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2 authors:

Anne de Bortoli
CIRAIG

Zoi Christoforou
University of Patras

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Consequential LCA for territorial and multimodal transportation policies: method and application to the emergence of free-floating e-scooters in Paris

Anne de Bortoli[1*], Zoi Christoforou[1]

1 University of Patras, Department of Civil Engineering, Panepistimioupoli Patron 265 04, Patras, Greece

* Corresponding author; e-mail: anne.de-bortoli@eurovia.com

ABSTRACT

This paper presents a method to use consequential Life Cycle Assessment (cLCA) to evaluate the environmental consequences of transportation disruptions or policies on a given territory. This method is applied to the case of the emergence of free-floating e-scooters (FFES) in Paris, to calculate its impact on climate change. The LCA is conducted on OpenLCA, using the CML characterization method, the ecoinvent 3.2 background dataset, the consequential system model, field data from diverse sources and modal shifts estimated through a dedicated survey. The study considers trip substitutions from all the Parisian modes concerned – personal or shared bicycles and motor scooters, private car, taxi, ride-hailing, bus, streetcar, metro and RER train. All these modes and the FFES are assessed for the first time in the Parisian context using cLCA. The results estimate that over one year, the FFES generated 13 thousand extra tons of CO2eq under an assumption of 1 million users. A scenario analysis shows that an extension of the lifetime mileage is not sufficient to get a positive balance, and that reducing drastically servicing emissions is required. Then, a sensitivity analysis switching the French electricity mix for 9 other country mixes suggests a better climate change effect potential of the FFES in metropolitan areas where electricity mixes have high-carbon contents, such as in Germany and China. Finally, an extended discussion comes to enlighten future refinements needed on such kind of studies.

Keywords: free-floating e-scooters; climate change; consequential LCA; territorial public policies; transportation disruptions; modal shifts;

1 Introduction and background

The 22nd of June 2018, Free-Floating Electric Scooters (FFES) started to be deployed in Paris by the leading company of the market (Kristanadjaja, 2019). After 6 months, the company reported two million rides made by 315 000 users in the city, representing almost 8% of its annual rides worldwide (Lime, 2019). One year after this launch, the city counted 13 operators and a total fleet estimated between 20 and 40 000 FFES (Cosnard, 2019), making Paris the first market for FFES in the world (6t, 2019a). The rapid and massive emergence of these microvehicles in a fragile urban traffic status quo has triggered resentments from other street users, and sometimes a mistrust from public authorities. In France, the Government developed a new section in the Highway Code to regulate motorized microvehicles usage, now strictly forbidden on sidewalks or at speeds over 25 km/h – 15 mph (French Department of Homeland Security, 2019). The city of Paris decided to launch an invitation to tender based on environmental and social criteria to select only 2 or 3 companies allowed to operate (Cosnard, 2019). But the environmental consequences of FFES are today highly uncertain and have just started being assessed.

The FFES has often been advertised in their operator communication campaigns as an opportunity to preserve the environment, as it would reduce congestion, air pollution, automobile usage, and, most of all, greenhouse gas (GHG) emissions (Lime, 2018). Some figures about the effect on climate change have been given, without information on the assessment methodology. For instance, the leading company has announced in its one-year activity report that its first 6 million rides would have saved 2.3 M kgCO_2eq in total, with around 14% of these savings occurring in Seattle, Washington, and 10% in Dallas, Texas (Lime, 2018). Nevertheless, no similar figures were presented in the following year's annual report (Lime, 2019). Indeed, the potential environmental benefit of FFES was severely contested in 2019 through the question of the FFES lifespan: a first study quickly estimated it equal to 29 days in Louisville, Kentucky (Quartz, 2019), based on an ambiguous FFES unique identification number from an open dataset formerly provided by the city (Mattingly, 2019). Without information on the distance traveled a day, this study does not provide any clue to the environmental performance of FFES. Nevertheless, a first life cycle assessment (LCA) attempt on FFES was performed by a consultant, using generic data and rough assumptions (Chester, 2019). Chester found that FFES would emit between 200 and 460 gCO2eq/km. More recently, 4 personal microvehicles have been assessed using LCA in the context of Paris. This study estimated the impact of the personal electric scooter between 12 and 32 gCO2eq/km for a life cycle mileage between 5 200 and 15 600 km (de Bortoli et al., 2020). Finally, Hollingsworth et al. conducted an LCA of FFES in the context of Raleigh, North Carolina, including uncertainty analysis. Based on local surveys and a material inventory obtained from the dismantling of a Xiaomi M365, they found very variable FFES carbon footprints depending on the assumptions made, and an average impact in Raleigh's context around 126 gCO2eq/km (Hollingsworth et al., 2019). Half of the impact would come from the manufacture of the microvehicle (mainly from aluminum and the lithium-ion battery), while the rest would mainly come from servicing, i.e. the collection and distribution of FFES to recharge the batteries. We now have a broad environmental performance range of electric scooters (ES) and first LCA models that have be adapted to every specific situation - to match the technosphere and the ES usage characteristics - to get a robust assessment. But to our knowledge, no assessment of the global environmental impact of the FFES breakthrough at a regional scale has been performed yet. In particular, the FFES are mostly used instead of other pre-existing transportation modes, but extra trips are also generated by this new transportation supply, as demonstrated by different surveys (6t, 2019a; Hollingsworth et al., 2019; Lime, 2018; Portland Bureau of

Transportation, 2018). Finally, we do not understand the total environmental effect of this general change in mobility consumption.

LCA is a method to calculate the environmental performance of a system over its entire life cycle, from cradle to grave. It is standardized by the ISO 14040 and 14044 (AFNOR, 2006a, p. 14040, 2006b, p. 14044), these standards still allowing a great flexibility in the way of using the method. Different approaches in LCA can be adopted. Attributional LCA (aLCA) is often opposed to consequential LCA (cLCA). While aLCA is most common and aims to assess the average environmental impact of a static system, cLCA is ambitioned to assess the environmental consequences of an action or a decision on a system. cLCA particularly includes economic market mechanisms into the analysis (Zamagni et al., 2012), and should be systematically used when a social responsibility paradigm is addressed by the assessment (Weidema et al., 2018). The cLCA concept appeared in 1993 (Weidema, 1993). It has been discussed and framed out since then, but it is still not consensual, thus still rarely and heterogeneously applied (Zamagni et al., 2012). In the transportation sector, cLCA remains rare. Sanden and Karlstrom first used it on bus fuel cell technology (2007). Then, Spielmann et al. applied it to high-speed transportation technologies and demonstrated the crucial effects of demand changes on the environmental performance of transportation projects (2008). Numerous applications for biofuels have also been performed - starting by the seminal study from Reinhard and Zah (2009) - as biofuel production implies heavy cross-sectoral systemic effects than must be addressed consequentially. More recently, a project of bus rapid transit in a Parisian suburb has been assessed hybridizing cLCA and the French socioeconomic appraisal, based on an attributional background data set but considering modal shifts (Bortoli, 2016).

Free-floating electric scooters have triggered an intense social debate about their value for society, and micromobility embodies a change in the mobility paradigm. Thus, a consequential approach will be selected to calculate the early evolution in the GHG emitted at the city scale after the arrival of FFES over one year, on the example of Paris as a hotspot for FFES. First, the generic method and its application to the case study will be explained, before detailing results and discussing them.

2 Method

The method is based on modal shift data and cLCA.

2.1 Consequential LCA for mobility: generic equations

Modal shift calculation

The first objective is to access the vector ΔPKT_{ms} of the modal shift mileage disaggregated by mode on the assessment period t. We will use the general Equation 1 to calculate its terms δpkt_i, with i the transportation mode considered, PKT_i the number of passenger-kilometers traveled (pkt) over the period of time t by the mode i in the reference scenario (no transportation disruption), PKT_i' the number of pkt under the alternative scenario, and ΔPKT_i the result.

Equation 1 Calculation of the terms of the modal shift modal vector on a time horizon of t

$$(\delta pkt_i) = PKT_i' - PKT_i = \Delta PKT_i$$

Environmental impact calculations

Then, the terms (ei_{ms}) of EI_{ms} - the vector of the environmental impact from the modal shift that has occurred over t - must be calculated following the Equation 2, with EF_i(resp. ‘) the environmental factor of the mode i under the reference scenario (resp. the alternative scenario). The total environmental impact is then calculated summing the terms of EI_{ms}.

Equation 2 Calculation of the terms of the vector of the environmental impact from the modal shifts

$$(ei_{ms}) = EF_i'.PKT_i' - EF_i.PKT_i = EF_i.\Delta PKT_i$$

Calculating Equation 2 requires estimating the environmental factor EF_i of each mode i affected by the arrival of FFES in Paris, an environmental factor being a unitary environmental impact, here the unit being the pkt. If the environmental factor does not vary significantly over time, the calculation can be simplified as followed by the last term of the equation, using an approximate EF_i factor. To calculate the Equation 2, we use Equation 3, with $EF_{veh,i}$ the environmental factor from the vehicle component of the mode i per pkt, $EF_{infra,i}$ the environmental factor from the infrastructure component of the mode i per pkt, $EF_{1veh,i}$ the environmental factor of one average vehicle of the mode i over its life cycle, $PKT_{1veh,i}$ the lifetime mileage of one vehicle, PKT_{ij} the number of passenger-kilometers traveled on the infrastructure j for the mode i, $a_{i,j}$ the "specific infrastructural demand" (Spielmann et al., 2007a) of type j by the mode i (see further explanations below), q_j the quantity of units of the infrastructure j used by the mode i, $EF_{1u,j}$ the environmental factor of one unit (surface or length) of the infrastructure j, b_{ij} the infrastructural allocation factor of the infrastructure j for the mode i, and VKT_{ij} the number of vehicle-kilometers traveled (vkt) by mode i on the infrastructure j.

Equation 3 Formula to calculate the environmental impact of a mode with a vehicle-infrastructure integrated approach

$$\boldsymbol{EF_i = EF_{veh,i} + EF_{infra,i} = \frac{EF_{1veh,i}}{PKT_{1veh,i}} + \sum_j \frac{1}{PKT_{i,j}}.a_{ij}.q_j.EF_{1u,j}}$$

$$\boldsymbol{= \frac{EF_{1veh,i}}{PKT_{1veh,i}} + \sum_j \frac{1}{PKT_{i,j}}.\frac{b_{ij}.VKT_{ij}}{\sum_i b_{ij}.VKT_{ij}}.q_j.EF_{1u,j}}$$

The term $q_j.EF_{1u,j}$ represents the environmental impact of the entire infrastructural network of type j in the perimeter studied.

Specific infrastructural demand

One kind of infrastructure can be shared by several modes: this is the case of roads, that are used by taxis, buses, e-scooters, motor scooters, bicycles, etc. Moreover, one mode can use several kinds of infrastructure: this is the case of microvehicles, using cycle lanes, roads and sometimes sidewalks. The specific infrastructural demand $a_{i,j}$ can vary depending on the type of vehicle i but also on the life cycle stage considered. Several approaches have been developed so far. In ecoinvent transportation LCIs, the impact of the infrastructure operation stage is allocated equally between vehicles (b_{ij}=1), while the burden from the rest of the life cycle is allocated linearly to the gross vehicle weight (Spielmann et al., 2007a). This approach has also been selected for the allocation of road burden to two-wheel vehicles by Leuenberger and Frischknecht (2010). Nevertheless, for roads, Chester developed a different approach, allocating the impact of the maintenance based on damage factors, linear to the axle weight raised to the power of 4 and neglecting the impact of light vehicles, while the rest of the life cycle burden was allocated equally between vehicles.

3 Calculation

3.1 Traffic pattern: modal shift data and assumptions

3.1.1 Paris survey protocol

The site

Paris region is divided into Paris inner-city ("Paris intra-muros", 2.1 M inhabitants (IAURIF, 2019)), roughly within a 6-km of radius circle, and Paris outer city, divided in two parts: the "inner suburbs", and the "outer suburbs". Most of the FFES are in Paris inner-city, while a few areas in the inner suburbs are also covered. Paris is very well served by public transportation, with 16 metro lines, 5 suburban railway lines, 4 tramway lines, and over 65 bus lines (OMNIL, 2018). Shared vehicle fleets have included over recent years: electric cars (2011-2018), electric motor scooters (since 2016), and bikes (since 2007).

Survey design

The survey has been carried out following a schedule and area sampling matrix designed to address both the spatial and time heterogeneities of the FFES usages. 7 locations have been preselected ranging from pure residential areas in the inner suburbs (Issy-les-Moulineaux) to Paris CBD (La Defense), also including two leisure sites (the banks of the Seine and the quays of St Martin canal), two major central public transportation hubs (Châtelet and République), and the area of Station F, the biggest startup campus in Paris. Varied time slots and days for the interviews have been selected to capture different user profiles.

Questionnaire and administering

A 15 minutes-long questionnaire has been developed to address different issues. In this paper, responses to the following questions will be used:

- Q1: How often do you use the electric scooter?
- Q2: If you had no access to an electric scooter, which mode would you have used primarily for this trip?
- Q3: If you had used this other mode of transportation, how long would it have taken you to reach your destination on the same route, in minutes?
- Q4: Where were you going?
- Q5: During this last trip, how long did you walk to reach the e-scooter, in minutes?

- Q6: With which transportation mode did you combine the use of an electric scooter during your last trip using it (several answers possible)?
- Q7: Did you take the scooter with you on board this mode (s) of transportation?
- Q8: What was the approximate distance of this trip (one-way, in km)?
- Q9: What was the approximate duration of this trip (one-way, in minutes)?
- Plus several socioeconomic characteristics questions: gender, age, household situation, income, education

The sampling method was made according to the rule of questioning the first person arriving at a fixed point after the completion of the previous interview. The interviewers provided a short explanation of the research objectives and no other incentive was offered to the respondents. With a response rate of around 85%, we only registered responses from people having already used e-scooters at least once in the past. After removal of people using exclusively personal ES, our sample counts n=445 responses.

3.1.2 New traffic patterns

FFES last trip length

The distance traveled using FFES, d_{FFES}, can be calculated using the following Equation 4, with $d_{lt,FFES}$ the total distance of the last trip given by question Q8, t_{walk} the walking time to access the ES given by Q5, and v_{walk} the walking speed, considered equal to 4.7 km/h (based on simulations made using Google Maps on 20 itineraries with different topographies in Paris):

Equation 4 Formula to calculate the ES ride distance during the last trip involving an e-scooter

$$d_{FFES} = d_{lt,FFES} - v_{walk} \times t_{walk}$$

Original transportation mode characteristics

Answers to question Q2 and Q3 give respectively the alternative mode and duration of the last trip made using an e-scooter if a FFES had not been available. Trips that were made by cars (taxi and ride-hailing, personal or shared cars), on foot or by personal two-wheelers are considered as single mode journeys. For the other modes, the trips are considered as combined with walking. Assumptions are made on the distances to be walked to access and leave each of the shared modes other than the FFES, based on expertise (see Table 1). The modal shifts due to FFES are reported in Table 1, as well as commercial speeds in Paris and the source of these figures. These modal shifts are trip-based: they are unweighted regarding the ES usage frequency of each respondent.

Table 1 Modal shifts characteristics: trip-based modal shift percentages, walking access assumptions and modal average speed

Mode	*Unweighted modal shift (%)*	*Accessing walking distance (m)*	*Previous data source*	*Average/ commercial speed (km/h)*	*Previous data source*
Walk	34.6	0		4.7	Calculated by authors from 20 itineraries in Paris, using Google Maps
Personal bicycle	3.9	0		15.0	Authors' estimation
Shared bicycle	3.5	400		15.0	Authors' estimation
Shared 2-wheelers	1.5	300	Calculated from Parisian data (6t, 2019b)	24.0	Considered equal to a motorbike (Andy, 2018)

Personal 2-wheelers	3.7	0	24.0	Calculated by authors from a Parisian experience (Andy, 2018)
Personal e-scooter	0.2	0	17.0	Authors (survey statistics)
Car	3.7	0	15.0	(Ville de Paris, 2016)
Taxi & ride-hailing	6.1	0	16.8	Average speed based on GPS data from a leading taxi company (Dell'oro, 2014)
Bus	11.5	400	12.5	(Carsuzaa, 2013); (ortferroviaire, 2018)
Metro	23.3	1200	30.0	(Carsuzaa, 2013)
RER	2.2	1200	49.5	(RATP, 2017)
Streetcar	0.4	1200	19.0	(ortferroviaire, 2018);(Carsuzaa, 2013)
Induced trips	5.4	NA	NA	NA

Thus, the distance that would have been traveled using the original mode, d_{om}, can be calculated using Equation 5, with $t_{lt,om}$ the duration of the last trip (including walking access) if no FFES had been available given by question Q3, d'_{walk} the total distance walked during the trip we assume in Table 1, v_{walk} the walking speed, and v_{om} the original mode average/commercial speed:

Equation 5 Formula to calculate the distance traveled with the principal original mode during the last electric scooter trip if no FFES had been available

$$t_{lt,om} = \frac{d'_{walk}}{v_{walk}} + \frac{d_{om}}{v_{om}} \Leftrightarrow d_{om} = v_{om} \times (t_{lt,om} - \frac{d'_{walk}}{v_{walk}})$$

The calculation of the traveled distance using the original mode calculated using Equation 5 considers average modal speeds and walking access distances, no multimodality, and is based on approximate individual declarations of time access to the FFES and durations of the trips. These uncertainties lead to unrealistic negative trip durations in 7% of the cases. An analysis of these cases shows the declared trip duration using the original mode seems too low to be consistent. To correct these values, we thus chose to keep the total length of the last trip using FFES instead.

Respondents weighting

The last trip distances traveled by FFES and the last trip distances that would have been traveled with the original transportation mode have now been estimated. Nevertheless, we want to obtain the total difference of kilometers traveled under the deployment of FFES, per mode, over one year. Each respondent gave the principal transportation mode he or she would have used if no FFES had been available. But some respondents are heavy users while others only used FFES once: we need to weight each answer based on each respondent FFES usage intensity to get a representative difference in mobility consumption from the sample. To do so, and considering the last trip is representative of the annual behavior, the weighting indicated in Table 2 will be considered, on an annual basis.

Table 2 Equivalent between the FFES usage frequency range declared and an average annual number of FFES ride

Declaration of FFES usage frequency range	Annual number of FFES ride	Explanation
"more than 5 times a week"	312	6 times a week, every week of the year
"4 to 5 times a week"	234	4.5 times multiplied by 52 weeks
"two to three times a week"	130	2.5 times a week multiplied by 52 weeks
"once a week"	52	
"Less than once a week"	15	
"I only used ES once" or "I stopped using the ES"	Not considered	

Generalization of the sample to the Paris usages

In Spring 2019, the pioneering and leading operator of FFES in Paris declared a total of 950 000 users in the city (6t, 2019a). 1/3 of the users have multi-memberships to increase their chance to get a FFES available (6t, 2019a), and they are very likely to be member of the leading company. We will consider that 1 M people have used FFES at least once in Paris. Considering our sample as representative of the users in Paris, we can calculate MC, the consequence of FFES deployment on mobility consumption in the city, using the Equation 6, with $N_{FFES\,users}$ the total number of FFES users in Paris, n our final calculation survey sample, WF_i the FFES usage intensity weighting factor for the respondent i, $d_{FFES,i}$ the last trip distance using FFES for the respondent i, and $d_{om,j,i}$ the last trip distance if using the origin mode of transportation j for the respondent i.

Equation 6 Differences in Paris mobility consumption generated by the FFES deployment

$$MC = \frac{N_{FFES\,users}}{n} \sum_{i,j} WF_i(d_{FFES,i} - d_{om,j,i})$$

The database has been cleaned following one criterion: all the responses leading to an average speed of the last trip using a FFES higher than 30 km/h have been deleted, considering these trips were probably made using personal ES, as maximum speeds of FFES available in Paris are limited (Maçon, 2019). The new sample size is n =411.

3.2 Carbon footprint by mode: Life Cycle Assessment

We want to know the environmental impact of moving about in Paris by 11 means of transportation: walking, personal bicycle, shared bicycle, personal two wheelers, shared two wheelers, personal cars, shared cars (taxi, ride-hailing, personal use shared cars), bus, metro, RER and streetcar.

3.2.1 LCA methodological choices and system boundaries

We will perform a process-based LCA. Our approach is consequential as it addresses the question of the environmental impact of a change of paradigm in the mobility. In order to reduce errors in our results, we will chose a consequential LCIs background dataset (Weidema, 2017) : we selected version V3.2 of the ecoinvent "Substitution, consequential, long-term database. We have focussed on climate change effects, and the CML characterization method with a time horizon of 100 years. The boundaries of each transportation mode system encompass both vehicle and/or equipment to move and infrastructure, as well as the entire life cycle: stages of production, use, maintenance and End-of-Life (EoL). The environmental factor of the mode i per pkt EF_i can be calculated using Equation 3.

We can classify the 11 modes in two categories of transportation: active and non-active modes. Their life cycles are illustrated in Figure 1. The main difference occurs in the use stage, where the motion energy comes from food in the case of active modes, but from fuel or electricity for non-active modes. Other stages include the production, maintenance, and EoL of vehicles or equipment and of the infrastructure that carry vehicles or pedestrians.

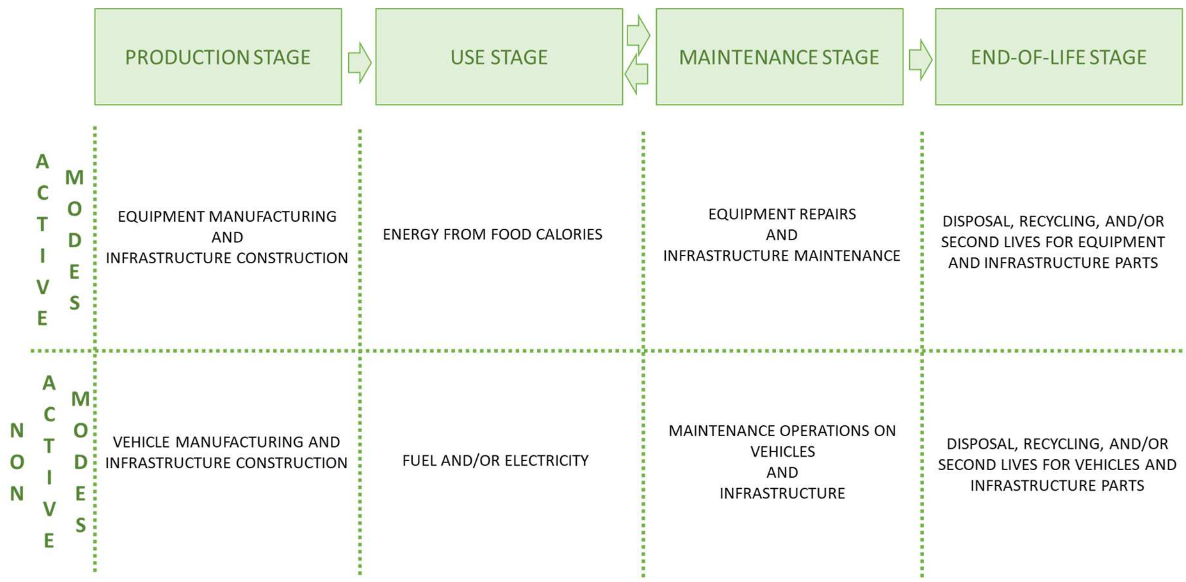

Figure 1 Life cycle of active Vs non-active modes

When ecoinvent processes are used in the LCA modeling of vehicle production, we will consider if the vehicle is bought on a global market or not. More precisely, global market processes will be chosen in the case of vehicles as consumer goods, namely personal vehicles but also vehicles provided by private operators. In the case of vehicles for public transportation, the choice of vehicle is not only driven by financial considerations, but also political and other aspects. Consequently, we will consider the most local markets for France.

3.2.2 Active modes

Choosing an active mode instead of a non-active one implies for the traveler extra output energy. This energy may or may not be considered in LCA of active modes. For instance, Dave (2010) considered commuters do not change their food consumption either by walking "given a reasonable walking distance and assuming sufficient nutrition is available", or by cycling.

But Thorpe (2016) considered the extra food consumed by cycling instead of driving and its related GHG emissions depending on the type of diet of the person. This second approach is interesting to study the impact of specific diets on physical activities impact. Nevertheless, more than half the population in the US (CDC, 2019) and in Europe (WHO, 2019) do not meet the recommendations on physical activity for good health from the World Health Organization (WHO, 2010) : we therefore chose not to consider the extra food consumed under active transportation, given the fact people should be generally more active. We also did not take into account the environmental impacts of shoes for walking, considering their multifunctionality. For bicycling, we considered the manufacture of an average bicycle on the global market and its maintenance (Leuenberger and Frischknecht, 2010).

3.2.3 Free-floating electric scooter Life Cycle Inventories

As a basis, we started from a LCA model previously developed for personal ES in the city of Paris (de Bortoli et al., 2020). This model considers a first-generation ES: the Xiaomi M365 with an autonomy range of around 20 km in Paris real traffic conditions and a 0.335 kWh battery capacity. The production, transportation, and EoL stages are considered to be similar when the ES model is the same. The only difference is the consideration of a treatment of the ES scaled down based on the weight, based on the electric bicycle LCI from ecoinvent. On the other hand, the use and maintenance stages will be different. The life cycle mileage of the ES, i.e. the number of kilometers traveled before breaking down, as well as the spare parts to be replaced and the maintenance operations, vary due to differences in the way personal and shared ES are handled. Indeed, rough usage or even vandalism are often reported by FFES operators. Last difference, a charging operation requiring transportation occurs in a FFES life cycle, while it is not the case for personal ES. As a base case, we considered a 500 charging cycle lifespan for the battery as specified by the manufacturer, and a 3 750 km lifespan for the personal ES, i.e. 1 year of total lifetime if used 11 km per day (average scenario in the study by Hollingsworth et al. (2019)). The ES collection baseline scenario to charge batteries is considered using light commercial vehicles (LCV) that come from and take the FFES to a suburban warehouse, 20 km outside Paris, and travel 10 km in Paris. Each LCV carries 100 ES, for a return trip distance of 0.9 km per ES every day to charge and distribute them. We consider the production, maintenance and EoL treatment of the LCV based on ecoinvent processes, and a lifespan of 150 000 km. The LVC consumption is 0.16 L/km and the tail-pipe carbon emission 0.403 kgCO2/km (ADEME, 2019). Each FFES would be used 11 km/day according to Hollingsworth et al. (2019).

3.2.4 Conventional original vehicles

The impact of the vehicle life cycle, not including the use stage, is calculated based on ecoinvent as synthesized in the supplementary material. We present the main assumptions and characteristics of the model.

The average car in France is 8.2 years-old with a 103771 km mileage (Kolli, 2012), for an annual mileage of 12 650 km. Considering a car can be operated for 2x8.2=16.4 years, its average lifetime mileage could be approximated around 200 000 km. Following the French statistics (Compte, 2018), we considered a fleet of personal cars made of 1278-kg vehicles, 61% of them using diesel and 39% gasoline. Consistently to most of the car LCA, we considered a mileage of 150 000 km over the life cycle. For taxis and ride-hailing, we considered a fleet composed of 82% diesel cars, 7% gasoline cars and 11% electric cars, representative of this market in the Parisian region (Ducamp and Tanca, 2019), a heavier weight of 1400 kg (+250 kg of electric battery if relevant) representing an average sedan car in the French market, and the same lifetime mileage.

The bicycles, electric or not, are manufactured in China and transported to Europe. A personal bicycle is supposed to weigh 17 kg like the ecoinvent reference, while the shared bicycles in Paris weigh 20.6 kg, with an additional electric motor of 2.2. kg and a lithium-ion battery of 3.9 kg on the electric version (Smoovengo, 2017). The lifetime mileage is assumed to be 15 000 km for a personal bicycle (Leuenberger and Frischknecht, 2010) and 4 500 km for the station-based bicycles, similar to the worst-case scenario assumption in Luo et al. (2019) due to vandalism and consistently with the lifespan of the electric bicycle battery according to ecoinvent assumptions.

The shared two-wheeler is an electric scooter of 120 kg with a 2.1 kWh fixed battery and a 1.9 kWh switchable battery (Fontanier, 2017), for a global battery weight estimated around 8 kg. We considered the personal two-wheeler to be a motor scooter. Both shared and personal two-wheelers are assumed to have a 50 000 km mileage (Leuenberger and Frischknecht, 2010).

The metro train was assessed by scaling down the process of regional train manufacture in ecoinvent. The ecoinvent train weighs 171 metric tons while a 5-carriage metro weighs around 131 metric tons. The RER train is scaled up based on an average mass of 230 metric tons. The streetcar is scaled up based on the ecoinvent process, a Parisian tram vehicle weighing 52 t while the model in ecoinvent weighs 21 t. The bus manufacturing, maintenance and EoL is approximated directly by the related ecoinvent process for a standard 13m-long bus, as Paris' bus fleet is composed of 80% standard buses, the rest being a mix of double buses and minibuses (OMNIL, 2019a). The theoretical mileages of the 4 previous vehicles come from Spielman et al. (2007b), except for the mileage of buses that comes from Parisian data (ADEME et al., 2018), and are specified in the supplementary material.

Assumptions for the use stage of these vehicles are now presented. Occupancy consumption and exhaust emissions are also synthesized in the supplementary material. Two original shared modes require servicing activities: the docked bicycle and the free-floating two-wheeler. We do not have data on the servicing for this latter. As the battery of the electric motor scooter is swappable, the impact is supposed to be low and we have not considered it. However, the docked bicycles need to be rebalanced between the stations: we considered a rebalancing distance of 27.5 m/bike-km, similar to the base scenario assumption in Luo et al. (2019), made by Euro 5 trucks (3.5 to 7.5 metric ton capacity).

The characteristics of the vehicle energy consumption during the use stage are detailed in the supplementary material. We considered data as close as possible to the Parisian context. We will consider that all the electric vehicles are fed with high-voltage electricity except the e-scooters. For public transportation, the main operator in Paris, RATP, gives the carbon emission of metros, streetcars and RER considering occupancy rates and electricity consumptions from the grid for 2017, and an emission factor of 48 gCO2e/kWh for the electricity. We can retro-calculate the consumption per passenger-kilometer based on these data, in order to calculate the carbon footprint for the use stage with a consequential approach instead of an attributional approach, and with the same background dataset, consistently with the rest of the model (SNCF, 2019). Metro and RER are powered with high-voltage electricity, from the French electricity market. Their occupancy is estimated with traffic data for the Paris metropolitan area (OMNIL, 2019b, 2019c), thus underestimated. The tail-pipe GHG emissions of gas-powered cars are taken from the French ADEME database and modeled using an elementary flow of carbon dioxide from fossil sources emitted in high density area, to which we added indirect emissions due to the supply chain of the fuels (ADEME, 2019). The gas burned is low-sulfur, with a density of 0.82 for diesel and 0.72 for gasoline. The consumption of the electric taxis is estimated around 25 kWh/100km. For taxi and ride-hailing, 50% of empty trips is considered according to a consultation of professionals (ADEME, 2019), and a 1.7 pax/vehicle occupancy when occupied based on a Parisian survey (6-t, 2015), leading to an average occupancy of 0.85 pax/vehicle. The direct emissions of buses per passenger-kilometer in Paris comes from SNCF for the year 2017 (2019), the average number of people in a 12 meter-long bus is calculated based on Parisian bus data (OMNIL, 2019c, 2019b) and the average consumption for indirect emissions taken as being equal to 0.35 kg/vkm (Spielmann et al., 2007b).

3.2.5 Infrastructure inventories, demand factor and allocation factor

To calculate the environmental burden from the life cycle impact of the infrastructure $EF_{infra,i}$ on each transportation mode i, we used Equation 3. In the case of an infrastructure type only used by one kind of vehicle, e.g. the metro tracks, the allocation is directly based on the demand factor, i.e. the inverse of the PKT on the infrastructure. This is also the case for a kind of infrastructure supporting vehicles with the same allocation factor and occupancy, e.g. cycle lanes that cater for bicycles and ES in this study.

First, we calculated $q_j.EF_{1u,j}$, i.e. the environmental impact of the Parisian infrastructural networks affected by the emergence of FFES: the metro railway, the RER railway, the streetcar railway, the roadway, the sidewalks and the cycle lanes. Each of these categories presents physical heterogeneity that are difficult to catch without proper asset management databases. The unitary impact of each type of infrastructure on a life cycle approach, $EF_{1u,j}$, was modeled using field data when possible, as well as generic data and ecoinvent (see details in the supplementary material). Because no specific data are available, the unitary LCIs for the streetcar infrastructure directly comes from the ecoinvent process “Tram track construction, CH", that models the impact of one meter of the infrastructure over one year based on the entire life cycle of a 6-meter wide double track concrete section, considering construction, renewal, operation, maintenance, and decommissioning. Some elements are considered out of the system boundaries, namely all the operations that happened only at the first construction stage or subsystems that will not be decommissioned, consistently with a consequential approach. This is the case, for instance, of the metro and RER tunnels, or the roadway earthwork. Thus, the ecoinvent process "railway track construction, CH" was used as a proxy to model metro and RER infrastructure LCIs for one meter and one year, as no data are available for these types of infrastructure in Paris. We did not consider coefficient ponderation based on width as most of the impacts may come from the rail (de Bortoli et al., 2019) and the operation. The other unitary LCIs are developed for the case study. The impact of pavement construction on climate change mainly comes from materials and manufacturing, then from transportation, while the impact of building machines is very low (Cuenoud, 2011; Kucukvar et al., 2014; Tatari et al., 2012; Vidal et al., 2013). This latter was not taken into account. Transportation over 50 km of the gravel and bitumen will be considered. A French process for the manufacture of Hot Mix Asphalt (HMA) is proposed (see supplementary material) based on field data. The type and quantity of energy consumed in asphalt plants for bitumen heating, gravel drying and HMA mixing come from Eurovia, a company that owns 35% of the national plants. Water consumptions and emissions to water and air come from a survey made on 8 asphalt plants in France (USIRF, 2016). The cycle lane network in Paris measures 742.1 km (Ville de Paris, 2016) for a surface of 106 hectares (Breteau, 2016), that is to say a width of 143 cm. It is delimited from the pavement and the sidewalk using two curbs of type T1 (54 kg of pre-casted concrete per linear meter according to manufacturer's catalogue). Its structure is modeled as a 15-cm layer of gravel covered with a 2.5 cm layer of hot mix asphalt (Conseil général des Yvelines, 2011) made of 6% bitumen and 94% gravel. The typical lifespan of the rolling course and the base are estimated to be namely 20 years and 60 years. For the sidewalks, we considered a lifespan of 20 years and a structure made of a subbase layer of 15 cm of gravel covered with 2.5 cm of mastic asphalt (10% bitumen and 90% gravels). Roads were modeled as a French T3 type of road (Corté et al., 1998), carrying up to 150 heavy vehicles per day and per direction, made of 15 cm gravel for the pavement subbase, 11 cm bitumen-bound graded aggregate (with 4% bitumen and the rest made of aggregates) for the base, and 4 cm HMA for the rolling course (with 6% bitumen). The lifespan of these layers is respectively 60, 30 and 15 years.

The volume of each network and supported mobility in Paris is synthesized in the supplementary material and comes from GIS treatments for the surfaces of sidewalks, cycle lanes and parking lots, roads and parking lots, as well as bus lanes (Breteau, 2016), and from the City of Paris for the length of the metro railways (Ville de Paris, 2016), approximated as if the entire network was in the inner city. The RER railway length is estimated at around 80 km, i.e. the length of the underground sub-network, while the streetcar tracks length measured on a map gives 29 km. This table also gives the demand and supply per mode in Paris - $PKT_{i,j}$ and VKT_{ij}. Public transportation data come from regional surveys for 2018 (OMNIL, 2019b, 2019c). For the other modes, the source of the data is the latest French transportation survey delimited to Paris inhabitants (DRIEA et al., 2013) corrected by the coefficient 2.08 to add traffic due to visitors. This coefficient has been calculated by comparing 14.6 billion, the total number of trips made in Paris every year, to 7.03 billion, the number of trips made by Paris' inhabitants in the inner-city. We need to estimate the vehicle-kilometers made by taxis and ride-hailing cars in one year. One taxi travels 57 700 km a year (CGDD, 2018). We assumed a ride-hailing car travels 25 000 km a year as many drivers deliver this service as a part-time job. Paris' prefecture counts almost 17 500 taxis in the city (CGDD, 2018), a figure close to the number of ride-hailing cars in the city estimated at 45% of the total of taxis and ride-hailing cars (CGDD, 2018), i.e. around 14 000. These figures lead to 1.36 billion vehicle-km traveled a year, and given that 4.85 billion of car-kilometers are traveled in Paris inner-city every year, this leads to a personal car traffic of 3.49 billion car-kilometers a year.

Finally, we calculated b_{ij}, to attribute a share of the environmental burden from the infrastructure to each mode. In the case of shared infrastructure – only the pavement is affected here – the relative use of the infrastructure for each mode has to be calculated through an allocation factor AF. If we consider that road pavements are designed based on axle weights over the lifespan, only heavy vehicles are responsible for these impacts (Chester, 2008). Nevertheless, a minimal mechanistic resistance is required to support light traffic as well. We hence considered that a heavy vehicle or a light vehicle are responsible for the same infrastructure burden. Bicycles and electric scooters can run on cycle lanes as well as on pavements with other kinds of vehicle. We did not allocate any of the pavement impact to the bicycles, considering pavements are designed for heavier vehicles. The figures about vkt on the Parisian roads by non-microvehicles come from the last data surveyed in the city in 2014 (AIRPARIF, 2018). Paris inner-city traffic and final allocation factors in 2017 and 2018 are detailed in supplementary material.

4 Results and interpretation

4.1 Consequences of the FFES disruption on Paris mobility

The annual mobility consumption changes in Paris, generated by the emergence of FFES over one annum, is calculated with the Equation 6. We present the results in Table 3. Under our hypothesis and despite the 5% of induced trips, the mobility consumption has decreased by 38.5% on a kilometer basis with FFES. A saving of 150 million kilometers traveled under a

1M users hypothesis. By comparing Table 1 and Table 3, we understand that the respondents weighting based on usage intensity, as well as the switch from a trip-based to a kilometer-based modal shifts, are two important stages to proceed with the consequential environmental assessment of mobility changes, as these stages have very important effects on the kilometers traveled results. Different explanations can be given. First, average trip distances vary significantly between transportation modes: walking trips are for instance relatively short compared to motorized trips. Secondly, the network density determines traveled distances between point A and B. Transit vehicles run on specific routes, not necessarily the shortest possible. These constraints create extra distances to travel from A to B, compared to FFES that allow to switch to more direct routes, only constrained by the existence of ridable streets. Table 3 shows that 2/3 of the weighted modal shifts come from PT: 50% from the metro, 9% from the RER and 6% from the bus. The modal shift from streetcar is negligible. Modal shifts from cars, either taxi and ride-hailing or personal and shared automobiles, accounts for 7% of the kilometers shifted. Bicycle, either shared or personal, accounts for 9%, and walk for 13%.

Table 3 Mobility consumption changes generated by the emergence of FFES at the scale of Paris over one year

		Survey sample (km traveled)	Paris base case (1M users)	Paris variant (0.5M users)	Weighted modal shifts (%)
FFES		9.73E+04	2.37E+08	1.18E+08	
Original modes	Walk	-2.09E+04	-5.09E+07	-2.54E+07	13.2%
	Personal bicycle	-8.30E+03	-2.02E+07	-1.01E+07	5.2%
	Shared bicycle	-6.33E+03	-1.54E+07	-7.70E+06	4.0%

	Electric motor scooter	-4.46E+03	-1.09E+07	-5.43E+06	2.8%
	Person motor scooter	-3.30E+03	-8.02E+06	-4.01E+06	2.1%
	Car	-7.35E+03	-1.79E+07	-8.94E+06	4.6%
	Ride-hailing	-3.37E+03	-8.19E+06	-4.10E+06	2.1%
	Taxi	-5.53E+02	-1.34E+06	-6.72E+05	0.3%
	Bus	-9.68E+03	-2.36E+07	-1.18E+07	6.1%
	Metro	-7.88E+04	-1.92E+08	-9.59E+07	49.8%
	RER	-1.48E+04	-3.60E+07	-1.80E+07	9.3%
	Streetcar	-4.04E+02	-9.84E+05	-4.92E+05	0.3%
	Total automobile	*-1.13E+04*	*-2.74E+07*	*-1.37E+07*	7.1%
	Total Public Transportation	*-1.04E+05*	*-2.52E+08*	*-1.26E+08*	65.5%
	Total kilometer shifted	-1.58E+05	-3.85E+08	-1.93E+08	100.0%
Total change in distance traveled (km)		-6.10E+04	-1.48E+08	-7.42E+07	-38.5%

4.2 Life cycle carbon footprint for most of the modes of transportation in Paris

Details of the calculation results from the application of the method described in part 2 can be found in the supplementary materials. The estimates of the GES emissions per mode of transportation in Paris are presented in Figure 2. They highlight the low contribution of the infrastructure in a city with very dense traffic, except for the streetcar mode where it represents 54% of the emissions. For all the modes powered by electricity, the impact of the use stage in absolute value is very low, but it contributes to respectively 80% and 58% of the total emissions for the RER and the metro modes. Taxi and ride-hailing is the most emitting mode with 296 gCO_2eq/pkt, due to low occupancy and large and heavy vehicles that consume thus emit more than the average personal car, presenting an emission of 204 gCO_2eq/pkt. Private motor scooters emit as much as private cars, with 210 gCO_2eq/pkt. The bus is the less environmentally friendly mode among the public transportation options in Paris, with 131 gCO_2eq/pkt, due to a rather low occupancy (17 passengers per vehicle) and a modeled fleet still using gas oil. Shared bicycles emit around 58.2 gCO_2eq/pkt due to the burden from the vehicle manufacture stage. Indeed, the rather short lifetime mileage of these bicycles in Paris is a problem in an environmental perspective. Nevertheless, it is still twice better than the shared e-scooters, that emit 104 gCO_2eq/pkt, half of the emissions coming from the servicing stage, and the other half from the manufacture also due to short lifetime mileage. The less emitting modes are shared motor scooters, streetcars, RER, metro and walking, respectively emitting 25.7, 20.1, 8.88, 7.59 and 1.93 gCO_2eq/pkt.

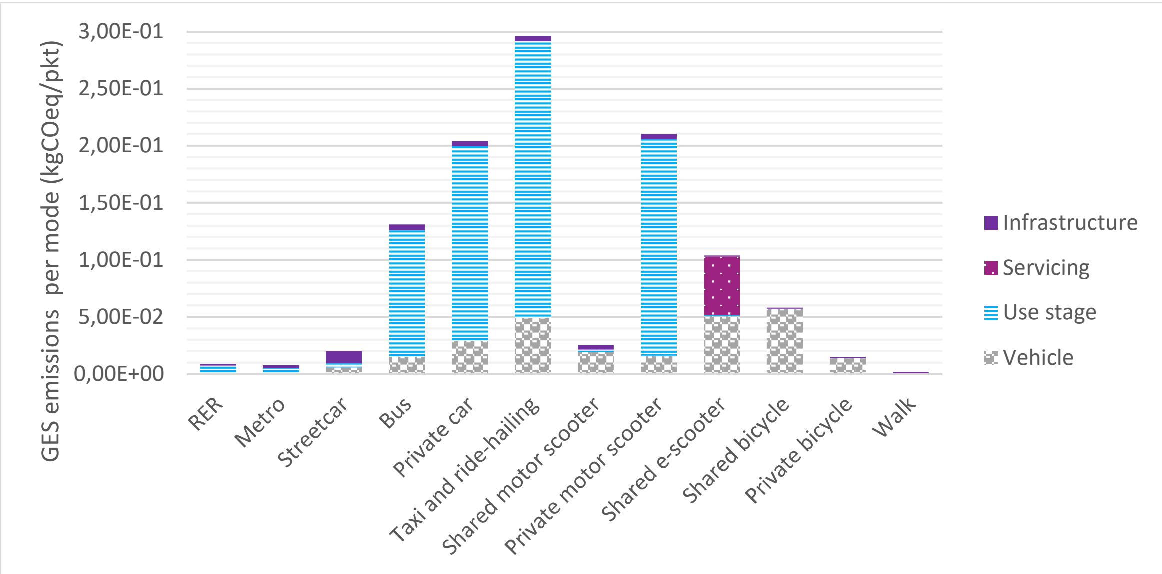

Figure 2 **Life cycle carbon footprint of the main modes of transportation in Paris**

4.3 Marginal effects of the FFES emergence on GES emissions in Paris over one year

Calculations show that the emergence of FFES raised the GES emissions of the mobility sector in Paris by 13 thousand tons of $kgCO_2eq$ over one year, if 1 million people were FFES users. Under a 0.5 M user assumption, this loss is cut by a factor of 2. Details of the marginal emissions over one year are presented in Figure 3. Most of the gains are brought by the modal

de Bortoli and Christoforou, Journal of Cleaner Production, Volume 273, 2020, 122898, ISSN 0959-6526, https://doi.org/10.1016/j.jclepro.2020.122898. Submitted version

shifts from buses, private cars, taxis, ride-hailing and private motor scooters. Most of the distance of the trips substituted by the FFES was traveled by metro as showed in Table 3. As this is a very low emission mode in Paris, the gain is far less than the losses due to the FFES. Figure 3 also highlights the feeble importance of infrastructure use change on this consequential study, while marginal impacts almost equally come from the use stage and the emissions from the rest of the vehicle life cycle. This is mainly due to the high contribution of the FFES' manufacturing to total burden over its complete life cycle.

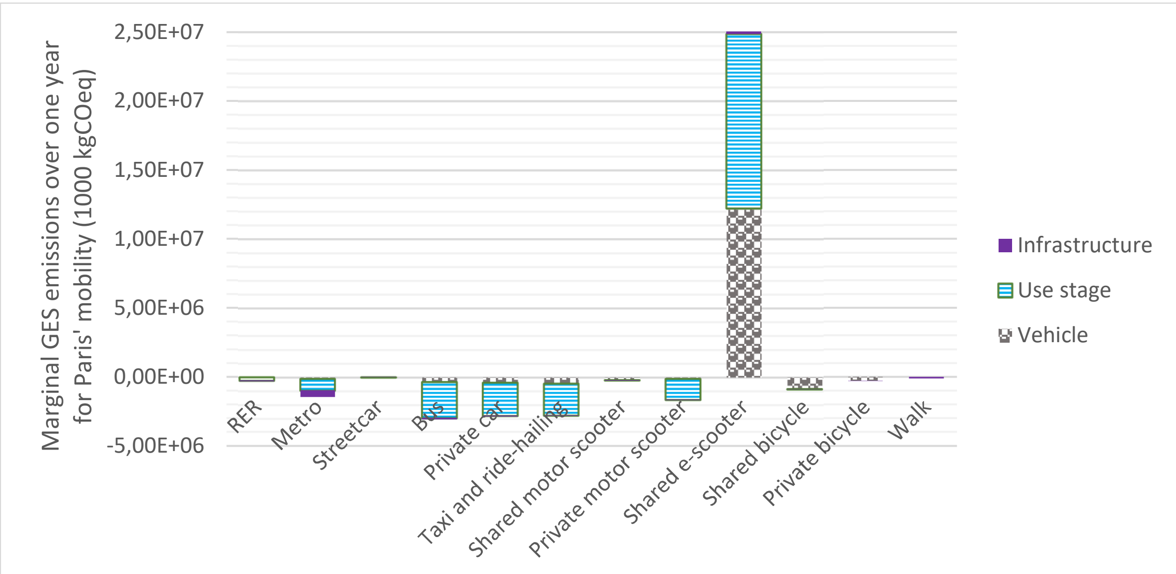

Figure 3 Marginal GES emissions, per mode, over one year for Paris' mobility (1000 kgCO2eq), with detailed contributions from the infrastructure, the use stage and the vehicles

4.4 Scenario analysis

We performed a simple sensitivity analysis, making three different factors changed one at a time (OAT SA): FFES lifetime mileage, FFES servicing scenario, and electricity mix.

4.4.1 FFES lifetime mileage

This first parameter was chosen for sensitivity analysis as the FFES lifetime mileage is frequently brought under the spotlight when it comes to their environmental performance, as discussed in the introduction. A range of [300;15000] km lifetime mileage was selected based on the worst-case scenario (Quartz, 2019) and the best case scenario observed on ES users forums. Results are presented in Figure 4. It shows that, in the Parisian context, with the current mobility system and the first observed modal shifts brought by the FFES emergence, whatever the FFES lifetime mileage, this disruption is a loss in terms of climate change.

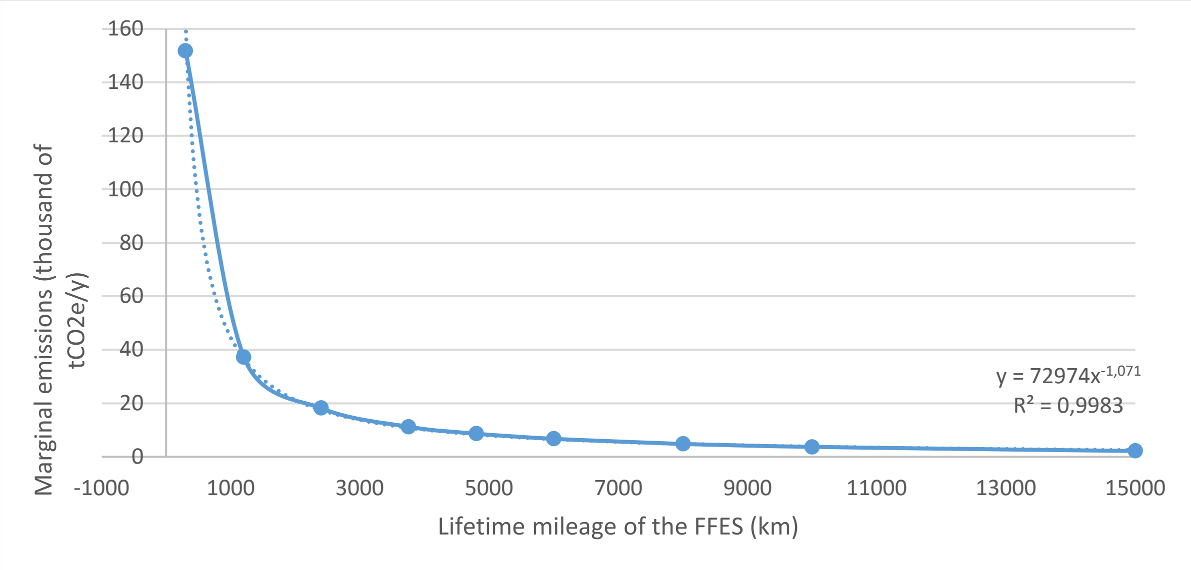

Figure 4 Consequential climate change contribution of FFES in Paris over one year depending on the lifetime mileage of the FFES

4.4.2 FFES servicing scenarios

This second parameter was chosen based on the observation of Hollingsworth et al. (2019), validated by our results in Figure 2 and Figure 3: half of the impact coming from using a FFES is generated by its servicing. This is based on the assumption of heavy gas-powered vehicles moving FFES over several kilometers every day. In Figure 5, we compare the results for our baseline servicing scenario (labeled "LCV 90 km 100 ES") with 6 alternative servicing scenarios, observed or not in Paris, presented in supplementary material: "LCV 90 km 50 ES" for a LCV charging only 50 ES and traveling 90 km, "juicer 10 km car" for an entrepreneur charging 11 ES in a car traveling 10 km, "swappable battery 90 km car" for 100 ES batteries charged in a car traveling 90 km, "swappable battery 90 km car" for the same scenario with only 45 km traveled, "riding juicer" for a person charging 2 ES on another ES over 4 km as a side activity; and "walking juicer" for a person taking 2 ES on foot over 2 km as a side activity. It shows that only the two juicer scenarios or the "swappable battery 45 km car" lead to a positive effect of FFES on the climate change in Paris.

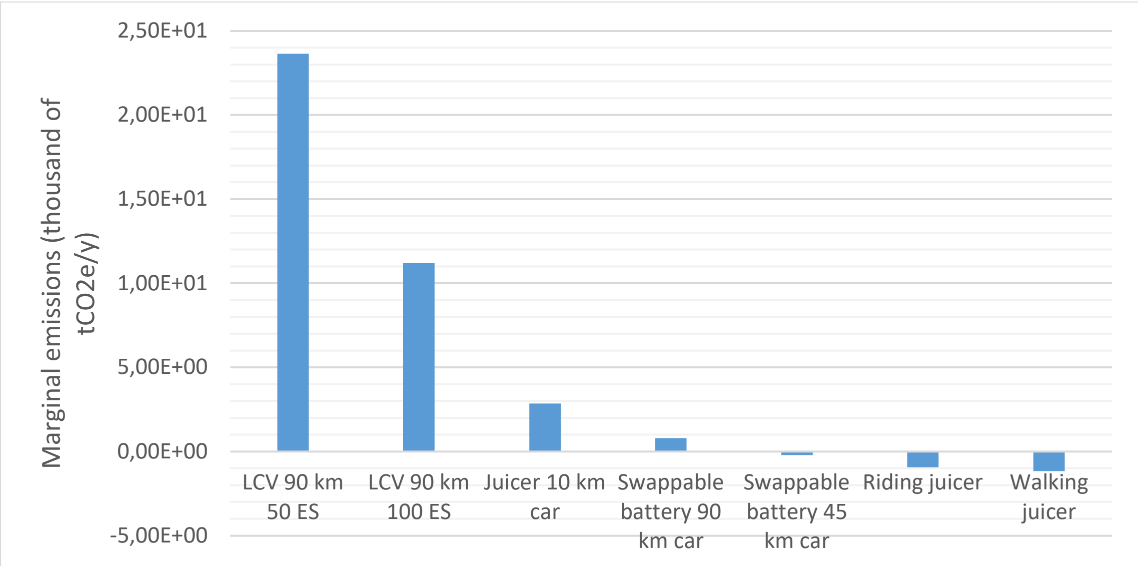

Figure 5 Consequential climate change contribution of FFES in Paris over one year depending on the FFES servicing scenario

Finally, in order to set simple servicing targets to get a positive influence of FFES for the climate, we studied the carbon footprint trends with the emergence of FFES in Paris depending on a continued distance for 5 different servicing modes: by LCV, fuel-powered car, electric car, ES or on foot. Results are presented in Figure 6. It shows a linear influence of the servicing distance on the final impact of the FFES. Moreover, using conventional means of transportation, only very short servicing distances would be allowed in Paris to made FFES a benefit for the climate: respectively under 7.5.10-3 km/pkm and 2.10-2 km/pkm using servicing LCVs and fuel-powered cars. The total servicing distance threshold will then depend on the number of FFES or batteries put in one vehicle and the number of kilometers traveled with the

FFES before charging it. E.g. if FFES are used 10 km before being charged and for a standard car accommodating 25 FFES, the servicing must not exceed 5 km, i.e. 2.5 km for a single trip. For electric cars, this threshold is multiplied by 3 *ceteris paribus*. This suggests a need for optimizing servicing rounds and charging locations, and probably even a necessity to switch from conventional ES to ES with swappable batteries to loosen operational organization constraints in dense urban contexts. Unless servicing is required to be made by active modes or using microvehicles. Indeed, using a FFES, the servicing distance threshold is 1.8.10-1 km, while on foot, this distance must be limited to 2.3 km to get a positive effect on the climate.

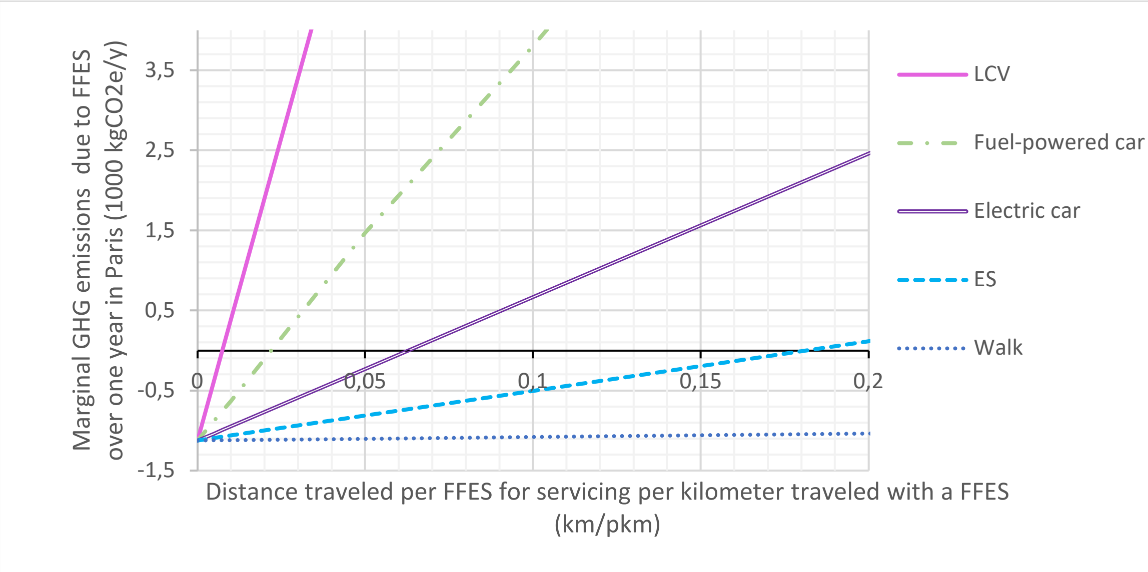

Figure 6 Extra GHG emissions generated by the emergence of e-scooters in Paris over one year (1000 kgCO2e/y) depending on the charging mean of transportation and the servicing distance (km/pkm)

4.4.3 Result sensitivity to electricity mix

This last parameter was chosen for sensitivity analysis because of the specificity of France and Paris. The French electricity mix comes 70% from nuclear plants, with a lower impact on climate change than electricity mixes based on fossil fuels like as the case in the United States (average mix), Germany or China (see supplementary material). We simulated the extra-burden generated by the FFES over one year with 9 alternative electricity mixes, *ceteris paribus*. In

Figure 7, the results show the linearity of the model to the carbon footprint of the electricity mix (R^2=0.999). The more carbonated the mix is, the better the FFES impact is on the climate. Indeed, the emergence of the FFES provokes a decrease in electricity consumption, as higher electricity consuming modes such as metro and RER are replaced by FFES (see detailed figures in supplementary material). Thus, under a high carbon content electricity mix scenario, the FFES disruption has a better footprint. Of course, in other countries, mobility systems would be different, and each specific case needs to be simulated precisely.

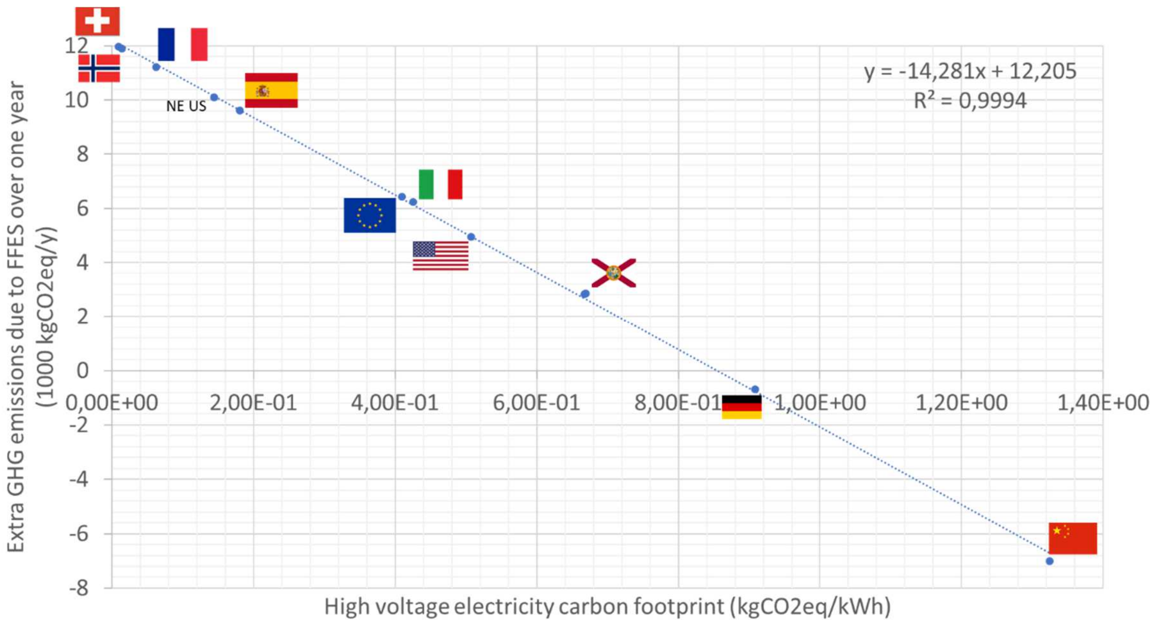

Figure 7 Extra GHG emissions due to FFES over one year, depending on the carbon content of different country's electricity mixes

5 Discussion: sources of errors and uncertainties

5.1 Limitations due to traffic data and survey

The carbon footprint impact of the FFES deployment was estimated under the assumption of 1 M FFES users in Paris, with only 15% of unique riders and 1.5% of droppers based on our survey. We made an extrapolation on the number of trips per year per type of users from the number of uses per week declared. It gives an estimation of the number of trips per year, equal to 72 M based on a weighted average trip length of 3.3 km. This number represents 0.5% of the number of trips in the Paris region. It seems consistent with another estimation made by 6-t, within 24 M and 59 M trips per year for the only people who both use the FFES in Paris and live there, i.e.1/3 of total users of FFES in Paris (6t, 2019a). In our model, the result is linear to the number of users: if it drops to 500 000, impacts are cut by a factor of 2. We did not consider seasonal effects, whereas micromobility behaviors depend on the weather, as shown in the example of shared bikes in New York city (An et al., 2019).

The question of intermodality is also very important. An intermodal trip is a trip made using more than one transportation mode. Rare are the trips not combined with walking, and the threshold to consider them intermodal or not is not clear. 74% of the trips in our study were combined with walking. The 26 other percent were combined with other modes: 26% with bus, 32% with metro, 21% with several modes, 5% with taxi or ride-hailing, 4% with bike (shared or personal) and 6% with cars (shared or personal). We excluded these trips from our estimate due to uncertainty on the modal share and thus the modal distances. A specific survey would be necessary to include intermodality data.

In transportation cLCA, a disregard for weighted and kilometer-based modal shifts calculations from trip-based traffic surveys may lead to serious flaws in the results. A simple kilometer-based comparison of transportation modes is highly inaccurate, especially in urban contexts, as the distance traveled to go from point A to point B depends on the transportation mode. In our study, we found a global reduction of 35% of the kilometer traveled with and without FFES, despite a 5% induction of new trips. In particular, FFES allows shorter trips than PT between A and B.

Finally, consistency regarding perimeters considered in different datasets – e.g. infrastructural network length or traffic – is an important point. Statistics on broader perimeters than in the study will undoubtedly bring uncertainty. For instance, we used data from the EGT 2010 for Paris's inhabitants. But 1/3 of the trips have a destination outside Paris inner city. These trips probably have different characteristics than the ones within Paris, bringing some uncertainties.

5.2 Consequential approach of disruptions

Other uncertainties in the model come from adopting a consequential approach instead of an attributional approach. When it comes to transportation public policies, this switch seems recommended to conduct prescriptive LCA made to enlighten decision-maker choices and to design regulations. But an LCA can be consequential to different extents and in different dimensions touching different phases of the assessment. Our goal and scope are consequential (phase 1), and we chose consequential LCIs (phase 2). Some uncertainty is due to the background dataset. The consequential LCIs provided up to ecoinvent 3.3 would have several shortcomings, and with regard to electricity mixes they could lead to unrealistic marginal mixes in several countries (Vandepaer et al., 2019). The use of energy scenarios instead of ecoinvent processes would allow the evolution of the electricity system to be considered within the definition of the marginal mixes. Moreover, the consequential phenomena considered are always limited due to lack of data. Especially, the LCIs to assess the original transportation modes need further investigations based on specific Parisian infrastructure maintenance data: which maintenance practices, and how are they really impacted by a change in mobility consumption? Maintenance models are probably non-linear to time as ageing models are often not, and traffic demand is not linear either. Relatedly, this consequential assessment is based on a general equilibrium hypothesis. We considered that the reduction in passenger-kilometers traveled had some environmental impacts. Nevertheless, this reduction really has an impact only under the condition that the PT offer is adapted to the new demand. Indeed, if the modal shift only empties buses, streetcars, metros and RER without changing the number of vehicle-kilometers traveled, there is an effect on comfort, especially in rush hours, but no environmental impact. Not to mention a possible rebound effect, leading to more mobility. A more complex model could be developed with more sophisticated data. And as cLCA is supposed to catch changes in production capacities (Earles and Halog, 2011), a longer time horizon than one year should be considered. Nevertheless, changes in ES production have already occurred, and this preliminary study is based on early traffic change evidences.

As FFES is a new phenomenon, the LCIs of the electric scooters bring many uncertainties. ES designs are evolving to make stronger and higher mileage microvehicles. Types of materials are evolving, as well as quantities of materials, battery range, lifetime mileage, maintenance and EoL treatments. From the basic Xiaomi M365 model that was not designed for shared usages, most companies have now switched to more robust designs, sometimes with higher autonomy ranges. A dependence between the ES design - thus material quantities – and its life cycle mileage is very likely, but no data are available to analyze this correlation. Some operators have now maintenance workshops where they are able to reuse up to 95% of the spare parts from out-of-order FFES (Lelievre, 2019). How many times these parts can be reuse and for which final mileage would be an information required to perform a more robust LCA. The question of the battery type and modeling, for its production and its EoL, must also be key to the result. Some FFES companies declared recycling them through dedicated channels (Lelievre, 2019). These channels are still rare, and do not provide information on the treatment and the fate of lithium-ion batteries, and, in fine, on the environmental impact of recycling them. Moreover, battery LCIA suffers huge variabilities and uncertainties (Cox et al., 2018).

5.3 Static model limitations

This static study aims at assessing the impact on GHG emissions in Paris under the deployment of FFES. We thus compared emissions with and without FFES, over one year. But the FFES are not the only change in the Parisian transportation system. For instance, RATP, the Parisian public transportation operator, owns around 4700 buses and is conducting a massive electrification of its rolling stock (RATP, 2019). The average impact of using a bus is thus changing over time. Other changes could affect other modes, and a dynamic model including these changes would be more accurate. Also, allocation factors for the infrastructure must be dynamic, i.e. calculated on a fixed time interval, for instance annually. Nevertheless, in the case of small modal changes like in this study, static allocation factors are accurate enough.

Finally, the limited availability of FFES has been pointed out as one of the limiting factors to its use (6t, 2019a; Portland Bureau of Transportation, 2018). But FFES are all the more environmentally-friendly as they reach long lifetime mileage. And multiplying the number of FFES could have the opposite effect. Resistant FFES designs to endure deterioration from weather conditions and rough shared usage as well as vandalism will be key to green performance, but also the adequation of the supply with the targeted demand through regulation.

6 Conclusions

A cLCA method to assess the environmental consequences of a change on a territory's mobility was formalized. This method was applied to calculate the impact of the emergence of FFES on the GHG emissions from the Parisian mobility. Results show that FFES have the potential to reduce urban mobility carbon footprint, but must be deployed carefully, with adequate regulations according to the city characteristics. In the case of Paris, the FFES emergence has very likely caused an increase in GHG emissions from the mobility sector. Raising the FFES lifetime mileage would not be sufficient to reverse this conclusion, contrary to limiting servicing impacts severely. Nevertheless, cities with high-carbon content electricity mixes may benefit from FFES more easily in a climate change perspective than those with low-carbon contents such as France.

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