Sustainable Cities and Society 71 (2021) 103012

Contents lists available at ScienceDirect

Sustainable Cities and Society

journal homepage: www.elsevier.com/locate/scs

Emissions assessment of bike sharing schemes: The case of Just Eat Cycles in Edinburgh, UK

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ARTICLE INFO

Keywords:
Mobility
Bike sharing schemes
Carbon emissions
Life cycle analysis
Rebalancing operations

ABSTRACT

Transport accounts for 40 % of global emissions, 72 % of which comes from road transport, and private cars are responsible for 60 % of road transport emissions. In cities, self-service bike sharing systems are quickly developing and are intended to offer an alternative and cleaner mode of transport than the car. However, the sustainability of such schemes is often taken as a given, rather than thoroughly evaluated. To address this gap, in this paper we undertake a life cycle assessment (LCA) of a public self-service bike sharing system in the city of Edinburgh, UK, modelling the production, operation and disposal elements of the system, but discounting additional food intake by users. Our results show that the bike sharing scheme is saving carbon dioxide equivalent emissions compared to the modes of transport by which its users previously travelled, but it is essential to optimize rebalancing operations and to manufacture bikes as near as possible to the point of use to further reduce carbon emissions; and that the overall emissions impacts of the scheme are critically dependent on how public transport providers respond to reductions in demand as users shift trips to bikeshare, since most trips transfer from walk and public transport, not private car. The policy implications for authorities seeking to use BSS as a GHG reduction intervention are not straightforward.

1. Introduction

Driving cars contributes to traffic congestion, GHG emissions and global warming, whereas cycling is more ecofriendly and provides opportunities for physical activity. Cycling is found almost everywhere, although some places have higher levels of cycle use than others depending on infrastructure, topography, local culture and weather amongst other factors (Rosen, Cox, & Horton, 2007). To promote sustainable development, cities often wish to facilitate access to bikes and have thus invested in bike sharing schemes (BSS). Initially rather experimental when the first cities tested them, BSS have now become common in cities across the world, although their contribution to overall mobility remains small in most cases due to limited fleet sizes. A core motivation for investing in these schemes is to bring about modal shift from car to bike in order to reduce greenhouse gas emissions, but there is a knowledge gap regarding how effective they are in so doing, particularly in the European context. Applying Life Cycle Analysis (LCA) to a study of such a scheme is an innovative approach to increasing our knowledge of their effects in this regard. The dual focus of the paper on LCA in the context of urban mobility addresses two of the core areas of the scope of this journal and that is reflected in the focus of other papers it has published recently on greenhouse gas emissions reduction in transport. The topic of BSS is highly relevant to a journal readership that is concentrated in Western Europe and East Asia, two parts of the world in whose cities BSS are most commonly found.

The structure of the rest of the paper is as follows. It first reviews the relevant literature and identifies knowledge gaps in terms of the LCA of BSS. It then presents the method for the paper including the data sources used. It then uses these data to calculate the LCA GHG emissions impacts of the BSS, and analyses the impacts on the calculation of changes in certain input data (sensitivity testing); and describes the limitations of the method used. It then calculates the GHG emissions savings resulting from the BSS due to mode shift from other forms of transport, before drawing conclusions and setting out policy implications and proposals for future research.

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https://doi.org/10.1016/j.scs.2021.103012
Received 17 November 2020; Received in revised form 9 April 2021; Accepted 9 May 2021

Nomenclature

BSS	Bike sharing scheme
LCA	Life cycle analysis
GHG	Greenhouse gases
CO_2	CO_2 is used as CO_2 equivalent

2. Literature review

A critical literature review is beyond the scope of our work but in this section we briefly review relevant literature that is either useful to offer input data for our analysis or to contextualise our own findings.

2.1. Definition of and different generations of bike sharing schemes

Bicycle-sharing schemes are defined as short-term urban bicycle rental schemes. They enable bicycles to be rented from any self-service bicycle station and returned to any other, making bicycle-sharing ideal for short to medium distance point-to-point trips within the area served by the scheme (Midgley, 2011). The definition now extends to so-called free-floating or dockless schemes where the station described above is simply any convenient public space to which the bike is returned after a ride – no fixed bike parking/locking infrastructure is provided, and bikes are locked digitally instead. BSS offer the advantage of using bicycles as and when required, without the responsibility or the maintenance resulting from ownership.

According to DeMaio (2009), BSS have developed across 3 generations over the past 45 years. The earliest version of a BSS was the *Witte Fietsenplan: The White Bicycle Plan*; conceived in 1965 by the Provo anarchist movement to counter the rise of pollution and cars in Amsterdam. This initiative was short-lived since the bicycles were immediately confiscated by the police, who were hostile to the Provo's activities. The second generation of BSS was marked by the *Bycykler København* programme in the Danish capital in 1995, which included fixed docks with a deposit paid by coin; but these suffered high levels of vandalism and theft due to the anonymity of the user.

To address these issues, the third generation of BSS incorporates a variety of technological improvements such as electronically-locking racks or bike locks, telecommunication systems, smartcards and fobs, and mobile phone access (DeMaio, 2009); making users much easier to identify, and bikes easier to keep track of. Latest development in this space involve the use of GIS-based approaches and multi-criteria decision-making to identify the optimal location of bike-share stations (Kabak, Erbaş, Çetinkaya, & Özceylan, 2018).

Bike-sharing slowly gained ground in the following years until 2005 when JC Decaux - a French multinational corporation known for its bus stop advertising systems - developed public bicycle rental systems in Rennes (*Vélo'v*) and in Paris (*Vélib'*), both in France, prompting a worldwide interest in BSS as a mode of transport.

With the introduction of many new technologies, free-floating bike sharing then appeared as an innovative BSS model that some consider to be a fourth generation. The earliest versions of the free-floating bike sharing system consisted of for-rent-bicycles locked with a combination code number, which a registered user would access by calling the bike management company. The user would then call the company a second time for details of the bicycle's location. In 1998 *Deutsche Bahn* further developed this dockless bike hire system, resulting in the launch of *Call a Bike* in 2000; with the added benefit of enabling users to unlock the bicycle via SMS or phone call, and more recently using a smartphone app.

Generally, the main advantage of free-floating BSS over station-based BSS is the money saved on the construction of docking stations. However, there are three disadvantages of free-floating schemes: firstly theft, secondly the blocking of public space by parked bikes, and thirdly management of the rebalancing of bikes around the city (although this latter also occurs with docked schemes). To discourage theft, GPS tracking systems are built into to the bike, and rebalancing is carried out to provide the required level to meet demand (Pal & Zhang, 2017). In recent years, free-floating bike-sharing systems have been heavily criticised for their use (and abuse) of public space as they do not have fixed-station parking locations and users sometimes park their bikes in a way that reduces sidewalk space for others, especially pedestrians.

One country where free-floating BSS have developed extensively is China and competition between Chinese bicycle-sharing companies is intense. Many brands of this type of BSS are found in the Chinese market, the most prominent being *OFO*, launched in June 2015 in Beijing and expanded internationally from 2016 to 2018; along with *Mobike* and *Bluegogo* (Ibold & Nedopil, 2018). Currently, around 500 bike-share services can be found in over 1,175 cities, municipalities or district jurisdictions in 63 countries worldwide (Meddin, 2019). With investment costs of USD3,000 to USD4,000 per bike, and operating costs of around USD1500 per bike (Midgley, 2011), much of which is covered in docked BSS by the public sector (Zhang, Zhang, Duan, & Bryde, 2015; Murphy & Usher, 2015), it is important to get a better understanding of the impacts of the schemes to assess whether this is money well spent. This paper, through its Life Cycle Analysis of the Edinburgh scheme, helps to provide that improved understanding required.

2.2. Previous research on carbon emissions from shared bike schemes

When a product such as a bike is produced, carbon emissions are released from the manufacturing process and continue to be emitted right through its life due to operations (such as, for example, "rebalancing" – moving bikes around to ensure that demand is served adequately in the whole area) and ultimately its recycling or disposal. None of the major manufacturers have published data on the overall greenhouse gas (GHG) emissions incurred in the process of manufacturing a bike, from extracting raw materials to end of production. However, Shreya (2010) calculated that manufacturing a bike releases 240 kg of greenhouse gases on average (cited in Lacap & Barney, 2015).

Duffy and Crawford (2013) led a study on the effects of physical activity on greenhouse gas emissions for common transport modes in European countries to measure the gases released in relation to manufacturing, maintenance, food consumption, fuel and non-fuel (maintenance, taxation and insurance). Cycling does not of course directly involve fossil fuel-related operational emissions. An estimated 86.4 g CO_2/km was emitted by cyclists in 2012, dominated by maintenance emissions (52 %), followed by manufacture (26 %) and food energy (22 %). The degree to which food energy used to power a bike is actually additional food consumption is returned to later in the paper.

Carbon emissions from individually owned bikes are not the same as those from BSS due to the very different life cycle process of the latter. For example, battery operated smart bicycle locks used in BSS result in increased carbon emissions through manufacturing, maintenance, and waste disposal. In addition, shared bikes are made using more plastic and metal to help protect them from vandalism, especially their electronic components. Moreover, a significant difference in carbon emissions exists through the rebalancing operations necessary to optimize a BSS offer (moving the bikes around to ensure that supply meets demand in different parts of the city).

Zhang and Mi (2018), used *Mobike*'s dataset to evaluate the environmental performance of bicycle sharing, calculating that the adoption of BSS in Shanghai decreased CO_2 and NOX emissions from surface transport by 25,240 and 64 tonnes per year. Their research only considered the use of shared bicycles to replace taxis or walking and did not include the life cycle of shared bikes; thus suggesting a likely underestimation of the BSS emissions. Conversely, another study aiming to measure the impact of the increasingly popular BSS on transport, sustainability, health, and community liveability in Barcelona considered all the substitute modes to BSS spanning public transit, motor vehicle, walking, private bike and taxi (Fishman, Washington, & Haworth, 2012) but, again, not LCA emissions.

Zheng, Gu, Zhang, and Guo (2019) carried out an LCA of BSS in China. Their system boundary included: producing a shared bike, using a shared bike, maintaining a shared bike, and recycling or non-recycling of a shared bike, but the activities of, and related carbon emissions resulting from, rebalancing operations were excluded. Compared to the modes used prior to bike sharing, they found that the GHG savings for one shared bike are 52.08 kg CO_2e. It is worth noting that they did not consider carbon emissions from bus use, but it is unlikely that small numbers of people shifting from bus to BSS would lead to reduced bus services and hence reduced emissions from buses. Luo, Kou, Zhao, and Cai (2019) also carried out a LCA of BSS and an analysis of total normalised environmental impacts (TNEI), comparing station-based to dockless schemes in the United States. They found that station-based had higher TNEI (due to the impacts of manufacturing the docks) but lower LCA (due to lesser requirements for rebalancing bikes between locations) than the dockless schemes. Bonilla-Alicea, Watson, Shen, Tamayo, and Telenko (2020) come to a similar conclusion in their study – not set in any particular country - of "smart bikes" used in dockless BSS but put this down mainly to the increased emissions involved in the production of such bikes. The proportion of trips transferring from private car was crucial in assessing TNEI and LCA for both types of scheme. The literature available to date indicates that this proportion is normally a small part of the overall trips made by BSS: the vast majority transfer from public transport or walking (de Chardon, Caruso, & Thomas, 2017; Midgley, 2011; Ricci, 2015). The degree to which any resulting fall in public transport demand translates into reduced public transport supply is crucial to calculating LCA impacts of BSS, but there is very little literature on this topic – Campbell and Brakewood (2017) find a significant reduction in bus ridership in New York due to transfer to bikeshare, but do not discuss how the public transport operator has or will respond to this in terms of service provision. The environmental performance of bike-sharing schemes seems therefore to be significantly bound to how such schemes are designed, implemented, managed, and agreed-upon as Mi and Coffman (2019) have shown. This is confirmed by current results in the existing literature (such as those of Luo et al., 2019, and Bonilla-Alicea et al., 2020), which vary a lot according to the definition of the BSS life cycle, the consideration of alternative transit modes' carbon factors, and assumptions made about levels of rebalancing activity. While rebalancing operations are often studied as a complex mathematical optimization problem, the carbon released by them is not dealt with as a topic. In fact, few papers have been published in Europe about the environmental benefits of using BSS. This study adds to such existing body of knowledge and represents the first integrated study of its kind of the LCA impacts of BSS in Europe, addressing research gaps such as the inclusion of balancing operations in the LCA, transport involved in manufacturing, and public transport responses to the BSS.

3. The empirical case: Edinburgh's bike sharing scheme *Just Eat Cycles*

Edinburgh's third generation BSS *Just Eat Cycles* was conceived in 2018 by Transport for Edinburgh (TfE), a public sector transport management organisation. *Just Eat Cycles* is operated by the outsourcing company Serco, under a three-year contract with TfE to implement and manage a new cycle hire scheme. To use a *Just Eat Cycles* bike, the process is as follows:

Users are required to buy a pass on the app; a pass costs £1.50 for the first hour, each additional 30 min costs £1, a day pass costs £3 and an annual one costs £90. Thanks to the location services of the app, the closest bike is then identified. After unlocking it, the ride can begin and last for up to 1 h. To return the bike it must be locked at a physical station or virtual one with markings on the ground.

Table 1
Comparison between Edinburgh and Glasgow BSS.

	Edinburgh	Glasgow
BSS name	Just Eat Cycle	Nextbike
BSS operator	Serco	Nextbike GmbH
Began operation	2018	2014
City population	482 640	606 340
City area	259	175,5
First year daily hires	284	202
Second year daily hires	304	280
Number of cycles (first year of operation)	500	400

The table below compares Edinburgh's BSS to nearby Glasgow's *Nextbike* BSS (running since 2013), against which TfE can reasonably benchmark its experience (Table 1).

Although not the primary focus of the paper, it is useful to consider how Glasgow's BSS operates in comparison to that of Edinburgh to the extent that they are two Scottish cities of similar population size working in line with broadly the same transport policy and objectives. As the Glasgow scheme was introduced earlier, its growth gives some indication of the trajectory that Edinburgh's BSS might be expected to follow.

Firstly, the renting process differs: the unlocking step in Glasgow includes a 4-digit lock code which is entered onto the bike's computer; the bike can also be unlocked by hotline. Secondly, *Nextbike* only operates with a physical station with a mechanical lock. Thirdly, *Nextbike* provides the same number of bikes as *Just Eat Cycles* which is a little surprising given that Glasgow has 120,000 more inhabitants more Edinburgh. In addition, more stations are located in Edinburgh (80 versus 62 in Glasgow), which could be explained by Edinburgh's larger city surface area (259 km^2 vs 175.5 km^2 for Glasgow). Lastly, *Nextbike*'s annual pass is more affordable than Edinburgh's; Glasgow having a 11 % lower cost of living (Cost of Living Comparison, 2020). The scheme quickly mushroomed following an increase in monthly hires: 6550 in March, 8177 in April and 10215 in June 2019. We can reasonably assume that the results of this paper – although it is not a study of the Glasgow scheme – will also have relevance to that scheme, given the similar operating context and conditions.

4. Method

This section sets out the goal and scope of the LCA, describes the sources of the data used, and the structure of the calculation for each of production, operation and disposal respectively. It also sets out the limitations of the method and the data used. An important factor for sourcing the data was the fact that one of the authors was seconded three days per week over a two-month period to Transport for Edinburgh (TfE), the organisation ultimately responsible for the BSS, to survey operations, understand procedures and, crucially, to gain access to an extensive range of data related to the BSS including production-to-maintenance life cycle stages, GPS tracking, and end of life scenarios for shared bikes.

The calculation of carbon emissions is conceived according to Life Cycle Assessment process and was supplemented by a street survey in order to gather primary data from users including one key factor: how the user would have made the trip instead, had the BSS not been available.

4.1. *Life Cycle Assessment (LCA)*

The LCA draws up an accounting balance sheet of the relationship between an object/system/organization and the ecosystem surrounding it: it is a question of counting the resources taken from and the waste put back into the environment throughout its life. Several essential concepts are explained here, such as the major stages of the life cycle, the functional unit and a sensitivity analysis.

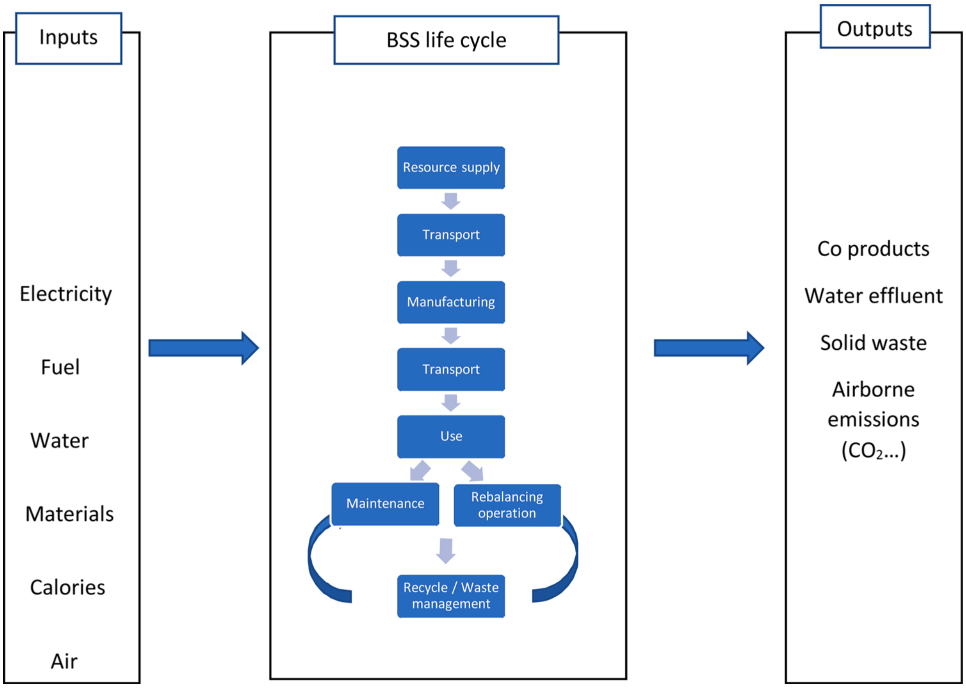

Fig. 1. Inputs, outputs and system boundary of the analysis.

The major stages of the life cycle are resource supply (supply of raw materials, transport), manufacture (transport, construction-installation process), use (maintenance, repair, replacement, rehabilitation, use of energy, water during the use stage), end of life (dismantling, transport, waste treatment, disposal), benefits and expenses (possibility of reuse, recycling). Each of these stages releases greenhouse gases. To quantify the environmental impacts of the BSS, Kg_{eq}. CO_2 will be used as a reference unit. The majority of greenhouse gas impacts can be expressed using the Kg_{eq}. CO_2 unit of measurement as per the Global Warming Potential (GWP) that measures the effect of a greenhouse gas on global warming compared to that of carbon dioxide. UK Government (DBEIS, 2019) carbon data is used to calculate carbon impacts.

The LCA of the BSS will relies on ISO 14040 and 14044 (Curran, 2008). LCA consists of 4 phases:

- goal and scope definition
- life cycle inventory (LCI)
- life cycle impact assessment (LCIA)
- interpretation

4.1.1. Goal and scope

The aim is to establish an approach for evaluating the environmental impacts of the BSS implemented in Edinburgh in September 2018. This approach will be applied over a relatively short period in the first instance of this paper, because the BSS has only been in operation for a short time, but it would be possible to apply the approach over a longer period as well, were data to be available. The purpose of this analysis is to quantify and evaluate the environmental consequences of the implementation of the BSS in Edinburgh, with an intent to identify opportunities for improving the scheme in the future. Our intended audience, in addition to scholars operating in this field, includes the wider public of the City of Edinburgh as well as key policy- and decision-makers that might benefit from the results of this assessment. The life cycle analysis method makes it possible to compare the environmental impact of the BSS with the use of another means of transport (car, bus, tram, motorcycle, personal bike, walking) through the functional unit. The functional unit of a product is the combination of a quantity and a function: here, transporting 1 person over 1 km. Clearly, not all means of transport can be equally employed for any distance, for instance if we were to evaluate a trip of 500 km there would not be an equivalence of choices. However, for the purpose of urban distances, especially in the case of a medium-sized city like Edinburgh, this functional unit allows for a meaningful comparison of all transportation alternatives. We adopt a cradle-to-grave system boundary, from resource supply to end-of-life activities. Like in every LCA, numerous assumptions are required in terms of input data, and life cycle inventory and these are detailed in the following sections.

4.1.2. Inventory of life cycle (ILC)

At different stages of the BSS lifecycle, there are incoming and outgoing flows, as shown by the life cycle inventory flowchart in Fig. 1, below.

The lifetime of a *Just Eat Cycle* is estimated at 5 years according Serco, the scheme operator. For this study, primary data comes from the first ten months of operation from September 2018, which is then scaled up to a 5 year-period.

4.2. Input data for LCA calculation

This section aims to present and explain the construction of the life cycle inventory (LCI) behind the carbon calculator for the BSS, to explain the inputs, to discuss certain adjustments and to detail the steps in the subsequent calculation. Input data and their source are shown in Table 2, below.

4.2.1. Emissions from production

The carbon emissions related to the production of 1,000 bikes are calculated according to the weight of each material constituting the bicycle. Carbon factors are then assigned to the materials, factors which take into account both the supply of resources, and their transformation:

$$C_{supply,\ manuf} = \sum_{i} C_{supply,\ manuf,\ material\ i} * W_{material\ i}$$

where $C_{supply,\ manuf,\ material\ i}$ is the carbon released per kg material i for supply and manufacture and $i = \{'metal' ; 'plastic'\}$, $W_{material\ i}$ the weight

Table 2
Table of the BSS and carbon impacts inputs, carbon factors are extracted from DBEIS conversion factor 2019.

0 – INPUTS		Source
Specific to bikes		
Number of bikes	1000	TfE data
Weight of plastic (kg/bike)	6	TfE data
Weight of metal (kg/bike)	10	TfE data
Number of batteries	1200	TfE data
Weight of 1 battery (kg)	0.1	TfE data
Bikes' kilometrage in a 5-year period (km) (1)	41 668 650	5 year extrapolation based on data from TfE for the first year of operation
Specific to materials constituting the bikes		
Metal supply and manufacturing factor (kg CO_2/kg)	4.3	UK Government GHG Conversion Factors, 2019
Plastic supply and manufacturing factor (kg CO_2/kg)	3.1	UK Government GHG Conversion Factors, 2019
Batteries supply and manufacturing factor (kg CO_2/kg)	12	UK Government GHG Conversion Factors, 2019
Metal closed loop factor (kg CO_2/t)	4.31	Bilan GES, ADEME
Plastic closed loop factor (kg CO_2/t)	877	Bilan GES, ADEME
Batteries landfill factor (kg CO_2/t)	75.492	UK Government GHG Conversion Factors, 2019
Specific to transport during manufacturing process		
China to London by sea (km)	21975	TfE data & Google Maps
Container ship factor (kg CO_2/km/t)	0.02	UK Government GHG Conversion Factors, 2019
London to Stratford-upon-Avon by road (km)	130	TfE data & Google Maps
Stratford-upon-Avon to Edinburgh by road (km)	540	TfE data & Google Maps
HGV (7,5-17 t) 100% laden factor (kg CO_2/km)	0.71	UK Government GHG Conversion Factors, 2019
Specific to the use (human activity & BSS operation)		
Human respiration factor (g CO_2/km)	*10,000*	http://rstudio-pubs-static.s3.amazonaws.com/11243_3bf3af25db65409c9a56b85166b54c77.html
Calories needed for cycling (cal/km)	*29.80*	*Harvard Health Publishing, 2014*
UK food factor (kg CO_2/cal) (2)	*0.00243*	*Scarborough et al., 2014*
Electricity consumption of an average depot (kW/m2/year)	10	U.S Energy Information Administration, 2012
Depot's surface (m2)	360	TfE data
kW factor (kg CO_2/kW) (3)	0,26	BEIS, Electricity generation and supply figures for Scotland, Wales, Northern Ireland and England, Energy Trends
Rebalancing operation - 2 vans kilometrage (km)	209170	TfE data
Diesel van factor (kg CO_2/km)	0.1945	UK Government GHG Conversion Factors, 2019

of material i

This paper uses UK Government data for the emissions impacts of plastic, metal and battery production. Other sources such as Cherry, Weinert, and Xinmiao (2009) and Chen, Zhou, Zhao, Wu, and Wu (2020) estimate lower emissions impacts for material produced in China; our approach therefore represents a conservative hypothesis for our case. After 5 years, it is assumed that all the bikes have to be replaced because of vandalism and wear and tear. As a consequence, we consider the production of 2,000 bikes for the scenario over a 5 year-period.

The components are made in China, then brought by ship and assembled in Stratford-upon-Avon, and finally transported an estimated 540 km by road to Edinburgh. It is interesting to note that the fleet of 1,000 bikes was formed in two stages: the first in September 2018, the second in early 2019 in response to the success of the BSS. On the one hand, it is assumed that the loading of the truck is at 50 % empty when selecting the carbon factor (favorable case: the way back is used for a second delivery). On the other hand, stemming from the supply of bicycles in two stages, it is necessary to count each trip twice. For the 5-year period calculation, this whole transport operation is included a second time to replace the 1,000 bikes that have reached their estimated end of life within the period.

4.2.2. *Emissions from use*

The period of use is the most interesting to explore. The carbon emissions specific to the operation of the BSS are apparent, while those from human activity generated by the physical effort of cycling are less so. Nevertheless, we know that cycling requires some more calories than driving a car or commuting by bus or tram, therefore the carbon footprint of food is worthy of consideration. Scarborough et al. (2014) studied dietary greenhouse gas emissions of meat-eaters, fish-eaters, vegetarians and vegans in the UK. To draw out the average 2,000 calories carbon emissions from UK food, it was necessary to rebalance the results due to a greater number of women taking part in the survey than men. With these proportions adjusted, the study found that a standard UK 2,000 kcal diet releases approximately 4.85 kg CO_2e per day. Knowing that 29.80 calories are needed to cover one km by bike (Harvard Health Publishing, 2014), it is possible to calculate carbon emissions based on diet, however that is not the only factor to consider (Scarborough et al., 2014). Whilst humans need “fuel” from food calories for exercise, the process is led by the breathing cycle during which the body inhales O_2 and exhales CO_2, a cycle which is related to the intensity of the activity. While cycling, 10 g of CO_2 is released by the human body per km. Thus, human activity generates carbon emissions as described as follows:

$$C_{human\ activity} = [cal * C_{cal} + C_{exh}] * K_{bikes}$$

where *cal* are the calories needed to cover 1 km = 29.80 kcal, C_{cal} are the carbon emissions released by one kcal = $\frac{4.85}{2{,}000}$ = 2.43 E-3 kg CO_2e, C_{exh} is the carbon emissions exhaled by breath cycle to cover 1 km = 0.01 kg CO_2e, K_{bikes}: km travelled by the BSS' users on a 5-year period = 41 668 650 km

The derivation of kilometres travelled over a 5 year-period is explained as follows. According Glasgow's public scheme numbers, between 2014, the year of launch, and 2019, the number of rentals increased fivefold. Assuming an equivalent growth in use as in Glasgow and based on actual data from the 10 first months of operation in Edinburgh, when 2,314 million km were travelled (Just eat cycles, Trip data, 2019)-, then over a 5 year period, usage would follow an arithmetic progression and hit 14,65 million km.

U_{2018} = 2 777 910; U_{2019} = 5 555 820; U_{2020} = 8 333 730; U_{2021} = 11 111 640; U_{2022} = 13 889 550km

Whilst the food consumption and breathing impacts of human activity (cycling) can be calculated as shown above, there is great uncertainty about the degree to which these impacts are higher or lower than travel on foot, by running, by scooter, car or bus (including walking between bus stop or car parking space and final destination). Thus, ultimately, due to this uncertainty, it was decided not to include food consumption and breathing impacts in the LCA calculations for the BSS compared to other modes of transport.

4.2.3. *Emissions from operation*

GHG are also released by the organisational operations of the BSS. Firstly, through rebalancing operations, which consist of moving some bikes from one station to another according to demand, and moving malfunctioning and repaired bikes to the depot or back into service; which is carried out by two vans running on diesel. There is a lack of information on the total km travelled by these vans but based on data for

Table 3
Adjusted carbon factor of 1 kW h.

Scotland 2018	Share	Carbon factor (kg CO_2/kWh)	Pro-rated kg CO_2/kWh)
Nuclear	28 %	0,006	
Coal	11 %	1,06	0,121811
Other	55 %	0,00642	
Renewables			
Onshore wind	40 %	0,0127	
Hydro	10 %	0,006	
Offshore wind	*5 %*	0,0148	

July 2019, it was estimated that they had travelled 37,000 km from the date of launch of *Just Eat Cycles* in September 2018, and thus that they would travel 210 000 km over a 5-year period.

Secondly, in the depot, electric machines are used to repair mechanical spares and computers; furthermore, the offices use heating and the depot requires regular maintenance (US Energy Information Administration, 2012). Thus, the electric consumption (kWh) resulting from the operation of the depot results in carbon emissions from energy generation. In 2018 in Scotland, the electricity generation mix was renewables (55 %), nuclear (28 %), gas and oil (17 % (see BEIS, 2019)). These proportions enable us to calculate the adjusted kW carbon impact based on the carbon impact of each mean of energy generation (Table 3).

Thus, the carbon released through the depot and bikes' operation is:

$$C_{exploitation} = K_{vans} * C_{diesel} + C_{elec} * Elec_{consumption}$$

K_{vans} : kilometrage made by the vans since the launch of the BSS, C_{diesel} : carbon released per km by diesel van, C_{elec} : adjusted carbon released per kW, $Elec_{consumption}$: the consumption of electricity by the depot since the launch.

In total, the use period is responsible for the following carbon emissions:

$$C_{use} = C_{human\ activity} + C_{exploitation}$$

4.2.4. End of life and disposal

How the end of life of a product is managed depends a lot on the regional culture for disposal and recycling of waste. In Scotland, steel and aluminum are recycled, plastic too depending on how many times it has been reused. Plastic is exported to be recycled which does increase the initial carbon impact of the operation; however, this observation is not taken into account in the calculation due to lack of information:

$$C_{ending\ life} = \sum_i C_{ending\ life,\ material\ i} * W_{material\ i}$$

$C_{ending\ life,\ material\ i}$: carbon released per kg of material for ending life treatment i where $i = \{'metal'; 'plastic'\}$, $W_{material\ i}$: weight of material i

4.3. Modal shift to BSS and previous modes of transport used

A critical factor for calculating emissions savings from the BSS is the mode of transport that would have been used in the absence of the scheme. Since the BSS data held by Transport for Edinburgh only covers sales, bikes' condition and GPS tracking, the street survey enables us to understand the circumstances of the users' journeys on a significant sample of 200 individuals of both sex and all ages. It is imperative to know which mode users would have taken if they had not had access to the BSS, to calculate the carbon emissions savings resulting from the use of the scheme.

It was fundamental to establish a diverse and representative sample, as follows:

- Finish the survey before the start of the festival[1], if not, adjust the results according to the proportions of residents and tourists observed in the previous period
- Vary the hours of observations according to the target audience: for workers, departure for work (8 h–9 h30) and departure from work (16-17h30), for tourists all day from 9am, for residents doing leisure activities (after 17h30)
- Different days of the week
- Varied survey locations: few users in the centre would use the car, but more would in the suburbs.

The survey took place at BSS stations and users were approached when taking or parking a bike. Each of the 200 BSS' user surveyed was asked the following about his/her travel:

- Kind of trip (travelling to/from, business, leisure, shopping, school, sightseeing).
- Distance between origin and destination.
- Alternative mean of transport (car, bus, tram, walking, school, uber/taxi, bike).
- Whether they had used their main mode of transport (e.g. train) in combination with another means of transport (e.g. bike)?

Table 4
Percentage of different life stages of BSS carbon emissions; HA: human activity.

Life stage	% with HA	% without HA
1–3 RESOURCE SUPPLY - MANUFACTURING	1.8 %	33.3 %
2–4 TRANSPORT	0.9 %	14.1 %
5 – USE	97.2 %	49.9 %
6 - ENDING LIFE - waste disposal	0.1 %	2.7 %

4.4. Limitations

The main limitations of the method are as follows. Firstly, not all of our input data come from the same source. This is due to data requirements and availability and the multi-disciplinary nature of our analysis, which ranges from material manufacturing to breathing cycles of human activities. Secondly, due to the mixed nature of our data and the fact that some of it comes from secondary sources, we are unable to offer a robust evaluation of the overall quality of our input data. In particular it was not possible for us to source manufacturing GHG data from the province in China where the bikes are manufactured, and so UK GHG standard factors were used instead, which is a further limitation. The greatest empirical uncertainties in the data are the kilometres travelled by van rebalancing the bikes around the city; the climate impacts of food consumption and activity of the riders compared to if they travelled by other modes; and the response of the bus company to reduced demand caused by riders switching from bus to bikeshare.

5. Initial results: carbon emissions from the BSS itself

Including human activity, the BSS will after the first 5 years of its operation have released 3,630 tonnes of CO_2e. Applied to 1 bike, its use constitutes 87 gCO_2e/km. Excluding human activity, the BSS will have released 195 tonnes of CO_2e (the human activity impacts are shown for reference) (Table 4).

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[1] The Fringe Festival happens in August each year in Edinburgh for 3 weeks, when the number of tourists in the city increases enormously.

5.1. Sensitivity analysis

A sensitivity analysis was carried out to assess the variations in LCA results through changing stated assumptions and parameters. In each stage of the scheme's lifecycle, we can observe how carbon emissions can fluctuate according to the parameters initially selected. The inclusion of emissions from human activity involved in cycling, the assumption of a round-trip or one way truck journey for the delivery of the bikes, the variation in km travelled for the balancing operation (if there is optimization or not), the variation of the kWh value according to how electricity is produced -which varies spatially and through time - and finally the way in which waste is managed will all affect the final result. This section shows the effect of making these variations.

Across most impact categories, the environmental intensity of the use phase is the single most influential variable (97.1 %). Within this, carbon emissions from human activity represent 97.2 % of the use period emissions and therefore 94.5 % of all emissions. Food constitutes 88 % of human activity emissions; however, the literature review highlighted some of the uncertainties in relation to this factor. As we could not reliably verify how much more, and of what foods, people eat as a result of cycling rather than using another mode, this factor was removed from the final calculation, as was the human breathing cycle, in order to enable consistent comparison. We could however assume that riding a shared bike is a significant indirect source of CO_2e emissions if up to 416 tonnes of CO_2e resulting from human breathing is included. However, if emissions from food and from the breathing cycle are excluded, riding a *Just Eat Cycle* bike releases 9.6 g CO_2e/km.

A 100 % laden HGV was assumed to make 1 trip (not a round trip) for the purpose of delivering the bikes from London/Stratford-upon-Avon and Stratford-upon-Avon/Edinburgh. If no delivery is planned for the way back, the bikes are assumed to contribute environmentally as per a round trip. The carbon factor decreases from 0.71 to 0.63 kg CO_2/km but distances are doubled. Emissions from transport during manufacturing and delivering would thereby increase by 1.7 % and the total emissions from 200 to 204 tonnes CO_2e.

The management of the rebalancing vans is not optimized at the present time. According to Liu and Sun (2016), mixed integer non-linear programming (MINLP), nature inspired algorithms (NNIA) and genetic algorithm (GA) are optimization models for efficient vehicle routing that can yield a reduction of up to 3.4 % in travel distances of such operations (Liu, Sun, Chen, & Xiong, 2016; Pal & Zhang, 2017). Today, the 37, 000 km traveled could be at least[2] reduced to 35,750 km which would save 244 kg CO_2e. However, this represents less than 0.1 % of all emissions. However, based on the intern's analysis whilst on site with the operators, the rebalancing operations are currently so poorly optimized that they could be improved by 30 % which would imply a 1% reduction in all emissions.

The kWh carbon factor was calculated based on Scotland's energy production infrastructure in order to be as realistic as possible and was estimated at 0.2550 kg CO_2 compared to 0.2556 from UK conversion factor, assuming no significant variation.

Product end life management has a relatively small influence on carbon impact (5.3 %), recycling was selected for metal and plastic based on shared bike treatment trends, since respectively 71 % and 46.2 % were recycled in 2017 (Department for Environment Food & Rural Affairs, 2019). It is interesting to note that the landfill aspect could modify the carbon factor, but no data is available to continue the calculation.

Table 5
Table of the inputs for carbon emissions savings' calculations, carbon factors are extracted from DEFRA conversion factor 2019.

0 – INPUTS		*SOURCE*
Specific to bikes		
Number of bikes	1000	TfE data
Bikes' km travelled since BSS launch (km)	41 668 650 km	TfE data
Total BSS carbon emissions (t CO_2)	X	this papers' calculations
Specific to other mode of transport		
Share of bus (%)	X	street survey
Bus carbon factor (kg CO_2/km/pass)	0.167	Bilan GES, ADEME
Share of car (%)	X	street survey
Car carbon factor (kg CO_2/km)	0.1733	UK Government GHG Conversion Factors 2019
Share of walking (%)	X	street survey
Walking carbon factor (kg CO_2/km)	0	

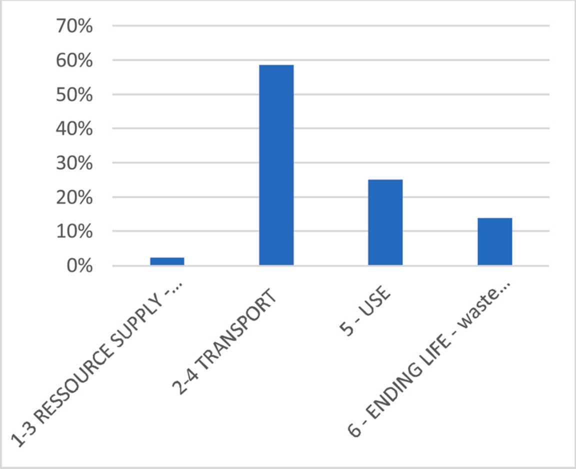

Fig. 2. Percentage of different life stages in BSS carbon emissions, excluding human activity.

6. Emissions savings of BSS compared to other modes

6.1. Method for carbon emissions savings

Based on the BSS total carbon emissions, the total km travelled since the launch and the share of alternative mode of transport, the carbon emissions savings can be calculated as follows:

$$C_{em\ sav} = C_{BSS} - \sum_i K_{bikes} * P_i * C_i$$

C_{BSS}: carbon released by the BSS since its launch, K_{bikes}: kilometrage made by the BSS users over a 5-year period = 41 668 650 km, P_i: the percentage of alternative mode i's use where $i = \{bus';'car';'walking'\}$, C_i: carbon released per km by mode i

The inputs are detailed further in Table 5, below.

One consideration was necessary to calculate the value: the car and bus carbon factors include manufacturing, use and waste disposal but do not include the human activity (breathing and food calories) so to maintain consistency, and as explained earlier, the C_{BSS} value does not consider carbon emissions from any human physical activity (breathing or food consumption). It is for this reason that the walking carbon factor is shown as zero in Fig. 2.

We have calculated that the carbon emissions of the BSS, excluding human activity, amount to 200 tonnes, extrapolated over a period of

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[2] We consider here the difference of efficiency between 2 optimization models but the difference between non-optimized and optimized must be even greater.

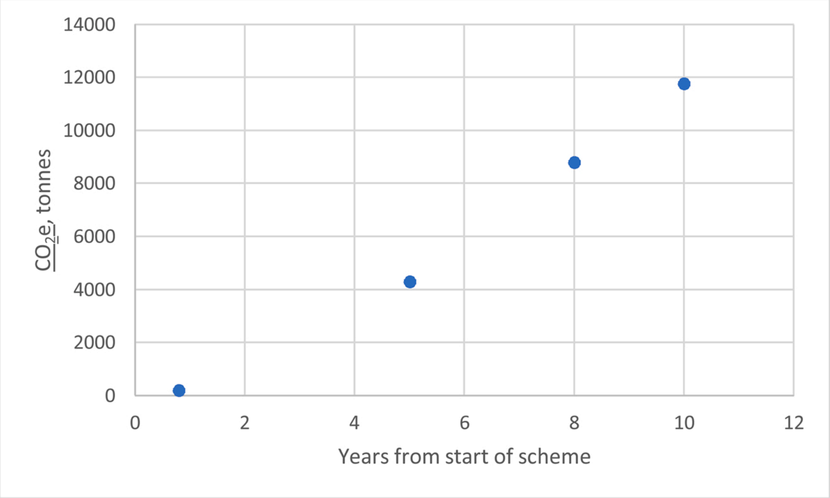

Fig. 3. Evolution of the carbon emissions savings through the years, on a 10-month period, 5, 8 and 10 years.

5 years (estimated lifetime of a *Just Eat Cycles* bike). At the level of the functional unit, a Just Eat cycle releases 9.6 g g CO_2e/km, which is 50 times less than an average car with petrol (259 g CO_2e/km). According to Cherry et al. (2009), an individual bike is responsible for 4.7 g CO_2e/km and an electric one 31.2 g CO_2e/km due in part to the battery management and the materials surplus, thus, the shared bike can be positioned between the individual bike –at almost the double its LCA carbon emissions - and the electric bike.

Moreover, the street survey enabled us to evaluate the proportion of alternative modes to cycling in the city, based on a diverse sample of 105 users (workers, students, tourists, etc.): 47 % would have traveled by bus, 17 % by car and 36 % on foot, had the BSS not been available. Assuming that these users travel the average distance for a journey by a car, bus or on foot in Scotland, then the carbon emissions savings realized by the BSS whole fleet over a 5-year period are estimated at 4,300 tonnes CO_2e, almost the equivalent to a hundred Edinburgh-London journeys by plane of 200 passengers.

To estimate the carbon emissions savings, carbon factors were allocated to alternative modes, including bus where 0.167 kg CO_2e/km/passenger was calculated. However, another assumption could be that since Edinburgh's bus company would be highly unlikely to reduce the number of buses in service in response to the relatively small reduction in passenger numbers resulting from the BSS, then zero carbon emissions savings should be assigned to bus as alternative mode. In this scenario, the BSS carbon emissions savings are much lower: 716 tonnes of CO_2e.

Thus, given the difficulty this presents in assuming either zero or 0.167 kg CO_2e/km/passenger emissions savings from bus travel, carbon emissions savings are estimated to vary significantly between the two scenarios, between 716 and 4,300 tonnes.

Starting from the 4,300 tonnes for a five year period of operation, it is possible to extrapolate emissions savings over a further five year period. Even if it is assumed that over these five years the number of users and the kilometres travelled remain constant, that the BSS continues to replace the same shares of walk, bus and car trips, that each bike is replaced and manufactured by an identical process, and that 1.2 batteries is the average for one bike, more than 12,000 tonnes CO_2e is forecast to be saved over the first decade of operation, as shown in Fig. 3.

7. Conclusions, policy recommendations and future research directions

This paper presents research findings on the environmental impact of the recently adopted bike sharing scheme *Just Eat Cycles* in the City of Edinburgh and demonstrates that it is not negligible (200 t CO_2e over 5 years of operation). From a policy point of view, it must be acknowledged that, in the context of all transport in Edinburgh, the BSS only reduces CO_2e emissions by 0.5 %, which is small but represents a move in the right direction. Other benefits resulting from the BSS should also be highlighted: some limited improvement to traffic flow (fewer cars), improving users' fitness and creating jobs locally (operating the BSS). It is notable that the BSS has proven to be a great success in terms of utilization of the bikes in spite of Edinburgh's mediocre average weather conditions and rugged terrain. However, our analysis has shown that the BSS as a policy intervention to reduce transport related CO_2e emissions has a small impact relative to other transport emissions due to the small number of trips made in comparison to total mobility, due to the short distances of trips made, and because most trips do not transfer from private car. Therefore, it is important for policy-makers to have other objectives in mind that they wish to achieve with the implementation of BSS, and not solely GHG emissions reduction.

Whilst the data for this paper are from 2019–2019, it is also worthy of note that the 2020 covid-19 crisis seemed help the BSS to flourish to the extent that people use public transport less in favour of green individual modes of transport. At the same time, vandalism appears to have increased which requires increased maintenance, waste management, parts and whole bike manufacturing orders (McPherson, 2017). Also, when bikes are stolen -which occurs more and more frequently-, Serco agents have to drive around the city to recover them via geolocation. This consumes additional fuel especially since the routes are non-optimized. All these operations generate additional carbon emissions, but these are not quantified in this paper.

An interesting future research direction is to consider how much the presence of BSS reduces the need to own a car and therefore reduce the total amount of travel undertaken, and therefore reduce carbon emissions. It would also be worthwhile to estimate by calculation the extent to which rebalancing operations can be optimized regarding the number of stations and bikes; and to incorporate food and human activity into emissions *savings* calculations, rather than just into the emissions calculations for the BSS itself.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Declaration of Competing Interest

The authors report no declarations of interest.

Acknowledgements

The authors would like to acknowledge the non-financial support of Transport for Edinburgh (TfE) in providing access to the data and research environment for this article.

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