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Potential last-mile impacts of crowdshipping services: a simulation-based evaluation

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Abstract

Crowdsourced delivery services (crowdshipping) represent a shipping alternative to traditional delivery systems, particularly suitable for e-commerce. Although some benefits in terms of reduced pollution and congestion could be obtained by replacing dedicated freight trips, the impacts of crowdshipping are unclear and depend on several factors such as the transport mode used, the match between supply and demand, length of detours, and possible induced demand. For example, private drivers could modify their existing routes or engage in new trips to pick up and drop off packages; similarly, public transport users could carry along packages on their trips and drop them off at lockers installed around the stations. In this paper, we analyze by means of a simulation-based approach the potential impacts of alternative implementation frameworks. In order to account more realistically for last-mile delivery operations, a hybrid dynamic traffic simulation is adopted such that the macroscopic features of traffic (triggering of congestion, queue spillbacks and interactions with traffic signals) are reproduced in combination with the microscopic features of delivery operations (delivery vehicles are tracked along their routes). The effects on traffic and emissions are investigated for the adoption of crowdshipping by carriers delivering parcels in the city center of Rome, Italy. Results show that not only is the mode employed by crowdshippers crucial for the sustainability of such a measure, but also operational aspects involving the length of detour, parking behavior, and daily traffic variations. Crowdsourced deliveries by car have generally higher negative impacts than corresponding deliveries by public transit. However, limiting the deviations of crowdshippers from the original trips, providing adequate parking options, and incentivizing off-peak deliveries, could significantly reduce crowdshipping externalities.

Keywords Crowdshipping · Crowdsourced delivery · City logistics · Dynamic traffic simulation · External costs

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Introduction

Freight transportation plays a fundamental role in the economic development of cities, but, at the same time, it threatens their livability given the increased road congestion, environmental impacts, and energy consumption. A crucial challenge to sustainable urban freight distribution is represented by the rise of e-commerce and door-to-door services that are determining significant changes in the delivery process.

Overall, more direct-to-consumer deliveries are likely to cause lower freight consolidation because of the smaller loads and more frequent deliveries (Taniguchi and Kakimoto 2003). This shift would inevitably generate a worsening of traffic and parking conditions, given the already limited road network capacity (even though some car shopping trips might be replaced). The growth of e-commerce at double-digit rates[1] calls for action in the near future to address the efficiency of the process and to internalize e-commerce's negative externalities. In fact, the European Union is actively promoting research aimed at developing sustainable solutions to growing on-demand logistics (Lozzi et al. 2018). The phenomenon of online selling is revealing new challenges for private stakeholders as well, especially for couriers and parcel carriers, as they are confronted with rising "last-mile distribution costs". Because of its low efficiency, the last mile represents the weak link of the supply chain, accounting for up to 50% of the total costs in the parcel delivery market (Dablanc and Rodrigue 2017). An appropriate urban freight transport policy-making/planning is needed taking into account stakeholders involvement (Le Pira et al. 2017; Marcucci et al. 2017a).

In recent years, the emergence of sharing economy models has enabled novel alternative services for parcel delivery such as the "crowdshipping," consisting of a declination of the "crowd sourcing" concept applied to the field of logistics. People can act as non-professional couriers and deliver small items for a monetary compensation (McKinnon 2016; Buldeo Rai et al. 2017). In crowdshipping, individuals traveling to a certain area can perform deliveries on their way, and businesses could rely on them to accomplish part of their deliveries. Such integration of personal and freight transport is based on a matching process between demand (for deliveries) and supply (of transportation) through on-line platforms.[2]

Crowdshipping can be implemented in different ways. Like in most of existing services, "crowdshippers" can pick up a parcel and deliver it to the final customers by using privately owned means of transportation (similarly to ride-hailing services, but for freight). Alternatively, they can rely on existing public transit services, similarly to Mumbai's dabbawalas (Baindur and Macário 2013). Due to several factors including mode, length of detours, and parking behavior, the societal effects of crowdshipping are still uncertain.

From the perspective of logistics companies, this solution seems promising for improving efficiency and meeting the growing demand for faster and cheaper home deliveries. Costs can be reduced thanks to a better use of spare capacity, a potential reduction of delivery trips (Miller et al. 2017), and a more flexible and cheaper on-demand workforce (Punel et al. 2018). In the U.S., some recent successful examples of crowdshipping are the delivery platforms like Deliv, Hitch, and Amazon Flex (Dolan 2018). However, it is uncertain

[1] Around 10% annually in countries like Germany and the US, and more than 25% in Asian countries like China and India according to Capgemini (2013).

[2] See, for example, *Take My Things* in Italy (www.takemythings.com) and *Hitch* in the US (http://www.hitchit.co/#home).

whether this service could easily scale up to large shares of the freight distribution market (especially for bigger or more expensive items).

From the perspective of public authorities, crowdshipping could be beneficial if properly integrated with existing movements and depending on the mode used by the crowdshippers. Ideally, freight trips would need to be replaced by public transit, walking, and bike trips (Gatta et al. 2019a). If crowdshippers rely on their own vehicles instead, the final number of delivery trips could be reduced only by means of an efficient consolidation and coordination of existing flows. Detours need to be minimized in order to reduce congestion and greenhouse emissions (Paloheimo et al. 2016). However, as often occurs in popular platforms for on-demand transportation services, crowdshippers might provide the service by engaging in new dedicated trips rather than by modifying existing ones (Sampaio et al. 2019). This rebound effect might result in overall worsened conditions (Qi et al. 2018).

Most of the research on crowdshipping has focused on identifying the determinants of the adoption and on modeling preferences for this service (e.g., propensity to act as crowdshipper, willingness to pay for crowdsourced deliveries, and potential customers' preferences for different crowdshipping features) With the exception of a few studies (Paloheimo et al. 2016; Buldeo Rai et al. 2018), no analyses of crowdshipping externalities have been performed. In this study, we perform a (dynamic traffic) simulation-based analysis of crowdshipping for parcel deliveries in the city center of Rome, Italy. The paper analyses externalities of crowdshipping services based on private transport or public transit, different levels of matched demand, together with crowdshippers' trip detour and parking behavior. Compared to the previous studies, this paper adopts a network-wide perspective that includes public transit as a delivery mode (in addition to car), and explicitly considers operational issues like curbside-parking.

The main contribution of this paper is to provide a systematic investigation of the scale-effects of crowdshipping from a "supply perspective," by analyzing the impacts of different operational features (e.g., mode, detours' lengths, availability of parking, and levels of traffic) on congestion and emissions. Dynamic traffic simulation is a valuable resource for providing an accurate indication of traffic and environmental impacts of freight policies (Wang et al. 2018). In addition, it allows deeper analyses of the relation between traffic and delivery routes, and their influence on carriers' delivery efficiency. Here, the simulation framework adopted (Simoni and Claudel 2018a, b), is consistent with the dynamics of congestion and reproduces delivery operations as temporary fixed-bottlenecks in case of double-parking. Its hybrid nature allows for large-scale analyses and, at the same time, detailed investigations of individual delivery tours and crowdshippers' deliveries. Thanks to this approach, freight related emissions and traffic congestion effects (including those related to curbside delivery) can be accurately estimated. In addition, since its hybrid nature allows the analysis of several different scenarios at very low computational costs (few seconds per simulation), it is possible to perform evaluations robustly accounting for uncertain freight demand and traffic conditions. Given the high uncertainty of aspects concerning the origins of crowdshippers' trips and the potential rise of induced crowdshipping trips, the analyses focus on the last-mile effects of the service.

The second contribution of this study is to investigate the effects of crowdshipping in a realistic large-scale scenario, by accounting for real traffic conditions, availability of commercial bays, and freight demand. For this purpose, simulations are performed for the implementation of crowdshipping in the city center of Rome. The city is very active in finding the most appropriate logistics solutions. This is evidenced by the upcoming Sustainable Urban Mobility Plan where innovative strategies such as crowdshipping will be considered among the possible interventions. The interest in this issue is also confirmed by recent research studies already performed in Rome (Gatta et al. 2019b; Marcucci et al. 2017b). Moreover, crowdshipping by public transport might be favored by the new road pricing scheme included in the latest Rome's Mobility Master Plan (Marcucci et al. 2018).

In this paper, after a brief presentation of previous research on crowdshipping, we provide a description of the methodological approach used for the evaluation and a description of the case study of Rome. In the second part of the paper, we present the analysis of alternative scenarios, suggest some policy recommendations and draw conclusions.

Related research

Understanding user response to crowdsourced delivery services and developing efficient implementation frameworks is fundamental to measuring external impacts, controlling unintended effects, improving business models and establishing a sustainable service. The body of literature on the topic of crowdshipping is quite limited due to its novelty and the lack of operational and behavioral data (Cleophas et al. 2018).

From a behavioral perspective, it is important to investigate crowdshipping acceptability from both the supply and demand side. Marcucci and Gatta (2017) investigate attitudes and conditions that might favor participation in crowdshipping initiatives. They perform a survey in the city of Rome, administering a questionnaire to 200 students who can be considered as "early adopters/providers." Results show that there is a large potential consensus in terms of both receiving goods via a crowdshipping service and acting as crowdshippers. Moreover, interviewees require a proof of crowdshipping sustainability to support it. In the same geographical context, Serafini et al. (2018), focusing on crowdshipping services deployed using the public transport network, perform a stated preference survey to identify the most important levers of acting as a crowdshipper. A sample of metro users have been interviewed and results from discrete choice models reveal that crowdshipping can be a reliable solution to a substantial number of delivery requests. Stated preference data have been used also by Punel and Stathopoulos (2017) who explore "senders' acceptability towards crowdshipping" compared to traditional shipping options. Findings from a US sample suggest the presence of heterogeneous preference patterns more in terms of driver performance attributes rather than for socio-demographic characteristics. Using the same data, Punel et al. (2018) focus on the differences between crowdshipping users and non-users, providing managerial suggestions to logistics companies to help them in tailoring the system. Miller et al. (2017) analyze the potential willingness to work as traveler–shipper based on a stated preference survey to a sample of US private car commuters. Results show that specific segments (middle-class earners, drivers engaging leisure and short trips) are more prone to crowdshipping and, overall, an increasing marginal rate of payment is needed for longer trips.

From an optimization perspective, some studies have investigated the implementation of crowdshipping in order to improve efficiency of the delivery process. Archetti et al. (2016) consider the addition of occasional drivers (crowdshippers) as a variant of the classical capacitated vehicle routing problem. Wang et al. (2016) formulate the crowd-logistic optimization problem as an extension of a network min-cost flow problem. Kafle et al. (2017) propose a crowdsourced system based on bids and relay points. Arslan et al. (2018) investigate the matching of tasks, drivers, and dedicated vehicles in real time adopting a new variant of the "dynamic pickup and delivery problem" (Savelsbergh and Sol 1995).

Table 1 Qualitative comparison of potential impacts from different delivery frameworks

Framework	Carriers' efficiency	Environmental impacts	Congestion impacts
Regular delivery	Depends on traffic	High	High
Crowdsourced delivery by public transit user	Depends on transit quality of service	Low	Low
Crowdsourced delivery by car user	Depends on traffic	Variable	Variable

From the perspective of city authorities, Paloheimo et al. (2016) analyze the environmental impacts of a trial crowdshipping library delivery service in Finland and identify an overall reduction of carbon footprint. The fact that a considerable part of crowdsourced delivery trips were performed by bike played a significant role in reducing resource use and carbon emissions. Buldeo Rai et al. (2018) perform a document analysis in combination with interviews to investigate the externalities of an operational crowd logistics platform in Belgium. Since crowdshippers mainly rely on motorized modes and over half of the crowdshipping deliveries are carried out by means of dedicated trips, the service does not achieve an overall reduction of external costs.

No study has systematically analyzed the potential impacts of alternative implementation frameworks on traffic and pollution (Table 1). Replacing delivery trips with crowdsourced public transit users would clearly have positive repercussions on environment and traffic. Substituting traditional deliveries with car trips instead depends very much on the possibility of exploiting existing vehicle movements and levels of detour (McKinnon 2016). In addition, consolidating delivery tours and introducing crowdshipping deliveries at different times of the day could have different impacts, depending on traffic conditions. In this study, by means of a simulation approach, we explicitly consider the influence of all these factors. In particular, the focus is on their influence on the overall traffic and emissions of last-mile delivery trips.

Modeling and analysis approach

The impacts of alternative crowdshipping solutions are investigated by means of dynamic traffic simulation. This approach allows a detailed representation of the evolution of freight movements (based on congestion) and their interactions with passenger traffic. For each link of the road network, and time interval, one can estimate traffic condition indicators such as travel times and queues.

In this study, we extend the hybrid simulation framework proposed by Simoni and Claudel (2018a, b) where traffic behavior is macroscopically reproduced at network level, while delivery movements are represented microscopically (Fig. 1). In such hybrid system, only delivery vehicles are modeled individually (and tracked throughout the entire simulation) whereas rest of traffic is modeled as a homogeneous fluid. This approach is suitable for large-scale simulations of freight traffic, since it is computationally very efficient (as independent of the overall levels of traffic), and at the same time, very accurate in reproducing delivery vehicles' movements and operations. Based on the features of this framework, one can reproduce and investigate the impacts of delivery operations on traffic ("Traffic and parking" section) and related environmental effects ("Carriers' last mile delivery and

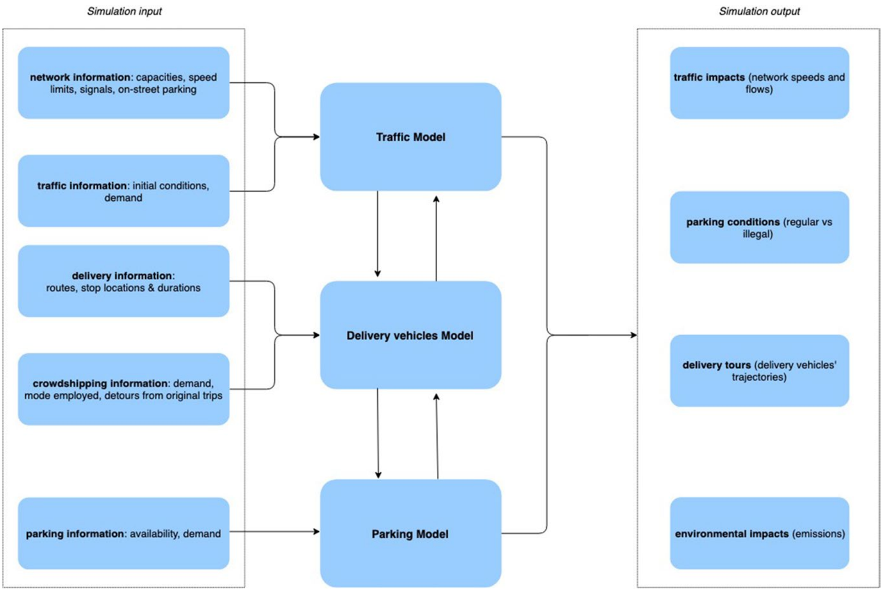

Fig. 1 Overview of the simulation framework adopted to evaluate crowdshipping

crowdshipping services” section). The hybrid framework is enhanced to reproduce different crowdshipping services by means of a dedicated simulation module (“Emissions” section).

Traffic and parking

The impacts of freight operations on urban traffic are measured by means of a simulation framework that derives dynamics of traffic flows based on general network characteristics (lanes, speed limits, signal settings) and traffic conditions (traffic demand). General traffic movements are simulated by means of the macroscopic LWR model (Lighthill and Whitham 1955; Richards 1956) where road traffic is assumed to follow the main properties of fluid streams. Such a model well reproduces traffic congestion phenomena like queue formation and spillback in urban networks, where traffic flow dynamics are mainly determined at (signalized) junctions (Papageorgiou 1998). According to the classical LWR formulation, there is no distinction among different vehicle types (except for those performing deliveries) that are treated as a homogenous flow. A Hamilton–Jacobi partial differential equation (PDE) formulation of the LWR model is solved by using a recent extension of the Lax–Hopf formula (Fast Lax–Hopf) proposed by Simoni and Claudel (2018a, b). This algorithm is suitable for simulation of large traffic networks given any initial and boundary conditions.

Freight movements are reproduced as moving bottlenecks (Gazis and Herman 1992; Newell 1993; Munoz and Daganzo 2002) traveling across the network, which become “temporary fixed bottlenecks” when they perform deliveries. Delivery tours of vehicles (with stops and corresponding paths) are derived by solving the traveling salesman problem (TSP) with average travel times and fed into the simulation as an input. In order to account for the contribution of freight movements to the overall levels of traffic on the network, boundary conditions at the entry links of the network are increased to reflect the additional freight vehicles entered in the network. In addition, the original traffic simulation algorithm is updated such that turning proportions at the nodes (representing flow splits at intersections) are dynamically updated to account for trucks' passage. When a delivery vehicle drives through an intersection, the turning proportion changes according to the delivery vehicle's destination (the following link in its pre-optimized route). This approach is in line with the LWR model as it respects the mass conservation law. Based on that, one can explicitly account for the movements of delivery vehicles at each junction, and ultimately reproduce the effects on overall traffic levels of different trip lengths and delivery routes. Since, in this study, delivery vehicles are assumed to have maximum speed equal to 'regular' traffic, the main traffic obstruction occurs when the commercial vehicle stops at the curbside for delivery operations in case of an unavailable dedicated parking place. Each time the vehicle enters the link of delivery, a "parking routine" is performed to check whether there is any unused commercial bay. In case of unavailable parking, the vehicle stops and double-parks, rather than cruising to find an alternative location for the stop. The tendency to illegally park is a rather reasonable assumption as carriers mainly care about proximity to the destination (Amer and Chow 2017) and typically transfer the overall costs of fines to customers (Hawkins 2013; Stock 2014). This is specifically true in Rome for the area investigated.

Information about parking availability and parking demand for each road of the network need to be provided as simulation input. An example of simulation of illegally parked delivery operation (and its effect on surrounding traffic) is illustrated in Fig. 2. During the delivery operation, the vehicle obstructs road's capacity and, when density (of regular traffic) is high enough, it triggers congestion that propagates upstream. Given this level of detail, a large amount of information on forthcoming deliveries (routes, location and duration of stops) is required in order to perform simulations.

Traffic impacts of crowdshippers relying on personal vehicles are modeled similarly to those of delivery vehicles, where the main congestion effects are due to delivery operations and increased traffic flows. To the best of our knowledge, there are no studies on parking behavior of crowdshippers. It is reasonable to think that crowdshippers would be more inclined than regular drivers to perform deliveries while illegally parked, but also less willing to risk fines than professional commercial drivers who are not (usually) directly affected by parking tickets. Also, unlike trucks, crowdshippers would most likely rely on regular parking rather than on commercial bay. Since performing a detailed investigation of crowdhippers' parking behavior goes beyond the scope of this study, here we consider alternative parking attitudes (i.e., more inclined to legal parking or to double-parking) and evaluate their impacts.

Carriers' last mile delivery and crowdshipping services

In this study, we evaluate the adoption of crowdshipping for a same-day parcel delivery service performed by carriers in a central area (Rome city center). The last mile delivery process is modeled in three alternative ways: by means of a "traditional" (i.e., existing) delivery service, and by means of two alternative crowdshipping frameworks: a "car-oriented" service and a "public transit-oriented" service, both of which can be integrated into

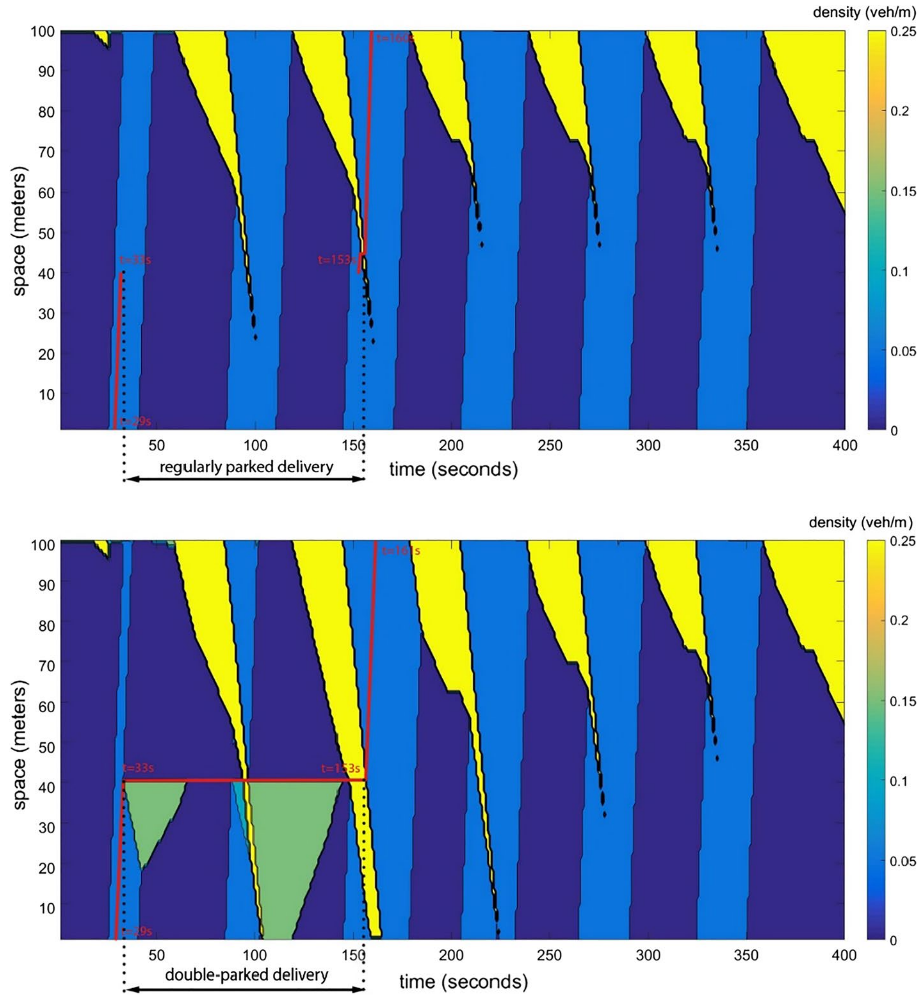

Fig. 2 Space-time-density diagrams representing traffic flows in case of (above) regularly parked delivery (below) and double-parked delivery. Adapted from Simoni and Claudel (2018a, b)

the original one (Fig. 3). In both crowdshipping frameworks, the crowdshipper is not the final recipient of the parcel.

In the traditional process, the delivery tours of each commercial vehicle are explicitly modeled by identifying the minimum cost routes given a list of daily customers and the carrier's depot. The problem is formulated as a TSP where the total distance traveled is minimized by adopting Dantzig–Fulkerson–Johnson (DFJ)'s formulation (Dantzig et al. 1954). The optimized tours are then fed into the simulation model and deliveries are reproduced sequentially according to them.

In the car-oriented crowdshipping service, the driver picks up a parcel from a dedicated pickup station and performs the delivery with his own private vehicle. This type of facility would correspond to depots or stores located in the periphery of the city. In this study, the crowdshipper can perform this service by modifying an existing trip or by means of a stand-alone trip.

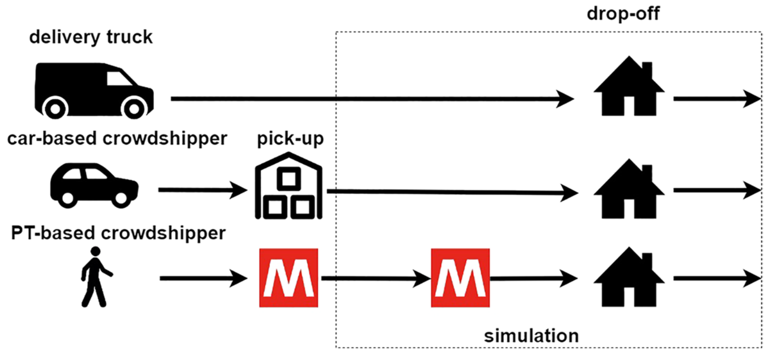

Fig. 3 Schematics of original delivery and the two crowdshipping-based delivery services

In the public transit-oriented service, crowdshippers are existing public transit riders, who pick up parcels at dedicated facilities (e.g. lockers) located at the exit of metro stations or in the surroundings of major transit line stops. The final leg of delivery is performed by foot.

Although it is possible for crowdshipping companies to integrate different delivery modes, for the scope of this study we simulate the two separately. Congestion and environmental impacts of the two services are clearly different. While crowdsourced deliveries made by public-transit users have no direct congestion or environmental externalities, crowdsourced deliveries performed by car users affect traffic and emissions to a different extent, according to factors like the detour from the origin and destination of existing trips, generation of dedicated delivery trips, and parking behavior.

In this study, we assume traditional deliveries could be replaced by a crowdsourced delivery if in the service range (maximum detour time or distance) for drivers or public transit users. Parcels delivered by means of crowdsourced delivery can be collected at dedicated pickup points located at the exit of subway lines in case transit-oriented service, or in the periphery of the city for car-oriented service. The maximum range for crowdshippers is an exogenous variable that is likely to be the result of a "matching procedure" between demand and supply for crowdsourced deliveries. Since in this study, we focus on the impacts of crowdshipping rather than on the behavioral aspects of this issue, crowdshippers and deliveries are considered "matched" a priori based on given levels of demand for such service. Hence, the proportion of customers switching to crowdshipping is fixed and exogenous. A centralized system would dynamically assign delivery orders to crowdshippers, based on their availability and compensation, and depending on customers' willingness to pay. Note that the several objectives (efficiency, timeliness, flexibility) and constraints (costs, capacity and weight, couriers' availability) involved in such an assignment problem, could significantly affect the results of the "matching procedure" and yield less intuitive results (i.e. longer routes and lower truck loads). Investigating this optimization problem and its influence on the final impacts of crowdshipping services goes beyond the scope of this research. The reader is referred to Wang et al. (2016), Archetti et al. (2016) and Arslan et al. (2018) for novel formulations of the crowdsourced delivery optimization problem. The time required for transshipment operations at pickup stations and depots are not explicitly considered in the model, as we focus on the last mile of the delivery process. Similarly, only crowdshippers' drop-off detours are considered, while pick-up detours are

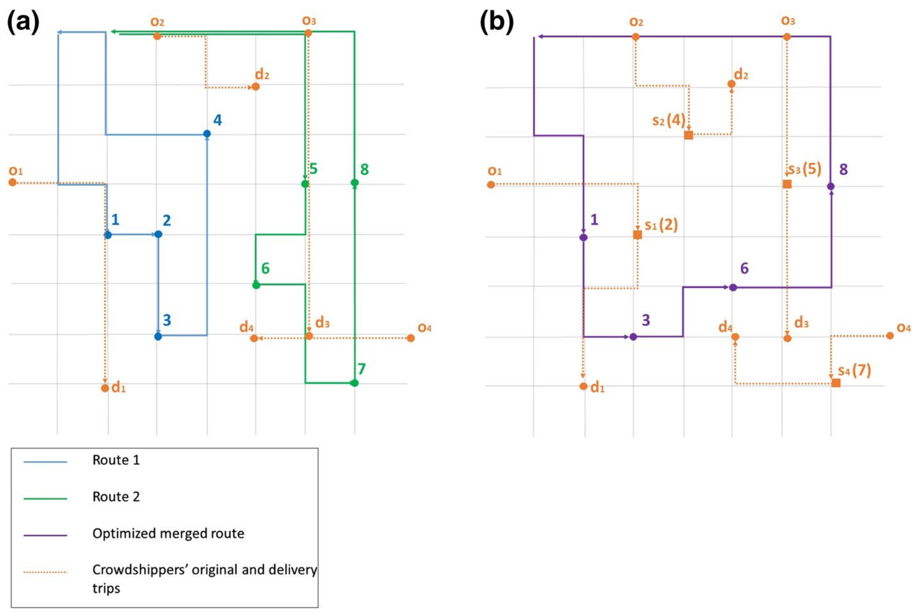

Fig. 4 Integration of truck deliveries with crowdshippers deliveries on a grid network

excluded from the analysis and simulation. In this study, pick-up stations are located in in the periphery of the city (for example, at the end stations of the two subway lines) where congestion levels are relatively low. For this reason, it is reasonable to assume that the traffic impacts of pick-up detours and operations would be minimal. However, depending on their length, the associated emissions impacts might become non-negligible. In both traditional delivery and crowdshipping services, no delivery failure is considered. Given the focus on short-term effects, only the effects of crowdshipping on existing trips (of crowdshippers) are investigated.

In order to reproduce the crowdsourced delivery process, we embed into the original simulation framework a new algorithm that derives crowdshippers original and new delivery trips, and integrates them in the original delivery framework (by replacing and consolidating existing trucks' tours) based on different input parameters (Algorithm 1). Such algorithm is employed in the first stage of the simulation framework and its outputs are used in both the simulation of the original delivery process and its corresponding crowdshipping scenario. Furthermore, it does not rely on any optimization procedure, as the assignment between customers and potential crowdshsippers is assumed to be done beforehand. First, customers switching to crowdshipping services are chosen from the original set following a binomial distribution based on the matched levels of demand (input). In case of a transit-oriented service, crowdshipping customers are assigned to the closest transit station. Customers whose location is not within a certain range from the stops cannot be selected for public-transit based crowdshipping. Although public-transit based crowshipping is not explicitly simulated, it affects the transportation system by reducing the overall length and frequency of truck tours. In case of a car-oriented service, customers of the crowdshipping service are assigned to a driver who deviates from his or her original trip in accordance with a maximum detour constraint. Based on that, crowdshippers can pick up orders as long as the difference between their new and original path (both derived as shortest paths according to links travel times) is below the imposed threshold. While the origin of crowdshippers' car trips consists of an entry link of the simulation network while their destination corresponds to any link. Crowdshippers' original and new routes are fed into two different simulations (without and with crowdshipping). Original trucks' delivery routes are updated in order to account for the different configuration, and in case of significant reduction of customers served (more than 50%), they are also merged together (consolidation) (Fig. 4). For lower reductions of deliveries replaced by crowdshipping trips, the truck would only reduce its number of stops, but would be less efficiently loaded.

Algorithm 1: Pseudo-algorithm for integration of crowdshipping into the simulation framework

Input: *matched crowdshipping demand (y), initial routes of carriers (ρ_v), delivery set V of delivery routes (D_v), PT stations (Φ), maximum range from PT stations (r), maximum detour (δ)*

Output: *new carriers' delivery tours ($\rho_{v'}$), crowdshippers' original trips ($c_s(o,d)$), crowdshippers' new trips (($c_s(o,s)$, $c_s(s,d)$)),*

% generation of a set S of crowdshipping customers based on crowdshipping demand level y
GENERATE $S = C(n \cdot y, 1)$
%if crowdshipping is public transit(PT) oriented, assign customer s to the closest PT station (if any)
FOR each s in S:
  FIND φ in Φ such that min(dist{φ, s}):
  IF min(distance{φ, s})$\leq$ r:
    $s \rightarrow s_\varphi$
  END IF
END FOR
%if crowdshipping is car oriented, for each customer s
FOR each s in S:
% assign detour length τ
  DERIVE $\tau = \gamma(0, \delta)$
%generate crowdshippers' original and new car delivery trips
  ADD $c_s(o,d)$ such that dist{o,s}+dist{s,d}-dist{o,d} <= τ
  ADD $c_s(o,s)$ and $c_s(s,d)$
END FOR
%update original routes into D'_v
FOR d in D_v:
  IF d $\notin$S:
    ADD d to D'_v
    REMOVE d from D_v
  END IF
END FOR
%if number of customers in two routes is lowered by 50% or more, merge them
FOR v in V:
  IF $|D'_v| < 0.5 \cdot |D_v|$ *and* $|D'_{v+1}| < 0.5 \cdot |D_{v+1}|$:
    MERGE D'_v and D'_{v+1}
  END IF
%recompute optimal route $\rho_{v'}$ for new delivery list
  IDENTIFY TSP(D'_v) $\rightarrow \rho_{v'}$
END FOR

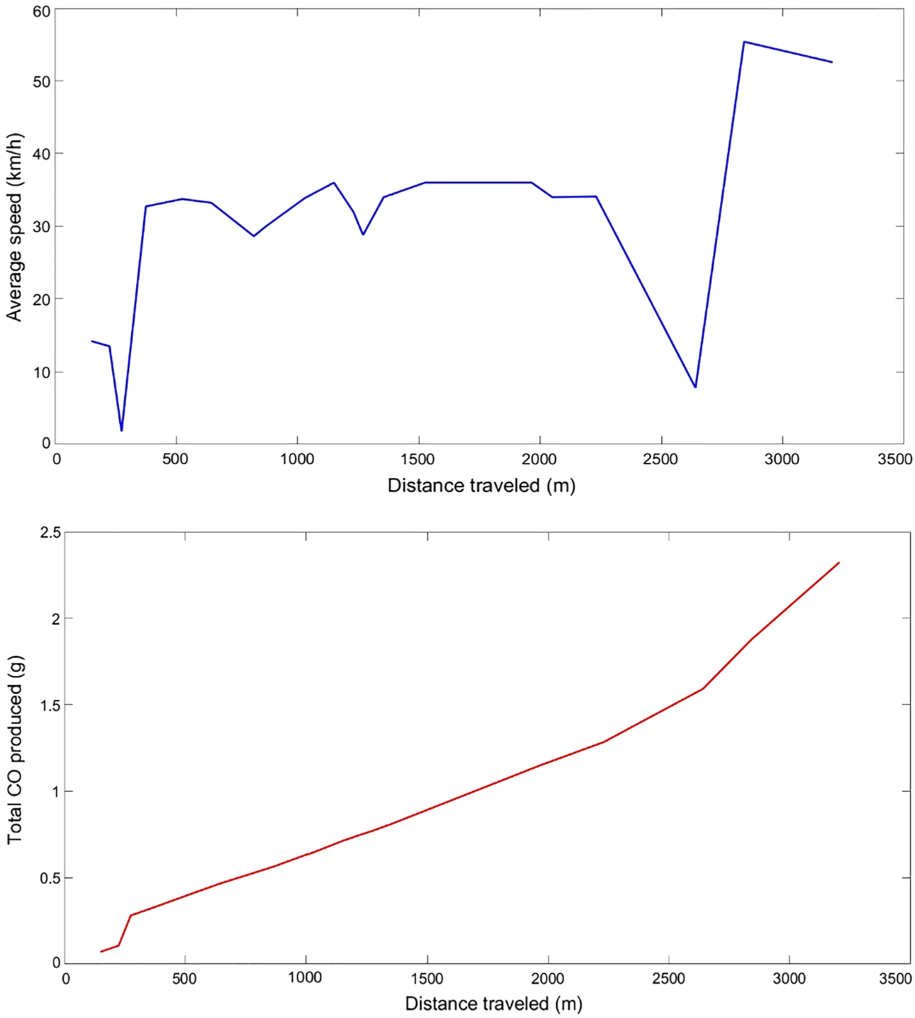

Fig. 5 Average speed during a vehicle's delivery tour (above) and corresponding cumulative CO emissions (below)

Emissions

The modeling of air pollution emissions due to freight-related movements includes widely used pollutants for measuring air quality standards: CO, NO_x and PM_{10}. These pollutants are derived as a function of the travel speed and distance traveled by each commercial vehicle. Thanks to the adopted hybrid simulation approach, it is possible to identify for each delivery vehicle the emissions produced along its route (Fig. 5).

The impacts of travel speed and vehicle technology are derived from an analytical relation proposed by the UK Transport Research Laboratory (Boulter et al. 2009) to obtain the amount of pollutant produced at link level based on the average speed and vehicle's typology. Hence, the cumulative production of pollutant per vehicle P_d (in grams), produced on its delivery route R can be calculated as the following 4th order polynomial function:

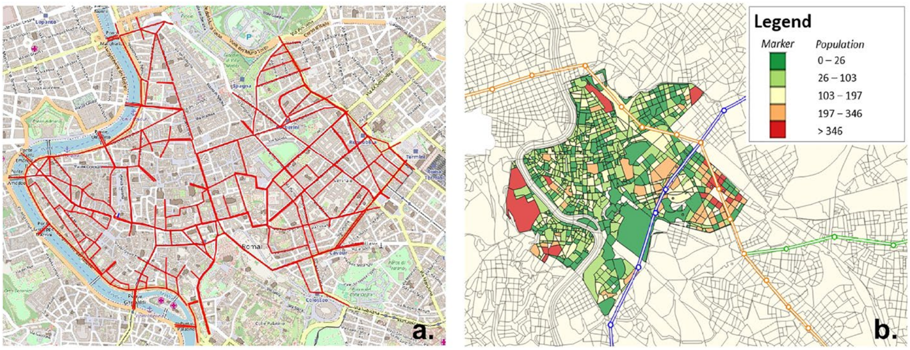

Fig. 6 Rome's traffic restricted area with simulation's network (**a**) and subway lines (**b**)

$$P_d = \sum_{r \in R} \left[\frac{\left(a + b \cdot v_r + c \cdot v_r^2 + d \cdot v_r^3 + e \cdot v_r^4 + f \cdot v_r^5 + g \cdot v_r^6 \right)}{v_r} \right] \cdot d_r \tag{1}$$

where v_r corresponds to the average speed of the vehicle on link r (km/h) of length d_r (km), and the coefficients $\{a, b, c, d, e, f, g\}$ corresponds to empirically derived parameters according to pollutant and vehicle typology. The effects of greenhouse gas emissions (CO_2) are derived based on emissions of the other pollutants that are oxidized in CO_2 by considering them as a constant (Boulter et al. 2009). The resulting speed-emission curves are similar to that of Barth and Boriboonsomsin (2008), which is characterized by a parabolic shape where higher emission rates are determined by low speeds (because of stop-and-go conditions) and higher speeds (because of the higher engine load requirements).

Case study

The impacts of two alternative crowdshipping services are investigated in comparison to a "Base Scenario" that corresponds to a realistic simulation of traditional parcel distribution in Rome's freight restricted traffic area (Fig. 5a). Despite the access restrictions, the studied area, which accounts for about 73,000 inhabitants, is characterized by serious congestion issues due to an undersized public transport network and a strong car dependency (Marcucci and Gatta 2017). TOMTOM (2018) data rate Rome as the 31st most congested city worldwide, with a congestion score or (average) extra travel time of 40%. In this study, we consider only the most central portion of the restricted area (about 5 km^2). The simulation's adopted network includes 411 aggregated links with detailed information regarding signalized intersections, number of lanes, and speed limits (Fig. 6b). The public transit network considered includes the two major subway lines (Line A and Line B) and 1 tram line (Line 8) with respectively 7 and 3 stops inside the studied area (Fig. 6a). In this study, only subway and tram are considered as crowdshippers' public transit-based travel options since the above mentioned lines connects the city center with the periphery of Rome (where pick-up stations can be installed). In addition, bus is not really suitable for crowdshipping because of its low level of service and lack of appropriate infrastructure to accommodate parcel-lockers.

As discussed in more detail in "Analysis" section, in order to account for the influence of traffic and parking conditions on freight externalities we perform network simulations of 60 min corresponding to two different times of the day: 10–11 AM, and 2–3 PM. The majority of leading companies delivery tours' in the city center starts around 10 AM and ends around 5 PM. Given this time window, the two chosen intervals respectively correspond to the most congested and less congested hour. While parking availability in the area is constant throughout weekdays' working hours, during the morning interval the average network speed is about 10% lower than in the afternoon interval.

Traffic demand and turning proportions are calibrated with real data (traffic counts and average speeds) obtained from the Mobility Agency of Rome, by means of a heuristic optimization process based on a genetic algorithm where the fitness function corresponds to weighted combination of average speed and volume errors (Cheu et al. 1998). The adopted stopping criteria corresponds to a GEH Statistic lower than 5 for 85% of the links, as suggested by the UK Highways Agency's Design Manual for Roads and Bridges (Highways Agency 1996) modeling guidelines. The resulting simulations are validated by comparing the average travel times between 20 randomly chosen origin–destination couples in the network with estimates from Google Traffic (Google Traffic 2018). Information about parking infrastructure and parking conditions is obtained from the Municipal Police in Rome, according to which illegal occupancy of loading/unloading bays is around 90%.

In this study, we consider the possibility of adopting crowdshipping services only for packages ordered online. The volume of online ordered parcels distributed in the studied area, based on an on-line daily purchase rate of 2.62% per inhabitant (Serafini et al. 2018), is estimated at 3500 parcel deliveries per day.

In order to gather additional information about parcel distribution and delivery operations in the area, a set of interviews with major carriers was carried out in connection with the activities performed for the Sustainable Urban Mobility Plan in Rome. Different questions ranging from strategic aspects of delivery tours (stops, length, and times) to operational details (availability of commercial bays) were asked of 12 leading delivery companies operating in the studied area. Based on the collected information, carriers' deliveries and vehicles' delivery tours were modeled as follows: each daily tour accounts for 50 stops corresponding to about 60 deliveries for a total distanced traveled of 60 km (from the main depot); each delivery requires a stop of 3 min. During a 1-h simulation these delivery trips translate into routes of approximately 8–9 stops. These values are in line with Allen et al. (2017), who estimated 72 customers per round and 4 min per delivery.

To calculate emissions, we consider delivery light vans for traditional delivery services (category Euro IV) and petrol car Euro IV for crowdshippers. This category represents the largest share of circulating vehicles in Rome (Comune di Roma 2016).

An investigation of the conditions for public transit passengers to act as crowdshippers and for people to receive goods with crowdshipping (Serafini et al. 2018) is used as a main reference for the implementation of crowdshipping in Rome. Here, crowdshipping demand/supply is estimated and compared, revealing the potential feasibility of this distribution system for different scenarios. In this study we do not consider induced crowdshipping trips. This is a reasonable assumption considering that in order to access the area studied drivers would need to purchase a special pass.

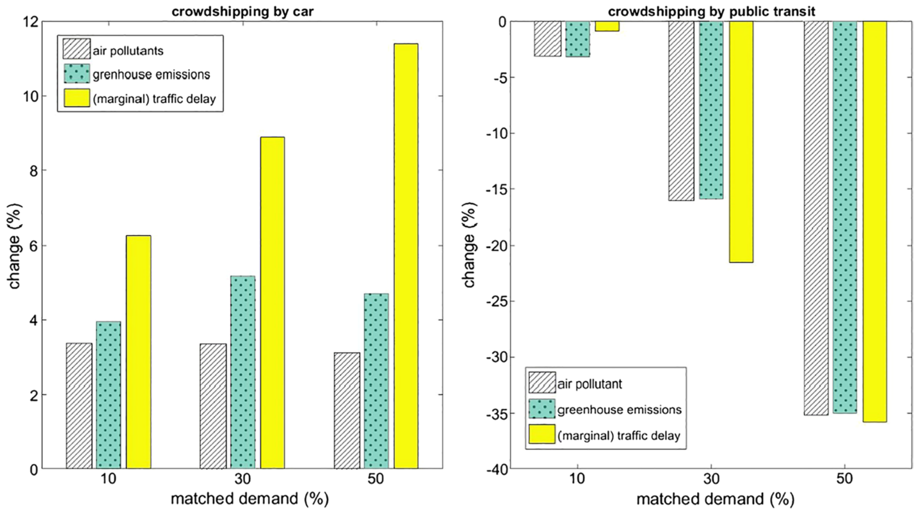

Fig. 7 Impacts of employed mode for crowdshipping at different levels of matched demand

Analysis

In this section, we study the impacts of different crowdshipping implementation features on the overall levels of pollution and congestion. Environmental impacts are distinguished in changes of air pollutants (CO, PM_{10}, and NO_x) and greenhouse gases (CO_2). Congestion effects are reported by the change of delay (measured at network level) attributable to crowdshipping operations in comparison to the delay due to traditional delivery operations (marginal delay). Given the random configuration of deliveries and the stochastic nature of the parking model, we perform 100 simulation runs per tested scenario.

First, we evaluate the potential influence of the chosen mode for crowdshipping services. Then, we explore more in detail the effects of operational aspects such as the length of detour made by and the parking behavior of crowdsourced drivers. Finally, we provide insights into the impacts of crowdshipping at alternative times of the day, characterized by different traffic conditions.

Influence of mode and matched demand

In order to understand the effects of adopting alternative crowdshipping modes, we perform experiments for three different levels of matched demand (10%, 30%, and 50%) by using car and public transit (Fig. 7). As expected, for higher levels of matched demand, crowshipping by public transit is beneficial from both an environmental and congestion perspective, showing an increasing trend. It is important to note that, while benefits are almost negligible for low levels of matched demand (particularly in terms of congestion), the gains significantly increase for 30% and 50% of traditional deliveries replaced. This result can be explained by the possibility of achieving higher consolidation of original truck trips. In case of car usage, crowdshipping does not generally generate improvements in terms of pollution and congestion. This result is in line with Buldeo Rai et al. (2018) who found crowshipping to be unsustainable, especially due to the rebound effect

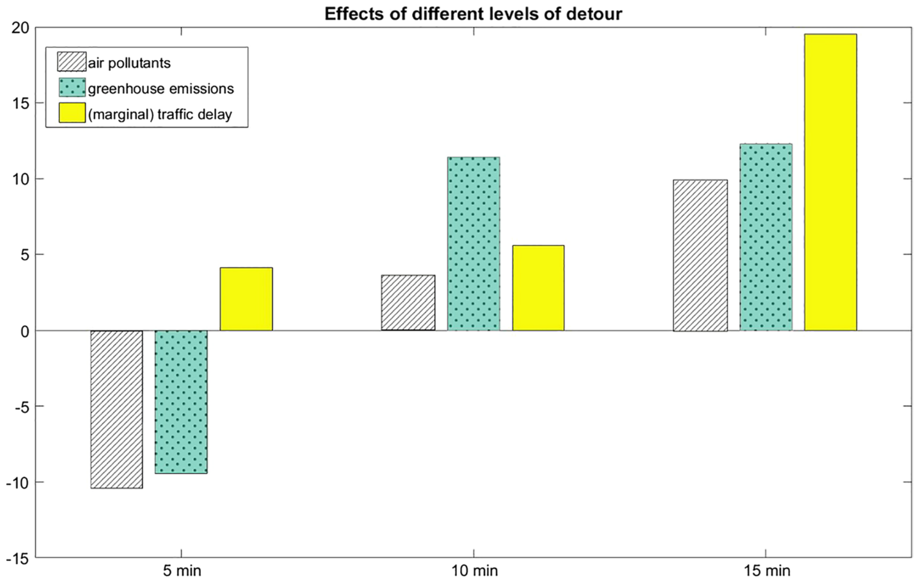

Fig. 8 Impacts of different levels of detour

of induced delivery trips. Here, even by considering only existing trips, deliveries made by non-professional drivers determine a worsening of emissions between approximately 3% and 5% and an increase of marginal congestion impact between approximately 6% and 11%. Increasing the number of trips and their length in an already congested area is clearly detrimental. Interestingly, while congestion impacts show an overall increase for higher levels of matched demand, the emissions effects are stable. This effect is due to the increasing savings coming from improved consolidation of truck tours and from replacement of trucks with cars (that are, according to the assumptions, less polluting) in the trip from crowdshipping stations to the city center.

Influence of detour length and parking behavior

In order to test the influence of different levels of detour on the overall impacts of crowdsourced deliveries made by car, three alternative maximum ranges of deviation from the original trips (5, 10, and 15 min) are tested for the same level of matched demand (30%). The results shown in Fig. 8, indicate that, while performing crowdshipping by car could be partially beneficial for deviations below 5 min, it becomes unsustainable for longer detours. Interestingly, for minor detours (e.g. 5 min), the overall marginal delay still increases because of the overall growth of vehicle miles traveled since several crowdshippers traveling (and parking) on the network to perform deliveries, results in higher traffic impacts than a few trucks (with optimized routes and higher loads). As to the emissions, the decrease corresponding to lower crowdshippers' detours is mainly due to the lower polluting levels of crowdshippers' vehicles (in comparison to trucks). Such benefit is eventually offset for increasing detour lengths.

As discussed earlier, there is little knowledge of carriers' parking behavior (see Allen et al. (2017) for an on-field study of parcel delivery tours) and even less concerning that

Fig. 9 Traffic impacts of different parking behavior

of crowdshipper behavior. Here, we investigate the congestion effects of three alternative behavioral trends (which could themselves be the result of several factors such as infrastructure supply, reward for crowdshipping services, and levels of enforcement): a "conservative" attitude wherein crowdsourced drivers always park legally; an "illegal" attitude wherein crowdsourced drivers always double-park; and a "mixed" attitude wherein legal and illegal parking are equally split. Just as in the previous experiment, we assume constant matched demand equal to 30% of deliveries. The results highlight how parking plays an important role in the final traffic performance of crowdshipping services (Fig. 9). While a "mixed" parking attitude would only increase marginal delay by approximately 2% in comparison to a completely "legal" attitude, consistent illegal parking performed by crowdshippers would yield a significant increase of marginal delay (15% in total). The outcome of this experiment shows how the creation of temporary fixed bottlenecks during illegally parked deliveries is a crucial issue for congestion.

Influence of daily traffic fluctuations

In order to investigate the impacts of performing crowdshipping deliveries under different traffic conditions, we conduct the same experiments of "Influence of mode and matched demand" section by simulating network traffic between 2 and 3 PM. During this time of the day, traffic congestion is milder than in the previous scenario (traffic delay is approximately 15% lower). As it is possible to see in Fig. 10, performing deliveries through crowdshipping at another time of the day, characterized by lower levels of traffic, implies different impacts. In case of crowdsourced deliveries by car, the impacts are still negative; however, increasing the level of matched demand does not increase congestion as in the morning scenario. Interestingly, for higher levels of matched demand (50%), the environmental impacts of crowdshipping by car are close to zero. Given the relatively low levels of traffic and the higher traveling speeds, having more vehicles performing deliveries (and often double parking) does not have significant effects, especially when counterbalanced

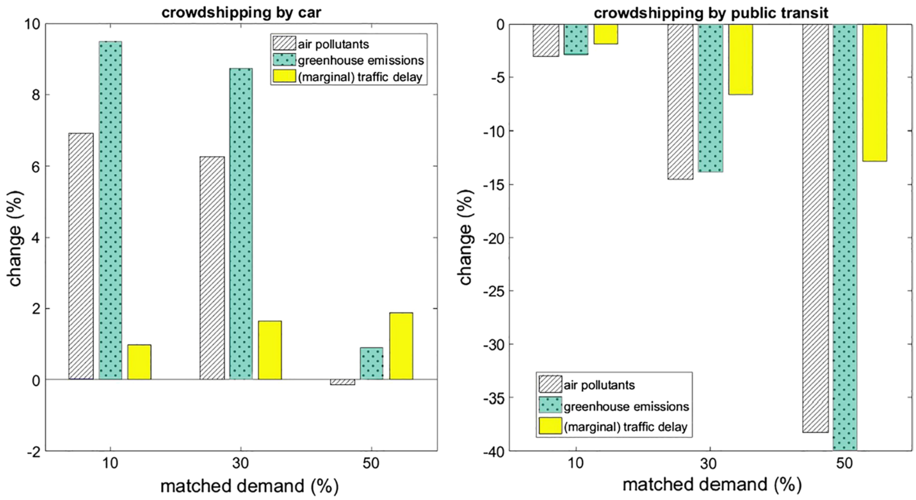

Fig. 10 Impacts of crowdshipping for less congested times of the day

by increased consolidation and reduced truck trips between the depot and the city center. Crowdsourcing deliveries by using public transit between 2 and 3 PM, shows a similar trend to the experiments performed at 10 AM. However, given the overall lower levels of congestion, it entails lower benefits in terms of reduced (i.e., marginal) delay. On the other hand, significant air pollutants and greenhouse emissions savings can still be achieved.

Policy implications

Thanks to the experiments performed, it is possible to determine a clearer picture of the potential opportunities and threats coming with the implementation of crowdshipping services.

It is interesting to see that even for a "mild" implementation of crowdshipping targeted to a very specific market segment (on-line parcel deliveries) and for relatively low levels of demand, the environmental and congestion effects are already appreciable.

The transportation mode chosen by crowdshippers is fundamental for the overall sustainability of crowdsourced deliveries. While crowdshipping can be beneficial (for the city) when relying on public transit, its impacts are always negative in case of car-based crowdsourced trips. If crowdshipping is implemented by private carriers (or companies) independently, thus leaving de facto such transportation choice to crowdshippers, a midway scenario is most likely to occur. However, without any supporting policy in terms of incentives or regulations, it would be difficult to steer crowdshipping practices in the public-transit oriented direction.

More operational aspects, such as the range of detour and parking behavior of crowdsourced drivers, are also affecting the overall sustainability of this service. Limiting the deviation of crowdshippers' delivery trips from their original trips and providing adequate parking for crowdsourced deliveries would be important actions to reduce negative externalities. In this context, logistic providers could play a critical role in adjusting the platform operations to obtain a more sustainable use, and public authorities would have the responsibility to identify adequate parking responses to this phenomenon.

Finally, investigating the impacts of crowdsourced delivery at different times of the day has shown how the negative effects of crowdshipping by car are lower during less congested hours. This information could be exploited by policy makers to encourage the use of crowdshipping by public transit particularly during peak hours.

Conclusion

This study investigates, by means of a simulation approach, the potential impacts on traffic and pollution deriving from the implementation of alternative crowdshipping practices. The externalities associated with several strategic (chosen mode) and operational (detour length, parking behavior, and traffic conditions) aspects of this service are analyzed by means of simulation in realistic settings.

Traffic simulation is adopted in order to model more accurately the effects on traffic and pollution of delivery operations dynamic. This modeling approach is relatively limited in the field of City Logistics and, to the best of the authors' knowledge, no systematic simulation-based study of crowdshipping has yet been performed. The adoption of a hybrid traffic simulation seems particularly appropriate for the evaluation of traditional and crowdshipping delivery services, as it reproduces traffic at a macroscopic level, while reproducing delivery operations and crowdshippers' trips at a microscopic level. This approach offers a good compromise between computational performance, real data requirements, and accuracy of the traffic model. Future research could address carriers' and crowdshippers' parking modeling in order to reproduce more accurately their behavior with the support of revealed and stated preference surveys. Considering the issue of failed deliveries is envisaged as well.

The externalities related to crowdshipping are investigated at the network level by analyzing the effects of the implementation of such service in comparison to traditional delivery framework for parcels, in the city center of Rome. The city is characterized by considerable congestion and parking issues and it would greatly benefit from innovative freight distribution solutions. Thanks to available traffic data and information about the parcel delivery process directly obtained from major carriers operating in the area, it was possible to perform realistic simulations corresponding to alternative implementation scenarios. The realism of the experiments could be further increased in future studies, by including more specific information about signal settings and parking, and by adopting a more detailed street network. As mentioned earlier, limited attention has been devoted to some behavioral aspects of crowdshipping (i.e., matching between demand and supply), that are considered as an input in the experiments. The way different operational and business aspects are addressed in the matching procedure could affect the overall traffic and emission impacts of crowdshipping. In future studies, it would be interesting to include this perspective in the modeling framework as well.

The analyses confirm that crowdshipping is a double-edged sword for sustainable freight distribution since, depending on different implementation features, it could result in very different changes in emissions and traffic congestion. The chosen transportation mode by crowdshippers plays the main role in identifying the effects of this solution. Car-based crowdsourced deliveries entail higher negative externalities from both a traffic and an environmental perspective than traditional deliveries. It is interesting to see that, even with a conservative approach where only existing trips and last-mile effects are included in the simulation, the impacts of car-based crowdshipping are already significant. For this kind of crowdshipping, operational aspects such as the availability of parking, the optimization of existing trips, and the implementation during off-peak hours can considerably influence the final traffic and emissions impacts. Further research is envisaged to investigate the overall impacts of crowdshipping including the effects of pick-up detours and induced crowdshipping trips. Since drivers might start dedicated delivery trips (similarly to current ride-hailing services) the negative externalities of car-based crowdsourced delivery could be considerably higher.

Finally, more research is needed to understand whether the crowdshipping services offered in current market are leaning more towards car-based or public transit-based (or other environmentally friendly) deliveries. Based on that need, ad hoc policy solutions aimed at optimizing existing crowdshippers' trips could be developed and evaluated by a similar simulation-based approach.

Authors' Contribution The authors confirm the contribution to the paper as follows: study conception and design: MDS, EM, and VG; Data collection: MDS, EM, and VG; Analysis and interpretation of results: MDS; Manuscript preparation: MDS, EM, VG, and CGC.

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