,133	26,747	**19,441**
alternative vehicles	4,658	4,898	11,409
of which:			
bicycles	324	324	333
electric vehicles	1,448	1,805	3,654
hybrid motor vehicles	79	79	5,782
petrol-natural gas-fueled vehicles	1,727	1,615	1,410
petrol-LPG-fueled vehicles	1,080	1,075	230
diesel-natural gas-fueled vehicles	0	0	0
LPG-fueled vehicles	0	0	0
percentage of alternative vehicles (%)	14.2	15.5	37

Emission factors (EF) for vans are derived from (*53*), which provides average fleet data for road transport of bulk/packaged goods. This study considers well-to-wheel emissions, offering detailed emission coefficients for different van types. For normal vehicles, the calculation is based on car emission factors from (*54–56*). These factors are detailed in Table 4.

TABLE 4 Emission factors

Emission Type	**van EF (g/km)**	**car EF (g/km)**
CO2-eq (Carbon dioxide equivalent)	**857.3**	**180**
SO2 (Sulfur dioxide)	0.89	0.03
PMc (Coarse PM)	0.08	0.005
NOx (Nitrogen oxides)	3.1	0.3
PMw (Fine PM)	0.044	0.02

RESULTS AND DISCUSSION

Demand share of parcels

We calculated parcel demand across Rome's urban areas based on socio-demographic characteristics and household structure of the population, employing MASS-GT's parcel demand and scheduling modules. The model integrates data to calculate parcel demand by considering two main factors: socio-demographic characteristics, network and supply data. The former includes the anticipated parcel demand based on aggregate population and household characteristics such as population size and income levels. The latter includes zoning structure of the network, depot locations of couriers and the courier market shares, as detailed in Section 4.1. With these data, the parcel demand of the courier companies is simulated per zone in the network, providing the destination zone of the parcels. Following this, the parcels are assigned to the closest depot of the courier to the destination zone of the parcel.

Figure 5 illustrates the distribution of parcel demand across different parcel couriers in Rome, which is derived from MASS-GT Demand module. The results show variability in parcel demand among different companies, with Poste Italiane dominating the market share. This highlights Poste Italiane's strong presence and customer base in Rome's urban logistics. Our simulation estimates an average daily demand of about 360,000 parcels in Rome, aligning with national statistics which reported that in 2022, Italy saw a 3.5% increase in parcel volume, reaching 1.5 billion parcels from 1.4 billion in 2021. The average number of parcels per person rose to 25, with households averaging 57 parcels each (*57*). Considering Rome's population and delivery trends, this daily estimate reflects the city's urban freight demand accurately.

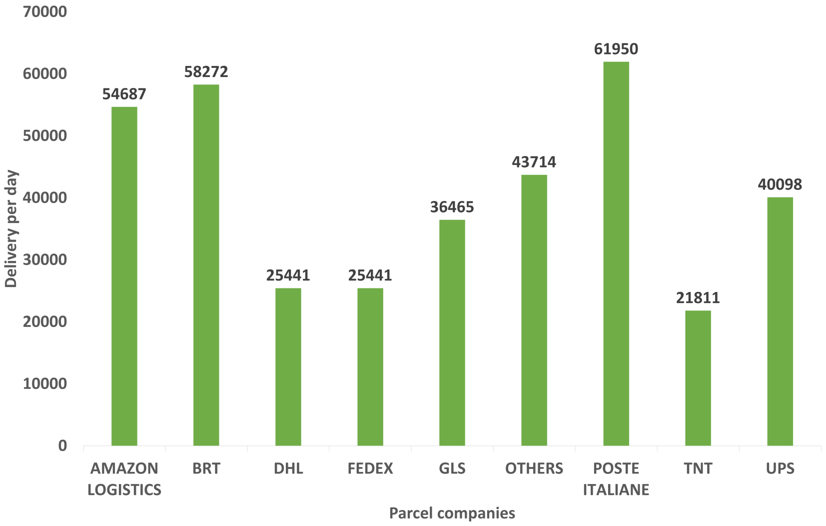

FIGURE 5 Number of parcel delivery for different companies in Rome per day

Parcel scheduling

Parcel scheduling involves creating delivery tours based on simulated parcel demand for each courier. This module allocates parcels to vehicles, typically vans with a capacity of 180 parcels per tour, and plans the delivery routes accordingly. Table 5 summarizes the key performance indicators of this scenario:

Analyzing traditional parcel scheduling in a large urban network like Rome reveals key insights. Frequent tours are essential for meeting delivery demands efficiently, while numerous stops indicate the need for substantial coordination. The long distances covered by vans and the significant time investment highlight the complexity and time-consuming nature of last-mile delivery. These findings underscore the need for optimization in network planning.

TABLE 5 Parcel scheduling without CS

KPIs	Value
Number of parcels	367879
Number of tours	2053
Number of trips	65311
Vans VKT	244203.6
Vans Travel Time(h)	4884.06

Parcel scheduling with CS

The demand module of the platform generates parcel demands for 8658 zones in Rome. However, due to the data, CS could only be simulated in 4000 of these zones, where travelers' origins and destinations are available through PSCL data. Therefore, out of the total parcel demand in the reference case, a total of 80,606 parcels were ordered within the system. Of these, 2449 parcels were eligible for CS. Among the eligible parcels, 1256 were successfully delivered through CS, resulting in a delivery rate of 51.28%. For the remaining parcels, van delivery is employed. The average distance traveled for CS parcel trips was 3.65 km, with an average detour of 2.39 km for delivered parcels. The CS deliveries contributed an additional 3004.43 kilometers of travel. Detours were distributed across modes as follows: 503 parcels by bike, totaling 1050 km (average 2.01 km per detour), and 753 parcels by car, totaling 1950 km (average 2.59 km per detour). Occasional carriers received an average compensation of 2.11 euros per delivery detailed in Table 6. The distribution of detours is discussed further.

TABLE 6 CS Metrics

Metric	Value
Total Parcels Ordered	80,606
Parcels Eligible for CS	2,449
Parcels Delivered through CS	1,256
% of Eligible Parcels Delivered through CS	51.28%
Average Distance of CS Parcel Trips	3.65 km
Average Detour for Delivered Parcels	2.39 km
Total Extra Kilometers Driven for CS Deliveries	3,004.43 km
Detours by Mode	
- Bike	503 parcels, 1,050 km total (2.01 km average)
- Car	753 parcels, 1,950 km total (2.59 km average)
Average Compensation for Occasional Carriers	2.11 euros

Traveler availability and willingness to carry parcels are crucial. Ideally, parcels should be placed in areas with accessible traveler data, aligning with their routes. Parcels far from common routes or in low-traffic areas may be less suitable. Future studies will include detailed sensitivity analysis to improve these decisions.

Mode choice

When examining the distribution of detours made by cars, we observe that some occasional carriers experience negative detours, with the minimum detour recorded at -2.25 km as in Figure 6. This phenomenon implies that, in some instances, less distance is covered when a traveler delivers a parcel. The underlying reason for this is that travelers often prefer the fastest route available rather than the shortest. Consequently, when these occasional carriers engage in parcel deliveries, they may find themselves traveling shorter distances even though the route may take longer to complete which is align with (*47*) result. This highlights the complexity of route optimization.

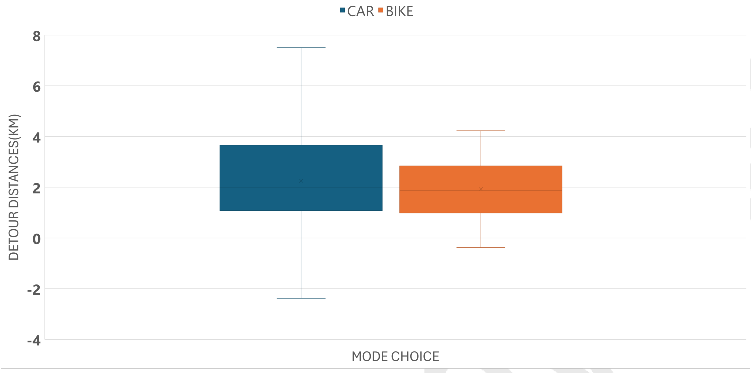

FIGURE 6 Caption

Compensation

Histogram analysis of car and bike compensation amounts Figure 7 shows distinct patterns. Both types range from 1.7 to 3 euros. Car claims peak at 2.2-2.4 euros and above 2.6 euros, while bike claims are concentrated between 1.8 and 2.2 euros. There is overlap from 1.8 to 2.4 euros: bike claims are more frequent in the lower segment (1.8-2.1 euros), while car claims increase with higher amounts. Bike compensation has a symmetric distribution around 2 euros, whereas car compensation peaks at 2.1 and 2.3 euros. Cars also show outliers beyond 2.6 euros, unlike bikes.

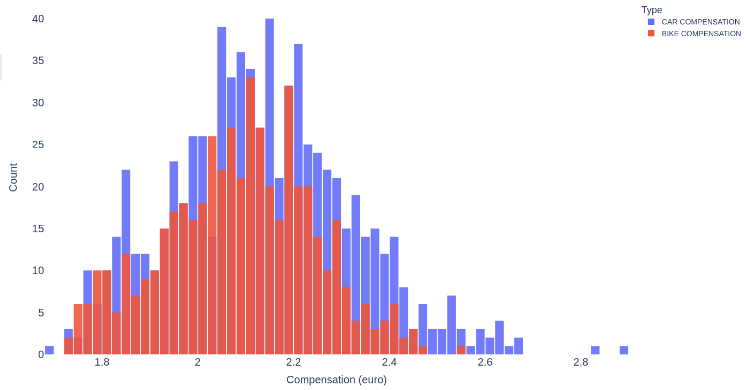

FIGURE 7 Compensation distribution of Car and Bike

Higher car compensation amounts, especially above 2.6 euros, encourage longer detours due to logarithmic VOT valuation. However, if detours require excessive time, drivers may find the compensation insufficient. Bike claims, generally between 1.8 and 2.4 euros, rarely exceed 2.6 euros, indicating less incentive for detours. This highlights how compensation and transport mode affect travel behavior and the complexity of compensation structures. Since both modes used the same formula, further testing with alternative compensation methods like linear or flat rates is needed for a comprehensive comparison.

Sensitivity analysis

The type of sensitivity analysis used in our analysis involves parameter sensitivity analysis and the primary focus is on understanding how variations in car usage, while keeping bike usage between 10% and 80% of employees, impact the detour distance of cars according to Figure 8. To address emissions concerns, our analysis shows that as car crowdshippers' willingness increases, detour distances rise more significantly for cars than bikes. This trend impacts environmental sustainability, particularly CO_2 emissions, as longer detours lead to higher emissions. This pattern persists regardless of the proportion of bikes and cars. A possible reason for this trend is incomplete zone coverage. Future research should include a transport model that covers all trips within each zone for better system insights. This finding could inform future research on CS compensation mechanisms and proactive policymaking.

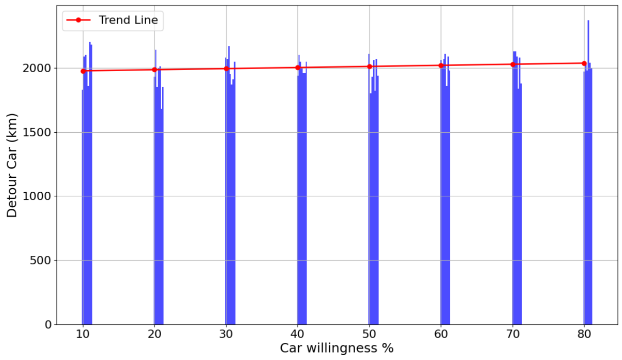

FIGURE 8 sensitivity analysis

Emission

This section compares CO_2 emissions between non-CS and CS scenarios. The table 7 displays total emissions and savings for each emission type in kilograms. The CS scenario shows reductions across all emission types, with CO_2 emissions being the highest. The CS scenario achieves a savings of 1,310.94 kg of CO_2, valued at 93 euros under the EU's Emissions Trading System (*58*). Although the CO_2 savings here might seem relatively small, it is important to recognize the significance of these reductions within the context of the current study. The amount of savings is limited by the fact that not all zones were covered due to data constraints from the PSCL dataset. If we had comprehensive coverage of all zones, the potential for increased savings would be substantial. This is because extending the analysis to additional zones would likely reveal more opportunities for reducing emissions through the integration of CS. Moreover, the results might not fully capture the potential benefits due to the use of a linear model for emissions analysis. Employing a more advanced modeling approach, such as the built-in emission calculation in MASS-GT network model (*45*) or COPERT, could provide a more nuanced understanding of emissions and potentially highlight more significant impacts. This suggests that the actual benefits of the CS scenario could be greater than the current analysis indicates.

TABLE 7 Emission Comparison

Emission Type	Total Non-CS Emissions(kg)	Total CS Emissions(kg)	Save (kg)
$CO_2 - eq$	125613.31	124302.37	1310.94
SO_2	130.40	128.75	1.65
PM_c (Coarse PM)	11.72	11.57	0.15
NO_x	454.21	448.84	5.37
PM_w (Fine PM)	6.44	6.30	0.14

CONCLUSION

This study demonstrates the potential of CS as a sustainable last-mile delivery solution for Rome under certain conditions, such as the use of environmentally friendly vehicles and leveraging existing trips. Using real-world data and advanced simulation techniques, we evaluated the possible impacts of CS in the city of Rome. By integrating parcel deliveries with employees' existing travel routes, our research highlights contributions and areas for future exploration. We demonstrated the feasibility of CS in Rome using the MASS-GT simulator and real-world OD trip data from employees-to-office. Our case study shows that CS can be effectively integrated into the city's urban logistics framework. By evaluating daily parcel delivery demand and optimizing scheduling, we achieved efficiency gains by utilizing existing commuter routes for parcel delivery. A comparative analysis indicated that CS could reduce CO_2 emissions in Rome. While the CO_2 savings presented may appear modest, their significance within the scope of this study cannot be overlooked. Consider the potential impact if these efforts were scaled up to encompass larger zones; the reductions in emissions could be more substantial. This reduction supports European emissions goals and underscores the environmental benefits of CS. We improved our CS model's accuracy by using socio-demographic data to estimate delivery demand, demonstrating the value of detailed data in optimizing logistics solutions.

In Rome, a city predominantly driven by private vehicles and facing significant environmental issues with high CO_2 emissions; CS presents a promising solution. Policymakers should consider supporting the development of CS platforms and incentivizing individuals and companies to participate. Encouraging employees who engage in CS reflects a commitment to sustainability and environmental responsibility. Our study highlights the need to compensate travelers for detours as crucial for CS success. Future research should develop incentive structures to boost participation and use richer employee-to-office data to refine models and outcomes. While our analysis addresses tailpipe emissions, it overlooks the lifecycle emissions of electric vehicles, which could provide a fuller environmental impact assessment. Future studies should consider lifecycle emissions and explore the impact of switching to sustainable transport modes like bicycles, potentially aligning with (*25*).

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AUTHOR CONTRIBUTIONS

S.S.: Conceptualization, Methodology, Software, Validation, Analysis, Investigation, Data curation, Writing original draft; **M.C.**: Conceptualization, Resources, Writing reviews & editing; **M.D.**: Methodology, Resources, Writing reviews; **M.T.**: Writing Draft & Edited draft; **M.R.**: Supervision, Writing reviews; **G.G.**: Supervision, Resources.

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