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Socio-economic assessment of shared e-scooters: do the benefits overcome the externalities?

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ABSTRACT

Shared e-scooters are a trending mobility service and are usually advertised as a sustainable transport mode which could improve urban transport. However, there are concerns regarding their overall impacts. This research conducts a socio-economic assessment of shared e-scooters, considering environmental (emissions and pollutants), social (physical activity, road safety and pollution exposure), and economic (vehicle operating costs and time savings) dimensions. Therefore, we used data from 1.4 million trips from a e-scooter operator in Lisbon and a user survey with 919 responses. Results show that while shared e-scooters do generate benefits, these are highly overshadowed by their safety issues (almost €6M in annual costs). Authorities and organizations should join efforts to improve shared e-scooters' safety and maximize its benefits. To our knowledge, this is the first study to quantify the socio-economic impacts of shared e-scooters, so the limitations of the used methods are identified and can be improved in future research.

1. Introduction

Shared e-scooters are a trending mobility service worldwide and are usually advertised as a sustainable transport mode that could reduce first/last mile problems, congestion, and other transport-related externalities (Sanders et al., 2020). In the US, NACTO (2019) reported 86 million shared e-scooter trips in 2019, which dropped to 35 million in 2020, along with the pandemic. In 2021, with the lifting of most COVID-related mobility restrictions, the industry began to recover, reaching 62 million trips in the US in 2021 (NACTO, 2022). Nevertheless, this behavior varied worldwide, with different patterns between regions and operators (Orozco-Fontalvo et al., 2022). In Europe, Lime (2019) reported 1.2 million shared e-scooter trips in Paris between 2018 and 2019, which increased to 16 million trips between 2020 and 2022 (Lime, 2022), indicating a rebounding effect following the pandemic.

However, there are concerns regarding their safety (Bloom et al., 2021; Cicchino et al., 2021; Kobayashi et al., 2019), possible environmental impacts (Hollingsworth et al., 2019), and questions about which modes those trips are shifting away from Fitt and Curl (2020), Orozco-Fontalvo et al. (2022), which, if confirmed, could overshadow their benefits. Current literature has focused on profiling users (Degele et al., 2018; Jiao and Bai, 2020; Sanders et al., 2020), assessing preference (Baek et al., 2021; Cao et al., 2021), life cycle analysis (de Bortoli, 2021), forecasting demand (Ham et al., 2021) and modal shift (Wang et al., 2022), land use and policy (Hosseinzadeh et al., 2021; Moran, 2021). While these approaches provide a baseline for understanding shared e-scooter operations, user behavior, and effects on urban transport (Orozco-Fontalvo et al., 2022), there is no specific study which quantifies the socio-economic impacts of shared e-scooters (besides environmental). Hence, a comprehensive analysis is needed to assess this impact objectively.

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The most widely used methodology is the cost–benefit analysis (CBA), with variations in input parameters (Hromádka et al., 2020). In transport, this is usually carried out through economic evaluation studies of the system, considering its impact on the environment, society, congestion, and vehicle operating costs (Sartori et al., 2014). In the literature review conducted by the Asian Development Bank (2019), they found 96 methodologically rigorous impact evaluations. Although most studies were published after 2012 (65%), they all focused on roads, driving restrictions, public transport, or complementary interventions. However, we did not find any studies applied to shared e-scooters, which may be due to several factors. The lack of reliable e-scooter crash databases, the unwillingness to share trip information from operators (for being commercially sensitive) or the scarce information about the shared e-scooters' life cycle.

This research proposes a method for estimating the socio-economic impacts of shared e-scooters on environmental, social, and economic dimensions based on the modal share of trips replaced by shared e-scooters for different distance ranges, using Lisbon as a case study. The results provide empirical evidence of the impacts of shared e-scooters for practitioners, policymakers, and stakeholders to identify opportunities for improvement and focus on reducing the negative impacts to exploit the full potential of this shared mode adequately. To the best of our knowledge, this is the first study to conduct a quantitative trip-distance-based socio-economic impact assessment of shared e-scooters.

This paper is structured as follows: Section 1 "Introduction"; Section 2 "Literature Review"; Section 3 "Data collection" provides information about the data collection and trip characteristics; Section 4 "Methods" presents the proposed methodology and the inputs considered in the evaluation; Section 5 "Results", explains the main results of the assessment; in Section 6 "Discussion", we discuss our findings, compare them with other studies found in the literature, highlight possible implications, and list our limitations. Finally, Section 7 "Conclusions" summarizes the most significant findings, presents current research gaps, and suggests possible future works.

2. Literature review

The socio-economic impacts of transport have been widely studied in the literature (e.g. Abbasi et al., 2020; Fageda, 2021; Márquez and Cantillo, 2013), usually using the externalities concept to identify and quantify them. Externalities are costs or benefits that do not affect those participating in a transaction or activity. In transport, external costs are not borne (and external benefits are not enjoyed) by travelers who make the travel decision (Fearnley, 2020), which makes most users unaware of the real or generalized cost of their trips (and mode choice). Hence the importance of conducting a socio-economic impact assessment (or economic evaluation), which is the baseline for informed policy-making.

Economic evaluations in transport have focused on infrastructure development, mainly because of the need to include the potential external benefits (environmental emissions, time saving, etc.) in the financial model to balance the high investment costs, support the project justification and obtain funding (Jones et al., 2014). There is much less attention to urban transport, with limited literature on active modes and none regarding shared e-scooters. The World Health Organization (WHO) developed the *Health economic assessment tool* (HEAT) (Kahlmeier et al., 2017) that assesses the impacts of walking and cycling, from a health and environmental perspective. HEAT evaluates part of the socio-economic impacts rather than a complete evaluation of transport socio-economic impacts. Also, it was not designed for shared services, although the WHO plans to launch an Integrated Sustainable Transport and Health Assessment Tool in 2023 (WHO, 2022).

Some studies in the literature which conducted economic evaluations of shared mobility services, mainly for shared bikes (Bullock et al., 2017; Pelechrinis et al., 2017; Qiu and He, 2018; Zhang and Liu, 2021). The most common parameters considered are trip duration and length, energy consumption by fuel type, emissions, crashes, modal shift effects, and convenience. Regarding the modal shift, it is common to assume that shared mobility services substitute trips made by car or walking. However, the literature suggests they also substitute public transport and even bicycles, which is a non-desirable outcome, and should be considered in the economic evaluation (Kong et al., 2020; Orozco-Fontalvo et al., 2022).

Some shared e-scooters' reviews (Bozzi and Aguilera, 2021; Orozco-Fontalvo et al., 2022; Useche et al., 2022) identify both positive and negative impacts and characteristics of this transport mode. While impact assessments of shared e-scooters exist, they are limited to a specific area (environmental, health, behavior, etc.), and there is no study encompassing the different dimensions and quantifying each of them. Demand for shared e-scooters is based on user's perceived benefits, which are: travel time savings, convenience, hedonic motivation, and perceived utility benefits to well-being (Cao et al., 2021; Fitt and Curl, 2020; Kopplin et al., 2021; Lee et al., 2021).

The negative impacts or concerns are as follows: safety, which was the most discussed issue in Caspi and Smart (2022)'s word count and is listed in most studies as the main drawback (although without quantitative support), loss of balance and riding under the influence of alcohol or narcotics being the most common crash motives, with 84% of accidents not involving other road users (Bloom et al., 2021), leading to injuries mainly to the head or extremities and with 1 of every 5 patients requiring intensive care (Dhillon et al., 2020); environment, where de Bortoli (2021) determined that it is the e-scooter lifetime mileage which affects the environmental performance, and Hollingsworth et al. (2019) who stated that manufacturing, logistics, and charging are the main factors of environmental impact; and, finally, modal shift, where Christoforou et al. (2021) identified e-scooter trips replacing mostly walking and public transport modes, with Kopplin et al. (2021) concluding that it substitutes walking in short distance trips. These are in line with the results of Severengiz et al. (2020) — that we must consider where e-scooter trips are coming from and that this varies from case to case.

According to the European Commission CBA guide (Sartori et al., 2014), the socio-economic evaluation of transport investments splits into social, environmental, and economic effects. The social dimension could encompasses the impacts related to health

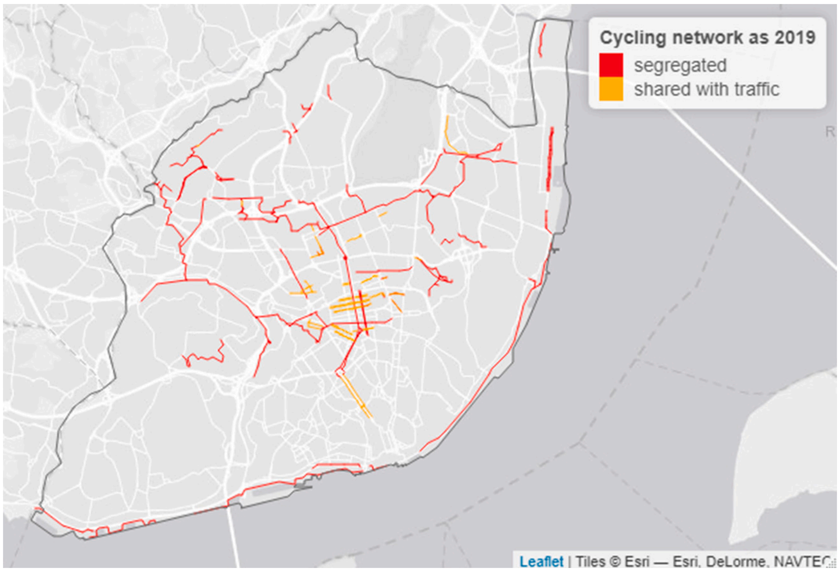


Fig. 1. Lisbon area and cycling infrastructure by 2019.

and well-being, the environmental consider energy usage and emissions, and the economic involves time and cost savings and accessibility (access to opportunities). The assessment of each dimension involves multiple variables and parameters. However, given the novelty of e-scooters, the availability of modeling, physical activity and economic-related parameters is scarce compared to other modes such as the bicycle or walking.

In this work we aim to present the first socio-economic evaluation of shared e-scooters, based on trip data from 2019 of an operator in Lisbon and a survey to users to minimize assumptions (e.g. mode substitution and trip generation), and to propose a methodological approach to deal with current data and calibrated parameters challenge.

3. Data collection

This section describes the methods employed to obtain and process the secondary data provided by the shared e-scooters' operator and the primary data we collected. A detailed description of the case study and the trip's descriptive statistics is presented in the following sections.

3.1. Case study

Lisbon, the capital of Portugal, is a city with 500,000 inhabitants which rises to 2.8 million if we consider the metropolitan area. The most recent mobility survey (INE, 2018) revealed that cars have a modal share of 46% of the trips, followed by active transport at 31% (30% walking and 1% cycling) and public transport with at 21%. Regarding trip distance, 69% of trips are below 5 km. In 2019, Lisbon implemented a 106 km cycling network (Fig. 1), and a public e-bike sharing system with 74 stations and 700 e-bikes.

On the other hand, shared dockless e-scooters were introduced in Lisbon in late 2018. By March 2019 seven different shared e-scooters' companies were operating, accounting for around 8,000 trips per day (Reis, 2020), and about 7,000 vehicles available then. With the COVID-19 pandemic, most of them shut down operations in 2020, leaving only four operators and about 2,000 vehicles operating. However, as the pandemic abates, e-scooters return to the city streets, which is reflected in the increasing fleet size.

In this context, we chose Lisbon as a case study because it is the second city in Europe with the most shared e-scooter trips per capita. It is also among the cities where e-scooters count for 61% of the whole shared mobility services, compared to the 43% of Madrid and 53% of Milan (Fluctuo, 2022). Lastly, obtaining the raw data from an operator in Lisbon was possible, which is uncommon for this type of company.

3.2. E-scooter trips

Data came from two primary sources: a dataset from a shared e-scooters' operator in Lisbon and a survey designed and implemented by the authors. Fig. 2 shows a flowchart of the procedures conducted for data processing and cleaning to obtain the final database.

3.2.1. Data

One of Lisbon's shared e-scooter operators provided data for this research, with roughly two million registered trips between Jan 1st and Dec 31st, 2019. For each trip, the dataset included origin and destination coordinates, traveled distance, and trip start

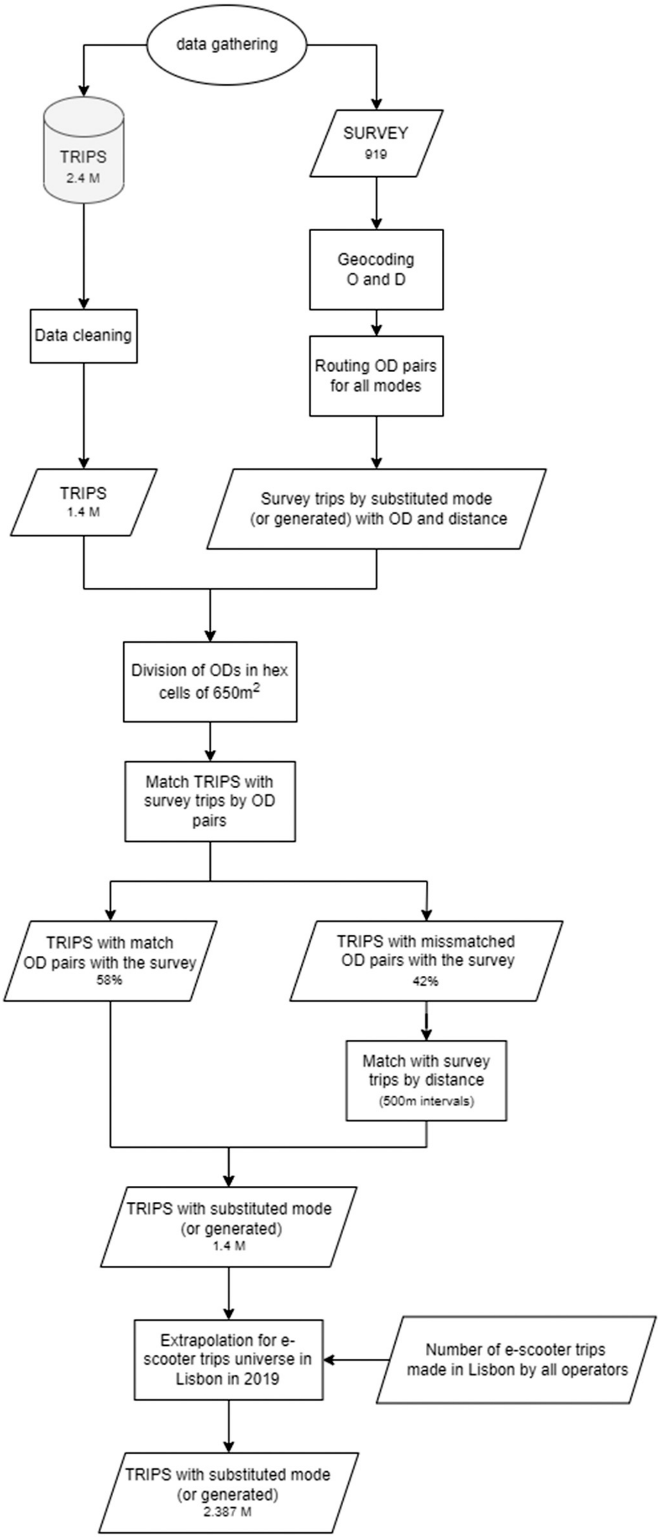


Fig. 2. Flowchart of the process of data collection, matching, and extrapolation, used in this research.

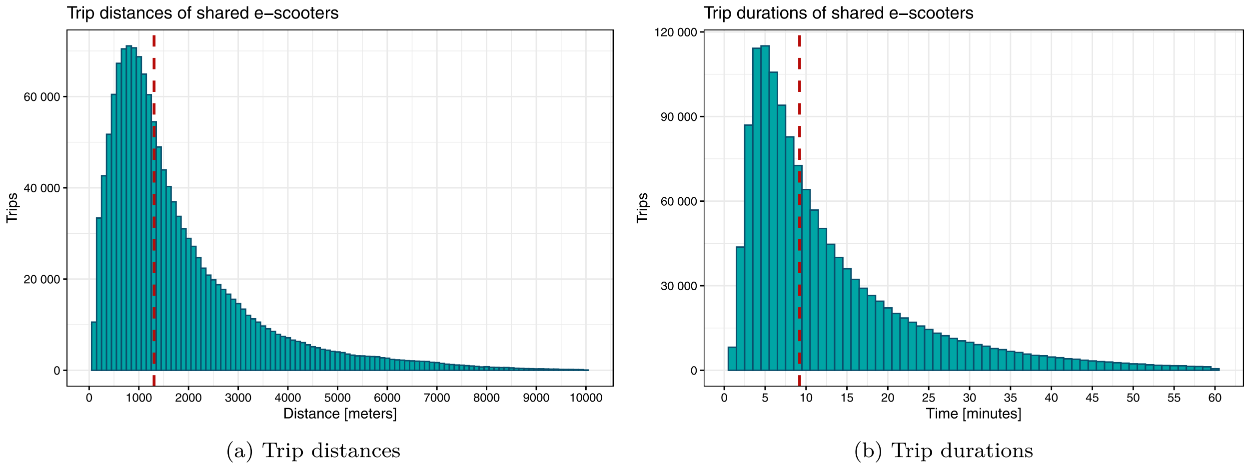


Fig. 3. Histograms of trip attributes of shared e-scooters. The vertical dashed lines represent data medians.

and end timestamp. We computed trip duration, average speed (based on trip length and time), and Euclidean distance between the origin and destination of all trips. We conducted a data cleaning process, discarding trips with the following characteristics: (a) travel time below 1 min or more than one hour; (b) travel distance below 100 m and more than 10 km; (c) speed below 2 km/h or more than 35 km/h.

The final dataset includes about 1.4 million trips (80.8% of the original data provided by the shared e-scooters' operator).

3.2.2. Data description

In 2019, shared e-scooter trips in Lisbon averaged 1792 meters (sd: 1512 m). Half of the trips made were less than 1307 m. The average trip duration was 2.9 min (sd: 10.73 min), while the median was 9 min (see Fig. 3).

When looking at the origins and destinations and the trip length, 25.4% of the trips were loop trips (origin = destination), 31.2% were short trips (below the median of 1,307 m, and the origin ≠ destination), and 44.3% were long trips.

In 2019, each e-scooter ran 360 km/year on average (sd: 265 km) and did about 4.5 km/day (median of 3.5 km/day). The average e-scooter rotation was 2.5 trips/day. Each vehicle lasted 170 days, on average (median of 158 days), and was used for 80 days on average (median of 71 days), i.e. roughly three months.

About a third of shared e-scooter trips occurred during the weekends (32.5%), and July and August were the months with a higher volume of trips, corresponding to the months in Lisbon with a higher volume of tourist visitors. On average, there were 3858 shared e-scooter trips daily (sd: 1450 trips). These trip characteristics and patterns are similar to other shared e-scooter schemes (Orozco-Fontalvo et al., 2022).

3.3. Survey

A survey was distributed to e-scooter users in Lisbon through two shared e-scooter operators' mobile apps in March 2020, obtaining a total of 919 responses after data cleaning. The main objective of this survey was to understand whether the shared e-scooter trips were replacing other modes (and which ones), or if they were used to make new trips (generating trips).

The survey inquired respondents about mobility patterns such as shared e-scooter usage frequency, trip motive, origin and destination, and if the shared e-scooters replaced another mode. For participants who used shared e-scooters at least once per week (frequent users), we asked about the origin and destination and replaced mode of their most frequent trip. For occasional users, we asked them to report on the last e-scooter trip they did.

Regarding demographics we inquired about users' gender, age, home location, and income, among others. To understand the shared e-scooter trip patterns, a spatial data analysis was performed, using the origins and destinations reported by the survey participants.

The respondents' profile was as follows: male (80%), young adults (48% between the ages of 18 and 35 years old), with high income (49.6% stated to be able to live without any economic difficulty). Regarding occupation, 83% were workers, and 12% were students. This profile is consistent the "DSDES user profile" presented by Orozco-Fontalvo et al. (2022) regarding age, income and occupation. The representativeness of gender was validated with field counts in Lisbon, where 83% of e-scooters' riders were male (Moura and Félix, 2021).

The survey was available in Portuguese and in English, to capture tourist and visitors' responses. Nevertheless, only 3.5% of the respondents stated that were visiting Lisbon.

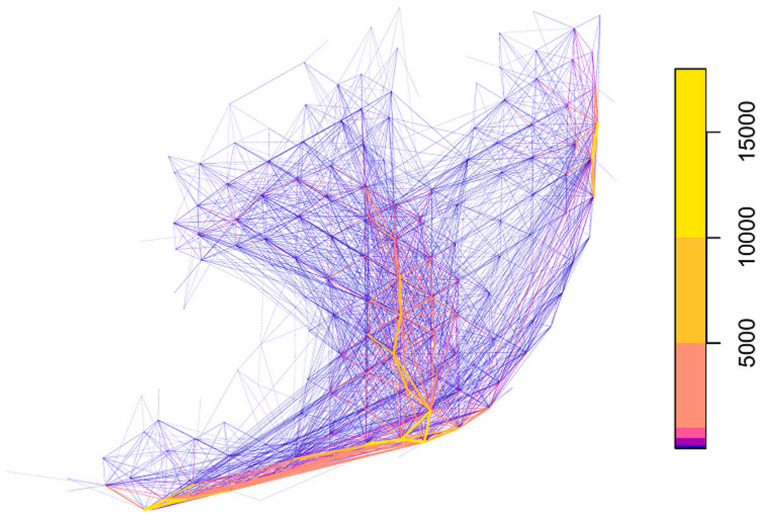


Fig. 4. Desire lines between cells, with color scale proportional to the registered trips between each origin and destination pair, covering the urbanized area of Lisbon. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3.4. Matching operators e-scooter trips and survey data

The secondary data provided by the e-scooters' operator did not include users' information, while the primary survey data did. This subsection explains how we reconciled both data sets, i.e., take advantage of the full e-scooter trip dataset provided by the operator and the users' trip profile information collected with the survey. We based the reconciling method on the trips' characteristics.

Firstly, we extrapolated the individual survey responses based on the annual trip frequency to estimate the trips replaced (and of which mode) and new trips generated. For example, respondents who declared using the system once per week would factor 52 times (52 weeks in 1 year), and one that reported using the system once a month would factor 12 times. Based on these expansion factors, from the 919 survey responses we estimated 44,980 annual trips, of which 6.7% were new trips (generated), and 93.23% substituted other modes.

With the declared origin and destination, we could match the geocoded origin and destination pairs with the trips registered from the operator, using a hexagonal grid of 1 km long (around 650 m^2 cells) to combine them. Trips with answers that could not geocode both origin and destination were discarded, as well as trips starting and ending in the same location since it was impossible to estimate their trip length. The final dataset was 625 surveys and 27.459 estimated annual trips.

Fig. 4 illustrates the registered trips' desire lines between 7,400 centroids of the hexagonal grid. As observed, most trips were made between the same OD pair, with 87% of the registered trips representing only 17% of the desire lines.

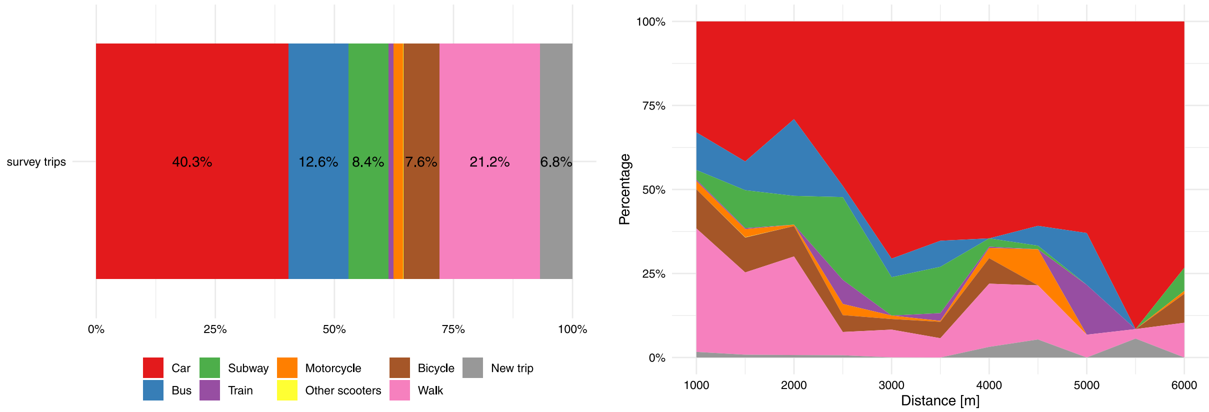
We estimated the percentage of trips replacing each transport mode and new trips for each OD pair and assign that information to the trip database, by matching the OD pair (48% of e-scooter trips). For the cases with no correspondent OD pairs between the operator trip and the survey database, we assumed distance intervals (in increments of 500 m) as a proxy of the trip pattern (new or replaced journey and from which mode). We were able to match 98.7% of e-scooter trips. With the remaining 1.3% of trips with no OD and distance interval correspondence with the survey (for instance, trips longer than 10 km that were not declared in the survey), we adopted the survey's average trip pattern. Fig. 5 presents the share distribution of substituted modes and new trips generated and the corresponding distribution according to trip-distance intervals (trips up to 6 km represent 99% of total shared e-scooter trips).

Out of the 27,459 analyzed trips, shared e-scooters mainly replaced car (40%), and their proportion grew with the trip distance. The trips substituting walking (21%) are higher for distances up to 4.5 km. The generated trips (7%) tend to be longer.

This method differs from others because (1) it does not assume that all trips are replaced by car, regardless of distance; (2) it takes into account generated trips, that would not be made if shared e-scooters were not available; (3) it adds more detail by considering that different trip distances have different modal substitution, based on the survey responses, instead of applying a general trip pattern (distances and modes replaced). It is interesting to note that with 625 survey responses we could match 98.7% of the 1.4 million shared e-scooter trips.

3.5. Collision data

The Municipality of Lisbon supplied collision data involving shared e-scooters. This database was crucial for the rigorous estimation of the socio-economic impacts of shared e-scooters for 2019 in Lisbon. In this year, 57 collisions were registered with



(a) From extrapolated trips reported in survey

(b) By distance interval

Fig. 5. Share of new trips and trips replaced from the respective mode, in total and by distance interval.

Table 1
Data on total shared e-scooters running in Lisbon in 2019 and comparison with the data provided by Operator X.

	Universe	Operator X	% of universe
Max available vehicles	5 943	2 330	39.21
Registered costumers	952 236		
Max trips /day	13 359	8 437	63.16
Max total distance in one day [km]	26 765	12 126	45.31
Total trips 2019	2 951 923	1 740 343	58.96
Total distance 2019 [km]	5 985 443	2 520 064	42.10

Table 2
Trips, distances and duration of extrapolated declared survey trips, by their replaced mode or new trip.

	Trips [n]	Distance [km]	Duration [h]
Car	770 565	2 319 169	100 359
Bus	217 756	441 828	45 824
Subway	25 973	69 406	6 520
Train	185 864	385 206	38 775
Motorcycle	40 243	103 657	4 586
Bicycle	250 980	407 589	22 936
Other scooters	718	930	93
Walk	798 202	1 059 973	192 422
New trip	96 859	172 309	19 160
Total	**2 387 160**	**4 274 466**	**513 084**

corresponding accident severity levels, resulting in 42 casualties with 1 severe injury and 41 slight injuries (no fatalities were reported).

3.6. Data extrapolation

The Municipality of Lisbon reported the operation data for 2019, for the total of shared e-scooters' operators, presented in Table 1.

Based on the information provided by the municipality, we extrapolated our results to the universe of all shared e-scooters operating in Lisbon for 2019. The total trips of the dataset supplied by the operator were nearly 58% of all trips. We estimated the trips replaced from each transport mode (or new trips generated). Data from Table 2 was used to compute the socio-economic impacts of shared e-scooters in Lisbon in 2019. Survey responses reported that e-scooters substituted 40% of car trips and 21% of walking trips, and only 7% were generated trips (i.e., trips that would not have occurred if shared e-scooter services were unavailable). A total of 2.387 million e-scooter trips were estimated, covering 4.27 million km, the equivalent of 335 trips around the Earth.

4. Methodology for estimating socio-economic impacts of shared e-scooters

For the socio-economic assessment, we considered three dimension : *social* — including the physical activity of shared e-scooter users, air pollution exposure, and road casualties; *environmental* — including CO_2eq emissions and other pollutants; and *economic* — including vehicle operating costs and travel time savings.

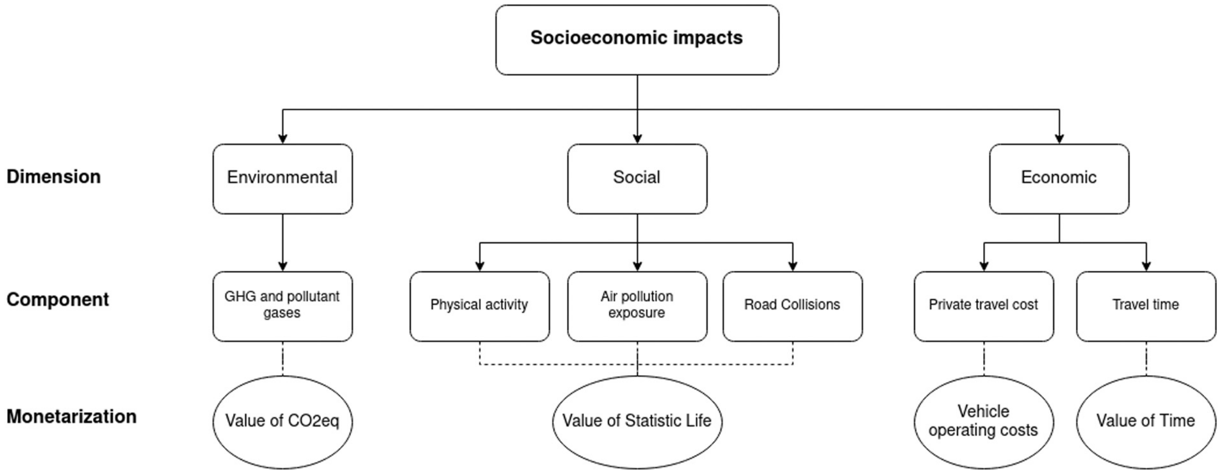


Fig. 6. Socio-economic impacts evaluated for each dimension.

Fig. 6 illustrates the dimensions and components assessed in this analysis. The following sections summarize the methods used to estimate the socio-economic impacts (Sartori et al., 2014).

Because e-scooters are relatively new and there is little research on the socio-economic impacts of this mode, we adapted some parameters calibrated for bicycles or e-bicycles, with supporting rationale. We updated all the monetary reference values of the literature based on the annual inflation rate in Portugal for 2019.[1]

4.1. Environmental impacts

Considering the substitution of the motorized modes and the rebalancing logistic operations of the e-scooters, we estimated the greenhouse gas and air pollutants emissions and avoidance by each mode and trip distance. These estimations were monetized in €, using conversion values by the ton, suggested by Bickel et al. (2006), Nash et al. (2003), Sartori et al. (2014) : 8.44 €/ton for CO, 2,867.85 €/ton for NO_X, 340,969.27 €/ton for PM_{10}, 7,169.62 €/ton for VOC and 35.85 €/ton for CO_2eq.

For the car and motorcycle trips, we used the methods and reference values from the *COPERT* software v5 (Ntziachristos and Samaras, 2020) for a TIER 3 detail level. We used a family-size vehicle, EURO standard, and gasoline or diesel fuel. All trips were considered to be made under urban conditions and at an average speed of 15 km/h during rush hour periods and 30 km/h during other periods. In addition, we considered that 66% of the light vehicle fleet in Portugal was diesel in 2019 and assumed an occupancy rate of 1.2 passengers per car. Regarding the public transport emissions, we considered the values from the environmental and sustainability reports of the public transport operators in Lisbon: Bus (Carris, 2020), Subway (Metropolitano de Lisboa, 2020), and Urban trains (CP, 2020). We used an emission factor of 40 g CO_2/km for the e-scooter logistics (Reis, 2020).

4.2. Social impacts

We used Kahlmeier et al. (2017) methods to estimate physical activity of e-scooter users, and the exposure risk to air pollution. The *Health Economic Assessment Tool (HEAT) for walking and cycling*, in version 4.2[2], estimates the health benefits per addition of daily physical activity in a population for conventional cycling compared to the substituted modes.

This tool uses 6.8 MET (Metabolic Equivalent of Task) values for regular cycling and 4.0 MET for walking as reference. The application of this method to e-scooters should be approached cautiously. On one hand, the physical activity using a conventional bicycle is higher than that of an electric bike, which in turn is higher than that of an e-scooter. We can then assume that the physical activity performed on an electric scooter is lower than that of an electric bicycle. On the other hand, it is also lower than walking, although it is slightly higher than driving a car (2.5 MET). Based on further research on physical activity with e-scooters and e-bikes (Langford et al., 2017; Wen et al., 2019) we considered a value of 2.2 MET.

The economic evaluation of a road crash can be divided into direct economic costs, indirect economic costs and a safety value *per se*. We employed the Willingness-to-Pay (WTP) / Accept (WTA) approach, usually adopted to estimate the human cost of road crashes. This social cost includes: (a) victim-related costs, such as personal damage costs (shortening of life, loss of quality of life, pain and suffering during medical recovery, for both victims and family), medical costs, and loss of production and consumption;

[1] See: StatisticsPortugaltoolforinflationrateestimatesbetweenyears.
[2] See: heat4.heatwalkingcycling.org/tool.

Table 3
Observed and estimated road collisions involving shared e-scooters, and their estimated social cost.

Severity	Underreport correction factor	Registered collisions	Estimated collisions Portugal 2019 [€]	Economic costs in	Total costs [€]
Fatality	1.02	0	0.00	1 663 445	0
Severe injury	2.75	1	2.75	222 272	611 247
Slight injury	8.00	41	328.00	15 253	5 002 936
Material damage only	18.50	15	277.50	300	83 250

Table 4
Monetary values (€) for GHG and pollutant emissions.

Mode	CO2eq	CO	NOx	PM10	VOC	Total
Car	13 456.99	6.17	2 475.50	19 812.35	773.26	36 524.27
Motorcycle	425.92	2.45	47.52	5 445.80	780.34	6 702.03
Bus	1 813.06	0.25	583.54	1 112.50	44.66	3 554.01
Subway	422.22					422.22
Train	39.03					39.03
Shared e-scooters	0.00					0.00
Shared e-scooters' logistics	−6 124.45					−6 124.45
Total	**10 032.78**	**8.86**	**3 106.56**	**26 370.65**	**1 598.26**	**41 117.11**

(b) crash-related costs, such as vehicle and property damages, administrative, and other costs (de Blaeij et al., 2003; Wijnen and Stipdonk, 2016; Schoeters et al., 2020; Silva et al., 2021).

For this estimation we used only the average values of direct and indirect economic costs suggested by Korzhenevych et al. (2014) for Portugal in 2010 (purchasing power parity factor prices in this year), updated to 2019. Accordingly, we used a property damage cost of €300 per injury-free crash.

An average correction factor for underreported road accidents was applied for each type of collision, as suggested by Bickel et al. (2006, p. S15), considering *cycling* mode, for the similarity of underreported casualties context: 1.02 for fatality, 2.75 for serious injury, 8.00 for slight injury, 5.38 for moderate injury, and 18.50 for damage only. Table 3 presents the registered and estimated collisions, by type, and their estimated social cost, based on the values suggested by Bickel et al. (2006) and Korzhenevych et al. (2014).

4.3. Economic impacts

The economic impacts consider the users' vehicle operating costs, both for using the systems (cost) and for replacing the modes (savings); and the value of time, for hours avoided or spent compared to the modes they replaced. Private motorized modes' operating costs included fuel and parking costs (considering travel distances, and on and off peak hours). Public transport costs included transport fares only.

The costs of using shared e-scooters were also considered based on the fares in use during 2019, which vary from carrier to carrier. Some had unlocking costs, while others offered it for free for the first few weeks of use. Some varied the price per minute. For this estimation we used a price of €1.00 for unlocking between January and May, and €0.50 from June to December 2019. The usage price was 0.15 €/min on average. It is well known that a large proportion of the trips in Lisbon were not paid due to fraud, the creation of fictitious payment methods, and reimbursements from the operators. We estimate that only 10% of the trips made were paid by users, resulting in an average cost of 0.19€/trip.

We estimated the travel times for each mode during peak and off-peak hours to account for congestion. The travel time includes trip duration (based on estimates from *Open Route Service* and *Google Maps*); waiting time for public transit, and parking time if applicable. We multiplied the travel times by a reference *value of time* for "short urban trips for other purposes" suggested by Bickel et al. (2006) (i.e., 6.85€/h). We assumed that no costs were associated with walking and cycling.

5. Results

5.1. Environmental impacts

Table 4 presents the monetary valuation of the GHG and pollutant emissions. These environmental impacts can be valued at a savings of €41k from substituting of more pollutant transport modes, where CO_2eq and PM_{10} emissions contribute more than 85%

Table 5
Summary of the results of health benefit estimates for shared e-scooters (k€)

Component	Prevented deaths	Total
Road crash		–5 697.43
Air pollution exposure	–0.08	–143.00
Physical activity	0.33	656.67
Total, in k€		**–5 183.77**

Table 6
Summary of economic impacts (€), in avoided direct mobility costs and time savings, per replaced mode.

Mode	Trips	Savings in direct costs	Savings in time	Total
Car	770 559	953 550	856 419	1 809 969
Motorcycle	40 243	11 810	31 421	43 231
Bus	217 757	132 614	415 374	547 988
Subway	185 867	116 055	355 250	471 305
Train	25 974	23 974	210 393	234 367
Bicycle	250 979	0	157 109	157 109
Other scooters	718	0	635	635
Walk	798 203	0	1 318 092	1 318 092
Shared e-scooters	2 387 160	–461 776	–3 514 624	–3 976 400
Total		**776 227**	**–169 932**	**606 295**

of the impact. Despite the low percentage of trips replaced by motorcycles (2%), they cause a considerable saving in gas emissions. It is from the trips replaced from car to shared e-scooters which comes most of the savings in gas emissions — almost 90%.

5.2. Social impacts

We estimated the health impacts of physical activity, exposure to air pollution, and reported road accidents, by applying the factors explained earlier and converting avoided and premature deaths to a monetary value estimated by the OECD for each country. Table 5 presents the balance of social impacts on these three components.

The estimated health benefits from increased physical activity resulting from e-scooter use, have little impact compared to the reported shared e-scooters' road crashes. The social impact estimates, adapted for e-scooters, suggest a total cost of 5.2 M€ in 2019.

5.3. Economic impacts

The economic impacts accounted for the users' vehicle operating costs and the hours avoided or spent on scooter trips, compared to the transport modes they replaced. Table 6 presents the balance of economic impacts on these two components. We estimated total costs savings of €776k for the end-users and additional costs related to longer travel times costing €170k, resulting in a final positive balance of €606k.

Trips replaced from motorcycles, bicycles, and other scooters have a more negligible impact because they represent lower transfer, savings and low vehicle operating costs. The positive impact of public transport substitution is mainly due to time savings, where 36% corresponds to waiting time. The cost of each public transport trip is not high.

Replaced walking trips have a massive impact on economic assessment, exclusively due to the time savings resulting from the trip transfer from walking to the e-scooter, as walking does not have a direct cost *per se*. Finally, survey participants reported that car trips were the most frequently replaced mode, and significantly impacted time savings and mobility costs since their fuel costs are high, and so are travel and parking times.

5.4. Socio-economic impacts

Table 7 summarizes the main indicators of the 2019 shared e-scooters' socio-economic impacts, for the environmental, social, and economic dimensions, according to the variables we could measure. Negative values correspond to a cost and positive values to a benefit (or reduction of impacts).

E-scooters saved €41k of environmental impacts related to pollutant and greenhouse gas emissions. The social benefits of physical activity amount to €657k, exposure to air pollution adds €143k to the socio-economic costs of shared e-scooters, and road accidents increase by nearly €6M. The final balance between social benefits and costs is negative and slightly more than €5M, i.e., the costs related to air pollution exposure and road accidents outweigh the positive impacts of physical activity. We estimated a total vehicle operating costs savings of €776k for the end-users and additional costs related to longer travel times of €170k, resulting in a final positive balance of €606k, i.e., operating cost savings compensate the e-scooters' travel time excess.

Table 7
Summary and balance of socio-economic impacts, in the three dimensions. Values in €.

Dimension	Component	Item	Value
Environmental	Greenhouse gas emissions	CO2eq	10 033
	Pollutant gas emissions	CO	9
	Pollutant gas emissions	NOx	3 107
	Pollutant gas emissions	PM10	26 371
	Pollutant gas emissions	VOC	1 598
	Energy consumption		
	Total		41 117
Social	Exposure to pollutant gases	Premature deaths	−143 000
	Physical activity	Avoided deaths	656 667
	Road collisions	Collisions	−5 697 433
	Total		−5 183 766
Economic	Private costs of mobility	Direct costs savings	702 880
	Time	Time savings	−169 941
	Total		532 939
Global			**−5 057 371**

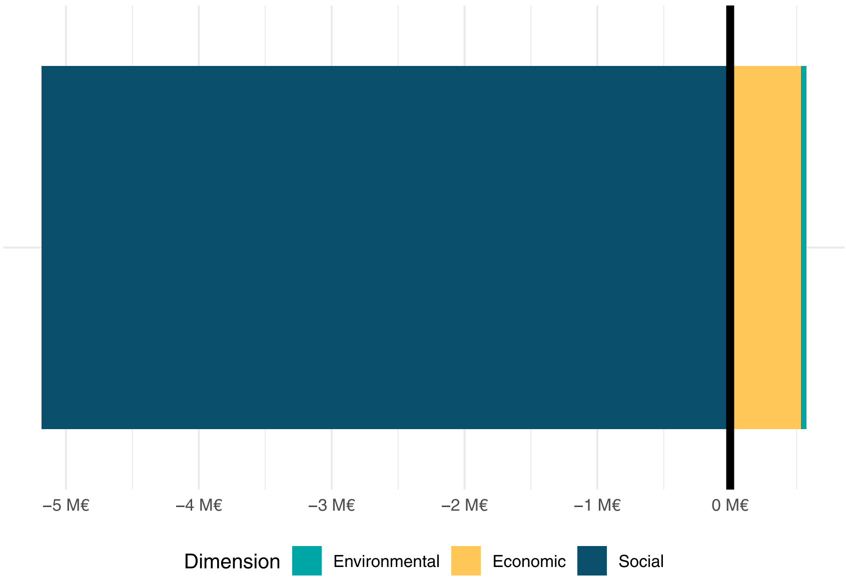


Fig. 7. Balance of socio-economic shared e-scooter impacts and weight of each dimension.

Fig. 7 shows the weight of each socio-economic dimension and related components, indicating that the negative impacts overshadow the positive ones, of which road injuries hold the highest burden.

Transferring motorized trips to shared e-scooters during 2019 saved 280 tons of CO_2eq, equivalent, on average, to a 117 g CO_2eq reduction for each trip made on a e-scooter (or 66 g CO_2eq/km). Still, the overall environmental impact reduction is negligible compared to the overall socio-economic benefits, i.e., around 7% of the positive impacts. The remaining 93% are due to the economic impacts (time and vehicle operating costs). The negative social impacts, related to increased morbidity and mortality (due to road accidents and air pollutants exposure), are 10 times higher than the positive overall impacts.

Shared e-scooters have a positive socio-economic impact on the environmental and economic dimensions (i.e., cost savings) and a negative impact on social impacts (i.e., increased health and road safety costs). However, we highlight that the lower share of monetized environmental impacts should not be interpreted as shared e-scooters having an insignificant environmental impact in Lisbon.

6. Discussion

There are clear socio-economic benefits from e-scooters, obtained from environmental, physical activity and vehicle operating cost savings with approximately €1.4 million, which shows the potential of these vehicles for improving urban mobility. The benefits could increase significantly if we consider that for instance, the value of CO_2eq ton has surged in the last couple of years, going from €35 in 2019 to almost €100 at the beginning of 2022, as it depends on worldwide macroeconomics. Moreover, we did not

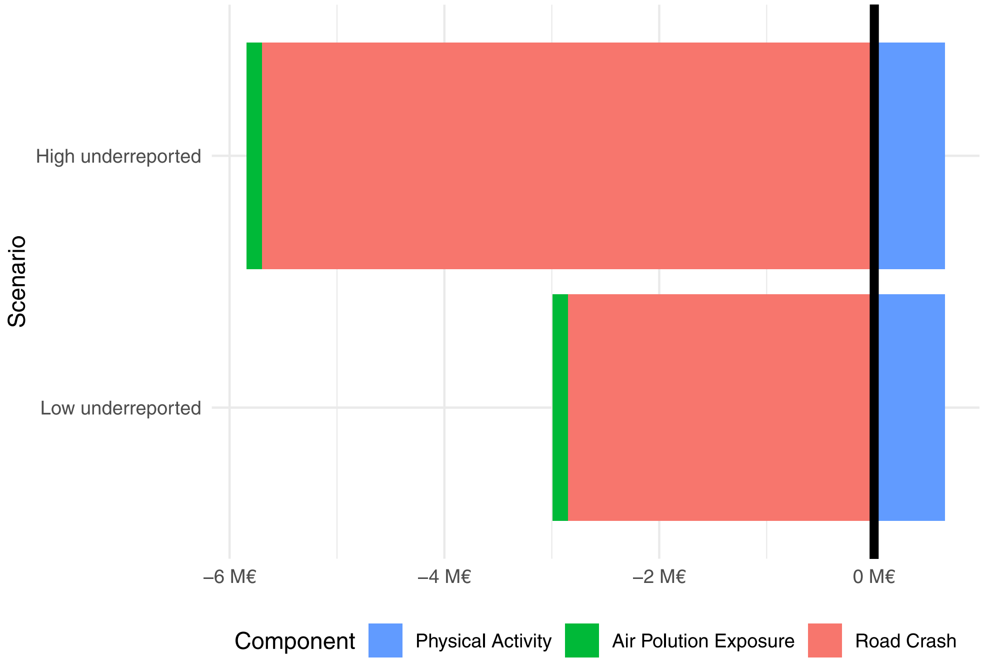


Fig. 8. Sensitivity analysis of the health impacts and road crashes.

consider employment creation, which would positively impact in the social dimension. It is worth mentioning that shared e-scooters replaced about 2,111 car trips per day, which is shows the potential for it to reduce car usage.

However, these benefits are overshadowed by the road safety assessment results, which cost about €5.7 million and are by far the central issue of shared e-scooters. Also, e-scooters are replacing a high amount of walking trips (33% in this case study), which is not desirable. Furthermore, while no fatalities were reported in our case study during our time window (2019), this was not the case in 2021 and 2022, when three fatalities were reported in Lisbon (Bastos and Albuquerque, 2023), and are also occurring in other cities (San Diego, Paris, Denver, Atlanta, and Madrid, among others), which would raise the negative impact substantially.

Shared e-scooter trips that are substituting other modes are also avoiding the social costs of the trips made in the original modes. However, we cannot estimate those avoided social costs because we do not have the required data, so rigorous estimation is beyond the focus of this paper. Still, this analysis should be further researched.

This work is the first attempt to measure the socio-economic impacts of shared e-scooters using real data from an operator. We could identify the high number of e-scooter parameters missing for an accurate assessment, and we present an approximation considering the available resources. As such, there are still several limitations and room for improvement. For instance, the adaptation of cycling health impacts' evaluation (HEAT) to e-scooters has caveats and assumptions which lack validation. Also, a more comprehensive economic benefit analysis is lacking — e.g., job creation. Regarding crashes, there may be underreporting as some users do not use emergency services for minor injuries, hence, e-scooter operators could install vehicle sensors in order to obtain more reliable data regarding minor falls or collisions.

The car trips replaced by shared e-scooters may also reduce congestion, impacting car travel times and economic costs. This component was not accounted for in this paper, as a different approach would be needed, such as meso or micro-simulation models, besides the need for more detailed data on traffic flows distribution in the city. However, further research should be conducted in this direction to estimate the benefits of modal shift beyond time savings, namely changes in accessibility or land use as a result of reducing car-dependency, which are not captured in the traditional CBA analysis but rather with Wider Economic Benefits approach.

We acknowledge that the methodology applied for the crash rate estimation may overestimate the underreporting, given it was designed for bicycles. Considering that shared e-scooters are operated by companies (not users), that have insurance and work through an app (and both facilitate the reporting of casualties or damages); the crashes and falls underreporting may be much lower compared with the privately owned bicycles. This being said, for sensitivity analysis purposes we present the results assuming a 50% reduction of underreporting in the parameters suggested by Bickel et al. (2006) which would lead to a reduction of the negative impacts in the social component of almost 3M€ (Fig. 8).

As we can see, even when lowering the underreporting rate, the road collision component still significantly impacts the overall assessment, highlighting the importance of addressing this issue. Lastly, considering accessibility impacts by using e-scooters for the first or last mile could provide a better overview of the feasibility or convenience of fully integrating them with public transport.

We could not analyze the COVID effects after the pandemic because our data was pre-COVID. Also, as was already indicated, these effects could vary worldwide. The usage of e-scooters following the pandemic is worth studying, particularly determining the potential health benefits of using them as an individual transport to prevent the spread of viruses like the common cold and COVID-19.

7. Conclusions

The present research assessed shared e-scooters' social, environmental, and economic impacts. The results show that although there are clear environmental and economic benefits, shared e-scooters' negative health impact (related to the high number of crashes and injuries) surpass the benefits, exposing the related safety burden and questioning their contribution to more sustainable urban mobility.

These results provide reference values for the accountability of the socio-economic impacts of shared e-scooters. Authorities and operators should mitigate the externalities to achieve positive results by internalizing the negative impacts, for example, considering a fee in e-scooters' fare that captures the related costs (e.g., insurance coverage). With safety being the main issue, we advocate implementing mandatory training programs that would increase risk perception, manoeuvrability, and correct usage while decreasing conflicts and crash likelihood among users. Several authors suggested it (Useche et al., 2022; Guo and Zhang, 2021; Raptopoulou et al., 2021; Löcken et al., 2020 but to date

few have changed.

This study may be a baseline for decision-makers to support the design and implementation of regulatory measures toward the operation of these shared mobility services, however, as already mentioned, one of the main issues with e-scooter data is its availability and quality, specifically regarding crashes, which in our case hindered the analysis by not having information about the location, infrastructure, collision type, and other relevant attributes. We highlight the importance of creating and structuring more comprehensive databases of these crashes to address this issue, as suggested by Elvik (2009). Collision spatial analysis such as a heatmap of black spots would help policymakers and operators to improve safety and thus reduce social impacts.

Given that our trips data and operational patterns are similar to those found in the literature, the evaluation results could also be identical. However, we suggest conducting this assessment specifically for each city, given the replicability of our methodological proposal, since the transport network of a given city influences the usage of shared e-scooters and the shifts between modes (Orozco-Fontalvo et al., 2022).

This paper uses some assumptions for the described scenario. Other scenarios should be assessed, considering adjusted parameters to the e-scooter context (which has not yet been explored in the literature), and implementing different policies that should mitigate the issues identified in this work. The economic value associated with mobility data not included in this study can be of substantial value in approximating what autonomous on-demand mobility might look like as a preliminary market assessment. Future works should include Wider Economic Benefits (WEBs) as an aspect of the socio-economic assessment.

Also, specific research should be conducted to estimate the e-scooter MET, accidents' unreported correction factor, and other parameters not currently available for e-scooters in the literature. This would avoid resorting to adapted values from different modes and more accurately analyze shared e-scooter impacts. Big data may help to address the information voids that hinder the accuracy of these evaluations. In addition, analyzing the effect of an integrated service (shared e-scooters + transit) would provide a better overview of the possible benefits for daily commuters.

Data availability

The authors do not have permission to share data.

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