European Transport \ Trasporti Europei (2023) Issue 90, Paper n° 3, ISSN 1825-3997

https://doi.org/10.48295/ET.2023.90.3

Last mile distribution using cargo bikes: a simulation study in Padova

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Abstract

The recent growth of e-Commerce has induced an increasing freight demand, which could lead to negative externalities, in particular in urban areas. To foster sustainable development of cities and increase their livability, many local authorities are implementing urban vehicle access regulations, such as low-emission zones, banning the circulation of polluting vehicles. These measures prompted the adoption of new sustainable freight transport solutions for last mile deliveries, such as cargo bikes. The aim of this paper is to describe the study for the implementation of such a system. The procedure was tested (1) to define the location of a transshipment facility where parcels are moved from vans to cargo bikes, (2) to estimate the environmental and economic sustainability of the system, and (3) to quantify the effects of uncertainty in the final results. The framework was applied to the city center of Padova (Italy), where two sets of delivery system were considered: the first with traditional vans starting from an existing urban consolidation center and the second with manual and electric cargo bikes starting from a micro-depot. In particular, demand of home deliveries was estimated for a typical weekday; routes of freight transport means were defined by an optimization procedure; these data were used as input to a Discrete Event Simulation model. A sensitivity analysis was carried out modelling the potential uncertainty associated with load/unload times and travel speed of means, due to traffic congestion. Several scenarios were tested considering three locations as potential transshipment points. Outcomes of the simulations were used to estimate key performance indicators, evaluating the environmental and economic effects of the two delivery schemes. Results highlighted the potentiality of cargo bikes as a sustainable delivery system, and the impacts of uncertainty on the ranking of alternative options (i.e. micro-hubs).

Keywords: city logistics; discrete event simulation; sustainability; last mile distribution; urban freight delivery

1. Introduction

For the last few years, online purchases have been growing in many countries (Niels, Hof & Bogenberger 2018) and have recently been boosted by the Covid-19 pandemic (Narayanan & Antoniou 2022). In Italy, the adoption of e-Commerce increased by 99% between 2019 and 2020, and by 68% between 2019 and 2021 (Idealo 2021). In addition,

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the United Nations estimated that by 2050 about 70% of the world's population will live in urban areas (United Nations 2018). Therefore, the rapid changes in customers' purchase habits, the growing urbanization and great diffusion of just-in-time solutions contributed to a significant raise of deliveries in urban areas (de Mello Bandeira, Goes, Schmitz Gonçalves, D'Agosto & Oliveira 2019; Llorca, Carlos & Moeckel 2021). This led to many negative impacts, such as traffic congestion and air pollution due to freight vehicles, as well as road capacity reduction due to their frequent stops to unload/load goods (Russo & Comi 2012; Melo & Baptista 2017; Carotenuto et al. 2018; Niels, Hof & Bogenberger 2018). These effects are even more problematic in historic city centers, where the low availability of parks often causes illegal truck parking and the presence of narrow streets, where traditional commercial vehicles can or cannot travel, significantly impacts safety and walkability (Choubassi, Seedah, Jiang & Walton 2016). For these reasons, mitigating these negative effects has recently become one of the primary goals of policy makers, with the aim of improving the air quality and livability of cities (Narayanan & Antoniou 2022). In many cities worldwide, local authorities imposed restrictions on access to urban areas depending on vehicle emissions and size, by creating zero- or low-emission zones and enforcing parking regulations (Dablanc, Giuliano, Holliday & O'Brien 2013). In order to increase the efficiency and sustainability of freight delivery in urban areas, many solutions have been proposed, such as electric vehicles (de Mello Bandeira et al. 2019), drones (Borghetti et al. 2022), lockers (Carotenuto et al. 2022), and cargo bikes (Llorca, Carlos & Moeckel 2021). In this paper, a study on the implementation of a cargo bike system is described. The aim of the work was to define the location of a micro-hub and to estimate the environmental and economic sustainability of the system, by considering the potential uncertainty associated with load/unload times and travel speed of means, due to traffic congestion. The study area was the central area of Padova, a typical medium-sized Italian city, which includes the historic city center where restrictions on freight vehicles are likely to be enforced. In particular, two sets of delivery systems were considered: the first with traditional vans starting from an existing urban consolidation center and the second with manual and electric cargo bikes starting from a micro-depot.

2. Literature review

In recent years, the study of urban delivery schemes based on or integrating cargo bikes has received increasing attention (Narayanan & Antoniou 2022). In particular, many previous works reported several benefits of their adoption (Llorca, Carlos & Moeckel 2021). Unlike parcels' deliveries with traditional vans, cargo bikes are not affected by traffic congestion and parking problems (Sheth, Butrina, Goodchild & McCormack 2019); they can travel in areas restricted to motorized traffic (Fikar, Hirsch & Gronalt 2018) and through narrow streets (Choubassi et al. 2016); they can park on sidewalks, thus getting closer to the destination (Dalla Chiara, Alho, Cheng, Ben-Akiva & Cheah 2020). This leads to a decrease in delivery times (Dalla Chiara et al. 2020) and vehicle-distance traveled (Niels, Hof & Bogenberger 2018), therefore reducing the cost of deliveries (de Mello Bandeira et al. 2019), and increasing their reliability (Sheth et al. 2019). Moreover, cargo bikes can effectively contribute to the reduction of negative externalities of transportation, by reducing emissions of air pollutants (Melo & Baptista 2017) and reducing the use of parking space (Robichet & Niérat 2021). However, the magnitude of these positive impacts depends on several factors. Specifically, substantial benefits can be reached in areas where the demand density is high (Llorca, C. & Moeckel

2020) and if delivery points are not so far from the rip origin (Sheth et al. 2019). Furthermore, cargo bikes can easily carry small parcels and an excessive loading weight can reduce their speed, therefore their positive effects could be mitigated depending even on the characteristics of the packages (Elbert & Friedrich 2020). The implementation of a cargo bikes system often requires a micro-hub, that is a transshipment point where goods are consolidated and transferred to bicycles (Fikar, Hirsch & Gronalt 2018). Parcels are sent from a distribution center to a micro-hub by using vans (Llorca, Carlos & Moeckel 2021). This facility is located close to the city center, thus leading to short delivery routes for cargo bikes and allowing consignment even where restrictions for freight vehicles are enforced (Fikar, Hirsch & Gronalt 2018). As previously highlighted, the potential benefits of cargo bikes are highly dependent on the network configuration, therefore defining the optimal location of a micro-hub is of paramount importance, in particular in urban areas where available space is often limited (Hofmann, Assmann, Neghabadi, Cung & Tolujevs 2017). The following main approaches have been adopted to evaluate the impacts of cargo bikes and to optimize their integration in an urban freight delivery system (de Mello Bandeira et al. 2019; Narayanan & Antoniou 2022): optimization techniques (Choubassi et al. 2016; Niels, Hof & Bogenberger 2018; Robichet & Niérat 2021), simulation models (often combined with optimization) (Hofmann et al. 2017; Melo & Baptista 2017; Fikar, Hirsch & Gronalt 2018; Zhang, Matteis, Thaller & Liedtke 2018; Dalla Chiara et al. 2020; Llorca, Carlos & Moeckel 2021) and the analysis of existing datasets (Browne, Allen & Leonardi 2011; de Mello Bandeira et al. 2019; Dybdalen & Ryeng 2021). For instance, Choubassi et. al (Choubassi et al. 2016) implemented a capacitated vehicle routing problem with time windows to perform an economic analysis of a last mile delivery system with electric cargo bikes replacing the postal service in three areas of Austin (U.S.A.); Melo and Baptista (Melo & Baptista 2017) developed a microscopic traffic simulation model to evaluate mobility and environmental impacts of electric cargo bikes in Porto (Portugal); Dybdalen and Ryeng (Dybdalen & Ryeng 2021) analyzed observations, GPS-tracks and questionnaires in Trondheim (Norway) to assess the performances of cargo bikes in winter roads. Among these methodologies, simulation allows to generate and test several scenarios and policies in a flexible and cost-effective way, even at large scales, providing many data for the analysis (Arnold, Cardenas, Sörensen & Dewulf 2018; Zhang et al. 2018; Elbert & Friedrich 2020; Narayanan & Antoniou 2022). Moreover, potential changes in the estimation of the impacts of a delivery system could be due to unexpected variations in input variables; for this reason, although several previous authors adopted deterministic and fixed values of input variables (Niels, Hof & Bogenberger 2018; de Mello Bandeira et al. 2019), some previous works consider stochastic demand patterns (Hofmann et al. 2017; Arnold et al. 2018) or dwell time (Dalla Chiara et al. 2020; Elbert & Friedrich 2020) to estimate the potential effects of cargo bikes.

3. Data and methodology

In order to reach the aim of the paper, results of two delivery schemes were compared: the first one with cargo bikes starting from a micro-hub which is fed by traditional vans, and the second one in which deliveries are carried out by traditional vans. In particular, the following steps were adopted. First, demand of parcels is estimated for each zone of the study area; then, the routes of both bikes and vans are optimally defined for each potential location of the micro-hub. After that, as regards the cargo bike system, several scenarios were simulated considering different places for the micro-hub, as well as a deterministic and stochastic dwell time and travel time; results of each of them were used to calculate indicators to define the best place for the micro-depot. Lastly, the corresponding scenario with manual and electric cargo bikes was compared to the scenario with traditional vans. Each of the methodological steps is described hereinafter.

- Demand estimation. The study area was divided into zones consistent with the census areas defined by the Italian National Institute of Statistics. The freight demand was quantified as the average number of deliveries in each zone, considering the characteristics of the population and data about online purchases in the area.
- Routing. In order to define the routes performed by both cargo bikes and vans, a Capacitated Vehicle Routing Problem (CVRP) was solved for each potential location of the micro-hub. The objective function minimizes the travel time of all vehicles. In particular, the travel time of bikes and vans between each pair of delivery zones, as well as between each of them and the micro-hub, for cargo bikes, and the distribution center, for vans, was estimated by using a traffic simulation software, that identifies the minimum path between each considered couple of origin and destination points. The number of vehicles was defined so that all required deliveries can be performed during a fixed time period (Choubassi et al. 2016). The output of this phase is a set of optimal routes for each cargo bike and micro-hub location, as well as for each van.
- Scenarios. To evaluate the potential impacts of the uncertainty of travel and dwell time, the following scenarios were tested for the delivery system with cargo bikes:
    - Scenario A: Fixed travel speed and fixed stop duration for manual cargo bikes
    - Scenario B: Stochastic travel speed and fixed stop duration for manual cargo bikes
    - Scenario C: Stochastic travel speed and fixed stop duration for electric cargo bikes
    - Scenario D: Fixed travel speed and stochastic stop duration for manual cargo bikes
    - Scenario E: Stochastic travel speed and stochastic stop duration for manual cargo bikes
    - Scenario F: Stochastic travel speed and stochastic stop duration for electric cargo bikes

  Moreover, for each scenario, potential locations of the micro-hub were evaluated; in addition, different time period limits for deliveries were considered.
- Simulation. Each scenario for both cargo bikes and vans was simulated using a Discrete Event Simulation (DES) model. This approach considers that an entity flows through steps that are the process of the system; each of them is an event, representing a discrete point in time that changes the value of the entity (Lebeau, Macharis, van Mierlo & Maes 2013). Entities include parcels and vehicles, whereas events could be the arrivals/departures of vehicles, or the acquisition/release of resources by them (Jlassi, Tamayo & Gaudron 2018). In this work, two systems were simulated: (1) a distribution scheme with vans which pick up parcels from a distribution center, directly travel to final customers following the tours defined in a previous step, stop in each residential area to deliver goods and come back to the distribution center; (2) a distribution system in which a van picks up parcels from a distribution center and travels towards a micro-hub, where goods are transferred to cargo bikes; each of them starts its pre-defined tour from the micro-depot to deliver parcels to customers and then returns to the micro-hub.

- Indicators. In order to evaluate each scenario, with the aim of identifying the best location of the micro-hub and estimate the potential benefits of cargo bikes, the following indicators were estimated: total time spent by vehicles in the system (i.e. travel time, stop time, loading/unloading time), distance traveled, total cost, average time and cost per delivery, polluting emissions and externalities. In particular, total cost was quantified considering both fixed (e.g. insurance, structural costs of the distribution center and micro-hub) and variable (e.g. fuel, tire, maintenance, labor for delivery and transshipment operations) costs. As regards the environmental assessment, cargo bikes were assumed to generate no emissions (de Mello Bandeira et al. 2019); CO2 emissions of vans were estimated using emission factors which were calculated in line with the procedure proposed by the European Environment Agency (Ntziachristos et al. 2019). Concerning externalities, the monetary value of emissions, noise and congestion was considered, since they have been largely adopted in previous works (Arnold et al. 2018).

The procedure was applied to the city center of Padova (Italy), which is delimited by a red line in Figure 1. Due to its high density, about 5000 inhabitants per square kilometer (Comune di Padova 2021), the area may be suitable for testing a delivery system with cargo bikes (Llorca, C. & Moeckel 2020). In addition, the zone includes the historic part of the city, where there are many narrow streets, one-way roads, and pedestrian zones; furthermore, several restrictions for motorized vehicles based on emission standards and size are likely to be enforced. The study area was divided into 182 zones representing the residential areas where final customers live. For the delivery system with traditional vehicles, vans were assumed to start from the existing distribution center (marked with a red square in Figure 1); as regards the cargo bike delivery scheme, three potential micro-hub locations (named D1, D2 and D3) were identified considering the real available places (that is large parking areas) (marked with green triangles in Figure 1). Four limits were set for the duration of delivery operations (8, 6, 4 and 3 hours).

Although there are many freight generation models (Holguín-Veras, Jaller, Sánchez-Díaz, Campbell & Lawson 2014), a simplified approach was used to estimate delivery demand, due to the lack of disaggregated data. Specifically, information about the frequency of online purchases depending on the age of customers was retrieved from a national survey (Idealo 2021); these data were combined with the number of people of different ages living in each zone, derived from the Italian National Institute of Statistics (ISTAT 2011). In this way, the number of parcels to be delivered to each zone was obtained. All parcels were assumed to have the same average size, thereby the total volume of freight demand for each zone was estimated. Since no real data were available, some assumptions had to be made (Elbert & Friedrich 2020); however, values of several variables were set in line with previous studies on the topic, thus contributing to increase the realism of results. The characteristics of existing diesel van and cargo bike types were used to estimate their capacity (580 and 21 parcels, respectively); specifically, load factors of 38% were assigned to the former when delivering parcels directly to customers, and 100% when feeding the micro-depot (Llorca, Carlos & Moeckel 2021); whereas cargo bikes were assumed to be full at the start of their tours (Llorca, C. & Moeckel 2020). The travel speed was set to 17 km/h for vans (Arnold et al. 2018). Moreover, concerning cargo bikes speed, in scenarios with fixed value, 15 km/h was used (Dalla Chiara et al. 2020), while in those with stochastic value, a triangular distribution was adopted with the same value as mean and a maximum value of 20 km/h for manual cycles (Llorca, Carlos & Moeckel 2021), and a mean value of 20 km/h (Melo & Baptista 2017) and a maximum value of 25 km/h (in line with the current speed limit) (Choubassi et al. 2016), for electric cargo bikes. Furthermore, stop duration, which includes parking, finding the customer location and delivering the parcels, was set to 2.5 minutes (Arnold et al. 2018) or was modelled as a lognormal distribution as reported by a previous work on the topic (Dalla Chiara et al. 2020). For each scenario with stochastic variables, 200 runs were performed in DES. The duration of transshipment operations was set to 5 minutes and an additional time of 1.5 minutes per m^3 of parcel was added (Elbert & Friedrich 2020). Moreover additional daily costs (e.g. structural costs) of the distribution center and the micro-hub were considered (46€ and 26€, respectively) (Estrada & Roca-Riu 2017; Elbert & Friedrich 2020). Lastly, Table 1 summarized the specific monetary values adopted for each type of vehicle.

Table 1: Monetary values adopted to calculate indicators

Variable	*Unit*	*Van*	*Cargo bike*
Fixed cost	€/day	48.79[1]	3.27[1]
Variable cost (distance)	€/km	0.37[1]	0.10[1] (0.21[2] for e-cargo bike)
Variable cost (labor)	€/h	22.60[1]	12.00[1]

[1](Zhang et al. 2018);[2](de Mello Bandeira et al. 2019)

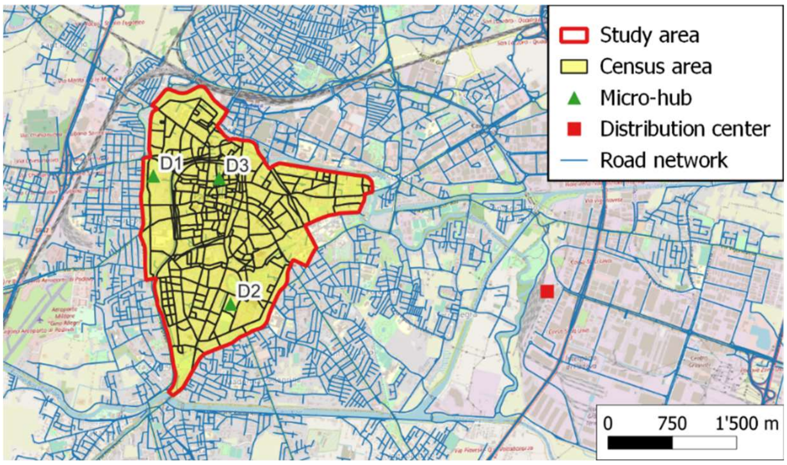

Figure 1: Study area

4. Results

The results of the six scenarios related to the implementation of a delivery system with manual and electric cargo bikes for each of the three potential locations of the micro-hub are reported in Table 2. By observing the table one can note that considering both travel speed and stop time as stochastic variables leads to changes in total delivery time of cargo bikes; in addition, a variation of the ranking of micro-hub locations was observed when travel speed is assumed to follow a probability distribution (Scenario D vs. Scenario E). This suggests that neglecting uncertainty in the analysis could alter the final outcomes both in absolute and relative terms. The adoption of electric cargo bikes was found to decrease their total delivery time (Scenario B vs. Scenario C and Scenario E vs. Scenario F) by 5-7%. These changes allowed to reduce the total cost, as well as the average cost and time per delivery. As expected, if the time limit on daily delivery operations increases, the total cost and the average cost per delivery decrease, with consequent benefits for the freight delivery operator; however, the average time per delivery increases, leading to a worsening of the performance of the service from the customer's point of view. As regards the choice of the best location for the micro-hub, the analysis of the indicators in Table 2 points out that D2 could provide the best results from both the company's and customer's perspectives. The values of indicators related to location D2 for scenarios considering uncertainties were compared with those obtained for the delivery system with only traditional vans (Table 3). As reported by previous authors (Llorca, Carlos & Moeckel 2021), adopting cargo bikes leads to a slight increase in the total delivery time; moreover, the reduction of the average time per delivery was observed to be mitigated and then deleted if the maximum delivery duration is shortened. However, with respect to vans, the total and average delivery cost is reduced by 27-45%, as found by other authors (de Mello Bandeira et al. 2019), with increasing benefits if the maximum delivery duration decreases and for electric cargo bikes. Lastly, confirming the results of previous studies (Melo & Baptista 2017), with the cargo bike delivery system, both CO_2 and negative externalities decreased by 71-79%.

Table 2: Total delivery cost and time, average cost and time per delivery for each scenario, micro-hub location and maximum delivery duration.

Maximum delivery duration [h]	*Scenario*	*Total delivery time [h]*			*Total delivery cost [€]*			*Avg. cost per delivery [€]*			*Avg. time per delivery [s]*		
		D1	*D2*	*D3*	*D1*	*D2*	*D3*	*D1*	*D2*	*D3*	*D1*	*D2*	*D3*
3	A	20.30	20.09	19.27	456.14	449.87	436.30	1.35	1.33	1.29	33.40	32.89	31.51
	B	21.31	20.91	20.08	467.17	458.28	443.88	1.39	1.36	1.32	32.30	32.11	31.66
	C	20.13	19.77	19.09	461.09	452.36	438.44	1.37	1.34	1.30	31.90	31.79	31.78
	D	20.34	20.22	19.22	454.55	449.24	432.50	1.35	1.33	1.28	32.28	32.08	31.72
	E	21.45	20.15	20.55	469.13	448.42	449.87	1.39	1.33	1.33	32.16	32.00	31.84
	F	20.04	18.69	19.31	459.81	438.05	441.14	1.36	1.30	1.31	32.13	32.04	32.10
4	A	20.30	20.09	19.27	452.87	446.60	429.77	1.34	1.33	1.28	38.96	38.38	44.12
	B	21.31	20.91	20.08	461.56	452.57	438.05	1.37	1.34	1.30	41.76	41.97	42.02
	C	20.13	19.77	19.09	455.13	446.61	433.02	1.35	1.33	1.28	42.59	42.20	41.88
	D	20.34	20.22	19.22	449.19	443.88	427.00	1.33	1.32	1.27	41.71	41.51	41.90
	E	21.45	20.15	20.55	463.25	442.96	444.42	1.37	1.31	1.32	42.06	41.64	41.20
	F	20.04	18.69	19.31	454.49	433.21	435.96	1.35	1.29	1.29	41.54	41.09	41.70
6	A	20.30	20.09	19.27	446.33	440.06	426.50	1.32	1.31	1.27	58.45	57.56	55.15
	B	21.31	20.91	20.08	455.81	447.21	433.31	1.35	1.33	1.29	59.71	58.95	57.23
	C	20.13	19.77	19.09	450.44	441.92	428.28	1.34	1.31	1.27	57.83	57.57	57.99
	D	20.34	20.22	19.22	443.33	438.00	421.77	1.32	1.30	1.25	61.31	61.28	60.27
	E	21.45	20.15	20.55	457.47	437.39	438.57	1.36	1.30	1.30	60.30	60.13	60.13
	F	20.04	18.69	19.31	448.79	427.92	430.45	1.33	1.27	1.28	60.55	59.48	61.14
8	A	20.30	20.09	19.27	443.07	436.80	423.23	1.31	1.30	1.26	77.93	76.75	73.53
	B	21.31	20.91	20.08	452.54	443.94	430.07	1.34	1.32	1.28	79.00	78.24	76.02
	C	20.13	19.77	19.09	447.25	438.91	425.78	1.33	1.30	1.26	76.41	75.11	72.76
	D	20.34	20.22	19.22	440.91	435.57	419.12	1.31	1.29	1.24	76.04	76.32	77.45
	E	21.45	20.15	20.55	454.48	434.65	436.01	1.35	1.29	1.29	77.74	76.97	75.31
	F	20.04	18.69	19.31	446.37	425.75	427.97	1.32	1.26	1.27	75.12	72.86	77.42

Table 3: Comparison between delivery systems with vans and cargo bikes.

Indicator	*Delivery system*	*Maximum delivery duration [s]*

		8	*6*	*4*	*3*
Total delivery time [h]	Vans	18.56	19.16	20.63	22.16
	Cargo bikes	21.41	21.41	21.41	21.41
	E-cargo bikes	20.10	20.10	20.10	20.10
Total cost [€]	Vans	612.18	713.33	852.22	993.22
	Cargo bikes	445.71	440.28	434.84	432.13
	E-cargo bikes	437.37	432.39	427.19	424.94
Average cost per delivery [€]	Vans	1.82	2.12	2.53	2.95
	Cargo bikes	1.32	1.31	1.29	1.28
	E-cargo bikes	1.30	1.28	1.27	1.26
Average time per delivery [s]	Vans	66.08	51.17	36.72	29.59
	Cargo bikes	31.96	41.61	59.70	76.22
	E-cargo bikes	31.95	41.33	59.56	73.65
CO2 [kg]	Vans	17.08	18.99	23.80	28.84
	Cargo bikes	4.84	4.84	4.84	4.84
	E-cargo bikes	4.84	4.84	4.84	4.84
Externalities [€]	Vans	52.02	57.09	72.45	87.73
	Cargo bikes	14.72	14.72	14.72	14.72
	E-cargo bikes	14.72	14.72	14.72	14.72

5. Discussion

The results suggested that the stochastic nature of travel and dwell time could lead to significant changes in performance indicators and ranking of potential locations of the micro-hub. Therefore, uncertainty due to traffic congestion and local conditions should be included in forecasting models, thus avoiding potential biased results. In particular, unexpected variations in time for travel and operations were found to impact not only economic performances of the delivery system, which may affect short-medium period decisions, but also the choice of the location of the micro-depot, thereby preventing potential benefits for the long-term planning. Furthermore, electric cargo bikes were found to reduce delivery time and cost, with advantages for both customers and operators. The former could benefit from an efficient and quick delivery system, and the latter could take advantage of a reduced cost of operations. Lastly, the comparison between the delivery systems with traditional vans and cargo bikes highlighted that, in the latter case, the total and average delivery time could increase, while the total and average cost, as well as polluting emissions and negative externalities decrease. For these reasons, the advantages of the cargo bike system could be different for freight operators and customers; however, significant benefits could be obtained for communities and cities.

6. Conclusion

In this paper, a delivery system with manual and electric cargo bikes in the city center of Padova (Italy) was simulated considering uncertainty of travel and stop time with the aim of selecting the best location of a micro-hub. The results are compared with those of a delivery scheme with traditional vans to quantify the potential effects of the new system. The analysis suggests that uncertainty should be incorporated into the design process of the delivery system in urban areas. In this way, biased outcomes on the economic viability of the system and the analysis of its performance could be avoided. In addition, a solid quantification of the advantages of each delivery option could be obtained.

In order to improve the work, future steps of the analysis include quantifying the impacts of a delivery system with electric vans, and creating an integrated optimization-simulation framework, so that results of simulation can be fed into the tour optimization procedure.

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Acknowledgements

The authors thank Marco Galimberti and Francesco Pastore for technical support.