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Assessing Environmental Performance of Micromobility Using LCA and Self-Reported Modal Change: The Case of Shared E-Bikes, E-Scooters, and E-Mopeds in Barcelona

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Abstract: Micromobility is often thought of as a sustainable solution to many urban mobility challenges. The literature to date, however, has struggled to find consensus on the sustainability of shared and electric scooters, e-bikes, and e-mopeds. This paper uses a Life Cycle Assessment (LCA) approach to calculate the impacts of micromobility modes in three categories: Global Warming Potential (GWP), Particulate Matter Formation, and Ozone Formation. It does so by incorporating the self-reported modal change of each transportation mode: shared e-moped, shared e-bicycle, shared bicycle, and personal e-scooter. The results show that modal change brought by the introduction of shared e-mopeds and shared e-bicycles caused an increase in greenhouse gas (GHG) emissions, while shared bicycles and personal electric scooters decreased GHG emissions. All micromobility modes except personal e-scooters increased particulate matter emissions, but decreased those which were emitted within the city, while they all decreased NOx. The findings of this study suggest new micromobility services are not always the best environmental solution for urban mobility, unless the eco-design of vehicles is improved, and they are strategically used and deployed as part of a holistic vision for transport policy.

Keywords: micromobility; shared mobility; modal change; life cycle assessment; environmental performance; greenhouse gas emissions; public health; two-wheeled vehicles

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1. Introduction

The transport sector is one of the main contributors to global warming [1]. It is projected that the GHG emissions associated with transport will barely decrease by 2030, and will likely be a barrier to climate neutrality objectives [2]. Emissions generated by transportation result in high concentrations of NO_x and $PM_{2.5}$ [3] and in the incidence of respiratory and cardiovascular diseases, and can lead to premature mortality and other public health issues [4,5]. Reducing transport-related emissions is thus a key step for cities worldwide to achieve climate emergency goals, but also towards improving the health of urban dwellers.

Historically, strategies to reduce transport emissions in cities have followed a number of routes, such as improving land use distribution, promoting energy-efficient vehicle fleets, and promoting low-impact transportation modes [6]. Among the initiatives that fall within the latter strategy, micromobility is recently gaining relevance as an increasingly extended transport solution. Micromobility, consisting of private or shared lightweight vehicles, which operate at low speeds and are used for short trips [7], includes vehicles such as e-bicycles, e-scooters, and e-mopeds. Many authors have theorized that micromobility characteristics, including its flexibility, sustainability, and affordability make them ideal for substituting more private vehicles that contribute to pollution [8].

Barcelona (Spain), like many other cities, has seen a recent surge of shared and private micromobility. In 2007, the first public docked bike-sharing system (BSS) (named *Bicing)* was launched by the Barcelona City Council [9]. The service has grown from the original 1500 mechanical bicycles to the current 6000 mechanical and 1000 Electrical bicycles (e-bicycles) that are accessible in different points of the city [10]. In addition to the public sharing scheme, several private sharing companies have emerged [11]. In 2019, the city council placed regulations that capped the number of shared vehicles from private companies to 3975 bicycles and 6958 e-mopeds [12]. Because the city has not allowed e-scooter sharing services to operate legally, privately owned e-scooters have boomed, being driven by convenience and low prices [13].

While micromobility adoption is often seen as a shift towards sustainable transportation [8], insufficient evidence is available on the true environmental performance of these modes. Aiming at this filling gap, this study aims to resolve the following issues (1): Comparing the environmental performance of different main micromobility modes in Barcelona. (2): Estimating the environmental impact of the introduction of these new modes. (3): Understanding how the environmental performance of micromobility can be improved, based on the life cycle of the vehicles and the observed modal changes. To do so, we first conducted a survey to identify the modal change caused by the introduction of micromobility modes. Then, we conducted an environmental Life Cycle Assessment of a privately owned e-scooter, a shared bicycle, a shared electric bicycle, and a shared e-moped operating in the City of Barcelona. Finally, we combine the survey and the LCA results to assess the environmental impact of the modal change.

2. Literature Review

Literature on the environmental performance of micromobility [14–17] with much of the literature focused on the use phase of the vehicles, which represents only a share of a vehicle's total emissions. However, a new body of literature uses Life Cycle Assessment to measure the environmental impact of the whole life cycle of the vehicles, which delivers more accurate sustainability assessments.

The first LCA studies were limited to comparisons between transport systems. [18]) for instance, compared the environmental performance of different modes of transport, including the bicycle. Del Duce [19] conducted a comparative LCA between two-wheeled vehicles, including conventional and electric bicycles, showing traditional bikes to be environmentally safer than the latter. Later papers in the literature studied the impacts of bicycle sharing schemes (BSS). Luo et al. [20] and Bonilla-Alicea et al. [21] both measured the environmental impacts of different BSS (both docked and free-floating) and compared them to that of regular bicycles, concluding that docked systems were more environmentally friendly. Cox and Mutel [22] first compared e-mopeds with traditional mopeds using Leuenberger and Frischknecht's [23]) LCA databases for electric mopeds. De Bortoli [24] was the first to compare all major micromobility vehicles after the introduction of e-scooters; conventional and electric bicycles and e-mopeds, thus showing that shared micromobility vehicles are more environmentally inconvenient than individually owned vehicles.

Although the above mentioned LCA studies compared the environmental impact of the life cycle of micromobility vehicles, they did not assess the actual impact that micromobility has on transport sector sustainability. For that global impact to be assessed, the modal change and travel mode substitution have to be taken into account. This means considering which type of transport micromobility does the replacing. This is of utmost importance, as these new modes will not have the same impact if substituting private transport than they will if they are actually substituting the walking mode. The global environmental impact of micromobility ultimately depends on which transport micromobility is replacing.

Only a few recent studies have considered modal change when assessing micromobility with LCA. Hollingsworth et al. [25], Moreau et al. [26]), and de Bortoli and Christoforou [27] all assessed shared e-scooters sustainability using both LCA and modal change indicators. A shared conclusion between those authors was that, on average, the new shared modes had a higher environmental impact than the modes they were replacing. Although shared e-scooters had a relatively good environmental performance, they were replacing walking and cycling the most, hence increasing their environmental impact. Zheng et al. [28] used the same methodology to assess bicycle sharing in Chinese cities and concluded that bicycle-sharing introduction was beneficial to the environment, regarding most indicators, including global warming and human health pollutants. However, the sharing services under study only included mechanical bicycles and did not incorporate any information on sharing logistics (rebalancing of bicycles, servicing, and special docks production). Incorporating the cost of rebalancing and servicing the vehicles is crucial, given that for most BSS services in Europe and the USA, this represents one of the main burdens of a sharing service [20].

No studies have yet assessed the environmental impact of the introduction of shared e-mopeds, shared docked bicycles, and shared electric bicycles using both LCA and modal change statistics. E-scooter sharing has been the only micromobility mode that is repeatedly reviewed by multiple studies in the literature. To date, to the best of our knowledge, no study has attempted to compare the environmental performance of all the different micromobility vehicles, while considering their combined operation in a city using surveys to account for modal change.

3. Methods

3.1. Survey

This study uses the NEWMOB survey, as the main source of information regarding modal change from conventional modes to micromobility modes. Through Computer Assisted Personal Interviewing (CAPI), private e-scooter, e-moped, and BSS users were randomly stopped and asked to answer a questionnaire during a period of 10–15 min. Participants were intercepted just before they would start a trip, during an ongoing trip, or immediately after finishing a trip. At the end of the two-week survey, a total of 942 users had participated. Survey responses were restricted to individuals living and/or working in Barcelona and reporting their age as 16 years or over. The survey included blocks of questions on socio-demographic characteristics, daily travel behavior habits (modal choice, number of trips, daily destinations, time spent on travelling, etc.), relation to other modes of transport and multimodality (weekly modal split, perception of other modes of transport), and the use of public space and mobility (sharing the space, circulation, perception of use of bike lanes, etc.).

The survey was designed to identify the changes in transportation modal choice brought about by the new arrival of four new modes of transport: Shared mechanical bicycle, Shared electrical bicycle, Shared electric moped, and Personal Electric Scooter (e-scooter).

Questions included information on the mode the users travelled with before switching to the new mode, with the potential answers being listed as: Walking; Electric scooter; Personal bicycle; Shared bicycle; Personal electric bicycle; Shared electric bicycle; Personal motorbike; Shared Motorbike; Personal electric moped; Shared electric moped; Private car, Metro (subway), FGC (regional train), Rodalies (regional-mid distance train), Those who would have not taken the trip; Other.

We unified the three modes of railway transport (Metro, Ferrocarrils Catalans de la Generalitat, and Renfe Rodalies). The total number of valid answers that were sampled was 902.

3.2. LCA

Life Cycle Assessment (LCA) is a type of study in which environmental impacts of the value chain of a product or service are accounted for [29,30]. LCA has been widely used to assess the environmental burdens of public transport, private transport [31,32], and micromobility [33,34]. Life Cycle Impact Assessment (LCIA) provides a wide range of environmental performance indicators, depending on the method selected. In this study, we performed a LCIA with the ReCiPe 2016 [35] impact assessment method, and with the APOS approach over the inventories of the ecoinvent 3.5 database using OpenLCA 1.10.3.

The chosen indicators were Global warming potential, Fine particulate matter formation potential, and ozone formation potential in order to assess both the global warming and the public health issues that urban transportation causes.

3.2.1. Reference Units and Processes Included

The following transport modes were analyzed: walking, private mechanical and electrical bicycle, shared mechanical and electrical bicycle, private electric moped, shared electric moped, private e-scooter, motorbike, car, bus, and train. We calculated the impact of transporting a passenger, setting the functional unit (FU) of the LCA as the transport of one person over one kilometer, measured in units of passenger-kilometer traveled (1 pkt) in the year 2021. The complete value chain of the vehicles was included: manufacturing of the vehicles, distribution, maintenance, the use stage (including infrastructure, fuel, operation emissions, and sharing service logistics), and the end of life (EoL) treatment. The sharing service logistics require bicycle smart docks, and rebalancing/servicing vehicle fleets, which are included in the LCA. Direct emissions from fuel consumption and friction wear by sharing logistics and bicycles were accounted for. All processes covered in the analysis are presented in Figure 1.

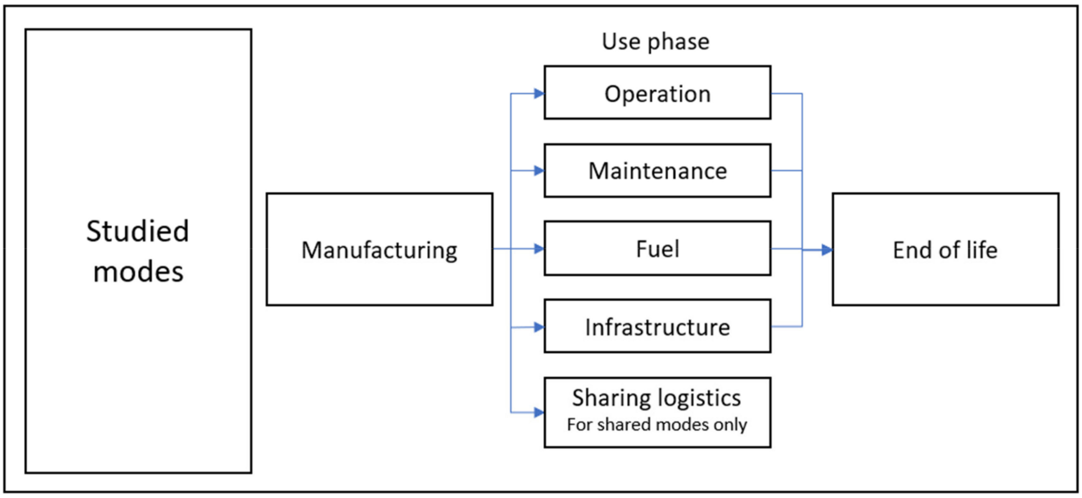

Figure 1. System boundaries of the Life Cycle Assessment used in this study. Foreground systems are the manufacturing and use of both vehicles and sharing logistics.

Below, we explain the main research and assumptions made for the construction of the life cycle inventory. The specifically used ecoinvent processes and adjustments are shown in Supplementary Material S1.

Shared Electric and Mechanical Bicycle

In Barcelona, most BSS trips use Bicing [7]. Thus, this service serves as the reference for electric and mechanical bicycle-sharing transport in this study. The weight of the mechanical bicycles is 24 kg, while the electric bicycle weighs 29 kg. The mechanical and electric bicycles were assessed by using the ecoinvent reference weights of 17 kg and 24 kg, respectively. The electric bicycle's extra weight comes from the added battery and electric motor. Ecoinvent processes for the production and end of life of mechanical and electrical bicycles were upscaled to Bicing bicycles weights for this study. In the production process, it is assumed the bicycle is produced in China and transported to Europe. The literature is still unclear regarding the life spans of shared bicycles [24]. We will assume the maximum lifespan of the shared bicycles, both electrical and mechanical, is 10 years, which is the length of the contract with the operator. The rate of replacement of the bicycles due to vandalism, theft, and misuse, 20.35% yearly, was calculated based on previous budgets from Bicing [36]. Given that the bicycles travel 4019 km yearly on average, the useful distance of shared mechanical and electric bicycles is 13,200 km. For electrical bicycles, the battery must be replaced 2.42 times during the bicycle life cycle on average [23].

In the use stage, used electricity, the use of the road infrastructure, and the wear emissions are considered. The brake, tire, and road wear emissions were not considered in the ecoinvent process when accounting for bicycle transport. However, since this output is important for the study, we computed this by downscaling the wear emissions from an electric moped [19,23] based on the weight difference with the bicycles. The estimated electricity to transport a passenger is 0.01 kwh/km [23], and the bicycles are charged at the docks with low voltage renewable energy [37].

The Bicing service has 517 stations placed around the city, with one Kiosk each and an average of 27 hybrid docks for every station [36] (thus, there are 517 kiosks and 13,959 docks in total. Since we had no physical access to the materials of the stations, an estimation has been undertaken for docks and kiosks, based on the previous LCA literature on bike-sharing stations. [20,21,24]. The inventory of docks and stations is detailed in the Supplementary Materials. The lifetime of the stations is assumed to be 10 years, which is the duration of the contract Bicing has with the current provider [36]. A grand total of 28 million kms are traveled yearly with Bicing bicycles, which means that one station is needed per every 54,437 Bicing pkt and one dock per 20,161 Bicing pkt.

To ensure bicycles are available in all stations, this BSS includes a rebalancing service that transports the bicycles from full stations to empty stations. The fleet is composed of 30 electric LCVs, Goupil G4, according to declarations from the operator. The vehicles are composed of a chassis weighing 634 kg and a battery weighing 140 kg, which has to be replaced once during the vehicle's life [38]. They are attached to a metal trailer to carry the bicycles, which has been estimated as having a weight of 500 kg after comparing its structure to similar trailers in the market. The average consumption of the vehicle is 0.19 kwh/km while loaded [38] and the renewable energy provider is used for charging. The travelled distances of the rebalancing fleet were estimated based on rebalancing data provided by Bicing. The total distance travelled is 0.012 km for every pkt travelled with Bicing.

The whole life cycle of those vehicles is included in the life cycle of regular and electric shared bicycles. Since no data were available for electric LCVs on ecoinvent, the manufacturing, maintenance, and transport processes for an electric car were adjusted to the weight of the Bicing vehicles, while taking the different battery weights and the different electric providers into account. To assess the trailers, the process of agricultural trailer production was considered due to high similarity and scaled to 500 kg.

Shared Moped

The model chosen as a reference for the vehicle impact is the standard e-moped used by Cooltra, since it is one of the most established providers. Cooltra is a Barcelona-based company that owned over 2300 vehicles in the city, before the regulations by the city council forced the company to reduce its fleet by 85% [39]. The provider uses the light Askoll eS2 mopeds, the chassis of which weighs 82.2 kg, including the pair of 7.6 kg Li-Ion batteries it carries [23]. We scaled the ecoinvent processes regarding electric moped production to the eS2 weight. The estimated life span of an e-scooter is 50,000 km and the batteries require one substitution over an e-scooter lifespan [40].

Road infrastructure and wear emissions are included in the ecoinvent processes [23]. The Askoll eS2 consumes 0.0294 kwh/km [41]. We assume most sharing moped providers use the regular electricity mix from Barcelona to charge their mopeds. The average occupancy of mopeds in Barcelona is 1.07 passengers per vehicle. We took that into account to comply with our functional unit in pkt.

All of Barcelona's moped sharing services are dock-less. The free-floating sharing systems require rebalancing as well as smart dock systems. Furthermore, free-floating sharing systems also need servicing, which in this case consists of swapping the empty batteries with charged ones on-site. We were not able to contact the major providers from Barcelona. Therefore, the distance travelled by the rebalancing/servicing fleet was approximated from the literature. The major moped sharing company in Paris (France) similarly uses electric LCVs for servicing and rebalancing, and they travel 0.02 km for every pkt travelled by e-moped [24]. Being similar to *Bicing*'s infrastructure, it was assumed the moped sharing uses the same electric LCVs fleet as *Bicing*; although, we assumed they use the regular electricity mix to charge the vehicles.

Private E-Scooter

E-scooters have surged recently and to our knowledge there are no datasets related to it in ecoinvent 3.5. To assess this transport method's production, we draw from the inventory of Hollingsworth et al. [25]) who disassembled a 12.5 kg Xiaomi M365, an e-scooter representative of the current market. In Hollingsworth's inventory, production and end of life are considered. We added shipping from China to Barcelona, by ship and road transport. The estimated life span of a private entry-level e-scooter is 4000 km according to the research conducted by De Bortoli [24].

To account for maintenance, we assumed e-scooter maintenance to be similar to that of a bicycle. Thus, we downscaled the process for bicycle maintenance to e-scooter weight. Due to the short life span of the vehicle, batteries do not need to be replaced.

E-scooter users in Barcelona cannot ride on the walkway and must share the space with bicycles [42]. Therefore, we considered that e-scooters use road infrastructure and accounted for it. We did the same for wear emissions since e-scooters have the same type of tires and brake pads as bicycles [25]. Electricity consumption for the Xiaomi M365 is assumed to be 0.011kwh/km, according to the company [43]; although, the data by the provider could be under- or overestimated. We assumed that private e-scooters are charged at home with the regular mix in Barcelona.

Conventional Modes

Life cycle impacts derived from the substitution of conventional modes of transport for new micromobility modes were calculated based on ecoinvent and adjusted to the vehicles used in Barcelona as we show below. The infrastructure impact is accounted for in all the conventional modes in their specific processes. The chosen processes are shown in Supplementary Material S2.

Personal bicycles weigh 17 kg on average, as in the ecoinvent reference, and electric bicycles weigh 24 kg. Their life span is 15,000 km; although, batteries for electric bicycles have to be replaced 2.75 times [23]. We assumed private electric bicycles are charged with the regular electricity mix. Personal e-mopeds weigh 90 kg and carry 32 kg batteries, according to ecoinvent. The life span of e-mopeds is 50,000 km, and the battery has to be replaced once. The average occupancy of mopeds in Barcelona is 1.07 passengers.

Due to the variability of the car market, we assumed a mixed fleet of 66% diesel and 34% of gasoline cars, according to a study undertaken by the city council [44]. We assumed both types of cars have an average weight of 1380 kg. We marginalized cars fueled with other technologies because they represent less than 1.5% of the fleet. Based on the Spanish traffic emission standards distribution in Barcelona and their equivalence to the European emission standards [44], we assume gasoline cars are EURO 4 and diesel cars are EURO 5 on average. The average occupancy of private cars in Barcelona is 2.24 passengers [45]. The average life span of a car is 150,000 km. For motorcycles, we considered an average gasoline 50 cc engine motorcycle weighing 90 kg with a life span of 55,000km [45]. Motorcycles in Barcelona have an average occupancy of 1.07 passengers.

In the public transport department: The public bus fleet of Barcelona is composed of 33.8% diesel, 34.2% natural gas, 31.2% hybrid, and 0.8% electric buses [46]. The electric buses were marginalized from this study's bus fleet because they represent a small share of the existing fleet. Hybrid buses use a diesel motor, consume 40% less fuel and carry a

210 kg battery, which has to be replaced 3.5 times during the life span of the bus [47]. The average occupancy of a bus in Barcelona is 13.59 passengers [46]. The average life span of a bus is 1,000,000 km [46]. To assess the train, we built an average train out of the three major rail transport services in Barcelona: Metro of Barcelona representing 52% of trips, Ferrocarils Catalans de la Generalitat with 14% of trips, and Renfe Rodalies with 34% of trips [48]. Metro trains weigh 170,000 kg on average [46,49]. FCG and Rodalies trains weigh 142,000 kg and 162,000 kg on average, respectively [50]. The train model from ecoinvent was downscaled based on the weight needed to fit the average train fleet in Barcelona. The occupancy of the metro, 108.3 passengers per vehicle [46] was taken as a reference. The average distance/lifespan of an urban train in Barcelona is 3,945,826 km [46]. The electricity consumption per passenger of a train is 0.083 kwh/pkt, according to Spielmann [45]. Due to differences in occupancy between the train noted in the literature and the Barcelona train, the consumption per passenger in Barcelona was calculated as 0.118 kwh/pkt.

Energy Sources

Throughout the life cycle of the operation, we distinguished between the electric and fossil-fueled vehicles, and between the different electricity mixes used for each process.

The electricity mix of cities in Spain can vary substantially [51]. For the sake of precision, since many of the studied modes are electricity powered, the assessed electricity mix is that of Barcelona. The electricity mix of Barcelona is not present in ecoinvent 3.5. Thus, the process containing the average electricity mix of Spain was changed by modifying the shares of the generation sources to match the Barcelona mix. The shares were obtained from the Barcelona City Council [52] Additionally, Barcelona's BSS uses electricity from the public system and 100% renewable electricity provider, Barcelona Energia [12,52], which mostly supplies public buildings and equipment. The adapted ecoinvent process was rearranged to extend the renewable generation sources to 100%.

3.2.2. Impact Assessment

The ReCiPe impact assessment method has been used previously on transport LCA studies [28]. For this study, we used the ReCiPe midpoint (Hierarchist). The Global warming potential indicator (GWP in kg CO_2 eq) was selected to assess the whole life cycle of the vehicles.

The Fine particulate matter formation potential (FPMFP in kg $PM_{2.5}$ eq) and ozone formation potential (OFP in kg NO_x eq) were also selected to assess the whole life cycle of the vehicles.

Exclusively for the "direct impact on the city" result (see Section 4.1), where we only take the emissions of the use stage into account, we excluded infrastructure use and fuel production, to leave only direct emissions (from combustion and friction wear) to be assessed. By setting this scope, we aspired to quantify the kg NO_x eq and $PM_{2.5}$ eq directly emitted on the streets, to assess the direct potential impact different vehicles have on the health of citizens.

3.3. Calculation of the Impact of the Modal Change

We relied on the survey and LCA data to consolidate the results. The consolidation was performed by combining the modal change shares obtained from the survey with the LCA results. The procedure we took for every selected micromobility means of transport is represented in this equation:

$$It = In - Iav = \mathrm{In} - \sum D \times Imode, \quad (1)$$

where It is the impact/pkt of the modal change from the old means of transport to the new one; In is the impact/pkt of the new mode, and Iav is the average impact/pkt of the replaced modes. In summation, D stands for the travelled distance where a substituted mode represents one substituted pkt (for example, if 20% of new e-scooter pkt travelled by bus before, D_{bus} will be 0.2), and $Imode$ stands for the replaced mode's impact/pkt.

Different modes have different average trip travel times and distances. Thus, we calculated the D instead of just considering the share of substituted vehicles to calculate the impact.

The equation to obtain the D (travelled distance where a substituted mode represents one substituted pkt) is shown below

$$D_{bus} = \frac{X_{bus} \times Y_{bus}}{\sum X \times Y} \quad (2)$$

With D_{bus} as an example, where X_{bus} is the share of users of a new micromobility mode that substituted the bus for the new mode, and Y_{bus} is the average distance traveled by the new micromobility users who substituted the bus for the new mode. D is obtained by dividing the multiplied X_{bus} and Y_{bus} by the summation (which contains the previous multiplication for each of the substituted modes).

To calculate the mean trip distances, we multiplied the mean trip times of the four micromobility modes when substituting every conventional mode by the mean trip speed of the four studied modes. The average trip durations for all the modal change cases were obtained from the survey (i.e., one of the questions asked for the trip duration) while average trip speeds (i.e., Regular bicycle: 10.16 km/h, Electric bicycle: 11.67 km/h, E-scooter: 12.5 km/h, and Electric moped: 23.9 km/h) were obtained from the literature [53–55]. Those average speeds represent city travelling speeds, pauses (as in traffic lights) into account. We assumed the traveled distance for the new micromobility trips was the same as the distance traveled with the previous vehicles. Different modes might have an impact on the travelled distance, making a significant change in their associated impacts. De Bortoli and Christoforou [27] showed that trips traveled with a shared e-scooter in Paris were 38% shorter than its displaced trips with conventional modes. However, those distance changes may depend on many factors including urban geography, road and public transportation grids, city cyclability, and average walking distance to public transport., Because such a study does not exist yet for our study area, these differences were not contemplated, in line with other LCA studies on micromobility [20,26,27].

Tables containing all average trip times and average trip distances are shown in the Supplementary Materials.

4. Results

4.1. Mode Replacement of Micromobility Users in Barcelona

Figure 2 shows the modal change results derived from the NEWMOB survey. The four modes caused a similar modal change. Almost half of the pkt who travelled on a shared (electric) bicycle or an e-scooter substituted traveling by urban train, and 15% replaced trips made by bus. Some differences to the general trend stand out; 20% of the pkt who travelled with an electric shared moped had substituted motorbike, which could be caused by the similarity of both modes. Electric shared bicycle had a high substitution rate from conventional shared bicycle, possibly due to the two options being available from the Bicing service and electric bicycles having gained market share in recent times. Shared Bicycle substituted walking to a higher degree than electrified and less active modes. Finally, the results show shared bicycle and shared electric bicycle's modal change mainly substituted public transport, while private e-scooters and shared electric mopeds had higher rates of private transport substitution.

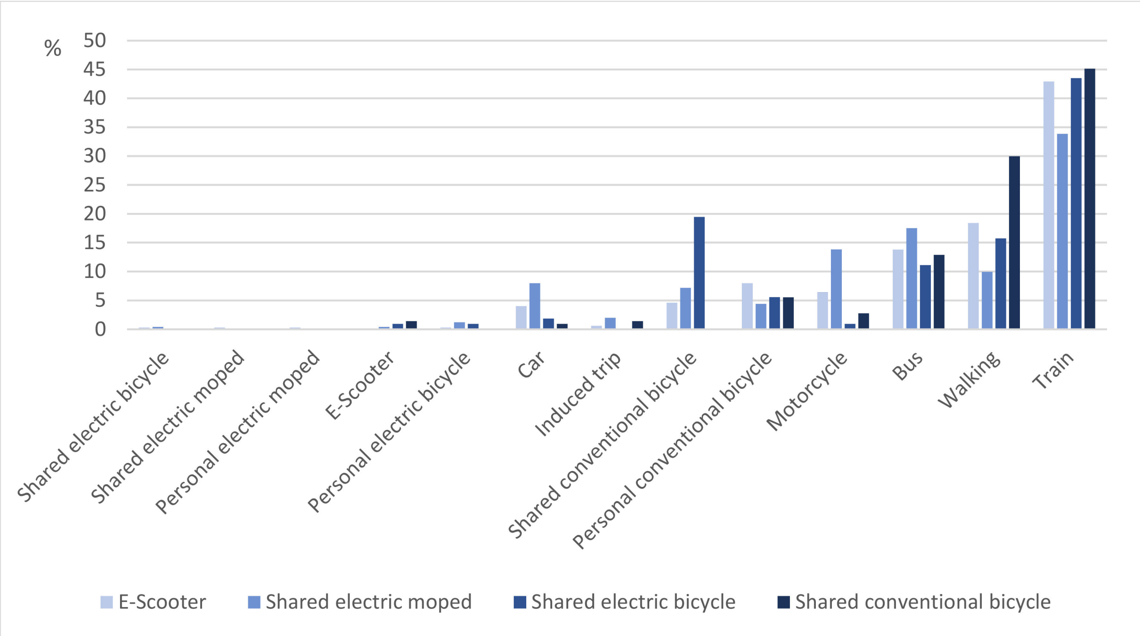

Figure 2. Modal change caused by the four studied modes of transport, in % over one pkt. S is shared, P is personal, and E is Electrical.

4.2. LCA Results

4.2.1. Global Warming Potential

After analyzing the whole life cycle of the modes of transport in Barcelona, results show target micromobility modes have a lower GWP (expressed in kg CO_2 eq) than the car, motorbike, and bus; although, only the e-scooter had a lower footprint than the train (Figure 3). As the figure below shows, rebalancing generates almost half of the CO_2 eq emissions of shared mopeds and more than half of the emissions for shared bicycles, making shared micromobility inconvenient compared to personal micromobility. The results also show dock sharing logistics (such as electric and regular shared bicycles) have a smaller environmental impact than free-floating sharing logistics (such as electric mopeds).

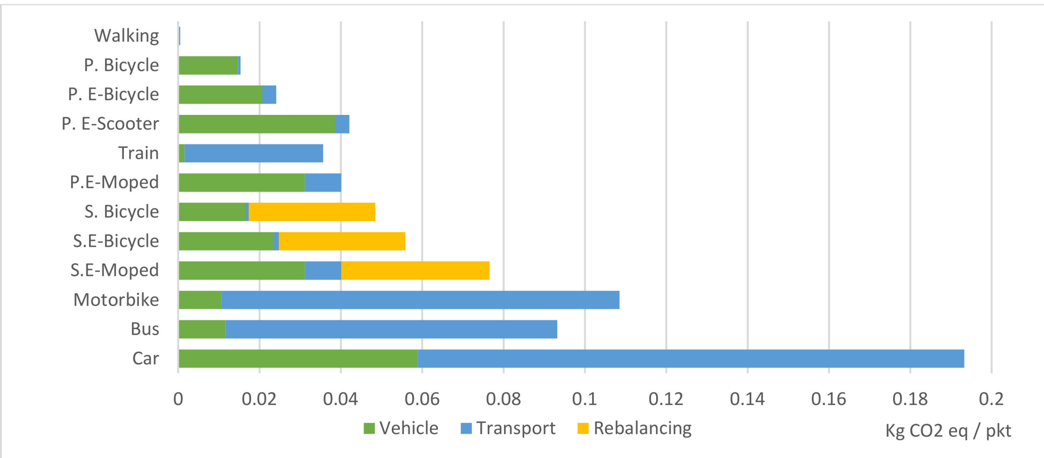

Figure 3. Global warming potential, in Kg CO_2 eq, for the whole life cycle of the different modes. 'Vehicle' represents the impact of manufacturing, distribution, maintenance, and end of life treatments of the vehicles per pkt. 'Transport' represents the impact of using fuel and wearing the road/wheels when transporting one passenger for 1 pkt.

The e-Scooter turned out to be one of the least harmful vehicles in terms of CO_2 eq emissions, and the least harmful of the four selected modes. Ninety-two percent (92%) of the CO_2 kg eq emitted from its life cycle came from the vehicle (production, distribution, maintenance, and end of life), while the use stage contributed the rest. In terms of CO_2 equivalent emissions, the shared electric moped was by far the most burdensome of the four micromobility modes studied. The sharing service logistics were responsible for 48% of the CO_2 eq. The shared bicycle's CO_2 eq emissions mainly came from the shared service logistics, which represented 64% of the said emissions in the case of the mechanical shared bicycle, and 55% for the electric shared bicycle. The shared electric bicycle vehicle stage was 40% more inconvenient than that of the shared regular bicycle (0.023 vs. 0.017 kg CO_2 eq/pkt) due to the higher weight and electric materials. Barcelona's BSS, using 100% renewable electricity, slightly reduced the use and logistics impact of traveling with a shared electric and regular bicycle.

4.2.2. Health

$PM_{2.5}$ and NO_x eq emissions of the selected modes mainly come from manufacturing and rebalancing (Figures 4–7). Taking the whole life cycle into account, the shared modes have emissions similar to those of combustion vehicles in $PM_{2.5}$ emissions, while they have a reduced NO_x impact.

$PM_{2.5}$ eq emissions from the life cycle are surprisingly high when we consider the whole life cycle of the new micromobility modes, especially those that are shared (Figure 4). The vehicle stage of the life cycle and the sharing logistics are the highest contributors. NO_x eq emissions of the four means of transport are much lower concerning other modes, in contrast with $PM_{2.5}$ eq emissions (Figure 5). Manufacturing and sharing logistics cause the most emissions throughout the life cycle. The positive impact of using renewable electricity stands out when comparing the use-based emissions from Barcelona's shared electric bicycle to other modes, such as personal electric bicycle, e-scooter, or electric mopeds.

Direct emissions to the urban environment are those $PM_{2.5}$ and NO_x emissions that occur only when the vehicles are being used; therefore, they are emitted directly into the city, and directly affect its citizens. Direct emissions come from fossil fuel consumption on transport, and abrasion from friction with the road, tires, and brakes. In this category, it is clear that our four modes plus all non-fossil modes have very low emissions of both $PM_{2.5}$ eq and NO_x eq when compared to fossil-powered vehicles (Figures 6 and 7). Shared services only have slightly increased emissions compared to their private counterparts due to the rebalancing of fleets.

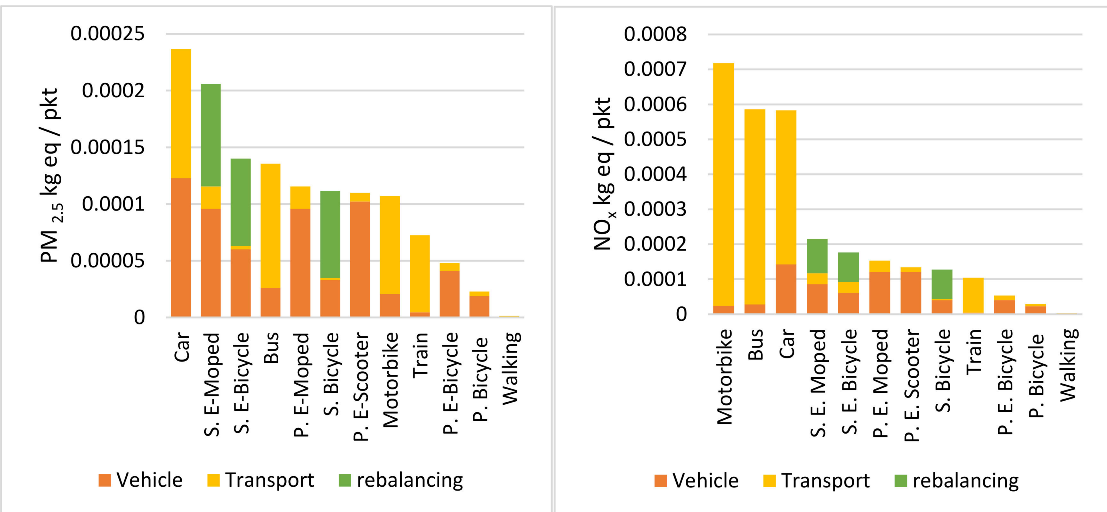

Figure 4. Fine particulate matter ($PM_{2.5}$ kg eq) and Ozone formation (NO_x kg eq) during the whole life cycle of the vehicles.

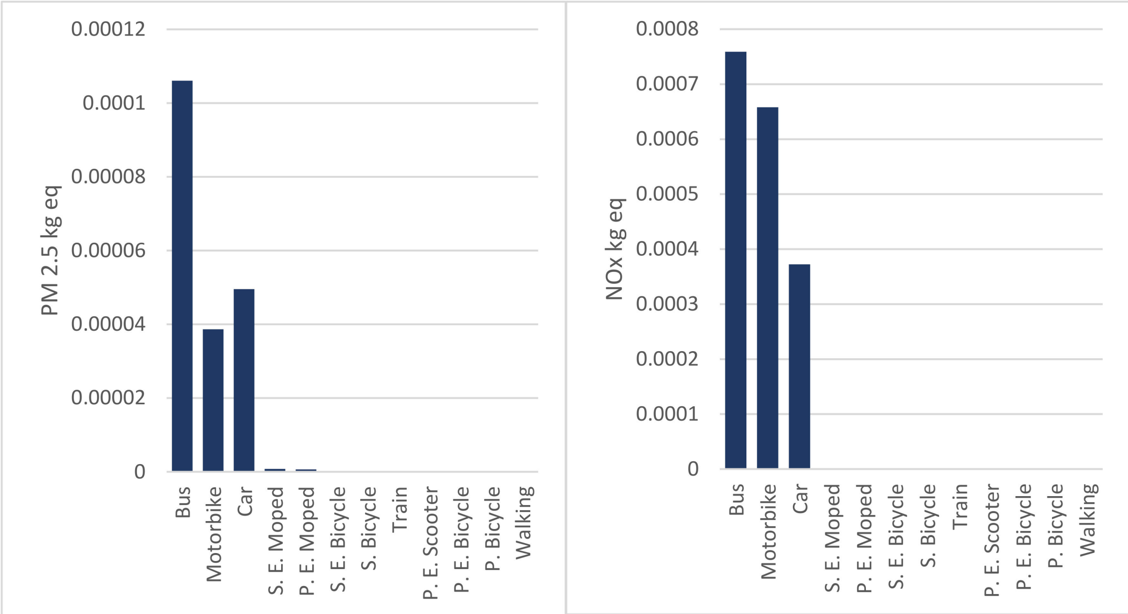

Figure 5. Human health hazards in Ozone formation potential (NO_x kg eq) and Particulate matter formation ($PM_{2.5}$ kg eq) of the direct use stage in the city (exhaust emissions and abrasion of brakes, tires, and road).

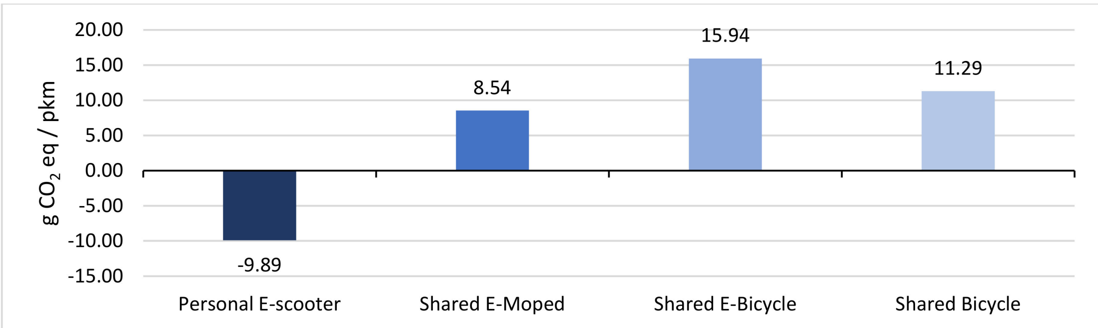

Figure 6. Global warming potential in CO_2 eq/pkt of the modal change caused by the four micromobility modes.

Figure 7. Human health hazard emissions of the modal change caused by the four micromobility modes during the whole life cycle of the vehicle (**left**), and pollutants being directly emitted to the streets (**right**).

4.3. Modal Change Environmental Impact

4.3.1. Effect of Modal Change on the Global Warming Potential of the Transportation Sector

When estimating the CO_2 eq emissions of each mode, while considering the modal change and the mode that these vehicles are replacing, personal e-Scooters appear to be the only mode that reduce their passenger's emissions, as they save 9.89 g CO_2 eq per pkt traveled with it (Figure 3). To contextualize, for every 19.54 pkt traveled with a personal e-scooter in Barcelona, the equivalent of a 1 pkt CO_2 eq by car is saved. This reduction is caused by the low impact of the e-scooter and the higher impact of the modes it replaces. In contrast, the shared e-bicycle appears to have the highest degree of negative impact (12.12 pkt traveled by electric bicycle causes as much CO_2 eq as 1 pkt traveled by car due to its caused modal change). Due mainly to the burdensome sharing logistics and vehicle processes, an e-bicycle's life cycle emits more greenhouse gases than the modes that it is replacing. Thus, modal change towards shared electric bicycles is causing a slight increase in the emissions of each trip. The impact of mechanical bicycles however is closer to net zero, which is mostly due to mechanical bicycles not needing batteries and not spending electricity to work. Shared e-mopeds, although emitting more CO_2 eq per pkt during their life cycle than shared electric bicycles, have a lower impact regarding modal change. This is because shared e-moped users were also those who polluted the most before switching to this new mode, as they used modes such as the motorbike or the private vehicle more often.

Personal e-scooters thus had the better performance in both LCA and modal change impact. This is caused mainly because of the absence of a sharing platform for those vehicles, which, as we have seen, makes up a large share of emissions for the other micromobility modes. It is noteworthy however that when only taking into account their vehicle and use stages, private e-scooters had a higher impact than electric bicycles.

4.3.2. Effect of Modal Change on Particulate Matter and Ozone Formation Potential

The modal change caused by e-scooters slightly reduced the emissions of $PM_{2.5}$ throughout their life cycle, while the other modes caused an increase (Figure 3) due to the impacts seen in the LCA results. NO_x emissions are lowered with all the studied modes except for the shared electric bicycle (Figure 4) since the main sources of NO_x are usually fossil-powered vehicles, and not enough shared electric bicycle users actually came from intensive NO_x modes such as cars and motorbikes to make it zero-impact.

Most particulate matter and nitrous oxide emissions from the four modes come from the vehicle and sharing logistics (Figure 5). Furthermore, the electricity needed to power the vehicles is produced outside the cities, so the only PM and NO_x city emissions attributable to our modes come from road, tire, and brake abrasion. These sources emit much less than the exhaust of motor vehicles, which explains why the modal changes brought by the four micromobility modes all reduced hazardous pollution on the streets.

5. Discussion

Any complete sustainability analysis of a specific mode of transport needs to incorporate the whole life cycle of the vehicle by using LCA methods. If we fail to consider the whole life cycle of micromobility we can plan mobility based on the wrong premises of what kinds of vehicles are desirable in our cities. In the case of micromobility, there are two additional key aspects to consider: (a) the importance of assessing the modal changes that have brought new users to these new modes of transport, and (b) the need to account for the impact of the sharing logistics phase. Our analysis was aimed at observing the environmental impact of micromobility in Barcelona using an LCA approach, and considering modal change and past transport habits of new micromobility users. To the best of our knowledge, this is the first analysis that provides such a complete analysis of micromobility modes in a dense and compact city that is characterized by high proximity and high rates of active mobility [56,57], making modal choice substitution analysis more important than ever.

Our results showed that shared micromobility increases the global emissions of particulate matter and NO_x, but because those emissions do not take place within the city, they also decrease the urban concentration of $PM_{2.5}$ and NO_x. Most emissions coming from micromobility modes, especially particulate matter emissions, come from the production of energy needed to run the vehicles and services, and the manufacturing of materials. Production of batteries, iron, and steel, which make up much of the weight of those vehicles, has been seen to emit substantially high amounts of $PM_{2.5}$ [58,59].

While micromobility has been deemed by some authors as a sustainable solution for cities [8], our results seem to challenge that assumption. Results suggest that, in fact, when considering modal change and substitution, all three shared modes studied caused an increase in GHG emissions and in $PM_{2.5}$ emissions. Our findings point to the personal e-scooter as the only mode that lowered the emissions of CO_2, $PM_{2.5}$, and NO_x eq, something that qualifies previous findings that explored the environmental burden of shared e-scooters [26,27].

Our results challenge the idea of current micromobility services as sustainable alternative transportation options. However, these shared services still hold significant promise in their capacity to become sustainable alternatives if they can implement the necessary improvements on the manufacturing and rebalancing phases of operation. By reducing the environmental costs of manufacturing through implementing eco-design, and rethinking/improving the rebalancing and servicing logistics, the impact of shared e-mopeds and shared e-bicycles would potentially decrease the negative environmental externalities, in order to provide an overall reduction in CO_2 and $PM_{2.5}$ emissions.

The results also suggest that a priority should be made of aiming to influence modal change and mode-replacement/substitution. As we have seen, the replacement of walking for micromobility is one of the greatest contributors to the environmental negative outcomes. For short-distance trips, encouraging shared and electric micromobility is counterproductive in environmental terms. On the other hand, encouraging modal change from cars and motorcycles to micromobility modes would result in an overall reduction in emissions, even with the current state of micromobility technology. That solution would be particularly promising in cities with a high share of private transport use, or in cities such as Barcelona where motorbikes represent a large share of private mobility [60,61]. Ultimately, the more sustainable and healthier way to integrate these new micromobility services could be to make them complement public transportation grids [62], and to tailor their use towards mid-distance trips. It has to be noted, however, that some research has already challenged the idea that micromobility can be an effective complement to public transportation systems [63].

In cities where private transport accounts for a large share of the modal split, such as many North American cities [64], the modal change brought by the new micromobility services is much more likely to have a positive impact on sustainability since private and more polluting modes would be substituted to a higher degree. Likely, cities connected to an electric grid largely dependent on fossil fuels would also benefit from a switch towards those micromobility modes, since electricity consumption per passenger of electric bicycles, e-mopeds, and e-scooters is lower than that of train passenger consumption.

To understand how the environmental performance of micromobility can be improved based on the life cycle of the vehicles and the observed modal changes, various scenarios have been carried out. Those are available in the Supplementary Materials.

6. Conclusions

This study aimed at performing a life-cycle analysis to fully address the contributions of modal change towards micromobility modes in Barcelona. To do so, we assessed emissions attributed to the whole life cycle of shared bicycles, shared electric mopeds, and personal e-scooters. To complete the analysis, we used an ad hoc survey to map modal change substitution and understand where the new micromobility users come from, in terms of modal change. That analysis allows us to estimate the environmental burden of micromobility, not only by considering the whole life cycle of the vehicles, but also the modal change that they are causing in Barcelona's everyday mobility.

Results of the combination of reported modal change and LCA data show the rise of shared electric mopeds and shared electric bicycles in Barcelona is causing an actual increase in GHG emissions. On the other hand, personal e-scooters substantially decreased GHG while shared traditional bicycles only slightly decreased them. All micromobility modes appeared to diminish NO_x emissions, while only the personal e-scooter decreased particulate matter emissions.

The largest environmental impact of the studied micromobility modes comes from the sharing logistics phase and from the modal shift that has brought new users to these micromobility modes (more than half of the substituted kilometers were formerly traveled by walking and train, two modes with a smaller environmental impact). On the positive side, shared micromobility appears to have potential if the ecodesign and the life span of the vehicles improve, and modal change is considered when this is implemented. In cities with a poor public transportation system and a high dependability on private transport, the new micromobility modes will probably have a more positive impact, while in European cities, they will have to be deployed carefully, keeping in mind that micromobility is not always the most sustainable solution.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su14074139/s1, S1: Used Ecoinvent processes and adjustments for the mode's life cycle inventory. S2: Components and processes for rebalancing infrastructure. S3: Calculation of Average trip distance. S4: Scenarios.

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Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: Data from this study is available upon request and subject to ethics and confidentiality criteria.

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Limitations of the Study: A few assumptions in the LCA have been made due to a lack of available data (see Section 3). Values such as the average lifespan of vehicles are still under debate. Additionally, while CO_2 eq emissions are equally impacting, no matter in which stage those are emitted, other emissions such as hazardous pollutants (NO_x, $PM_{2.5}$) will have a different impact depending on the stage, time, and space in which they have been emitted. LCA cannot assess the impact those pollutants will have on human health; it can only quantify the emitted quantity per process. The analyzed human health pollutants have a local effect rather than a global effect, which is why we separated their emissions into the global emissions during the whole life cycle and the pollutants directly emitted in the city. Regarding the pkt difference per trips from point A to point B travelled with different modes, it has been assumed said distance is equal, following the steps of previous studies that made the same assumption. Although some literature has estimated the pkt differences between different modes, the results of those may vary greatly between different cities. For future research, it would be interesting to calculate that difference for the city of Barcelona, to obtain more precise results on the impact of modal change.

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