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Original research article

A greener last mile: Analyzing the carbon emission impact of pickup points in last-mile parcel delivery

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A R T I C L E I N F O

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A B S T R A C T

This paper analyzes the carbon emission impact of pickup points in last-mile parcel delivery. Pickup points provide customers and delivery companies with an alternative to attended home delivery. The delivery company can drop a parcel off at the pickup point, such as a service desk in a grocery store or a parcel locker, from where the customer collects the parcel. Because of the potential efficiency gains for the delivery vehicle, pickup points are often presented as a sustainable alternative to home delivery. The efficiency gains for the delivery vehicle need to be weighed against customers traveling to the pickup point by car, however. The mathematical analysis presented in this paper integrates continuous approximation techniques to assess the potential for improved delivery route efficiency with multinomial logistic regression for estimating the travel distance and mode choice of customers collecting their parcels. The results challenge the suggestion that pickup points are a universally sustainable alternative to home delivery. The potential for a net positive carbon emission impact is greatest when pickup points are established in urban settings, while in rural settings, the carbon emission benefits derived from improved delivery route efficiency are quickly offset by the carbon footprint associated with customer travel.

1. Introduction

Since the popularization of e-commerce in the 1990s, there has been an ongoing debate regarding its sustainability implications [1–5]. When compared to conventional shopping, e-commerce has the potential to reduce environmental impact by consolidating multiple customer trips into efficient home delivery routes [6–12]. However, this advantage is highly context-dependent [13,14], and the substantial growth in online sales over recent decades has intensified concerns surrounding the negative externalities associated with last-mile parcel deliveries [15–17]. This paper adds to this ongoing debate with a focus on the introduction of pickup points in last-mile parcel delivery. Pickup points – defined in this paper as facilities where customers collect goods purchased online, including attended service points in shops or postal offices and fully-automated parcel locker systems – offer advantages for delivery companies. By using pickup points for parcel delivery, the number of stops a delivery vehicle must make is reduced, and the need for re-delivery after a failed first attempt is eliminated [18–21]. Both factors contribute to more efficient use of delivery vehicles, resulting in decreased operational costs and carbon emissions associated with delivery routes [22–24]. However, the positive environmental impact provided by the delivery company may be quickly offset if customers travel to pickup points using polluting passenger cars.

The aim of this study is to analyze the carbon emission impact of pickup points. Using multinomial logistic regression, we model the mode choice and trip chaining decisions of customers in relation to travel distance to a pickup point, based on survey data from 54,397 respondents who recently used a pickup point in the Netherlands. The resulting multinomial logit model is combined with a model approximating the route efficiency gains for the parcel delivery company. In doing so, this study extends prior research, which has predominantly focused on the impact of pickup points on the operations of the delivery company and/or made strong assumptions about the way in which customers travel to collect their parcels. Because the last-mile parcel delivery system is modeled analytically, our approach provides a more general understanding of the conditions under which pickup points can positively affect carbon emissions in last-mile parcel delivery. To demonstrate the model's applicability and evaluate the robustness of its outcomes, we apply it across various levels of urbanization, adoption rates of pickup point delivery, the attribution of trip chaining, and emission levels of the delivery vehicle and passenger cars.

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2. Background

Last-mile delivery models that include pickup points form an alternative to the more traditional models delivering parcels directly to customers' homes. Instead, the delivery company can drop parcels off at a pickup point, usually nearby a customer's home, from where the customer collects the parcel. There are different types of facilities that enable customers to self collect a parcel, going by different names, such as collection-and-delivery points [21], pickup points [25], automated parcel stations [26], automated delivery stations [27], parcel lockers [22], parcel machines [28], smart locker banks [29], shared reception boxes [30], or self-delivery boxes [31]. Generally, the literature makes a distinction between facilities that involve human interaction – usually at a counter inside a retail outlet – and unmanned machines, where customers can access their parcel after entering a reference code or using an application on their mobile phone [32]. For the purpose of our study, the distinction between attended and automatic pickup points is not directly relevant and we will henceforth refer to all types of facilities that enable customers to self collect a parcel simply as a pickup point. The introduction of pickup points in last-mile parcel delivery has several implications for delivery companies, their customers, and the environment. Below, we discuss the related literature.

2.1. Impact of pickup points on customers

Many customers prefer home delivery over self collection at a pickup point [26,27,33]. This may help explain why in most countries the adoption of pickup points has been slow. A survey from the Authority for Consumers and Markets [34], for example, revealed that only 18% of Dutch customers in 2018 opted for self collecting their parcel at a pickup point. When looking at parcel locker usage, 74.6% of Italian citizens aged between 18 and 76 living in the metropolitan area of Turin stated they had never used a parcel locker [35]. A commercial survey among 3589 customers aged 18 and older across the UK, US, France, Germany, Spain, the Netherlands, and Italy showed a 12% parcel locker use on average, with 31% in Germany being the highest adoption rate [36]. Several studies have sought to identify conditions under which pickup points would create value for customers [37]. Generally, customers expect a pickup point to be located conveniently and appreciate broad opening hours, short waiting times, an easy retrieval process, and the possibility to return parcels [38]. When looking at parcel lockers specifically, customers appreciate the flexibility offered by their 24/7 availability [39]. They also value convenience, reliability, and privacy security, [40,41], albeit customers worry about whether delivery via a parcel locker is indeed safe and secure [39].

The introduction of pickup points in last-mile delivery implies that customers will have to travel some distance to collect a parcel. From the perspective of the environmental and societal impact of pickup points, it therefore becomes important to understand how customers travel to a pickup point. Data from a survey filled out by 2933 users of InPost parcel lockers in Poland shows that 51% traveled to a parcel locker by passenger car—36% did so on foot, and 13% by another transport mode [42]. In a survey among 234 students at two Polish universities, Moroz and Polkowski [28] find that 56% of the trips to a pickup point are made by passenger car and 44% on foot. Hofer et al. [43] designed an online panel survey to study the mobility behavior of customers related to parcel delivery. Specifically, the panel consisted of 141 residents in the city of Graz (Austria) and surrounding municipalities. Overall, 44.5% of the reported trips to a pickup point were made by passenger car, 29.8% on foot, 20.8% by bike, and 4.9% by public transport. Verlinde et al. [39] carried out an online survey among customers living in the city centre of Ghent (Belgium). Among the 40 respondents that answered a question about their mode of transport used for picking up a parcel, 17.5% indicated they use their passenger car, while 50% traveled by bike, 30% on foot, and 2.5% by means of public transport. Analysis of the Swedish National Transport Survey data from 2011 to 2013 reveals that 70.9% of the 1458 completed trips aimed at "picking up/leaving things" was done by passenger car, against 23% by bike or on foot, 4% by bus, and 2.1% with other transport modes [44]. Buldeo Rai et al. [45] surveyed 385 customers at different pickup points, at different times of the day, and in different parts of Brussels (Belgium) and found that 47% of them traveled to the pickup point by passenger car, 21.6% on foot, 9.1% by bike, and 22.3% by public transport.

Studies aimed at estimating the potential use of pickup points also provide indications for the modes of transport customers would use when collecting a parcel. In a survey asking how customers would travel to a pickup point if a parcel were to be dropped off there after a first attempt to deliver at home failed, 43% of the 790 respondents from the Winchester area (UK) indicated they would pick up the parcel by passenger car, while 48% would walk, 5% would cycle, 4% would take the bus [18]. In a similar survey, 40% of 379 respondents living in the West Sussex region (UK) would consider walking to the pickup point while 48% would take the passenger car, 6% would travel by bike, and 4% would take the bus [20]. Out of the 534 respondents to a survey aimed at obtaining revealed preference data about e-commerce behavior of customers living in the Belo Horizonte metropolitan area (Brazil), 59% indicated they would use a passenger car to travel to a pickup point, 32% would go on foot, 1% by bike, and 7% would take the bus [27].

In sum, prior research strongly suggests that customers (would) often use their car to travel to a pickup point instead of opting for a more environmentally-friendly mode of transport. Generally, it is understood that passenger car usage of customers traveling to a pickup point will increase as the pickup point is located farther from the customer's home—albeit empirical studies on this subject are scarce. The work of Liu et al. [44] is an exception, and reveals a non-linear relationship between the distance of a trip and the probability a customer opts for using a car to pick up or drop off something.

The use of a passenger car to visit a pickup point becomes particularly problematic when this visit is the sole purpose of a customer's trip. If a customer would be traveling anyway, and the visit to a pickup point can be combined with some other purpose without much extra mileage, this would mitigate the impact of using their car. This phenomenon is called "trip chaining" and plays an important role in the environmental impact associated with pickup points [33,44,46]. From the perspective of the customer, prior studies have therefore recommended to locate pickup points so that they are easily accessible for customers by bike or on foot [47], or nearby places visited frequently, such as supermarkets, shopping areas, or public transport facilities [42,48].

2.2. Impact of pickup points on delivery companies

From the perspective of a delivery company, the largest benefit of including pickup points in their last-mile delivery operation results from more efficient delivery routes. The more customers opt for self collection, the less customer homes have to be visited by a delivery vehicle. Prior research has shown that this translates into shorter delivery routes [12]. Another driver behind increased delivery route efficiency is that pickup points can reduce the number of parcel deliveries that fail because the customer is not at home [46]. Reducing the number of failed deliveries reduces the number of parcels that have to be included in a subsequent route, and thus increase the overall efficiency of delivery routes [14,18,20,21,49]. There are several reports on the extent to which failed deliveries are in fact an issue, with percentages of failed deliveries ranging from 2% to 60%. Fig. 1 plots the reported percentages and seems to suggest a declining trend—with more recent papers generally reporting failed delivery percentages below 20%.

Whether the benefits in terms of more efficient routes from pickup points are positively affecting the overall bottom line of a delivery company also depends on the investment and variable cost associated with

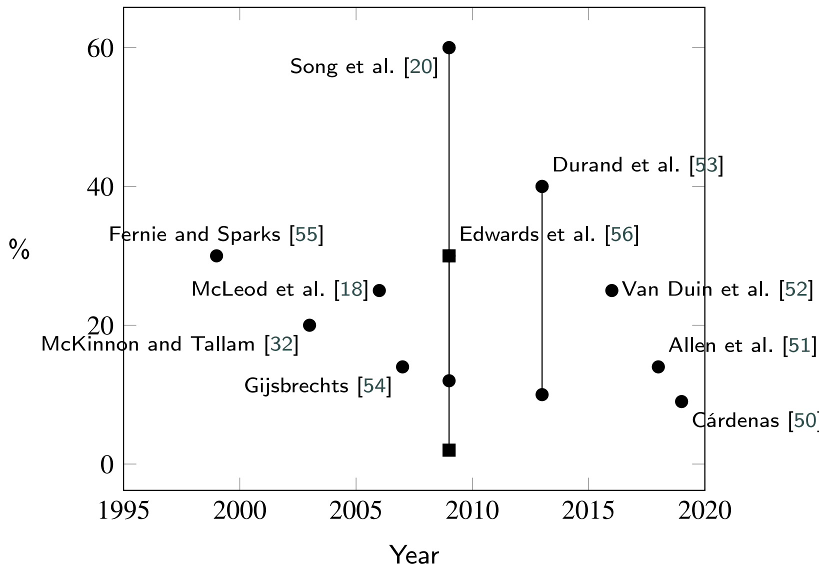


Fig. 1. Failed delivery rate estimates in prior studies [18,20,32,50–56].

operating the pickup points [22–24]. One important set of decisions in that regard is related to network design, including choices about the number of pickup points, their size, and location. In the academic literature, these network design decisions are often addressed from an operational research perspective [48,57–60] or from the perspective of public policy and spatial sciences [47,61]. New innovations in the use of pickup points focus on the introduction of mobile parcel lockers [62] and the use of pickup points for transshipment before the final stretch of delivering the parcel [63,64].

2.3. Impact of pickup points on the environment

The introduction of pickup points in practice is often motivated from a sustainability perspective. Likewise, most academic studies about pickup points at least mention a positive environmental impact in motivating their research. Far fewer studies, however, have explicitly included an environmental impact assessment of pickup points. To analyze the carbon emission impact of pickup points, we therefore draw upon the methods and insights from prior studies that assessed the environmental impact of various last-mile distribution configurations more broadly.

The overview presented in Table 1 consists only of studies that assess the environmental impact of last-mile configurations explicitly, and consider the perspective of both the delivery vehicle and customer travel. These configurations include some combination of traditional brick & mortar stores (B&M), home delivery (HD), pickup points (PUP), and/or customer pick up at a delivery company's depot (DPU). Most of these studies compare different distribution configurations in the context of a specific case [10,12,19,21,46]. Four studies take a model-driven or analytical approach [2,11,49,65], while including empirical data for either model validation or analysis. Goodchild et al. [13] is the only study to develop an analytical model aimed at providing insights beyond a specific context.

The distribution configurations differ greatly over the different studies. Goodchild et al. [13], for example, compare a configuration where customers collect goods at a local depot of the delivery company with a configuration where the goods are delivered at home via the local depot. Two other studies focused on mitigating the impact of failed deliveries [19,21]. That is, one configuration assumes that when a delivery fails, the company either attempts to re-deliver the parcel later or the customer travels to the company's depot, which is at least 13 km away, to collect the parcel. This situation is then compared with a configuration where the customer must collect the parcel at a (more local) pickup point after the first delivery attempt failed. Several studies compare conventional shopping, where customers pick up goods at a brick & mortar store, with a configuration where (a proportion of) customers opt for home delivery or delivery via a pickup point [2,10–12,49]. Prandtstetter et al. [46] examine the impact of implementing white label parcel lockers within the vicinity of customer homes in comparison to mostly serviced pickup points with limited opening hours, proprietary to a specific delivery company. Schnieder et al. [65] compare a configuration where all goods are delivery to customers' homes with one where all goods are delivered via a pickup point.

Estimating the route length of the delivery vehicle is an important element of assessing the environmental impact across different distribution configurations. The length of the delivery route is commonly modeled as a traveling salesman problem [10,11,21,46,49,65]. One study uses route length approximation (RLA) [13], while three consider a fixed travel distance per delivery [2,12,19]. The delivery company's vehicles are often considered to be internal combustion engine (ICE) vans, while three studies analyzed a setting with a ICE truck [2,10,12]. Hardi and Wagner [11] and Schnieder et al. [65] consider the possibility of an electric van. Early studies often analyze a setting with a single vehicle, while more recent studies consider settings with multiple vehicles. The number of locations where customers can collect their goods differs across the studies. While Mangiaracina et al. [2], Hardi and Wagner [11], and Brown and Guiffrida [49] model a setting with a single location for self collection by customers, other studies consider two [12] or more locations.

In most studies, the mode of transport of customers traveling to pickup their goods is assumed to be a passenger car. Some studies also consider other modes of transport [11,12,19,46], such as non-polluting (NP) transport modes (e.g., foot or bike) and public transport (PT). Song et al. [21] state that customers should walk for self collection to be effective. Trip chaining is considered only in two studies [46,49]. We note that even when studies addressed mode choice and/or trip chaining, they did not do so extensively. Overall, the results of prior studies are highly sensitive to assumptions made about the proportion of customers that is actually willing to use a pickup point. Most studies made use of case-specific data to justify their assumptions, which were either collected among the citizens living in the case area via a survey or based on nation-wide data. All studies rely on the academic literature or online available databases to obtain general information about, for example, the emission of passenger cars and delivery vehicles.

Table 1
Overview of the modeling choices in prior studies comparing home delivery (HD) with several self collection configurations (PUP, B&M, DPU).

	Edwards et al. [19]	Wiese et al. [12]	Song et al. [21]	Brown and Guiffrida [49]	Carling et al. [10]	Mangia-racina et al. [2]	Goodchild et al. [13]	Hardi and Wagner [11]	Prandtstet-ter et al. [46]	Schnieder et al. [65]
Analysis driven by	Case	Case	Case	Model	Case	Model	Model	Model	Case	Model
Scenario 0	HD + DPU	B&M	HD + DPU	B&M	B&M	B&M	B&M/PUP	B&M	HD + PUP	HD
Scenario 1	HD + PUP	HD	HD + PUP	HD	PUP	HD	HD	B&M + HD	HD + PUP	PUP
Route distance calculation method	Fixed distance	Fixed distance	TSP	TSP	TSP	Fixed distance	RLA	TSP	TSP	TSP
Delivery vehicle type	ICE van	ICE truck	ICE van	ICE van	ICE truck	ICE van & truck	Not specified	ICE & electric van	ICE van	ICE & electric van
Number of delivery vehicles	1	1	1	Multiple	Multiple	Multiple	Multiple	Multiple	Multiple	1
Number of collection locations	Multiple	2	Multiple	1	Multiple	1	Multiple	1	Multiple	Multiple
Mode of transport customers	Passenger car, PT	NP, passenger car, PT, Other	Passenger car	Passenger car	Passenger car	Passenger car	Passenger car	NP, passenger car	NP, passenger car	Passenger car
Trip chaining taken into account	No	No	No	Yes	No	No	No	No	Yes	No
Empirical data	Case	Case + Survey within case	Case + Survey	Survey	Case + Survey within case	Case	N/A	Case	Case + Survey within case	Case + Survey within case

3. Methodology

The aim of our study is to assess the carbon emission impact of pickup points relative to home delivery. To this end, we develop a model approximating the efficiency gains from introducing a pickup point in a delivery route and analyze customer mode choice and trip chaining behavior. Multinomial logistic regression is employed to estimate the carbon footprint of customers traveling to and from the pickup point, and is integrated into a single model describing the net carbon emission impact of pickup points.

3.1. Model development and data

We model a single delivery area as a circle with radius R and area A. This delivery area is served by one delivery vehicle operating from a depot (e.g., a sorting station or city hub of a delivery company). The distance between the depot and the edge of the delivery area is d. The locations of the customer addresses are assumed to be uniformly distributed across the delivery area. Throughout our analysis, we consider two scenarios, as shown in Fig. 2. Scenario 0 represents a setting where all deliveries are made to the home addresses of customers. Hence, the delivery vehicle travels to the delivery area and then visits all addresses (n_0). Scenario 1 represents a setting with a combination of home deliveries and deliveries via a pickup point. The delivery area and number of customers are the same as in Scenario 0, but now a single pickup point is included and a proportion α of customers is using it. This proportion also determines n_1, the number of addresses that still have to be served by the delivery vehicle. In Scenario 1, trips of customers to and from the pickup point are included in the analysis, as indicated by the dashed lines.

The model positions the pickup point in the center of the delivery area. While this is a simplifying assumption, it results in the lowest expected distance between the customers and the pickup point [66], and hence yields a conservative estimate of the distance traveled by the customers. Note that the delivery area in Scenario 0 has the same size of that area in Scenario 1. In practice, the introduction of a pickup point often does not result directly in a change of the delivery area of the vehicle involved. It could be that the design of the delivery area is changed to gain further efficiencies as more customers are adopting pickup points. These longer-term delivery area design decisions are beyond the scope of this paper.

We rely on well-known route length approximation techniques to assess the efficiency gains from introducing a pickup point in a delivery route. Using the formula introduced in Beardwood et al. [67], the distance traveled by the delivery vehicle in Scenario 0 (T_v^0) and in Scenario 1 (T_v^1) can be closely approximated with a constant k (typically 0.92 [68]) for larger values of n_0 or n_1, respectively:

$$T_v^0 = 2d + k\sqrt{n_0 A} \tag{1}$$

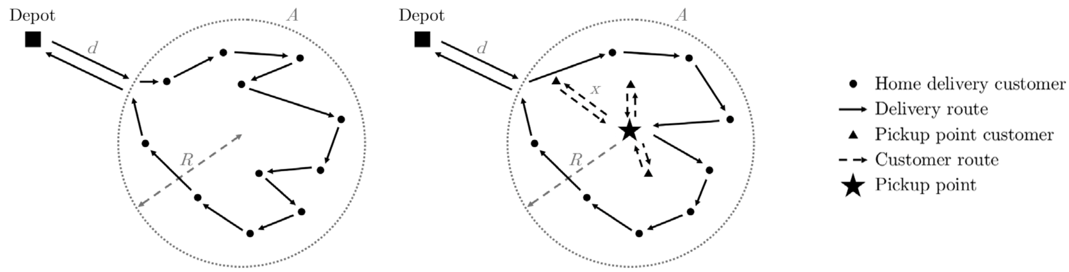
$$T_v^1 = 2d + k\sqrt{n_1 A} \tag{2}$$

The total number of customer home addresses served in Scenario 1 (n_1) is some proportion $1-\alpha$ of the total number of customers (n_0) plus an extra stop at the pick up point. However, for large values of n_0 this extra stop can be neglected:

$$\lim_{n_0\to\infty} \frac{n_1}{n_0} = \lim_{n_0\to\infty} (1-\alpha+\frac{1}{n_0}) = 1-\alpha \tag{3}$$

$$n_1 \approx (1-\alpha)n_0 \tag{4}$$

Scenario 0 only involves the vehicle of the delivery company. The resulting carbon emissions c_v are assumed to be directly proportional to the distance traveled by that vehicle, ignoring dynamic factors such as vehicle speed, vehicle acceleration, and traffic congestion. While being a somewhat simplifying assumption, Stead [69] has demonstrated that travel distance serves as a good proxy for a vehicle's carbon emissions. In Scenario 1, the distance traveled by the delivery vehicle can be reduced, but this scenario also involves customers traveling to collect their parcel. c_c denotes the average emission factor in amount of carbon per unit distance traveled by a passenger car. Multiplied by the total distance traveled by customers for the specific purpose of visiting the pickup point, this yields the carbon footprint of customer travel that must be consider alongside the efficiency gains of the delivery vehicle when assessing the carbon emission impact of a pickup point.



(a) Scenario 0 - Home delivery (b) Scenario 1 - Home delivery and one pickup point

Fig. 2. Schematic overview of Scenario 0 and Scenario 1.

Customers may choose to combine their trip to the pickup point with some other purpose—that is, trip chaining. And, not all customers travel to the pickup point by passenger car, as they may also choose to travel by a non-polluting mode of transport such as by bike or on foot. To gain insight into customer travel mode choice and trip chaining, we obtained survey data from 54,397 Dutch respondents that recently made use of a pickup point of a large parcel delivery company in the Netherlands. The data includes the postcode of a customer's home address, the address of the pickup point, the mode of transport used by the customer when collecting the parcel, and whether or not this trip was part of a trip chain. A detailed description of the data as well as our data cleaning and conversion steps is included in Appendix.

The probability of a customer choosing mode m at a distance x between the customer and the pickup point can be estimated by means of a multinomial logistic model.

$$P_m = \frac{e^{\gamma_m + \delta_m x}}{\sum_{i \in M} e^{\gamma_i + \delta_i}} \tag{5}$$

The expected distance of a customer's trip to and from the pickup point driven by passenger car (E_{car}) in delivery area (A) can then be expressed by

$$E_{car} = \frac{1}{A} \int_0^R 2\pi x (P_{car_{dedicated}} + \beta P_{car_{tripchain}}) 2x \, dx \tag{6}$$

where we make a distinction between the probability that a car trip is made for the sole purpose of going to the pickup point ($P_{car_{dedicated}}$) or is combined with some other purpose ($P_{car_{tripchain}}$). For the latter, where a customer is trip chaining, a proportion β of the travel distance is attributed to collecting a parcel. The total travel distance is then determined by integrating the expected passenger car travel distance to and from the pickup point ($2x$) of all customers at a specific distance x from the pickup point over the radius R.

The following equations link the model to approximate the change in carbon emissions for the delivery vehicle (ΔC_v) with the multinomial logit model estimating customer mode choice to arrive the carbon footprint of customer travel (ΔC_c) and the net carbon emission impact of opening a pickup point in a delivery area (ΔC).

$$\Delta C_v = (\sqrt{1-\alpha} - 1) k \sqrt{n_0 A} c_v \tag{7}$$

$$\Delta C_c = \alpha n_0 E_{car} c_c \tag{8}$$

$$\Delta C = \Delta C_v + \Delta C_c \tag{9}$$

An overview of the key parameters used in further analyses is provided in Table 2.

3.2. Carbon impact analysis

The goal of our carbon impact analysis is to compare the performance of a last-mile parcel delivery route with and without a pickup point, while considering both the resulting efficiency gains for the delivery route and the carbon footprint of customer travel to and from the pickup point. The unit of the analysis is hence the delivery area, as portrayed in Fig. 2. A full life cycle assessment of this unit would include raw material extraction, manufacturing, distribution, operations, and disposal/recycling of the passenger cars used by customers as well as the delivery vehicle and equipment used to establish the pickup point. The resulting primary data collection is beyond the scope of our study. Rather, our focus is on the carbon emission of the delivery vehicle and passenger cars used to deliver or collect the parcels. Data about these emissions are available from prior studies.

Table 2
Key parameters used in the mathematical analysis.

Symbol	Parameter description
A	Surface area of the delivery area
n_0	Total number of addresses to be visited by the delivery vehicle in Scenario 0
n_1	Total number of addresses to be visited by the delivery vehicle in Scenario 1
α	Adoption rate (i.e., the proportion of customers using a pickup point)
β	Proportion of a trip chain attributed to collecting a parcel
c_v	Carbon emission of the delivery vehicle
c_c	Average carbon emission of passenger cars
ΔC_v	Carbon emission impact of pickup point for the delivery vehicle
ΔC_c	Carbon emission impact of pickup point for customer travel
ΔC	Net carbon emission impact of pickup point

The 2022/23 edition of the European Vehicle Market Statistics [70] provides information about the CO_2 emissions of newly registered light commercial vehicles and passenger cars produced by well-known original equipment manufacturers (e.g., Renault, Mercedes-Benz) for the European market. Average CO_2 emissions of newly registered light commercial vehicles in the EU in 2021 were 196 g/km—that is, the tank-to-wheel emissions as measured in the laboratory via the World-wide Harmonized Light Vehicles Test Procedure (WLTP). For passenger cars, those emissions were 116 g/km. These values are used in the main part of our analysis. Delivery companies are quickly transitioning to fleets with electric delivery vehicles—generally at a much faster rate than changes in the fleet of passenger cars. Also note that tank-to-wheel emissions only involve a part of the total life cycle impact of a vehicle. Therefore, we will perform a robustness analysis taking these aspects into account.

4. Results

To set the stage for a deeper mathematical analysis, this section starts with an exploration of the survey data by presenting a few descriptive statistics that highlight the respondents' transport mode choice. Overall, 32.8% of the trips respondents made to a pickup point was done by passenger car. These trips account for 53.5% of the total

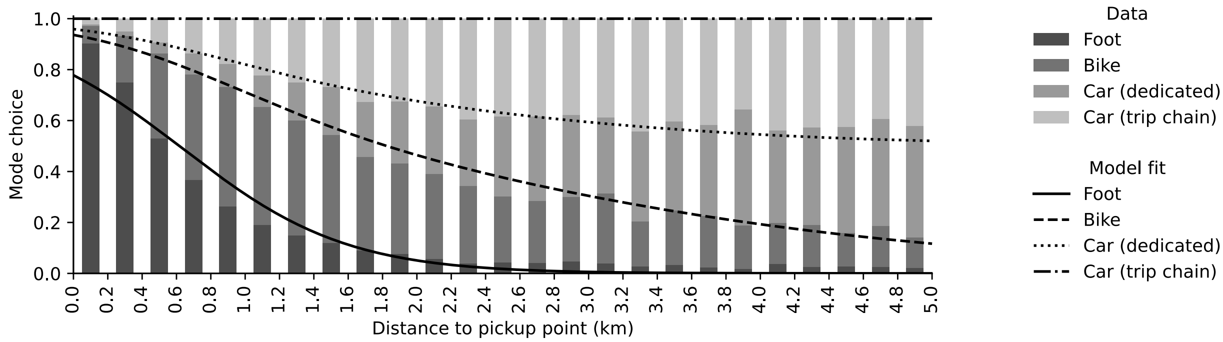


Fig. 3. Multinomial logit regression model fit of total dataset.

customer travel distance. 35.1% of respondents went on foot (accounting for 18.2% of total customer travel distance), and 32.2% by bike (accounting for 28.3% of total travel distance). From the respondents taking the car, 60.0% was part of a trip chain while 40.0% of the car trips were fully dedicated to collecting a parcel. The data set includes a fourth mode of transport, namely public transport, but since only 185 of the respondents reported a trip to a pickup point by means of public transport these were omitted from further analysis.

A preliminary visual inspection of the data (see the bars in Fig. 3) suggests that the transportation mode customer chose is strongly related to the distance to the pickup point. When respondents were located no more than 200 m from the pickup point, 91.1% chose to go on foot while a mere 2.7% used a car. However, the proportion of environmentally-friendly transport modes decreases rapidly as the distance to the pickup point increases. Interestingly, 28.5% of the respondents were located 500 m or less from the pickup point they visited, a distance considered walkable by the Dutch Authority for Consumers and Markets [34]. Nonetheless, only 75.8% of these respondents actually traveled to the pickup point on foot.

In addition to the impact of distance on mode choice for collecting parcels at pickup points, the data suggests a relationship between the level of urbanization and mode choice (see Fig. A.1). Customers in densely populated urban areas may prefer traveling on foot or by bike for reasons other than the distance to the pickup point. One possible explanation is that urban residents may not require or own a passenger car, and thus do not use one for traveling to the pickup point. Address density, as obtained from the Dutch Central Bureau for Statistics [71], is used as a proxy for urbanization level. We define rural areas by an address density below 1000 houses per square kilometer, while urban areas have more than 4000. On average, respondents in urban areas primarily traveled to the pickup point by bike or on foot. Passenger cars were used for only 8.6% of the trips in urban areas, regardless of the distance required. In contrast, respondents in rural areas used passenger cars for 43.7% of the trips and rarely traveled on foot.

4.1. Model estimation results

The general model parameter estimates for γ and δ can be found in Table 3. It shows estimates and general fitting information for four models: One for the total data set and separate models for different levels of urbanization. The Pseudo-R-Squared values suggest a reasonable fit for all models. A visual representation of the fitted model for the total data set is presented in Fig. 3.

The fitting information is obtained after removing outliers. Specifically, a very small number of responses report an exceptionally high travel distance to the pickup point. The frequency response as a function of distance appears to follow a lognormal distribution (see Fig. A.2). To transform the lognormal distribution into a normal distribution, the natural logarithm is taken. Subsequently, the interquartile range (IQR) method is employed to identify outliers for each of the four models separately. In Table 3, the cutoff distance is determined

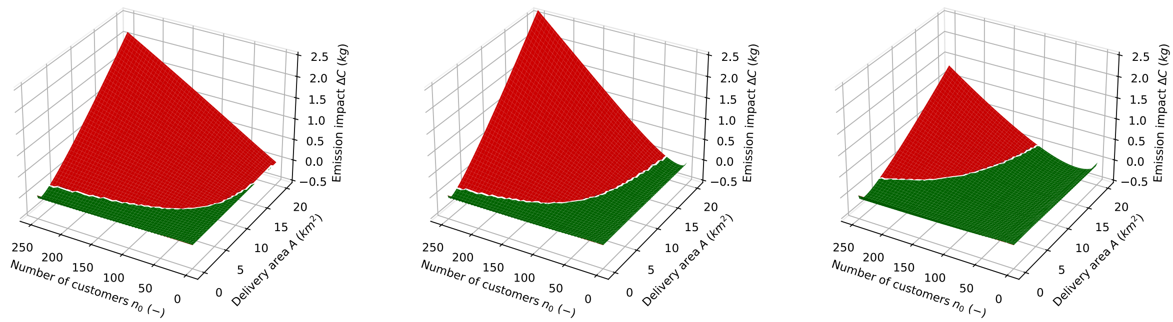
Table 3
Multinomial logistic regression results.

	Total	Rural	Suburban	Urban
Address density (km^{-2})		<1000	1000–4000	>4000
Data points	43 130	12 225	26 799	4106
% of total data set	100%	28.3%	62.1%	9.5%
Distance to pickup point				
Upper quartile (lognormal distr.)	0.48	0.98	0.39	−0.15
IQR (lognormal distr.)	1.22	1.46	1.13	1.05
Cutoff distance (km)	10.04	23.64	8.01	4.17
Outliers	362	57	201	43
Outliers (% of data points)	0.8%	0.5%	0.8%	1.0%
Model estimate				
Foot (reference category)				
γ	0	0	0	0
δ	0	0	0	0
Bike				
γ	−1.593	−0.563	−1.792	−2.243
δ	1.845	0.938	2.074	2.457
Dedicated car trip				
γ	−3.532	−1.997	−4.001	−5.533
δ	2.481	1.343	2.924	3.450
Car with trip chain				
γ	−2.944	−1.401	−3.318	−4.722
δ	2.398	1.291	2.749	3.237
Pseudo R-Square				
Cox and Snell	0.319	0.223	0.324	0.220
Nagelkerke	0.343	0.239	0.350	0.262
McFadden	0.146	0.093	0.151	0.135

by converting the obtained upper whisker back to an actual distance through exponentiation. During this process, at most 1.0% of the data was excluded.

Fig. 4 graphically presents the main study results, illustrating the carbon emission impact of introducing a pickup point (ΔC) as a function of the number of customers (n_0) and the delivery area (A). Each of the graphs plots the model outputs based on the multinomial logit model parameter estimates for a different urbanization level. Across all graphs, the adoption rate α is set at 18% (typical for last-mile parcel delivery in the Netherlands [34]), with the carbon emission of the delivery vehicle c_v fixed at 196 g/km and the average emission of passenger cars c_c at 116 g/km. None of the emissions of passenger car trips that are part of a chain are attributed to collecting parcels (i.e., $\beta = 0$).

The green parts of the graphs in Fig. 4, where $\Delta C < 0$, represent the conditions under which pickup points have a positive effect on carbon emissions in last-mile parcel delivery. The potential for positive impact is clearly greatest in urban settings. In rural settings, introducing a pickup point only reduces carbon emissions when the delivery area includes a very small number of customers n_0 and/or when the delivery area A is exceptionally small. It is important to note that even in an



(a) Rural (b) Suburban (c) Urban

Fig. 4. Carbon emission impact of opening a pickup point per urbanization level.

Table 4
Three cases in Amsterdam: Rural (Monnickendam), Suburban (Amsterdam Nieuw-West), Urban (Amsterdam City Centre).

	Rural	Suburban	Urban
Address density (km^{-1})	991	2901	8517
Number of customers n_0 (–)	100	150	200
Delivery area A (km^2)	10	5	1
Total delivery vehicle distance in delivery area (km)	29.1	25.2	13.0
Total customer travel distance (km)	42.8	45.4	27.1
Allowable travel distance by passenger car (km)	4.643	4.021	2.077
Actual travel distance by passenger car, i.e., $\alpha n_0 E_{car}$ (km)	6.732	4.536	0.360
Emission impact delivery vehicle ΔC_v (kg)	−0.54	−0.47	−0.24
Emission impact customers ΔC_c (kg)	+0.78	+0.53	+0.04
Emission impact ΔC (kg)	+0.24	+0.06	−0.20

urban setting, the delivery area cannot be too large—otherwise, the number of customers should be relatively low. The large red sections of the plots and the steep increase in emissions under conditions where introducing a pickup point does not offer environmental benefits are notable, especially in relation to the comparatively limited carbon emission reduction when a pickup point does provide benefits.

4.2. Case study & robustness analyses

To demonstrate the practical applicability of the model, three regions in and around Amsterdam, the Netherlands, are used as case studies. Each region is characterized by a distinct urbanization level. The input values for each region are presented in Table 4. The table also presents the main case study results, including insight into the maximum distance customers would be allowed to travel by car in order to avoid a negative carbon emission impact from a pickup point. In the rural setting, customers would be allowed to travel 4.643 km by passenger car for the purpose of collecting their parcel, which equals 10.8% of all customer trips. Instead, based on the multinomial logistic regression analysis of the survey data, our model suggests customers in this setting would travel 6.732 km by car, resulting in 0.24 kg extra carbon emission in this rural delivery area. For the suburban and urban settings, the percentage of customer trips that can be done by passenger car slightly decrease, mainly because of a smaller delivery area and thus shorter distances. In the suburban area the negative carbon emission impact of a pickup point therefore is much smaller (0.06 kg), while introducing a pickup in the urban setting would have a net positive carbon emission impact of 0.20 kg. Here, the efficiency gains of the delivery vehicle outweigh the carbon footprint of customer travel.

The three cases are also used to evaluate the robustness of the insights presented thus far. Specifically, the robustness analyses consider various values for the adoption rate α, the emissions of the delivery vehicle c_v and passenger cars c_c, and the proportion β of the distance driven in a trip chain attributed to parcel collection. The role of each of these parameters is analyzed ceteris paribus, with the other parameter values being fixed at an 18% adoption rate α, none of the trip chain distance being attributed to parcel collection, a delivery vehicle emission of 196 g/km and an average passenger car emission of 116 g/km.

The effect of changes in adoption rate and the proportion of trip chain distance that is attributed to parcel collection are illustrated in Fig. 5. This figure highlights the important role the adoption rate plays in the magnitude of carbon emission changes. In rural settings, a higher adoption rate increases the negative carbon impact of a pickup point up to the point when about 60% of customers use the pickup point to collect their parcels. Beyond that adoption rate, the value for ΔC decreases, and for adoption rates exceeding 90%, a pickup point would have a positive carbon emission impact. In suburban settings, the adoption rate does not have a substantial effect up to approximately 50%, after which a pickup point would result in a carbon emission benefits. The higher the adoption rate in urban settings, the larger the positive carbon emission impact of a pickup point.

As expected, Fig. 5 reveals a linear relationship between the carbon emission of a pickup point as the proportion of trip chain distance attributed to parcel collection. It is important to emphasize that changes in this attribution do not influence whether a pickup point can or cannot be expected to yield carbon emission gains in any of the three cases—the carbon emission impact is consistently positive in the urban case and consistently negative in the rural and suburban cases.

Fig. 6 provides insight into the role of delivery vehicle and average passenger car emissions. In these graphs, delivery vehicle emissions are varied over a range from 0 to 500 g/km. On this range, one can observe the zero tank-to-wheel carbon emissions of an electric delivery vehicle as well as the full life cycle carbon impact of a delivery vehicle, which according to Marmiroli et al. [72] is 231 g/km for an electric van and 466 g/km for a diesel van. For passenger cars, the robustness analysis considers five alternatives. In addition to the 116 g/km from the main analysis, these include 0 g/km for the tank-to-wheel emissions for an electric car, 24 g/km for the life cycle emissions of a Tesla Model 3 with renewable energy, 76 g/km for the life cycle emissions of a Tesla Model 3 with a conventional energy mix, and 215 g/km for the life cycle emissions of a Volkswagen Passat on gasoline, as reported in Buberger et al. [73].

Note that, overall, improvements in the environmental performance of the delivery vehicle negatively affect the ability of a pickup point to reduce carbon emissions in the delivery area. This is because, as delivery vehicles becomes less polluting per driven kilometer, there is less environmental benefits to route efficiency gains. The opposite is

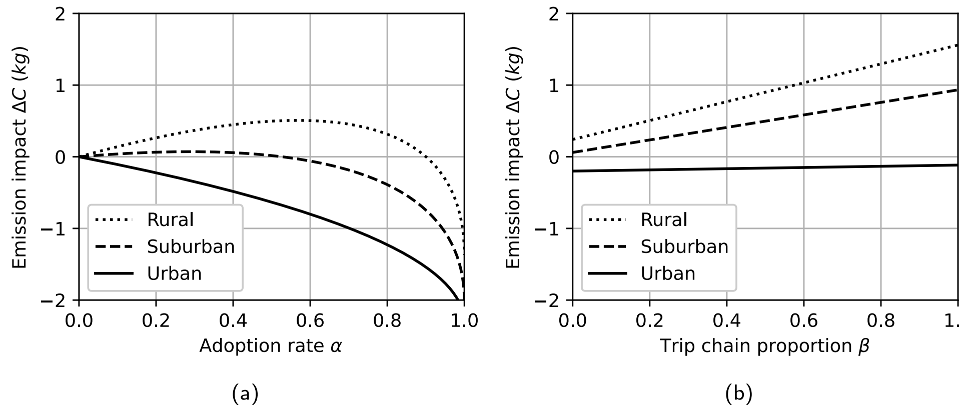


Fig. 5. Carbon emission impact of a pickup point as a function of the adoption rate and trip chain proportion.

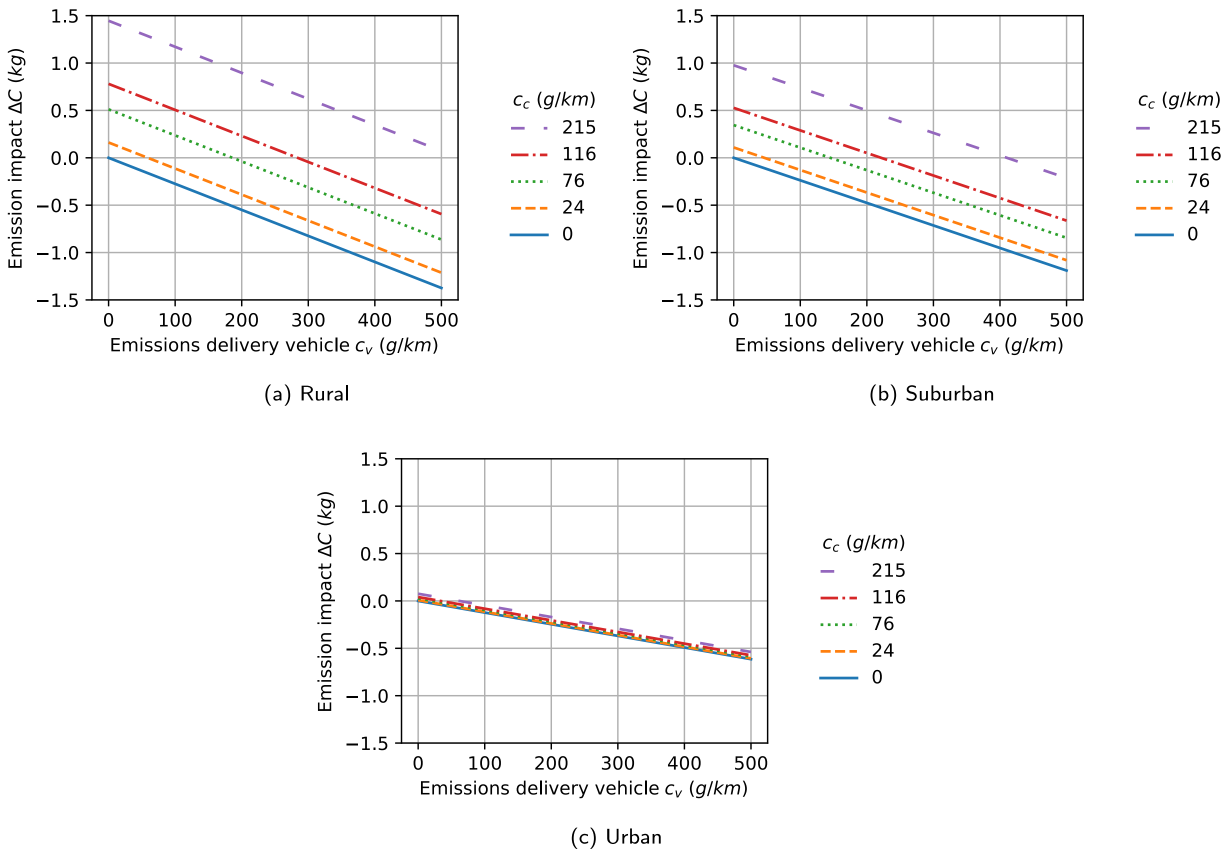


Fig. 6. Carbon emission impact of a pickup point as a function of delivery vehicle and passenger car emissions.

true for the average emission of passenger cars—the less polluting they get, the higher the potential environmental benefit from introducing a pickup point. Both effects are strongest in the suburban and rural setting, where the travel distance for passenger cars is generally high, and so too is the potential efficiency gain for the delivery vehicle when a pickup point is introduced. In urban settings, a pickup point is generally more likely to result in carbon emission benefits. Moreover, the impact of passenger car emissions is less substantial in urban settings because the expected car travel distance is low.

4.3. Implications for theory, managers, and policy makers

This paper contributes to debates about the role pickup points can play in last-mile parcel delivery, and provides important insight for policy makers and managers active in the e-commerce sector.

Prior research assessing the impact of pickup points in last-mile delivery mostly relied on simulation or optimization approaches to compare specific scenarios. The complexity of the last-mile delivery system in which pickup points are commonly opened necessitates making important assumptions about the specific parameters to consider and about the values those parameters can take. This either results in precise, but strongly context-dependent insights [10,12,19,21], or in the more generic, but less concrete conclusion that the impact of pickup point is contingent on the context in which it is implemented [2,11,46,49,65]. In line with Goodchild et al. [13], our study employs well-known continuous approximation techniques. It extends this analytical approach with a multinomial logit model. This key advancement allows for the estimation of mode choice and trip chaining decisions of customers collecting their parcels at the pickup point, providing more comprehensive insights into the conditions under which pickup points can reduce carbon emissions in last-mile parcel delivery.

Pickup points increasingly become part of delivery strategies in the e-commerce sector [74]—often with the intention to reduce the environmental and societal impact associated with last-mile delivery. The rationale is that the introduction of pickup points helps improve the efficiency of delivery routes because less customer homes have to be visited and more parcels are successfully delivered at the first attempt. One of the aspects complicating the assessment of pickup points is that it involves customer travel behavior and that the carbon emissions from customer travel is difficult to model accurately. In our study, we therefore use a large set of empirical data to gain insight in the carbon emission impact of customers traveling to a pickup point.

A first important implication of our study is that for pickup points to become a viable means to reduce carbon emissions, generally, their implementation needs to bring about a shift in customer travel behavior. One of the levers to facilitate such a shift is the distance customers have to travel to the pickup point. That is, our analysis of the empirical data clearly shows that the less a customer has to travel, the more likely the customer is to use an environmentally-friendly mode of transport. This strongly suggests managers and policy makers should aim for last-mile delivery networks with a high density of pickup points, such that (almost) every potential customer lives within walking or cycling distance from a pickup point. Alternatively, delivery companies could limit the option of delivery via pickup point to only those customers living at walking or cycling distance from a pickup point. While unfavorable from the perspective of customer value and efficiency, it would be a viable option from the perspective of making a positive environmental impact.

Our study also implies that the introduction of pickup points and cleaner delivery vehicles are not necessarily complementary from an environmental perspective. Freight transport companies worldwide are considering incorporating battery electric and hydrogen fuel cell vehicles into their fleets [75,76], or utilizing biomass-based fuels [77]. These measures improve the environmental performance of delivery vehicles. Simultaneously, delivery companies are expanding the number of pickup points, for example by installing fully-automated parcel lockers. Often, the implementation of pickup points and the adoption of cleaner delivery vehicles are presented as part of a unified effort towards sustainable last-mile parcel delivery. However, as the delivery fleet becomes less polluting, the environmental benefits of efficiency gains in the delivery route diminish. Our findings demonstrate that customer travel, which inevitably accompanies the shift towards using pickup points, involves significant passenger car use, particularly in suburban and rural areas. Generally, the adoption of clean delivery vehicles by delivery companies appears to be progressing more quickly than the adoption of electric passenger cars by customers. Consequently, the introduction of pickup points could have a negative impact on carbon emissions associated with last-mile delivery, at least in the short and mid-term.

5. Conclusions

This paper presents a study assessing the carbon emission impact of pickup points in last-mile parcel delivery. The study combines a continuous approximation approach with multinomial logistic regression to analyze the trade-off between the travel distance reduction for delivery vehicles, achieved through the introduction of a pickup point, and the additional travel distance required by customers collecting their parcels. In doing so, it offers novel insights into the net carbon emission impact of pickup points under various conditions. The analysis challenges the—sometimes implicit—suggestion in prior research that pickup points are a universally sustainable alternative to home delivery. Through a case study in urban, suburban, and rural settings, it becomes evident that the potential for positive impact is greatest in urban settings. In rural settings, the carbon emission benefits derived from improved delivery route efficiency are quickly offset by the carbon footprint associated with customer travel.

As with any study, ours is not without limitations. While the analytical approach results in generally applicable insights, interpreting these insights should be done considering a few important assumptions. First, our model considers a stylized setting with a single delivery vehicle, where we compare a scenario without a pickup point to a scenario with a pickup point located in the center of the vehicle's delivery area. These modeling choices enabled isolating the effects of the size of the delivery area and the number of customers as well as the adoption rate, customer travel behavior, and carbon emission factors of different vehicle types. In practice, the delivery area covered by a single vehicle may include more than one pickup point. Moreover, as more customers adopt parcel delivery via a pickup point, and delivery routes become increasingly efficient, the delivery company could change the delivery area design, resulting in even more efficient routes. Future research could explore the carbon emission impact of pickup points in settings with multiple pickup points, delivery vehicles, and delivery areas.

Second, our model assumes that customers are uniformly distributed across the delivery area and that the probability that a customer adopts delivery via a pickup point is independent of its location in the delivery area. The assumption regarding customer adoption of pickup points is worth discussing in particular—both because it is a strong assumption and because it has implications for our results. For approximating the delivery vehicle efficiency gains, this assumption may result in an underestimation of the route length reduction made possible by a pickup point. Given the relatively limited weight of the delivery route in the net carbon emission impact of a pickup point, the effect of this underestimation on the emission factor is small. For estimating customer travel distance, the assumption of uniformly distributed adoption results in an overestimation of travel distance. This is because customers living closer to a pickup point may be more likely to opt for parcel collection. Moreover, our empirical data show that customers are more likely to use an environmentally-friendly mode of transport for shorter distances to the pickup point. This may result in an overestimation of the carbon footprint of customer travel. Generally, the implication of these assumptions is that the range of conditions under which pickup points can have a positive net carbon emission impact may be slightly larger than indicated in our analysis. This opens highly interesting areas for future research, both in obtaining new empirical data about which customers choose to self-collect parcels at pickup points and in developing more complex mathematical models allowing for non-uniformly distributed customers and adoption rates.

CRediT authorship contribution statement

R. Niemeijer: Methodology, Formal analysis, Writing – original draft, Visualization. **P. Buijs:** Conceptualization, Methodology, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

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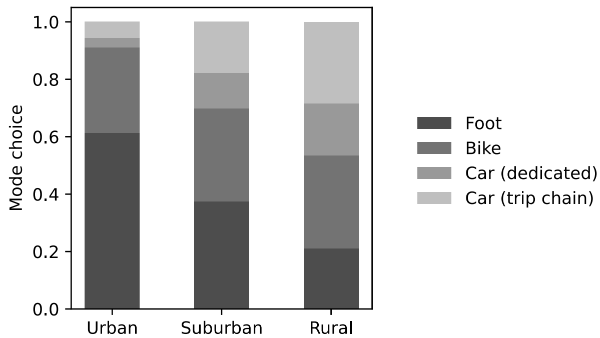

Fig. A.1. Mode of transport used by level of urbanization.

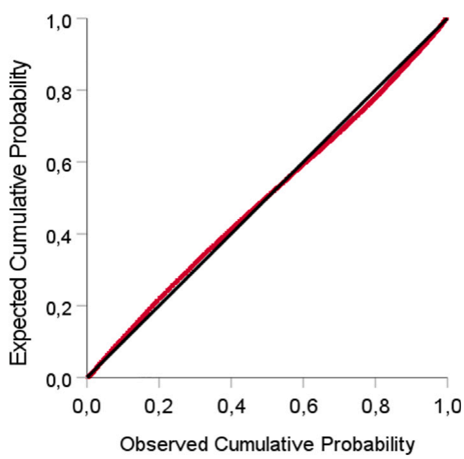

Fig. A.2. P-P plot of the lognormal distribution of distance to pickup point.

Appendix. Empirical data cleaning and analysis

We received empirical data from a large parcel delivery company in the Netherlands. They distributed a survey among their customers between 30 March and 2 June, 2021. The survey was distributed only among customers that had self collected their parcel at a pickup point, and the questions referred to that specific parcel pick up. The data set does not include responses from customers about home delivery. In the nation-wide survey 54,397 Dutch respondents have participated. The following questions were included in the survey:

1. Response ID (the customer data was anonymous)
2. Date & time of response
3. Postcode of the customer's home address
4. Address of the pickup point
5. Mode of transport the customer used to visit the pickup point
6. When the respondent took the passenger car, the respondent is asked whether the trip was part of another route (i.e., trip chaining)

The following steps were taken to calculate route distances and clean the data.

1. Start with a total data set of 54,397 entries.
2. Exclude entries with incomplete data (51,412 entries remain).
3. Only 185 entries reported the use of public transport. These responses are excluded (51,227 entries remain)
4. Retrieve (approximate) coordinates of customer's home address and pick up point using Open Street Maps.
5. Exclude entries with incomplete coordinates (51,210 entries remain).
6. Calculate route distance between customer's home address and pick up point by foot, bike and passenger car using Open Source Routing Machine (OSRM).
7. Exclude entries for which OSRM could not find a feasible route (46,264 entries remain).
8. It was concluded that entries with a distance of zero (3134 entries) do not add any information to our analysis. These were also excluded. (43,130 entries remain)
9. We assume the frequency response as a function of distance is distributed in a lognormal fashion. This is confirmed by Fig. A.2. We convert this distribution to a normal distribution and perform the interquartile range method to exclude outliers to obtain a usable dataset for the multinomial logistic regression.

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