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Big-data-driven approach and scalable analysis on environmental sustainability of shared micromobility from trip to city level analysis

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ABSTRACT

Shared e-scooters (SES) have recently gained popularity, but their environmental sustainability remains debatable. This study develops a data-driven and scalable method based on big data and data fusion from multiple sources to comprehensively analyze substitutions and the environmental impacts of SES from trip to city level analysis. Field trip transaction data in three major Swedish cities (Stockholm, Gothenburg, and Malmö) are leveraged for empirical analysis considering mode choice behavior. The results reveal that most SES trips (86.7% in Stockholm, 85.6% in Gothenburg, and 85.3% in Malmö) replace walking or public transport, while the proportion substituting private car and taxis is less than 12%. On average, each SES trip increases in CO_{2-eq} emissions (34.58 g in Stockholm, 21.18 g in Gothenburg, and 24.07 g in Malmö). Only a limited percentage of SES trips (19.20% in Stockholm, 24.22% in Gothenburg, and 23.94% in Malmö) and a small percentage of urban areas with SES (8.3% in Stockholm, 7.48% in Gothenburg, and 2.02% in Malmö) demonstrate positive environmental effects from SES. The substitution and environment impacts of SES vary significantly across different trips spatially and temporally, emphasizing the importance of conducting trip-level analyses. The analysis provides quantitative insights into the sustainability of SES in Nordic contexts, offering potential support for sustainable management in a variety of urban contexts.

1. Introduction

The rapid advancement of technology has facilitated the emergence of shared micro-mobility services, encompassing dockless and docked bikes, electric bikes, and shared e-scooters (Gao, Li, Liu, Gil & Bie, 2023; Reck, Martin, & Axhausen, 2022). The shared micro-mobility services have become more widespread in urban areas, broadening the range of transport alternatives for travelers and addressing the 'first- and last-mile' dilemma. In particular, the rise of shared stand-up electric scooters, designed for single riders and fitted with a compact electric motor, has become a suitable alternative for short-distance urban travel (Hollingsworth, Copeland, & Johnson, 2019; Reck et al., 2022; Zhou, Yu, Wang, He, & Yang, 2023). Consequently, shared electric scooters (SES) have seen a marked rise in popularity in the European Union since 2018. Furthermore, the global market is projected to grow at a compound annual growth rate of 11.61% between 2023 and 2027, leading to an estimated market of 2813 million vehicles by 2027 (Statista, 2023).

While shared micro-mobility has undergone rapid expansion, policymakers continue to grapple with the challenges arising from shared micro-mobility systems. The complexities of these challenges are exacerbated by a dearth of comprehensive quantitative insights into SES usage patterns and their systemic impacts (Badia & Jenelius, 2023). SES has potential benefits, such as emission reduction, flexibility, low-cost, and positive health impacts (Gao, Yang, Gil & Qu, 2023; Peng, Nishiyama, & Sezaki, 2022; Reck et al., 2022; Zhou et al., 2023). One pivotal potential benefit of SES is that they may play a significant role in decarbonizing road transport and mitigating carbon emissions by replacing energy and emission-intensive transport modes (e.g., private car) (Hollingsworth et al., 2019; Sun, Feng, Kemperman, & Spahn, 2020; Wang et al., 2023). Substituting private cars or taxis by SES can significantly reduce carbon emissions for trips. Conversely, if SES substitutes transport modes such as walking, private bikes, and public transport, it may increase carbon emissions. This is because the life-cycle emission (i.e., the estimated emission per km per passenger based on a life-cycle assessment) of SES could be higher than these transport modes if the life-cycle emissions of SES are considered, including production, operation (e.g., electricity consumption, and the use of trucks for operational activities such as battery swapping and e-scooter

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relocation) and disposals (Li, Gao, Zhao, Qu, & Axhausen, 2021; Luo, Zhang, Gkritza, & Cai, 2021). Existing studies have often relied on simplified assumptions or aggregated-level investigation to estimate the substituted transport modes by SES trips and have not delved into real-world usage patterns to investigate substituted transport modes by SES and corresponding environmental consequences in a high resolution (e.g. trip level) (Abduljabbar, Liyanage, & Dia, 2021; Gebhardt, Ehrenberger, Wolf, & Cyganski, 2022; Kou, Wang, Chiu, & Cai, 2020; Zhou et al., 2023). Therefore, a crucial step in assessing the environmental impacts of SES is the quantitative estimation of how SES replaces other transport modes and the life-cycle emission estimation of SES, grounded in actual usage patterns and diverse travel contexts.

Motivated by the aforementioned challenges of SES, this study aims to estimate the substitutions of SES to other transport modes (including walking, private bike, public transport, private car, and taxi) and corresponding environmental impacts based on field shared e-scooter trip data and data-driven inference methods (instead of surveys). Especially, the proposed method can realize the estimations about replaced transport mode and reduced emission (i.e. CO_{2-eq}) by an SES trip at the individual trip level, leveraging data infusion from multiple resources and travel behavior modeling. This innovative approach considers various parameters such as the starting and ending locations, departure time, and the intricacies of road and public transit networks between the origin and destination of each SES trip. These factors are comprehensively taken into account for the precise estimation of the substituted transport mode and the corresponding emission reduction from each individual SES trip. This granular and trip-level methodology, different from aggregated-level analyses, allows for high-resolution and scalable analysis of the substituted transport mode and environmental impacts of SES in different urban contexts. Using the proposed approach, this study leverages one year of field data from SES trips across three major Swedish cities, Stockholm, Gothenburg, and Malmö to conduct a comprehensive empirical analysis and facilitate cross-city comparisons. The results from these diverse urban environments enable the derivation of quantitative and nuanced insights into the environmental sustainability of SES among different cities in Sweden. The results obtained from this cross-city analysis contribute valuable quantitative support and evidence for the effective and tailored management and planning of SES as well.

The subsequent sections are organized as follows. Section 2 offers an extensive review of existing literature about modal substitution and the environmental impacts of shared micro-mobility. Section 3 presents our dataset and contextualizes the study. The methodology employed in this study is expounded upon in Section 4. The main results and findings are presented and discussed in Section 5 with practical implications. Finally, Section 6 encapsulates the conclusions drawn from this study and potential future work.

2. Literature review

2.1. Impacts of shared micromobility on modal shift

The environmental impact of shared micro-mobility is intrinsically tied to the spatiotemporal usage patterns and the degree to which shared micro-mobility replaces other transport modes (Fishman & Cherry, 2016; Gao, Li, et al., 2023; Kazemzadeh & Sprei, 2024). In the realm of the shared micro-mobility system, comprehensive analyses on bike-sharing systems have been conducted, as evident from a series of reviews that summarized the existing evidence on the substitution impacts of bike sharing (Kroesen, 2017; Reck et al., 2022; Zhou et al., 2023). Yan, Yang, Zhang, Xu, Bejleri, and Zhao (2021) conducted a comparative analysis between public transport and docked non-electric bike sharing using data from Washington, DC. The findings of this study indicated the presence of inter-modal competition and complementarity. Teixeira, Silva, and e Sá (2021) concluded that most trips replaced by bike-sharing systems (including both non-electric and electric bike-sharing) originated from sustainable modes of transport, primarily walking and public transport, and the replacement to private car usage was a less frequent choice. In their comparison of 19 survey-based studies across Australia, China, Europe, and North America, they found that, on average, 10% of respondents replaced car trips with bike-sharing. In contrast, the median value of the percentage of replacing public transport or walking was 70%. Zhou et al. (2023) observed that only about 5% of electric bike-sharing system trips integrated with public transport within a 2 km range substituted car trips. A similar observation was made by Fishman and Cherry (2016). Maas, Attard, and Caruana (2022) investigated the utilization of non-electric bike sharing systems and how bike sharing replaced other transport modes in Limassol (43%, 7% and 12% replacing walking, public transport and cycling, respectively), Las Palmas de Gran Canaria (31%, 28% and 9% replacing walking, public transport and cycling, respectively), and Malta (34%, 18% and 14% replacing walking, public transport and cycling, respectively). Meanwhile, the study employed surveys and statistical analyses to explore the demographic and environmental factors influencing shared bicycle usage, distinguishing between frequent and infrequent users to identify motivators and barriers affecting bike sharing adoption.

Some studies have explored the replacement of shared e-scooters with other transport modes as well. Specifically, Luo et al. (2021) analyzed trip data from Indianapolis to model the degree of overlap between shared e-scooter demand and the public transport system. Their findings indicated that approximately 27% of shared e-scooter trips had the potential to replace public transit trips. At the same time, less than 1% could be considered as potential first-last mile trips using shared e-scooters. Ziedan et al. (2021) employed shared e-scooter data in conjunction with economic data on public transport services in Nashville and Louisville. Their observations showed that introducing shared e-scooters led to a decline in local bus ridership and increased express bus usage. Hence, it could be inferred that the overall impact was negligible and did not significantly contribute to the decrease in bus ridership. Liu and Miller (2022) examined the possibility of shared e-scooters to enhance accessibility based on hypothetical journeys from real-world trips in Columbus, Ohio. Their study revealed that the distribution of accessibility enhancement was uneven across different spatial areas. According to a study in Portland by McQueen and Clifton (2022), survey data indicated that shared e-scooters were not typically preferred over private automobiles in their then-current state. Nevertheless, when a shared e-scooter trip did occur, it was highly likely to replace private car traveling. The two aforementioned studies focused on US cities, and their results diverged from the anticipated outcomes observed in surveys conducted in European contexts, where higher public transit ridership was typically observed before the introduction of shared e-scooters. According to Nawaro (2021) in Europe, shared e-scooters could serve as a complementary mode of transport to public transit in Warsaw. Additionally, studies from France and Norway indicated that about one-third of respondents used shared e-scooters instead of public transit trips. This percentage is considerably higher than that observed in North American cities due to the comparatively lower modal share of public transport in many US cities (Wang et al., 2023).

2.2. Environmental life cycle analysis and impacts of SES

While some studies have focused on the environmental impact of micro-mobility, research explicitly addressing the environmental impacts of shared e-scooters remains limited (Sun & Ertz, 2022). Cherry, Weinert, and Xinmiao (2009) noted that e-bikes in China produce emissions similar to buses, greater than traditional bicycles, but less than motorcycles and cars. Analyzing Swiss data, Bucher, Buffat, Froemelt, and Raubal (2019) deduced that electric bicycles offered current and potential emissions reductions of 10% and 17.5%, respectively, compared to diesel and petrol vehicles. Philips, Anable, and Chatterton

(2022) claimed that e-bikes could reduce car CO_{2-eq} emissions by 24.4 million tonnes in England and would achieve high capability in rural areas. However, Reck, He, Guidon, and Axhausen (2021) argued that shared e-bikes and e-scooters could help spark sustainable mobility transitions in the long term if the usage led to ownership, even though they might increase CO_{2-eq} emissions in the short term.

The study by Hollingsworth et al. (2019) stood as the pioneering investigation that comprehensively assesses the environmental life cycle assessment of shared e-scooters. This study delved into the entire life cycle of shared e-scooters and highlighted potential negative environmental consequences unless significant improvements were made in operational techniques. Notably, their research unveiled that the environmental impact associated with charging e-scooters was relatively minor compared to the environmental costs tied to their raw materials, production, and moving scooters to overnight charging facilities. Furthermore, other transport modes replaced by shared e-scooters exhibited lower greenhouse gas (GHG) emissions over their lifespans than those e-scooters themselves in 65% of their evaluation using Monte Carlo simulation. Results show an average carbon footprint equal to 126 g CO_{2-eq} per passenger-kilometer traveled (pkt) (Hollingsworth et al., 2019). In Brussels, dockless and private e-scooters were evaluated on four midpoint indicators using life cycle assessment and the ReCiPe2016 characterization factors. This assessment found that shared e-scooters emitted 131 g of CO_{2-eq} per passenger kilometer traveled, and private e-scooters emitted 67 g of CO_{2-eq}/pkt (Moreau et al., 2020). Additionally, a separate study conducted in Paris identified lower environmental impacts for both shared and private e-scooters, with emissions of 109 g and approximately 60 g of CO_{2-eq}/pkt, respectively (de Bortoli & Christoforou, 2020). Additionally, life cycle assessments conducted by Christoforou, de Bortoli, Gioldasis, and Seidowsky (2021) and Severengiz, Finke, Schelte, and Wendt (2020) about shared e-scooter systems in Brussels and Berlin, respectively, have highlighted several environmental challenges of shared e-scooters. According to current usage patterns and operational practices, shared e-scooters do not inherently reduce environmental impact compared to the replaced transport modes such as public transit, potentially resulting in more life cycle emissions.

Research on the environmental impacts of shared e-scooter usage remains limited, focusing on different aspects. Zhou et al. (2023) noted that electric bike-sharing systems have led to a 75.52% decrease in CO_{2-eq} emissions compared to other transport modes. Gebhardt et al. (2022) found that replacing 13% of daily car trips in Germany with shared e-scooters could reduce CO_{2-eq} emissions by up to 5.8 kt daily. However, Reck et al. (2022) identified an opposing trend where shared e-bikes and e-scooters emitted more CO_{2-eq} than the transport modes they replaced in Zurich, unlike personal e-bikes and e-scooters. This implies that, in the short term and present conditions, only personal e-bikes and e-scooters aid in achieving environment benefits. At the same time, their shared counterparts increase CO_{2-eq} emissions (Reck et al., 2022). Papaix, Eranova, and Zhou (2023) also pointed out that while the growing popularity of shared e-scooters may enhance road equity by improving accessibility, developing and frequently rebalancing these systems might introduce other negative environmental effects.

2.3. Research gap

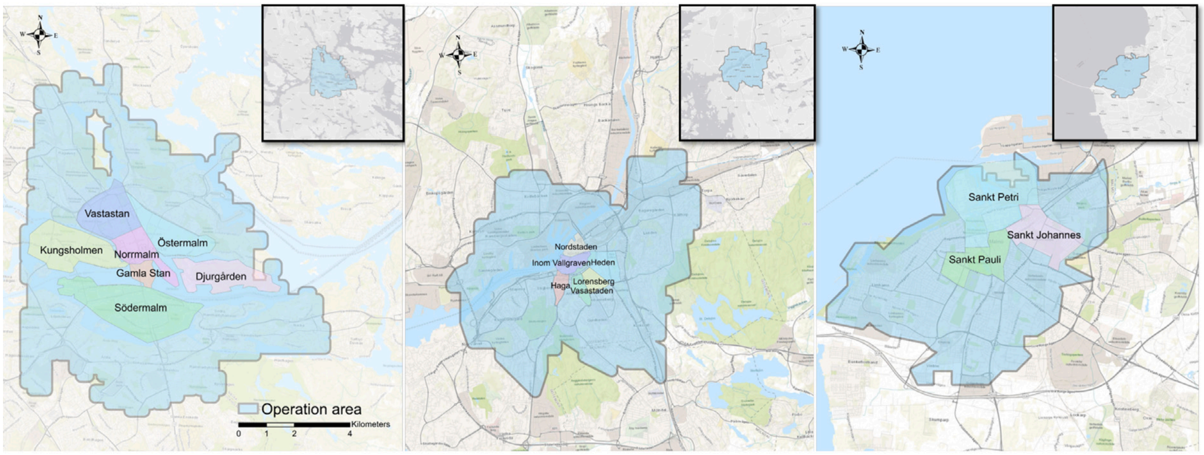
The modal shift and environmental consequences of non-electric bike-sharing system and privately owned e-bikes have been extensively discussed in the studies mentioned. However, the SES has received limited attention. The findings about non-electric bike sharing may be inapplicable to the SES for the following reasons. First, e-scooters are more powerful and faster than standard bikes, allowing them to be utilized on longer trips and mountainous routes. Second, while non-electric bicycles leverage human effort predominantly, stand-up shared electric scooters rely mainly on electricity and have higher production emissions. This can result in higher greenhouse gas emissions in terms of energy consumption and life cycle emissions of SES. Third, the SES has a higher price than non-electric bike sharing, indicating that it may serve different users and usage patterns. Meanwhile, unlike privately owned e-bikes, SES customers do not have significant upfront expenses or concerns about parking and charging issues, making the SES appealing to individuals who cannot manage private e-bikes. Because of these differences, the modal shift impact and environmental effects of the SES may differ from that of the non-electric bike sharing and privately owned e-bikes. A thorough assessment of the environmental impact of SES necessitates using real-world data in actual operational contexts.

From the perspective of analysis methods, most existing studies used surveys to get the average substitutions of SES to other transport modes based on small samples. They extrapolated the results to all trips, which is not precise. The likelihood of an SES trip substituting a specific transport mode is inherently trip-specific, contingent upon various characteristics such as origin, destination, time, road structure, and transit networks. As a result, the conventional analysis paradigm, which relies on aggregated-level substitution rates, may not accurately capture the intricacies of these trip-specific dynamics. To quantify the impacts of SES precisely, there is a need to transition towards a more high-resolution approach considering trip-level substitution rates. Therefore, this study will present a quantitative analysis of the modal substitution and environmental impacts of SES based on trip-level analysis and field big data from three different cities in Sweden.

3. Data

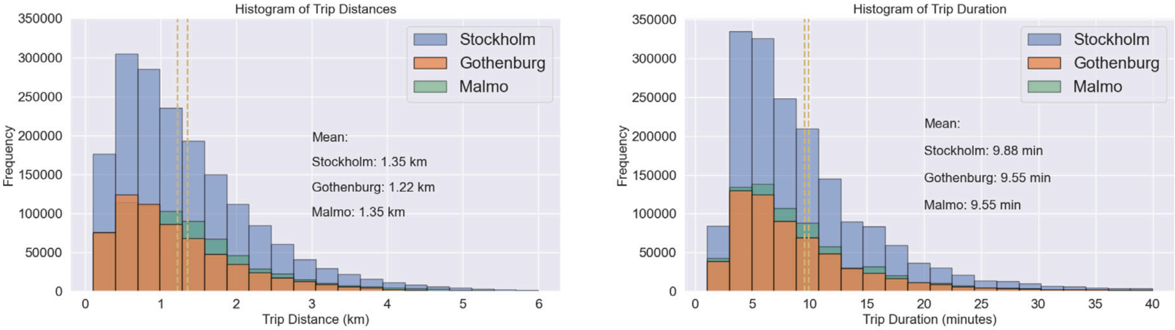
This study focuses on the three largest cities in Sweden, namely Stockholm, Gothenburg, and Malmö, all of which have well-established public transit systems. Sweden positioned itself as an early adopter of SES services, with VOI and TIER initiating commercial operations in May 2019 (Aarhaug, Fearnley, & Johnsson, 2023). The selection of these cities for our research is underpinned by their status as the three largest cities in Sweden and the availability of readily accessible data, which facilitates our investigation. The municipal area of three Swedish cities and the operation area of shared e-scooters system are demonstrated in Fig. 1. A noteworthy characteristic of these cities is their extensive public transport, as illustrated by the public transport seat kilometers metric. This metric refers to the annual calculation of the product of the number of seats and the distance that these seats are offered per person, which serves as a measure of capacity in public transport. Higher seat kilometers suggest a higher level of service in public transport. In 2015, Gothenburg had a capacity of 9376 seat kilometers, Stockholm 8294, and Malmö 5837 (Kenworthy, 2020).

Our dataset encompasses trip data for shared e-scooters from 1 January to 31 December 2022, sourced from TIER and VOI. Each trip record includes detailed trip information, such as the coordinates (longitude and latitude) and timestamps of the starting and ending points of the trip when the user started and ended using SES in the application software of SES. Based on the starting and ending locations (i.e., coordinates) of each SES trip, we calculate the shortest route of using SES for the trip using the OpenTripPlanner open-source multimodal routing engine (Morgan, Young, Lovelace, & Hama, 2019), and then determine the average speed for each trip by the route distance and trip duration recorded in transaction data. Due to inconsistencies and potential technical errors in GPS measurements, some trips are identified with unrealistic attributes, such as excessively long distances or unusually high or low speeds, which may not accurately reflect actual trips. For example, some users utilize e-scooter sharing for multiple trips in a row and “loop” trips (e.g. going to shop from home and return to home) without ending the trips in the application software of SES. These trips will affect our estimation about replaced transport modes and corresponding emission reduction estimation. Therefore, we focus on trips without stops during a journey using SES. To ensure the reliability of SES trips used in our analysis, we implement specific criteria below to filter out these outliers:



a) Stockholm b) Gothenburg c) Malmö

Fig. 1. Research area of three Swedish cities.



(a) Trip distance

(b) Trip duration

Fig. 2. Descriptive statistics about SES trips in Stockholm, Gothenburg, and Malmö.

(1) We exclude trips with average trip speed lower than 2 km/h (0.556 m/s) to filter out potential outliers such as 'loop' trips and slow-moving trips that do not refer to regular trips without stops.

(2) The trip duration must range from a minimum of 1 min to a maximum of 1 h.

(3) The distance between the starting and end points must fall within a range of at least 0.1 to a maximum of 20 kilometers.

(4) The average speed should not exceed 20 kilometers per hour. This is the speed limitation of SES in Sweden.

Based on the outlier criteria, 76,773 (4.20%), 15,877 (2.45%), and 26,230 (3.54%) trips were eliminated in Stockholm, Gothenburg, and Malmö, respectively. The finally used dataset includes 1,752,237 trip transactions in Stockholm, 630,896 in Gothenburg, and 714,378 in Malmö in 2022. The data indicates the presence of 8889 e-scooters in Stockholm, 5840 in Gothenburg, and 5730 in Malmö. The average usage frequency per e-scooter in Stockholm is the highest and nearly twice that in Gothenburg and Malmö. The distance distributions of SES trips are illustrated in Fig. 2(a) and reveal right-skewed distribution across all three cities. The mean trip distances are 1.35 km, 1.22 km, and 1.35 km for Stockholm, Gothenburg, and Malmö, respectively. Fig. 2(b) presents the trip duration distributions. Stockholm, Gothenburg, and Malmö exhibit similar trends and mean trip duration of 9.88, 9.55 and 9.55 min, respectively. It is noted that SES in Gothenburg exhibits the lowest average trip speed, which may be attributed to distinctive topography and significant elevation variations in Gothenburg.

4. Methodology

The fundamental step of evaluating the environmental impacts of SES is determining the specific transport mode that each SES trip replaces. The environmental impacts of an SES trip could be measured by the difference between the emissions from using SES and the emissions from using alternative transport modes for the same trip if SES was not to exist. To estimate the replaced transport mode by a specific SES trip, it is imperative to obtain information about other feasible transport mode alternatives for the same trip, considering starting and ending locations and starting timestamps. This is indispensable information to infer the specific transport mode that the user would utilize for the same trip in the hypothetical scenario where the SES was not existing. The environmental impacts of SES within a geographical area can be expressed through the cumulative emission reduction in stemming from SES trips within that locale. Fig. 3 delineates the schematic representation of the analytical framework designed for evaluating the environmental impacts of SES. This framework comprises three steps: extraction of trip-specific information, estimation of trip-specific mode substitution, and evaluation of GHG emission reductions due to each SES trip.

4.1. Extraction of trip-specific information of alternative modes for each SES trip

A crucial aspect of our analytical framework involves estimating the transport mode replaced by an SES trip. To achieve this objective, it

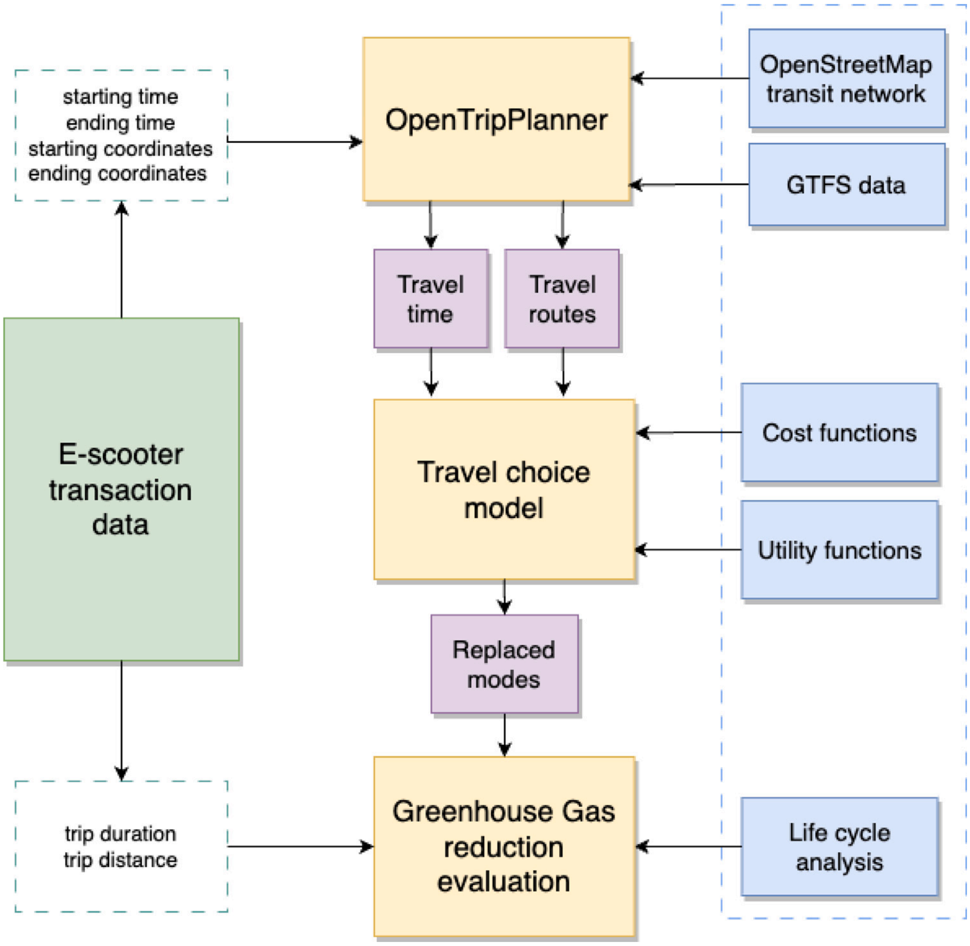


Fig. 3. Flowchart of the analytic framework.

is imperative to extract information regarding the feasible transport modes and their associated level-of-service attributes, such as travel time and cost. This depends upon a lot of factors including the starting location, ending location, departure timestamp, and the intricacies of road and public transit networks between the origin and destination of a particular SES trip.

In our dataset, each record includes the starting coordinates, ending coordinates, and departure time of an SES trip. Leveraging this information, we employ the OpenTripPlanner (OTP) open-source multi-modal routing engine (Morgan et al., 2019). OTP utilizes the road network data from OpenStreetMap and General Transit Feedback Specifications (GTFS) data as inputs to derive routes for various transport modes. This approach has been validated in prior studies (Liao, Gil, Pereira, Yeh, & Verendel, 2020; Stewart, 2017). Specifically, based on the starting and ending coordinates and the departure time of an SES trip, OTP is utilized to identify the optimal routes of using different transport modes: walking, private bike, public transit (PT, bus or tram), private car, and taxi. The extracted information encompasses travel time and distance details for a trip using walking, biking, public transit, private cars, and taxis, accounting for the actual public transport schedules and road networks. The total travel time of public transit is segmented into four distinct periods: the walking time to the PT station, the waiting time at the station, the time spent inside PT, and the walking time from the PT station to the final destination. Therefore, the “travel time of public transit” in this study denotes the total travel time of a public transport trip. Furthermore, we retained the travel distance associated with PT, which is crucial for emission estimation in Section 4.3. The public transport service, such as timetables, differ between workday and non-workday, as reflected by GTFS data. The variation is also considered in the analysis.

Utilizing the travel time, distance, and specific route data associated with each transport mode for a trip. We conduct a detailed calculation of the travel costs of using the transport in the cities of Stockholm, Gothenburg, and Malmö. This is achieved by incorporating the standardized fares for public transit, the operational costs for private vehicles, and the tariff rates for taxis within Sweden. The resultant calculation of travel expenses reflects an approach tailored to these three Swedish cities. For example, a single public transport (Västtrafik) ticket is 35 SEK and valid for 90 min. For each SES trip recorded in our data, we extract the trip-specific information of alternative transport modes and their attributes, which will be utilized in the next step of inferring the replaced transport mode by an SES trip.

4.2. Estimation of trip-specific mode substitution of SES

The replaced transport mode by an SES trip is defined as the mode that the travelers would use for the same trip (in terms of similar departure time, starting and ending coordinates) if the SES did not exist. Our study considers five modes that SES could potentially replace. Based on the trip-specific information extracted in 4.1, we make the best of a mode choice model building on discrete choice theory to infer which transport mode would be chosen if there was no SES for a trip (namely the replaced transport mode by an SES trip). In particular, we select a multinomial logit model (MNL) (McFadden et al., 1973) for analysis, a widely used travel choice modeling in transport research. Let $M_i (i = 1, 2, 3, 4 \text{ or } 5)$ represent available transport modes for a trip if SES did not exist, including walking, private bike, PT, private cars, and taxis. In this study, shared e-bikes are not considered due to their limited availability in Stockholm and the complete absence

Table 1
Variables in the utility function.

Variable	Parameter	Description
ASC	Constant value	Alternative specific constant
$distance$	Distance	Trip distance(in 10 km)
$time_{PT}$	Public transport time	Total travel time of public transport
$cost_{PT}$	Public transport cost	Total travel cost of public transport
$time_{car}$	Car time	Total travel time of private car
$cost_{car}$	Car cost	Total travel cost of private car
$time_{taxi}$	Taxi time	Total travel time of taxi
$cost_{taxi}$	Taxi cost	Total travel cost of taxi
I_{inner}	Inner city location	1 if located in inner city, otherwise 0
I_{PTcard}	Public transit card	1 if possessing PT card, otherwise 0
I_{car_male}	Male	1 if male, otherwise 0
I_{car_lic}	Driving license	1 if having driving license, otherwise 0
I_{car_acc}	Car ownership	1 if owning a car, otherwise 0

in Gothenburg and Malmö in 2022. P_{M_i} is defined as the probability of choosing transport mode M_i for the trip given the level-of-service attributes and other factors of different transport modes if SES was not to exist. P_{M_i} that we estimate for a specific SES trip denotes the likelihood of the SES trip replacing transport mode M_i for this trip. It should be noted that if the trip distance of an SES trip is less than 300 m, we assume that the SES trip replaced walking. Only for SES trips with a trip distance greater than 300 m, we use the following MNL model to estimate replaced transport modes by SES. This is to avoid potential biases of using MNL for very short trips (Gao, Yang, Li, Li, & Yu, 2021).

In the MNL model, the utility of choosing a specific transport mode M_i for a trip denoted as U_{M_i} is calculated by a function of attributes of transport mode M_i and other influencing factors. Referring to a study and calibrated MNL model in the Stockholm (Bai, Li, & Sun, 2017), we define the utility function of a transport mode as shown in Eqs. (1)–(6) comprising three distinct parts. The first part includes the level-of-service attributes of a transport mode for a trip, including travel time, distance, and cost extracted in Section 4.1. The second part considers socio-economic, area, and car ownership factors, which are also essential factors affecting mode choice. The third part is the alternative-specific constants (ASC) for different transport modes, representing the effects of unobserved preferences or other factors. The definitions and meanings of factors and corresponding terms are summarized in Table 1.

$$U_{walk} = \beta_{walk\_distance} \cdot distance + ASC_{walk} \tag{1}$$

$$U_{bike} = \beta_{bike\_distance} \cdot distance + ASC_{bike} \tag{2}$$

$$U_{PT} = \beta_{time\_PT} \cdot time_{PT} + \beta_{PT\_cost} \cdot cost_{PT} + \beta_{inner} \cdot I_{inner} + \beta_{PTcard} \cdot I_{PT\_card} \tag{3}$$

$$U_{car} = \beta_{car\_time} \cdot time_{time} + \beta_{car\_cost} \cdot cost_{car} + \beta_{lic} \cdot I_{lic} \tag{4}$$

$$+ \beta_{male} \cdot I_{male} + \beta_{acc} \cdot I_{acc} + ASC_{car} \tag{5}$$

$$U_{taxi} = \beta_{taxi\_time} \cdot time_{taxi} + \beta_{taxi\_cost} \cdot cost_{taxi} + \beta_{male} \cdot I_{male} + ASC_{taxi} \tag{6}$$

After calculating utilities of using transport mode M_i for a specific trip, the probability of choosing transport mode M_i is estimated using the MNL model in Eq. (7). The model coefficients in our analysis are derived from the work of Bai et al. (2017), calibrated through empirical survey data collected in Stockholm. These used coefficients are summarized in Table 2. We employ the MNL model for each recorded SES trip to estimate the probability of choosing transport mode M_i in the hypothetical scenario where SES did not exist. This estimation allows us to infer the replaced transport mode for a given SES trip.

$$P_{M_i} = \frac{e^{AV_{M_i} \times U_{M_i}}}{\sum_{i=1}^{5} e^{AV_{M_i} \times U_{M_i}}} \tag{7}$$

$$\sum_{i=1}^{5} P_{M_i} = 1 \tag{8}$$

Table 2
Parameters in utility functions.

Parameter	Estimate	*t*-value	Parameter	Estimate	*t*-value
ASC_{walk}	2.01	6.14	ASC_{bike}	0.71	3.02
ASC_{car}	−0.786	−2.81	ASC_{taxi}	−0.786	−2.81
$\beta_{walk\_distance}$	−9.18	−14.9	β_{PT_card}	3.18	35.2
$\beta_{bike\_distance}$	−2.19	−14.9	β_{car_male}	0.253	3.68
β_{PT_time}	−1.38	−5.66	β_{car_lic}	0.575	4.00
β_{PT_cost}	−0.0388	−4.97	β_{car_acc}	1.77	15.9
β_{car_time}	−0.0309	−5.65	β_{taxi_time}	−0.0309	−5.65
β_{car_cost}	−0.482	−6.53	β_{taxi_cost}	−0.482	−6.53

where AV_{M_i} denotes the availability of transport mode M_i for a trip. $AV_{M_i} = 1$ and $AV_{M_i} = 0$ mean the transport mode is available and not available, respectively. OTP obtains the availability of public transit in 4.1 according to GTFS. The availability of taxis and walking is set to be 1, namely always available.

The availability of private cars and bikes for a trip is determined by statistics in Sweden and Mote Carlo Simulation techniques. The percentages of private car ownership in Stockholm, Gothenburg, and Malmö are 0.199, 0.26, and 0.27, respectively, according to government statistics data from Transport Analysis (Trafa) in Sweden (Trafikverket, 2021). Taking advantage of the information, we use the Monte Carlo Simulation technique to generate a random number in the range [0,1] based on the Bernoulli distribution for each record SES trip in Stockholm. If the random number falls in [0,0.199], the availability of a car for the trip is set to 1 for the trip; otherwise, it is set to 0. The same technique is used to obtain the availability of private cars and bikes for a trip. Moreover, our analysis accounts for several additional factors, including gender, whether the trip occurred within central urban areas, and whether the traveler possesses a public transit card. These factors are recognized to influence mode choice behavior and thus the replacement of transport mode by an SES trip. For example, individuals possessing a public transit period ticket (monthly or yearly) might be more inclined to use public transport if SES were not available. However, obtaining information on whether a traveler has a public transit period ticket for a specific trip is highly challenging (if not impossible). To address these complexities, we employ Monte Carlo Simulation techniques, guided by Swedish statistics as detailed in Table 3. It is crucial to note that while Monte Carlo methods do not guarantee precision for individual trips, their efficacy is demonstrated through aggregation over a substantial number of trips. Inferring the availability of private car and private bike for a trip based on ownership statistics is not perfect but the best solution for data-driven analysis in this study due to data limitation. Importantly, compared to studies that entirely overlook the effects of these factors, the utilization of Monte Carlo methods to account for the influences of availability, gender, trip location, and public transit card possession represents an enhancement. This approach has also been employed in relevant studies (Hollingsworth et al., 2019; Zhou et al., 2023).

4.3. Evaluation of GHG emission reductions

As previously outlined, quantifying GHG emission reductions resulting from an SES trip involves calculating the difference in GHG emissions between using SES and other transport mode for the same trip in the absence of SES. The life-cycle analysis approach is employed to assess the GHG emission factors associated with using a particular transport mode. This approach considers emissions throughout various phases of the life cycle, including production, operation, and disposal. The emission factor, expressed in CO_{2-eq} per passenger per kilometer, serves as a standardized metric linking the quantity of GHG emissions (equivalent CO_2) from a specific transport mode to the emissions of a corresponding trip using that transport mode (Chen, Cai, Zhou, Chen, Wan, & Li, 2023; Li et al., 2021). The emission factors of different

Table 3
Inputs for Monte Carlo simulations.

Parameter	Scale	Distribution	Reference
I_{inner}	1	Constant	Geofencing of VOI and TIER
I_{PTcard}	$p = 0.5$	Bernoulli distribution	Estimated
I_{car_male}	$p = 0.50$	Bernoulli distribution	Statistics Sweden[a]
I_{car_lic}	$p = 0.78$	Bernoulli distribution	Trafa of Sweden[b]
I_{car_acc}	$p_{stockholm} = 0.199$ $p_{goteborg} = 0.260$ $p_{Malmö} = 0.270$	Bernoulli distribution	Trafa of Sweden

[a] Statistics Sweden (2024).

[b] Trafikverket (2021).

Table 4
Life-cycle CO_{2-eq} emission factors for different transport modes (CO_{2-eq} gram per passenger-kilometer).

Emission factors	Walking	Bike	PT	Private car	Taxi	Shared e-scooter
Production	0	18.75	7.14	29.45	29.45	35
Operation	0	18.3	8.09	131.25	131.25	32.1
Total emission	0	37.05	16.04	160.7	160.7	67.1

transport modes are determined referring to a study conducted in London (Cottell, Connelly, & Harding, 2021). Table 4 summarizes the adopted emission factors per passenger-kilometer. As walking does not involve any vehicular transport, its emission factor is designated as zero.

Let k_{M_i}(where $i = 1, 2, 3, 4, 5$) denotes the emission factor for transport mode M_i. The formula for calculated CO_{2-eq} E_{M_i} for a specific transport mode M_i of a trip with distance of d_{M_i} is given by

$$E_{M_i} = k_{M_i} \times d_{M_i} \tag{9}$$

In 4.2, we can obtain the probabilities of using different transport modes for a recorded SES trip if there was no SES. Using emission factors of different transport modes, we can calculate the estimated expected average CO_{2-eq} of using other transport modes E_{A_j} for the same trip of a recorded SES trip in the scenario where SES did not exist using Eq. (10).

$$E_{A_j} = \sum_{i=1}^{5} (E_{M_{ij}} \times P_{M_{ij}}) \tag{10}$$

where j is the index of an SES trip. Subsequently, calculating the GHG emission associated with using SES for the recorded SES trip becomes straightforward by multiplying the emission factor k_{SES} with the trip distance d_{SES} of using SES for the trip

$$E_{SES_j} = k_{SES_j} \times d_{SES_j} \tag{11}$$

Finally, the emission reduction E_{r_j} attributed to the SES trip j is quantified by the difference between the GHG emissions that would occur in a scenario without SES and the emissions of using SES for the same trip.

$$E_{r_j} = E_{A_j} - E_{SES_j} \tag{12}$$

Please note that Eqs. (8)–(10) are employed to compute the expected value of emission reduction resulting from a Shared Electric Scooter (SES) trip using a probabilistic approach. The rationale for adopting this methodology lies in our intent to ascertain the mean emission reduction for an SES trip when it is hypothetically repeated multiple times (e.g., 500 times). This approach is particularly pertinent given that our dataset encompasses only one-year data across three Swedish cities. Although this dataset is representative, it does not span multiple years to capture varying annual conditions. By employing a probabilistic framework, we aim to illuminate the systemic impacts of SES usage, incorporating life-cycle emission factors into our analysis. Thus, the expected value of emission reduction for an SES trip quantifies the average emission reduction per trip, assuming the identical SES trip is conducted repeatedly. We use the proposed framework for each recorded trip using SES in our data to estimate its impacts in reducing GHG emissions measured by CO_{2-eq}. By aggregating the data in one city or area in that city, we can have overviews of the environmental impacts of SES in a particular urban context. More importantly, the approach used is trip-specific analysis, and it can analyze the environmental impacts of SES from both spatial and temporal dimensions in different resolutions per different research aims.

5. Result and discussions

5.1. Substitution of SES to other transport modes

Fig. 4 summarizes the average percentages of SES trips replacing other transport modes. Based on the proposed methods, we can estimate the probability of every SES trip replacing another transport mode (e.g., walking), and the result in Fig. 4 denotes the average value of the results across all trips in a city. The average percentages of SES trips in Stockholm substituting walking, biking, PT, private car, and taxi are 43.44%, 4.60%, 43.29%, 6.81%, and 1.85%, respectively. Most SES trips (over 80%) in Stockholm are estimated to replace walking and public transit. The high probability of SES replacing walking in Stockholm (43.44%) may be ascribed to the short distances of SES trips as illustrated in Fig. 2(a) and the convenience of walking infrastructure. 43.29% of SES trips are found to replace public transit, but a very low probability of replacing taxi (1.85%) is found, which may be ascribed to the high expense of taking taxis and short distances of SES trips. It is estimated that 6.81% SES trips were substituting private cars, while only 4.60% of SES trips are estimated to replace private bikes. The results in Malmö are very similar to those in Stockholm. Nevertheless, the probabilities of SES trips replacing public transit and private cars in Gothenburg are larger and smaller, respectively, compared to Stockholm and Malmö.

Fig. 5(a) illustrates that roughly 54.5% of SES trips in Stockholm of distances less than 500 meters replace walking. A similar pattern is noted in Gothenburg (50.6%) and Malmö (48.8%). As trip distances increase, we can observe a reduced likelihood of SES substituting walking. This pattern is accompanied by a surge in the likelihood of SES replacing PT with increasing trip distance. Yet, the likelihood of replacing walking drastically drops when distances exceed 2 kilometers. This is easily understandable as users would like to take other transport modes (e.g., PT) for longer distance trips (especially more than 2 kilometers), which are not walking-friendly anymore. The patterns in the three cities are very similar. Another common finding across the three cities is that the likelihood of SES trips replacing walking at a certain trip distance varies significantly. This is reasonable as the likelihood of replacing walking relates to the availability and convenience of other transport modes (e.g., level of service attributes of PT). Different

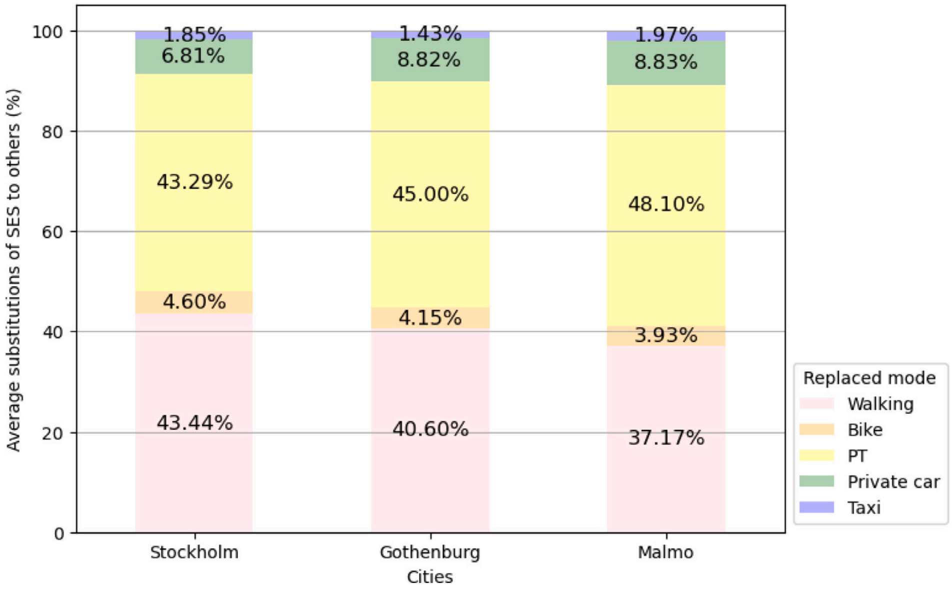
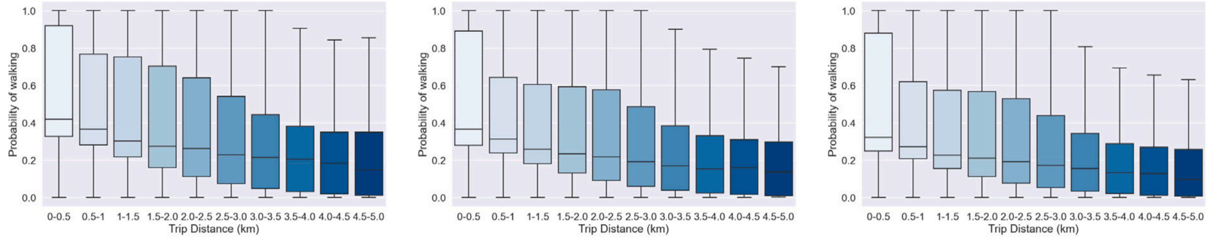
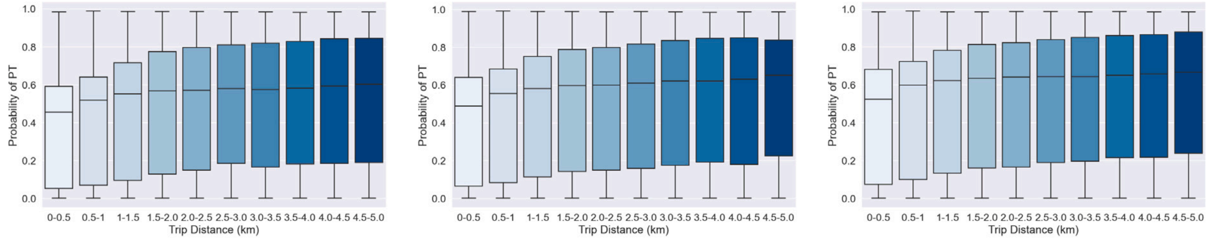


Fig. 4. The probabilities of SES trips replacing other transport modes in three cities.



(a) Stockholm (b) Gothenburg (c) Malmö

Fig. 5. The relation of distance and substitution likelihood of SES to walking.



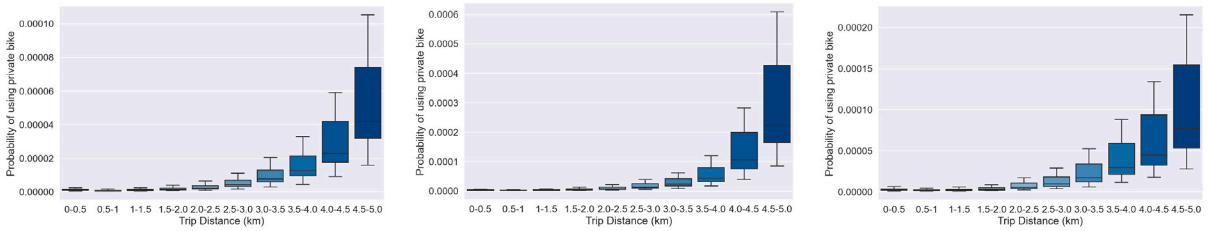
(a) Stockholm (b) Gothenburg (c) Malmö

Fig. 6. The relation of distance and substitution likelihood of SES to PT.

SES trips have different origins, destinations, and departure times and thus have distinctions in availability and convenience of using other transport modes for the same trip. This indicates that the likelihood of SES substituting walking is trip-specific, highlighting merit and superiority of our proposed method compared to aggregated analysis.

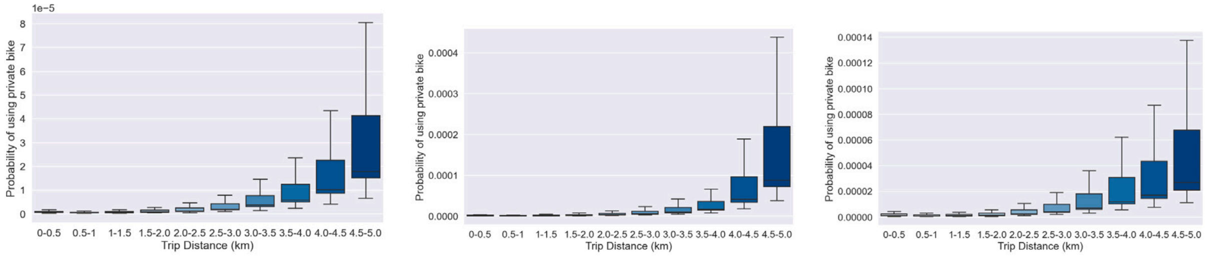
Within the 500-m distance range, 35.1% of SES trips replace PT usage in Stockholm, which is lower than those in Malmö (39.6%) and Gothenburg (37.7%), as shown in Fig. 6. Besides, for trips exceeding 4 kilometers, the substitution of SES to PT in Stockholm is still the lowest among the three cities. With trip distance increasing, the likelihood of SES substituting PT increases in all three cities. This is reasonable as walking is unsuitable for long-distance trips, so a higher proportion of users would use PT for long-distance trips instead of walking. A finding is that the substitution of public transport by shared e-scooters in Gothenburg and Malmö is more pronounced than in Stockholm, suggesting that shared e-scooters were replacing a greater proportion of PT trips in the two cities compared to Stockholm.

Fig. 7 shows that, in Stockholm, the average substitution of SES to private car incrementally rises from 5.4% to 8.9% as the trip distance extends to 5 kilometers. Similarly, the substitution for private cars in Gothenburg increased from 7.2% to 12.7%, while in Malmö, it grew from 7.1% to 11.8% with increasing trip distance. Similar patterns can be found for substituting SES for private bikes in Fig. 8. The substitution rate to bike rises from 3.7% to 5.2% in Stockholm, 3.4% to 4.7% in Gothenburg, and 3.2% to 4.2% in Malmö. The substitutions to taxis also increase with trip distance but are not notable due to the low likelihood that SES replaces taxi trips as shown in Fig. 9. The substitution of SES for taxi varies, ranging from 1.2% to 6.2% in Stockholm, 1.0%



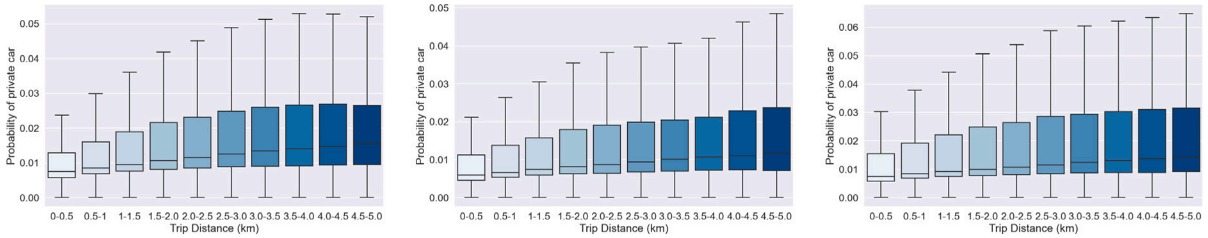
(a) Stockholm (b) Gothenburg (c) Malmö

Fig. 7. The relation of distance and substitution likelihood of SES to private car.



(a) Stockholm (b) Gothenburg (c) Malmö

Fig. 8. The relation of distance and substitution likelihood of SES to bike.



(a) Stockholm (b) Gothenburg (c) Malmö

Fig. 9. The relation of distance and substitution likelihood of SES to taxi.

to 4.9% in Gothenburg, and 1.3% to 5.3% in Malmö. It has been observed that the substitution effect for private cars is correlated with the availability of private cars, as determined through Monte Carlo simulation. We conducted a sensitivity analysis to assess their impact. The sensitivity analysis revealed that changes in the availability of cars and bikes exert a relatively minor influence on the outcomes. Specifically, a 50% alteration in the availability of cars leads to an approximate 12% relative change in substitution of SES to car, while a similar 50% change in bike availability results in about a 28% relative change in substitution of SES to private bike. However, given the overall low availability probability associated with both bikes and cars, these factors are deemed to not have significant effect on the overall results. The primary reason may be that the travel distances associated with e-scooter trips significantly limit the likelihood of replacing cars.

The results highlight the intricate variations in substitution of SES to other transport modes with trip characteristics such as distance, origins, and destinations. This necessitates the trip-level analysis to have reliable and high-solution insights about substitutions of SES to other transport modes, compared to the aggregated-level analysis based on surveys.

5.2. GHG emissions reductions from SES

Fig. 10 and Table 5 encapsulate the average reduction in GHG emissions per trip (EM_i), expressed in equivalent CO_{2-eq} units, arising from SES trips in Stockholm, Gothenburg, and Malmö. The positive values in Fig. 10 denote that SES trips contribute to a decrease in CO_{2-eq} emissions in comparison to the substituted transport mode for the same trip in the hypothetical scenario wherein SES was not to exist. Oppositely, negative values represent SES trips increasing in CO_{2-eq} emissions. On average, SES trips in Stockholm, Gothenburg, and Malmö increase CO_{2-eq} emissions by 34.58 g, 21.18 g, and 24.07 g per trip, respectively. This observation suggests that SES is not anticipated to yield a reduction in CO_{2-eq} emissions in these cities. These results can be attributed to the comparatively higher life-cycle emission factors associated with SES in contrast to other sustainable transport modes (such as walking, cycling, and public transit) and the large likelihood of SES substituting these transport modes, as indicated in Fig. 4. The average daily number of trips in our data from Tier and VOI in Stockholm, Gothenburg, and Malmö, were 8343, 3004, and 3277, respectively. Tier and VOI took about 35% of the SES market in the three cities (Miljöbarometern, 2023; Skoog, 2023), so it can be approximately inferred that the daily demand of SES in the three cities are 23837, 8583, and 9363, respectively. At the aggregated level considering the number of SES trips, the estimated environmental impacts of SES in Stockholm, Gothenburg, and Malmö are increases of 300.86 t, 66.35 t and 82.26 t CO_{2-eq} per year (365 days), respectively.

Nevertheless, it is noteworthy that a subset of SES trips yield positive effects in reducing CO_{2-eq} emissions. In Stockholm, 19.20% of SES trips result in CO_{2-eq} emission reduction, and the numbers are 24.22% and 23.94% in Gothenburg and Malmö, respectively. The substantial variation in trip-level CO_{2-eq} emission reductions exist,

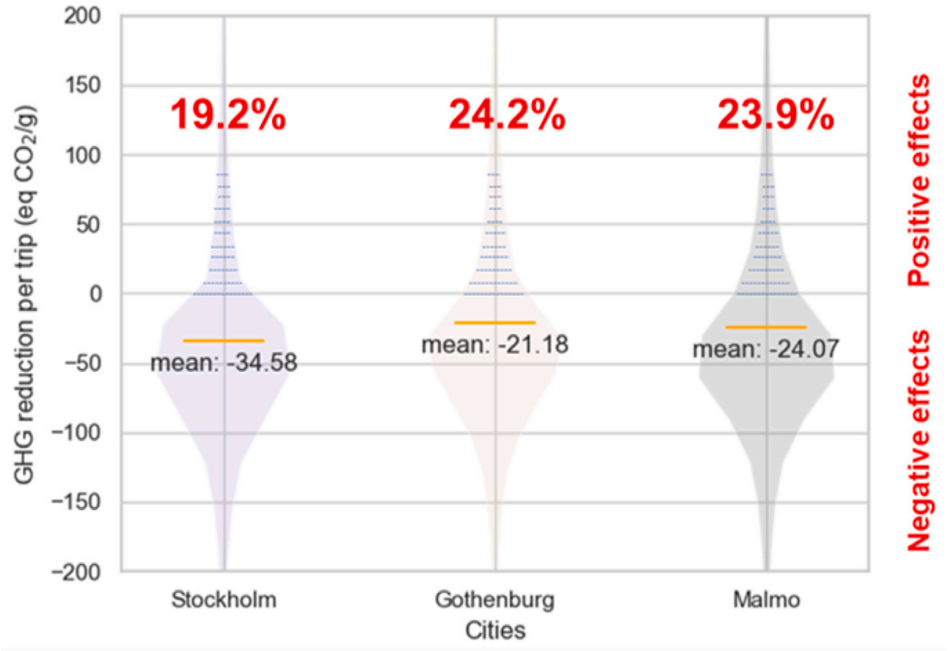


Fig. 10. CO_2 reduction per SES trip (g).

Table 5
GHG emission reduction from SES trips.

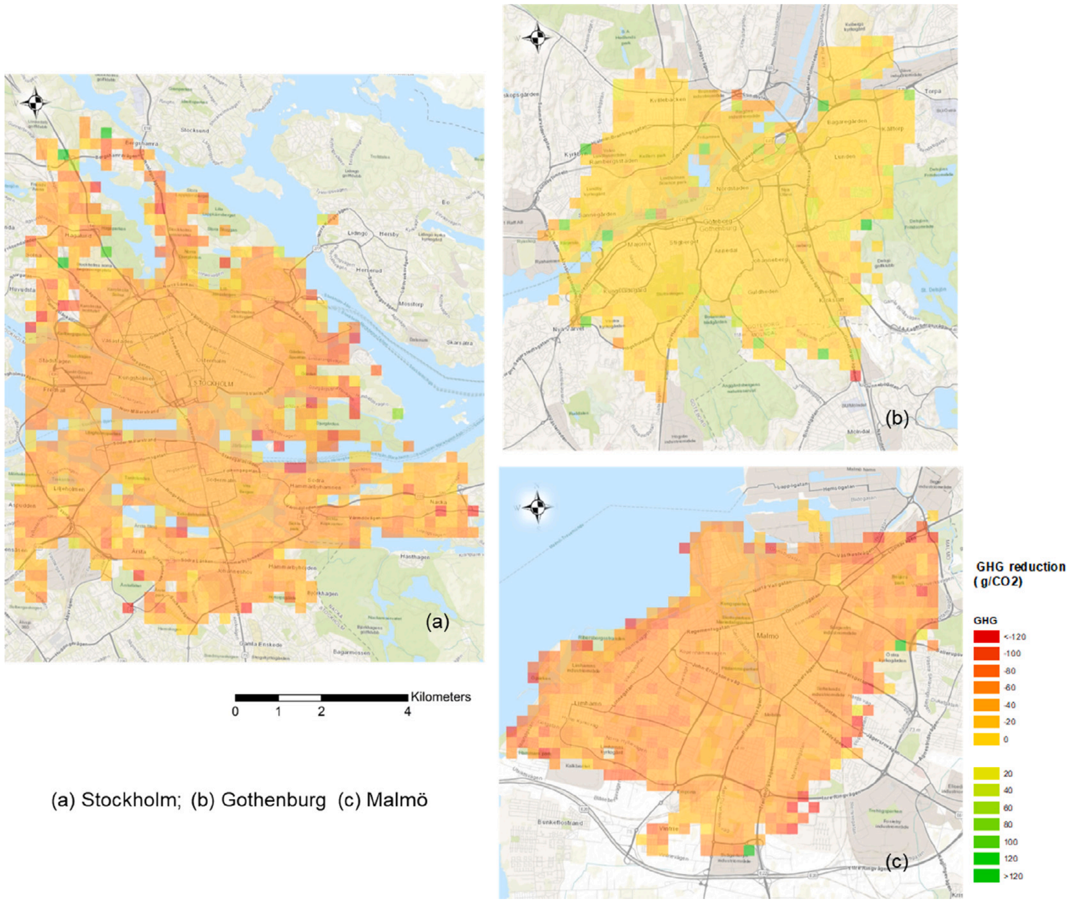
GHG reduction (CO_2-eq g per day)	Trip level			Grid level (avg.)			Grid level (aggregated)		
Cities	Stockholm	Gothenburg	Malmö	Stockholm	Gothenburg	Malmö	Stockholm	Gothenburg	Malmö
No. of trips/zones	1 752 237	630 896	714 378	1047	695	740	1047	695	740
Daily trips (avg)	8343	3004	3277	–	–	–	–	–	–
Mean	−34.58	−21.18	−24.07	−37.01	−24.71	−29.57	−158.57	−52.67	−63.66
Std	106.91	109.69	114.06	61.35	43.71	21.49	284.62	88.59	110.19
Min	−1442.58	−971.94	−1216.91	−424.20	−294.11	−208.77	−2409.43	−906.23	−1012.04
25%	−81.98	−72.82	−75.61	−50.80	−35.34	−33.89	−200.05	−62.67	−73.72
50%	−46.90	−39.09	−42.20	−37.38	−24.00	−25.97	−39.71	−19.64	−21.36
75%	−14.68	−2.52	−3.24	−27.12	−16.46	−21.37	−1.23	−3.99	−5.18
Max	1825.86	1412.21	1795.12	682.62	409.90	105.59	2.53	13.11	3.22
Positive impact	19.20%	24.22%	23.94%	8.30%	7.48%	2.02%	8.30%	7.48%	2.02%
Negative impact	80.80%	75.78%	76.51%	91.70%	92.52%	97.98%	91.70%	92.52%	97.98%

as depicted in Fig. 10 and outlined in the statistical summary in Table 5. This is evident through large standard deviations of 106.91, 109.69, and 114.06 in Stockholm, Gothenburg, and Malmö, respectively. The variability in CO_{2-eq} emission reduction from an SES trip is contingent upon factors such as the substituted transport mode and trip-specific characteristics (e.g., distance). These characteristics exhibit considerable diversity across trips with varying origins, destinations, and starting timestamps in different urban contexts with distinct road and public transit networks. Moreover, the observed large variation in the reduction of CO_{2-eq} emissions underscores the need for a trip-level analytical approach, a key aspect of our proposed methodology. Previous methodologies in the literature primarily rely on aggregated-level analyses such as surveys, and lack the granularity to consider trip-specific information. Consequently, they cannot unveil the nuanced environmental impacts of SES at the trip level.

5.3. Spatial variation in environmental impact of SES

To evaluate the spatial variations in the environmental impact of SES across diverse urban contexts, we partition the study area into rectangular analysis zones of 250 × 250 meters. Within each zone, we compute the average $CO2 - eq$ emission reduction per trip for all trips originating from that zone, a value that is reported in the column labeled "Grid level avg.". This metric enables an assessment of the average $CO2 - eq$ emission reduction per trip that is comparable across various zones, shedding light on emission disparities across different areas. Furthermore, acknowledging the variability in demand of SES across different areas, we calculate the cumulative emission reduction from all SES trips within each analysis zone over the study year. This total is represented as the sum of emission reductions for all trips within that zone and is documented in the column “Grid level aggregated”. This result provides a quantification of the total annual emission reduction attributable to SES trips within each zone, thus offering a comprehensive perspective on the overall environmental impact of SES in different city areas. This results are further visually depicted in Fig. 11 and summarized quantitatively in Table 5.

Fig. 11 illustrates that SES tends to yield an increase in CO_{2-eq} emissions (depicted in red) in the majority of zones within the three Swedish cities, particularly in central areas. A plausible explanation for this phenomenon lies in the well-established public transport infrastructure and shorter trip distances within the central areas. These factors elevate the likelihood of SES trips replacing eco-friendly transport modes such as walking and public transit, increasing in CO_{2-eq} emissions considering life-cycle emissions of SES. Table 5 further highlights this trend, indicating that merely 8.3% of analysis zones in Stockholm, 7.48% in Gothenburg, and 2.02% in Malmö exhibit CO_{2-eq} emission reduction



(a) Stockholm; (b) Gothenburg (c) Malmö

Fig. 11. Average GHG reduction per trip (CO_{2-eq} g) in different zones.

derived from SES. Notably, the positive environmental impact of SES is discernible in only 2.02% of urban contexts in Malmo, underscoring the importance to reevaluate the environmental sustainability of SES deployment in certain metropolitan areas. The zones manifesting CO_{2-eq} emission reductions from SES are predominantly situated in some suburban areas of the three cities delineated in Fig. 11. This tendency may be attributed to the less accessible public transit options in these suburban areas and longer average trip distances, thereby enhancing the likelihood of SES replacing private cars or taxis associated with higher emissions. However, it is noteworthy that SES in most suburban areas in Fig. 11 still exhibit an increase in CO_{2-eq} emissions, potentially due to short-distance SES trips predominantly replacing walking or private bike. A consistent finding across the three cities is the marked variation in terms of CO_{2-eq} emission reduction from SES in different contexts. This nuanced spatial variation underscores the necessity of tailoring SES deployment strategies based on the specific urban context. From an environmental perspective, SES promotion should be judiciously implemented in areas exhibiting positive effects in reducing CO_{2-eq} emission, while caution is warranted in regions with pronounced negative impacts. This analytical insight reinforces the merits of our trip-level analysis, as traditional aggregated-level analyses based on surveys found in prior literature often fall short of revealing such spatial differentials in the impacts of shared micro-mobility.

We calculate the cumulative reduction in CO_{2-eq} emissions for all trips originating from a specific zone on a daily basis. This result enables us to ascertain the cumulative CO_{2-eq} emission reduction across different analysis zones presented in Fig. 12 and Table 5. The results show that the daily cumulative CO_{2-eq} emission increases stemming from SES are more pronounced in the central regions of the three cities. By integrating the findings concerning the average CO_{2-eq} emission increases per trip in Fig. 11, it can be inferred that the higher cumulative CO_{2-eq} emission increases in central zones are a consequence of higher daily demand within these areas. Conversely, the cumulative CO_{2-eq} emission reductions in analysis zones exhibiting positive impacts are relatively inconspicuous, potentially stemming from limited demand in these analysis zones. Once again, these outcomes underscore that SES in the three Swedish cities failed to yield discernible environmental benefits. This necessitates a reconsideration by city planners concerning the environmental sustainability of SES within urban contexts of such nature.

5.4. Practical implications for improvement

The impacts of SES in mitigating CO_{2-eq} emissions hinges significantly on the transport modes replaced by SES and the life-cycle emission factors of SES. If travelers use SES for a trip instead of a transport mode with higher emission factors, it will generate CO_{2-eq} emission reduction. Conversely, using SES instead of lower-emission alternatives results in an increase in CO_{2-eq} emissions. Enhancing the environmental impact of SES necessitates, among other considerations, a deliberate effort to augment the likelihood of SES substituting emission-intensive transport modes such as private cars and taxis. Such substitutions are more pronounced in suburban areas with limited accessibility to public transit and long-distance trips, as illustrated in Fig. 11. However, despite the potential environmental benefits associated with deploying SES in some suburban zones, a paradox exists owing to the commonly low utilization rates of SES (i.e., the daily usage frequency of a scooter) in these areas. While deploying SES in such areas may be

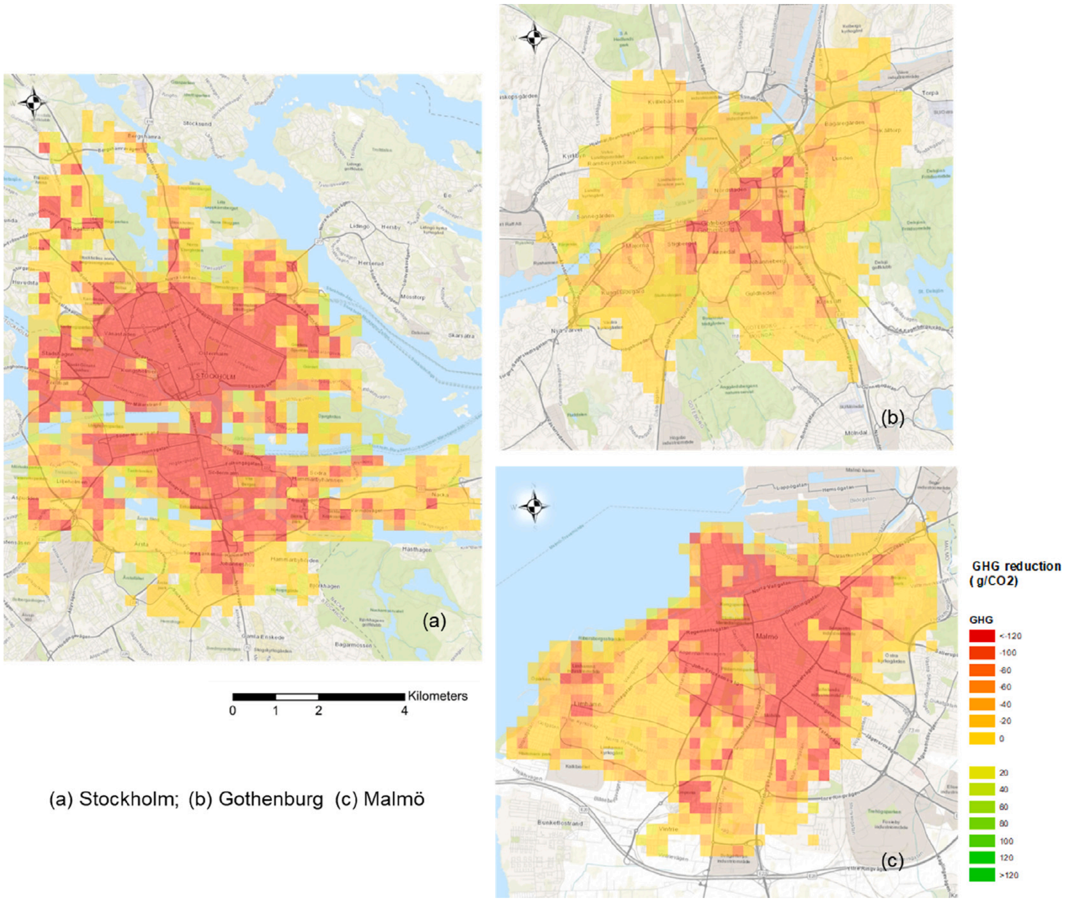
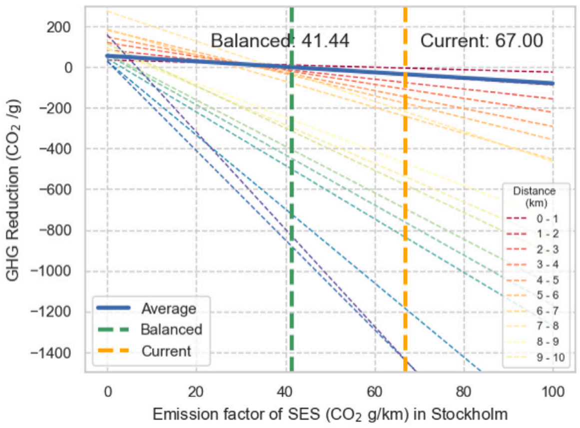


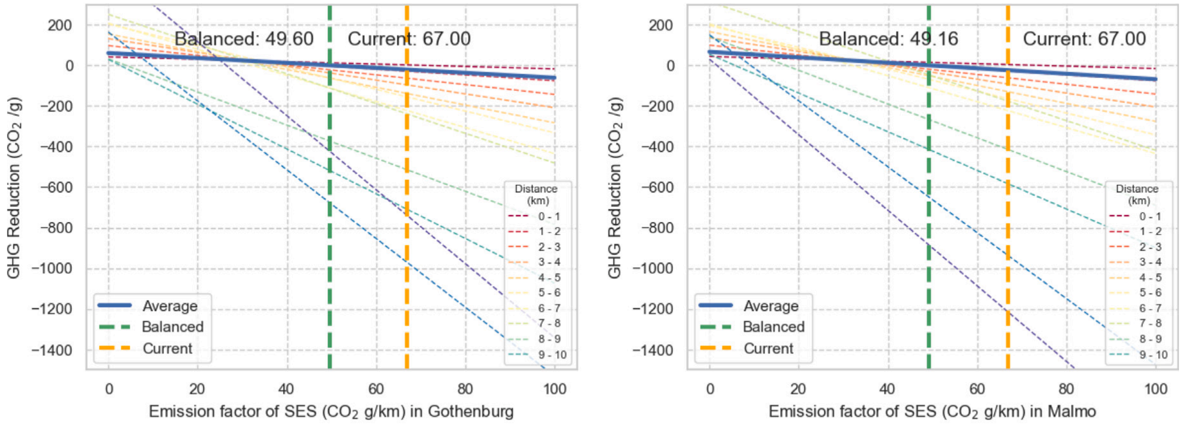
Fig. 12. GHG emission reduction of daily all trips (CO_{2-eq} g) in different zones.

environmentally advantageous, it presents a challenge concerning the operational efficiency of SES. It conflicts with the vested interests of SES operators, who may prioritize higher turnover and profits. Furthermore, substituting SES to other transport modes is intricate, contingent upon factors such as origin and destination of trips, starting timestamp, and road and public transit networks. Formulating effective strategies to systematically bolster the substitution of SES to a transport mode with higher emission factors poses a complex challenge. Addressing this dilemma requires a nuanced approach that balances environmental considerations with operational efficiency and the economic interests of SES operators. Although our results indicate that SES does not result in significant emission reductions in the central areas of the three Swedish cities studied, this does not imply that the development of SES in these areas is unwarranted. Environmental impact is only one aspect of the overall performance of SES. SES has been found to reduce travel time and increase travel efficiency for users. A scientific decision about whether to develop SES in a specific area should comprehensively consider various performance metrics. However, if SES does not yield environmental benefits or significantly reduce travel time in certain city areas, after comprehensive evaluation, city planners should reconsider the necessity of geo-fencing in these areas.

A more direct aspect of enhancing environmental impact involves reducing the life-cycle emissions of SES through improvements in sustainable production, efficient operational practices (e.g., effective rebalancing and deployment), and disposal methods (e.g., recycling). Fig. 13 encapsulates the anticipated changes in average CO_{2-eq} reduction per trip associated with varying SES emission factors, leveraging field spatiotemporal usage data in the three Swedish cities. Apparently, a decline in the average CO_{2-eq} reduction per trip is linked to increasing emission factors of SES. Of paramount importance is identifying the balance point of SES emission factors to achieve emission neutrality. In Stockholm, if the emission factor of SES is 46.93 CO_{2-eq} g/km, the emission impact of SES attains net-zero, as depicted by the green dashed line in Fig. 13(a). Comparatively, the current emission factor of SES reported by Cottell et al. (2021) is 67 CO_{2-eq} g/km. Accordingly, Stockholm city necessitates a reduction in the emission factor of SES by at least 25 CO_{2-eq} g/km to systematically curtail CO_{2-eq} emissions due to SES within its urban context. A similar balance point is estimated for Malmö (49.16 CO_{2-eq} g/km), while Gothenburg exhibits a close balance point (49.60 CO_{2-eq} g/km) based on spatiotemporal usage patterns of SES. These quantitative findings furnish valuable benchmarks and guidance for city planners and managers, offering targets for enhancing SES sustainability through improvements in production, operation, and disposal practices. These results provide specific thresholds derived from field big data, thereby enhancing the practical applicability of strategies. The practical implication is that city managers should incentivize SES operators to lower life-cycle emission factors by adopting the latest versions of e-scooters with less life-cycle emissions, improving operational efficiency, and promoting the recycling of disposed e-scooters. Another implication is that city planners should leverage mobility-as-a-service models that integrate SES with public transit. This approach would complement existing public transit systems and encourage a shift from car trips to SES, rather than merely replacing walking and public transit, thereby leading to better environmental outcomes. For instance, offering cost discounts for using SES as a feeder to public transit could attract more users to shift from car usage.



(a) Stockholm



(b) Gothenburg

(c) Malmö

Fig. 13. Descriptive analysis for CO_{2-eq} reduction per trip with different SES emission factor.

6. Conclusion

This study conducts quantitative and grained assessments of the substitutions of SES to other transport modes (including walking, private bike, public transport, private car, and taxi) and corresponding environmental impacts based on field shared e-scooter trip data and data-driven inference methods. The assessment method is at the individual trip level and allows for high-resolution analysis of the environmental impacts of SES in different urban contexts. A comprehensive empirical analysis is conducted for cross-city comparisons using field data from three major Swedish cities (Stockholm, Gothenburg, and Malmö). The results enable the derivation of quantitative and nuanced insights into the environmental sustainability performance of SES among different cities in Sweden. The main findings based on estimation can be summarized as follows.

- 86.7%, 85.6%, and 85.3% of trips using e-scooter sharing replace walking or public transport in Stockholm, Gothenburg, and Malmö, respectively. In contrast, the proportion of e-scooter sharing substituting private cars and taxis in the three cities is less than 12%. The substitution of SES to a transport mode varies significantly among different trips, highlighting the necessity for trip-level analysis.
- An SES trip in Stockholm, Gothenburg, and Malmö increased CO_{2-eq} emissions by 34.58 g, 21.18 g, and 24.07 g per trip on average, respectively. The estimated environmental impacts of SES in Stockholm, Gothenburg, and Malmö are increases of 300.86 t, 66.35 t, and 82.26 t CO_{2-eq} per year, respectively, suggesting that shared e-scooters are not environmentally friendly in the studied cities.
- The environmental impacts of SES in the three cities vary significantly among trips and urban contexts. Based on our analysis, only 19.20%, 24.22%, and 23.94% of SES trips in Stockholm, Gothenburg, and Malmö are estimated to have positive environmental effects (i.e., reducing CO_{2-eq} emissions). Only 8.3%, 7.48%, and 2.02% of areas with SES in Stockholm, Gothenburg, and Malmö benefit from positive environmental effects from SES.
- The life-cycle emission factors of SES need to be improved through more sustainable production, more efficient operation and disposal to realize net-zero effect of implementing SES in Stockholm, Gothenburg, and Malmö, respectively. Our results provide some quantitative reference target emission factors of SES to be more sustainable.

The results obtained from this cross-city analysis contribute quantitative and granular results about the environmental sustainability of SES in Swedish cities. However, the results should be interpreted as implications based on big data instead of deterministic quantitative conclusions due to the limitation of data we have and factors considered. The results provide support and evidence for management of SES to be more sustainable in different urban contexts.

While our study provides detailed insights, there are avenues for future work to enrich this research stream further. Firstly, the parameters for life cycle GHG emission analysis are derived from average values from a study in Cazzola and Crist (2020), among the most thorough known to us. Future research could conduct a sensitivity analysis and consider more specific values for local emission factors of SES, given the wide variation across different vehicle types, charging methods, and scheduling operations. Secondly, external factors such as socio-economic distributions of population, weather conditions, land use, and policies significantly influence SES usage and its impacts. Due to data limitations, our study does not consider these factors extensively. Future work could explore incorporating these external factors for a more comprehensive analysis. Our analysis is based on detailed trip transaction data from SES trips and primarily examines the first-order substitution of these SES trips to other transport modes, along with the corresponding emission effects. Due to the limitations of our data and the scope of this study, we do not delve into the long-term or second-order effects of SES on mode shift, travel patterns, and car ownership. Moreover, even though we tried our best to model the users' availability of car and private cars for trips using Monte Carlo simulation, many details can be improved based on more data such as the dependence of owning private bikes and cars. These aspects, although currently unexplored in our research, are significant and present substantial challenges for future investigation. Comprehensive studies employing more extensive data sets and innovative methodologies are essential to fully understand these complex dynamics. Due to the absence of SES trip trajectories in our data, we have endeavored to utilize OTP to infer the routes of each SES trip. However, incorporating trajectory data from SES trips would provide more precise and comprehensive information. Trajectory data would also enhance our ability to analyze complex trip patterns, such as "loop" trips and trips with multiple stops. The integration of transaction and trajectory data from SES could significantly deepen our analysis if such data become available in the future.

Moreover, it is essential to explore advancements in travel behavior models by incorporating more detailed factors such as trip purposes and user heterogeneity. It is naturally very hard to determine if a user has access to car or private bike for a specific trip. Car and private bike ownership statistics used in this study cannot perfectly reflect the user' feasibility of using car and private cars for every trip. Additionally, researchers have found that SES usage can induce new users, such as those who walk between 60 and 200 meters to access shared e-scooters (Reck et al., 2022). This suggests that the induced demand for shared e-scooters could contribute an additional portion, ranging from 2% to 8% (Moreau et al., 2020). In our study, this induced demand is not separately identified in the e-scooter transaction data, which is a limitation of our analysis and may cause slight variations in the results. This is a dilemma of data-driven methods, which may be improved by further calibration from survey data in analyzed cities. These would improve the accuracy of the estimated transport modes replaced by SES. Another potential enhancement lies in deriving more localized model parameters based on the latest field behavior data from Swedish cities or other urban areas, which would better reflect actual travel behavior. Meanwhile, using a small-sample survey to collect the average substitutions of SES to other transport modes will be also beneficial to corroborate the average results estimated by our data-driven methods. Conducting comparative studies across multiple cities would be particularly valuable for assessing the sustainability of SES in various urban contexts and investigating the underlying mechanisms.

CRediT authorship contribution statement

Kun Gao: Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Project administration, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Ruo Jia:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Yuan Liao:** Writing – review & editing, Validation, Methodology. **Yang Liu:** Writing – review & editing, Validation. **Arsalan Najafi:** Writing – review & editing, Validation, Resources, Data curation. **Maria Attard:** Writing – review & editing, Validation, Resources, Investigation.

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

Data will be made available on request.

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