Life cycle assessment to quantify the impact of technology improvements in bike-sharing systems

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Abstract
The reduced environmental footprint of bicycle sharing systems (BSS) is one of the reasons for their rapid growth in popularity. BSS have evolved technologically, transitioning from smart dock systems to smart bicycle systems, and it is not clear if the increased use of electronics in BSS results in a net environmental benefit. This article provides an evaluation of the impact of incorporating additional technology into BSS and uses that analysis as guidance for future BSS development. By comparing the impacts of a private bicycle, a smart dock BSS, and smart bike BSS using a life cycle assessment (LCA), this work reveals breakeven points and tradeoffs between the technologies. This study is also the first published empirical LCA of a smart bike known to the authors. In the production phase, smart bikes generate approximately three times the amount of greenhouse gas (GHG) emissions compared to the smart dock bikes per kilometer ridden over the lifetime, and when considering the endpoint categories of human health, ecosystem, and resources, smart bikes have approximately 2.7 times the environmental impact. The results suggest that shifting from smart dock to smart bike requires an increase in ridership by a factor of 1.8 to overcome the increased environmental impact based on the GHG emissions. We find that smart docks become preferable at a population density between 1,030 residents/km² (in a bike friendly city) and 3,100 residents/km² (in a city that is less likely to bike).

KEYWORDS
electrical and electronic equipment (EEE), life cycle assessment (LCA), product service systems (PSS), smart bike sharing, transportation, technological change and innovation

1 INTRODUCTION

Bicycle-sharing systems (BSS) are sometimes used to encourage lower transportation environmental impact by replacing vehicle trips with bicycle trips. Early BSS overcame issues of theft, lost bikes, and repairs by increasing use of electronics. Current smart dock systems track which user rents each bike, allowing accountability for lost, stolen, or vandalized bikes. These improvements allowed BSS to become economically feasible and enabled their recent rapid growth, from 11 systems in 2004 to approximately 855 systems in 2014 (Goodyear, 2018). Docked systems, however, require that bicycles be returned to a docking station at a fixed location. Newer smart bike systems do not require fixed docks and are now make up 44% of U.S. BSS (National Association of City Transportation Officials, 2017). In a smart dock BSS, the central docking station contains all the electronic equipment needed to manage the shared bikes, such as mobile global positioning systems (GPS), information technology, and solar panels. In 2015, researchers estimated there were almost 1 million BSS bikes worldwide, with three-fourths of those in China (Fishman, 2016). By the year 2016, 31% of all U.S. BSS were smart bike BSS. In the United States, an additional 57,500 bicycles were added from 2016 to 2017, of which 77%
were smart bikes (National Association of City Transportation Officials, 2017). In 2018, China had between 16–18 million BSS bicycles (Campbell, 2018).

Use of smart bike instead of smart dock BSS has not led to reliable ridership increase, but has addressed the needs of different types of users. DC bikeshare reported that adding smart bike systems did not reduce smart dock system ridership, but by incorporating both systems, they increased the overall diversity of the BSS user population (Smith, 2018). A Virginia Tech Survey of Washington, DC smart dock and smart bike BSS users revealed that smart bike users were more racially diverse, had a higher proportion of female riders, and had a lower income (Virginia Tech, 2018).

Evidence indicates, however, that smart bike BSS users may have less sustainable usage patterns. In the United States, smart bike systems averaged 0.3 rides per bike per day, while smart dock systems averaged 1.7 rides per bike per day in 2017 (National Association of City Transportation Officials, 2017). Other smart bike ridership estimates range from 0.5 to 1.6 rides per bike per day (Mynorthwest.com, 2018; Relay Bike Share, 2017; Runyan, 2017). In Seattle, smart dock systems demonstrate usage patterns that correlate with commuting rush hours, while smart bike systems exhibit trip patterns suggestive of recreational use (National Association of City Transportation Officials, 2017). In Washington, DC, smart bikes have more geographically diverse usage, most likely because trips are not constrained to docking stations (Virginia Tech, 2018). Despite fulfilling different functional needs, both smart dock and smart bike BSS trips in Washington, DC are generally less than 3 miles.

Without strong evidence of increased ridership, increasing the use of electronics may undermine the environmental sustainability of BSS schema. Experts caution that there is no standard method for evaluating the overall success of a city's BSS implementation (Fishman, 2016; Fishman, Washington, & Haworth, 2013; Midgley, 2011). In this paper, we contribute toward this larger goal by calculating the break-even points and environmental impacts of individual BSS technologies via a life cycle assessment (LCA) and suggesting technology development recommendations.

Based on the essential role of technology in the success of BSS, we raise the following question: What ridership conditions warrant the increased use of electronics in smart bike BSS? How can BSS operators improve environmental impact from a technology selection standpoint? By means of an Environmental LCA, we quantify the difference in the environmental impact of the production, use, and disposal phases of private bikes, a smart dock, and a smart bicycle BSS. The smart bikes in our study have a dedicated touchpad, screen, and solar panel. The LCA was conducted with the functional unit of per kilometer biked. By using the functional unit per distance traveled, the results can be compared to the impact of other modes of transportation. As a secondary benefit, this functional unit emphasizes the importance of the shared travel aspect of the BSS.

The LCA determines the environmental impact per kilometer among a smart bike, smart dock, and private bicycle for the production, repair, disposal, and rebalancing lifecycle phases. This assessment achieves the following goals: First, this paper is the first published LCA of a smart bike known to the authors. Second, we compare the impact of a smart dock and smart bike system to determine how many more rides per bike per day are necessary to overcome the increased environmental impact of switching in a city. Third, we provide an estimate of the total increase in impact if the evolution from smart dock to smart bike is completed in the United States and caution that it may undermine the environmental sustainability of the BSS. Fourth, we leverage our LCA results to provide recommendations as to the preferred configuration based on the number bikes fitted per dock. Finally, because these results indicate that smart dock systems may not be environmentally preferable without additional advances in BSS smart bike technology, we provide recommendations for future technology development efforts to reduce the environmental impact of future smart bike BSS. The following sections describe prior studies of bike-sharing environmental impact, the method of data collection and analysis, and the results.

2 | BACKGROUND

2.1 | Benefits of BSS and need for a systematic method to evaluate BSS

BSS growth has been fueled by city, personal, and environmental benefits as a substitute for fossil fuel–powered transportation (Shaheen, Guzman, & Zhang, 2010). When announcing the implementation of their BSS, officials from Barcelona, Lyon, and Paris referred to BSS as a sustainable transportation option (Midgley, 2011). In a recent survey, 40% of BSS users in Melbourne, Australia responded that a reason they use the system is for the environmental benefits (Fishman, Washington, & Haworth, 2014). BSS can also promote economic growth by increasing real estate development, helping companies secure more talented workers, and increasing retail visibility and sales (Boland, Murphy, Armstrong, & Barry 2012; Bullock, Brereton, & Bailey, 2017; Urban Land Institute, 2016). BSS also improve the physical, social, and mental health of communities by increasing access to transportation and recreational facilities (Grabow et al., 2012; de Hartog, Boogaard, Nijland, & Hoek, 2010; Mueller et al., 2015; Otero, Nieuwenhuijsen, & Rojas-Rueda, 2018; Sallis et al., 2015).

Bike sharing, however, increased the overall motor vehicle usage when the effect of bike rebalancing was considered in London, United Kingdom (Fishman, Washington, & Haworth, 2014). Rebalancing refers to the process of relocating bicycles by vehicles and personnel to compensate for asymmetric demand patterns between BSS stations. These asymmetric flow patterns can be driven by topography or mismatches in the underlying demand for bicycles (Fishman et al., 2013). Rebalancing in London required approximately 2.2 km of car travel for every 1 km of bike travel. Reducing need for rebalancing is a primary BSS research topic because improving the rebalancing process directly reduces BSS environmental and monetary costs (Fishman, 2016; Rudloff & Lackner, 2014; Schuijbroek, Hampshire, & van Hoeve, 2017). Some cities have attempted to avoid using fossil fuel vehicles to perform rebalancing by incentivizing users to reposition the bikes (Shaheen, Martin, Cohen, & Finson, 2012).
2.2 Previous bicycle LCAs

Previous LCAs of personal bicycles highlight the production phase as the highest environmental impact (excluding off-set vehicle emissions) relative to the other phases of the lifecycle, but do not consider factors unique to BSS, such as the evolution of bicycle technology or the role of rebalancing bicycles. Studies of traditional bikes show that the component with the greatest environmental impact is the aluminum bicycle frame (Dave, 2010; Leunberger & Frischknecht, 2010; Luna, 2016). The increased impact of the aluminum bicycle frame motivated a comparative LCA study using other materials for the bicycle frame such as Bamboo (Agyekum, Karen Fortuin, & derHarst, 2017).

The need for an objective evaluation of the environmental impact of BSS has been identified in the literature (Fishman, 2016; Fishman et al., 2013; Midgley, 2011). Amaya, Lelah, and Zwolinski (2013) use BSS as a case study for an LCA of product service systems (PSS). The focus of their study was to evaluate how variations in the system design parameters of a PSS affect its environmental impact. Different BSS scenarios were analyzed to understand how the intensification in the use phase of PSS affects its sustainability. The researchers varied the total number of bicycles in the system, the amount of maintenance time, and bicycle redistribution. Their results showed that environmental benefits of PSS increase with the amount of use. Their study, however, did not include details on the life cycle impacts of the BSS and it only considered the smart dock technology.

3 METHODOLOGY

3.1 LCA goal, scope, and functional unit

The goal of this LCA is to compare the environmental impacts of increasing electronics in smart dock and smart bike BSS. The comparison reveals which components have the most environmental impacts and what increase in bicycle usage is needed. These results also evidence potential technology improvements. Our goal with this study is not to validate or refute the environmental benefits of using a bicycle as a means of transportation, but rather to have a better understanding of the tradeoffs that exist when implementing technology and electronics in BSS with respect to their environmental impact.

The LCA scope is a cradle-to-grave analysis of smart bike, smart dock, and private bicycles in a hypothetical city X over 10 years. The cradle-to-grave analysis includes the production, disposal, and use phases. For the three systems, the disposal scenario is similar, where 100% of the components are disposed in a landfill (0% recycling). Although previous LCA studies on personal bicycles highlight the production phase as the one with the highest environmental impact relative to the other phases of the lifecycle (Dave, 2010; Leunberger & Frischknecht, 2010; Luna, 2016), BSS add an additional environmental impact because of the maintenance and rebalancing operations. Implementing BSS can decrease traffic congestion, though implementation of BSS increased vehicle traffic in London (Fishman et al., 2014). This LCA, however, does not incorporate reduced vehicular congestion into our analysis or otherwise consider the impact of nonuser private vehicle travel. We also assume that the percentage of rides that replace cars is not going to increase relative to other modes because there is no evidence that increased electronics changes the percentage of bicycle kilometer that replace vehicle kilometer.

To compare the environmental impact of the private bike and two BSS, the total environmental impact is normalized by the functional unit kilometer of bike travel.

3.2 Life Cycle Inventory (LCI) data collection

The inventory data for the two BSS bicycles and the private bicycle were obtained from multiple data sources. A U.S. smart bike BSS operating company provided access to the individual smart bicycle BSS components. The components of this smart bicycle BSS were individually weighed using a scale and classified according to their material type. The measurements were taken with a Grawor Digital Luggage scale, which has a maximum capability of 50 kg. The digital readability for this scale is 5 g for measurements between 2 × 10⁻² and 10 kg, and 10 g for measurements above 10 kg. The data for the private bicycle were gathered from a bicycle starter program on a U.S. college campus. The private bicycle components were also individually weighed and classified according to their material type.

Without physical access to an electronic docking station, the most relevant electronic components were estimated using literature data. We contacted BSS operating companies in the southeast region of the United States, but the companies expressed their unwillingness to provide access to an electronic docking station. A literature review of electronic stations based in academic journals, design patents of docking stations for bike-sharing systems, and company documents for electronic kiosks provided data for the components and sizes of a docking station and kiosk. Each document was reviewed, and a list of the most common components distilled as follows: a solar panel, a battery, a printed circuit board (PCB), a display screen, a keypad, a radio communication module, and a GPS module.

For smart docks, the estimated solar panel area, the weight of the battery, and the PCB weight are all divided by 10 to obtain the values per bike. Ten bicycles per docking station is the average bicycles per dock across 52 BSS located in the United States (Cohen, Simons, Martignoni, Olson, & Holben, 2014).
3.3 | Rebalancing impact estimation

Currently, operator rebalancing data are only available for smart dock BSS in Washington, DC, London, Minneapolis-St. Paul, and Melbourne (Fishman et al., 2014). Although operators of smart bike BSS provide incentives for riders to return bikes to designated areas, smart bikes may be more distributed than smart docked bikes and require more vehicle travel. Thus, using the smart dock rebalancing distance for the smart bike rebalancing in our LCA may provide a conservative estimate.

The impact of rebalancing per kilometer biked depends on: the number of bikes in the system, system size, types of vehicles used for rebalancing, and how often rebalancing occurs. This investigation will evaluate the rebalancing impact for a fictional city referred to as City X. City X has 1,240 bicycles, 804,900 trips annually, and requires 105,582 km of rebalancing. City X was created by averaging the reported values for Melbourne, Washington, DC, and Minnesota (Fishman et al., 2014). U.S. LCI data for operating a gasoline-powered light commercial truck (0.68 kg CO$_2$/km driven) were used to estimate the environmental impact of driving the rebalancing vehicles in City X (National Renewable Energy Laboratory, 2012).

3.4 | Maintenance impact estimation

BSS maintenance for the drivetrain and braking systems is estimated from manufacturer user manuals and web sources (Aarons Bicycle Repair, 2013; Bike Forums, 2015; Shaddy, 2015; Shimano Inc., 2015; Stone, 2014). Bicycle experts report a large variation in the life expectancy for the drivetrain and braking components, so the average values were used. Table 1 shows the assumed service life of the components in the private and BSS bicycles. The maintenance impact is calculated based on the number of component replacements required in the 10-year lifetime.

Using the component data shown in Table 1, we determine the environmental impact of each of the components at the endpoint and midpoint levels per bike using RECIPE 2008. The climate change impact is 8.30 kg of CO$_2$ Eq. for the private bike, 28.39 kg of CO$_2$ Eq. for the smart bike, and 23.91 kg of CO$_2$ Eq. for the smart dock bike. The human health, ecosystem, and resources impacts are 1.27 Points (Pts) for the private bike, 3.36 Pts for the smart bike, and 3.34 for the smart dock bicycle.

3.5 | Conversion of total impact estimation to functional unit

Once the environmental impact from each of the lifecycle phases is calculated, it is normalized into the functional units of kilogram CO$_2$ Eq./km biked and Pts/km biked. To convert the lifetime into kilometer, it is assumed that the average trip distance is 2.49 km/trip, based on BSS data, (Fishman et al., 2013). For City X, the BSS bikes are assumed to travel 1,616 km annually and private bikes travel 1,387 km a year. To verify this assumption for the private bicycle mileage in a 1-year time frame, average daily ridership values for the country of Netherlands were found to vary between 1.4 and 6.2 km/day (Colofon, 2016). Assuming that 6.2 km is ridden per day, a total of 1,387 km are ridden in 1 year. Changes in ridership patterns, the number of bikes in City X, or rebalancing strategy over 10 years would affect the impact and are not taken into consideration in this study.

4 | RESULTS AND DISCUSSION

4.1 | Bill of materials and LCI data

The RECIPE 2008 impact results are provided for the endpoint categories of human health, ecosystems, and resources in total impact Pts and for the midpoint category climate change. Endpoint categories provide an overall comparison of the two systems, and climate change in terms of CO$_2$ equivalent may be more relevant from a policy perspective.

For this study, we assumed that most smart dock and smart bike component weights are equivalent. The drivetrain for the smart bike model measured empirically in this study uses a driveshaft instead of a chain and cassette to be more robust. The driveshaft has a higher environmental impact.
Table 2 shows the LCI for the smart bike, smart dock, and private bicycle. The higher total impact of the BSS bicycles is due to an emphasis on durability, achieved with larger elements and special components such as nonremovable seats (Shaheen et al., 2012). Table 2 also shows the LCI data for the stand-alone electronic system used in the smart bicycle system. Regarding the smart bike BSS, the only component that required estimation was the PCB weight. The weight of the battery and the solar panel area were measured empirically by the researchers. The researchers weighed the electronic unit fitted in each smart bicycle that included the PCB, the LCD screen, and a plastic case that protected all of the components. To estimate the weight of the PCB from the total weight of 0.86 kg, the material composition results from the work of Kasulaitis, Babbitt, Kahhat, Williams, and Ryen (2015) was used. Their work suggests that 35% of the total weight is attributed to the PCB, which results in a weight of 0.3 kg.

The docking stations for both BSS arrangements are assumed to be made of steel. The smart bike station consists of modular steel designs that do not require permanent fixtures. The docking station weight was measured empirically as 30 kg and it was added to the LCA analysis for both BSS arrangements.

4.2 Production phase impact results

Table 3 shows the production phase GHG in kilogram CO$_2$ Eq. using RECIPE 2008 and the percent of the total environmental impact (%). The PCB, solar panel, bicycle frame, and steel alloy components account for greater than 95% of the total production phase environmental impact for both
**Table 3** Components that account for the most environmental impact in the production phase. Results are shown for GHG emissions and the endpoint categories of human health, ecosystems, and resources (*10 bikes per dock*)

| Component      | Private bicycle kg CO₂ | % of total | Smart bicycle BSS** kg CO₂ | % of total | Smart dock BSS** kg CO₂ | % of total |
|----------------|-------------------------|------------|-----------------------------|------------|--------------------------|------------|
| Circuit board  | –                       | –          | 545.70                      | 37.40%     | 0.32                     | 0.10%      |
| Solar panel    | –                       | –          | 573.90                      | 39.30%     | 139.40                   | 29.10%     |
| Bicycle frame  | 70.72                   | 78.80%     | 175.70                      | 12.00%     | 175.70                   | 36.70%     |
| Alloyed steel  | 6.04                    | 6.70%      | 147.80                      | 10.10%     | 147.80                   | 30.90%     |
| Total          | 76.80                   | 85.50%     | 1,460.00                    | 98.80%     | 478.60                   | 96.80%     |

**Table 4** Production phase GHG emission impact in kg CO₂ per bicycle at the climate change category and production phase impact for the human health, ecosystems, and resources endpoint categories for the private bike, smart bicycle, and smart dock BSS (*10 bikes per dock*)

| Midpoint category | Unit | Private bicycle kg CO₂ | Smart bicycle BSS** kg CO₂ | Smart dock BSS** kg CO₂ |
|-------------------|------|-------------------------|-----------------------------|--------------------------|
| Climate change    | kg CO₂ | 89.63                  | 1,459.00                    | 478.35                   |

| Endpoint category | Unit | Private bicycle Pts | Smart bicycle BSS** Pts | Smart dock BSS** Pts |
|-------------------|------|---------------------|-------------------------|----------------------|
| Human health      | Pts  | 4.97                | 77.35                   | 25.04                |
| Ecosystems        | Pts  | 2.06                | 23.26                   | 9.40                 |
| Resources         | Pts  | 4.90                | 47.29                   | 20.31                |
| Total             | Pts  | 11.93               | 147.90                  | 54.75                |

Table 4 compares the environmental impact per bicycle for the human health, ecosystems, and resources endpoint categories and the climate change midpoint category. The smart bicycle BSS production phase impact is approximately 3.7 times the climate change impact of a smart dock BSS. The smart bike also has approximately 2.7 times the endpoint impacts of the smart dock bicycle. The increased environmental impact of the BSS bikes relative to the private bike is due to the reduced amount of electronics required per bicycle relative to the smart bicycle arrangement.

The production results provide the basis for our recommended technology development agenda. The production phase GHG emissions for the electronic components were 7,453 kg CO₂ Eq./m² for the solar panel, 13.95 kg CO₂ Eq./kg for the PCB, and 1.01 kg CO₂ Eq./kg for the battery. BSS technology developers should target the solar panel as the main component for reducing the environmental impact of the electronics, followed by the PCB and the battery. The solar panel impact could be reduced by improving solar panel technology or minimizing the required electrical loading of the battery. For example, the solar panel could be used only to initiate a bike checkout and some of the user’s pedal energy could be harvested to recharge the battery during trips, transmit location data, and other energy intensive operations.

4.3 Cradle to grave impact results

Figure 2 shows the environmental impact per kilometer biked for the three evaluated designs with all cradle-to-grave phases included. The smart bike resulted in the highest environmental impact per functional unit with a value of 0.013 kg CO₂ Eq. (0.013 Pts) per kilometer biked over its
lifetime, compared to 0.068 kg CO$_2$ Eq. (0.0071 Pts) per kilometer biked for the smart dock and 0.0015 kg CO$_2$ Eq. (0.0024 Pts) per kilometer biked for the private bike. The additional impact of the electronics in the BSS results in a significant difference in GHG emissions from private bicycles. The impact of a private passenger vehicle 0.186 kg CO$_2$ (0.017 Pts) per kilometer is plotted for comparison. The three bicycle solutions provide a net environmental benefit, but the vehicle substitution rate to bicycle must be evaluated to provide the complete picture.

The impact per kilometer will further decrease if we include the offset emissions from vehicle substitution rate. Vehicle substitution rate is the percentage of BSS trips that would otherwise have been by private automobile. Optimizing bike sharing in European countries reports vehicle substitution rates as high as 79%, whereas other studies have reported rates as low as 1–2% (Bullock et al., 2017; European Cyclists Federation, 2011; Fishman et al., 2014). The lowest vehicle substitution rate of 1–2% is probably related to an overall shift in the modal share of cities, and variance in vehicle substitution rate between the examined cities is likely related to the transportation mode mixture within each city. For 21 cities in the United States, Canada, and Europe, the average vehicle substitution rate is 22% (Bullock et al., 2017; European Cyclists Federation, 2011; Fishman et al., 2014; Fishman et al., 2013; Rojas-Rueda, de Nazelle, Tainio, & Nieuwenhuijsen, 2011). If only peer-reviewed sources are used, the average vehicle substitution rate of the remaining nine cities drops to 9.7%, with a maximum reported vehicle substitution rate of 21%. Using these minimum and maximum vehicle substitution rates reduces the per kilometer impact by 0.018–0.15 kg CO$_2$ Eq. (0.0017–0.013 Pts) per kilometer biked. At a 22% vehicle substitution rate, the expected reduction is 0.040 kg CO$_2$ Eq. (0.0037 Pts) per kilometer.

To result in a net positive environmental impact, a vehicle substitution rate of 38% (kg CO$_2$) or 43% (Pts) is required for the smart dock, and a rate of 71% (kg CO$_2$) or 76% (Pts) is required for smart bike. When evaluating the minimum vehicle substitution rate (worst case impact scenario), only the private bike usage results in a net environmental reduction (~0.0099 kg CO$_2$ Eq. [~4.7 × 10$^{-4}$ Pts] per kilometer biked). These large necessary vehicle substitution rates illustrate the importance of modal shift from high-impact modes of transportation like private vehicle to BSS compared as users shifting from other sustainable modes of transportation such as private bike or walking.

Using the impact per kilometer biked in City X, we can estimate the additional number of rides needed for a smart bicycle system to have the same impact as an equivalent smart dock system. A replacement smart bike system would need to increase demand from 1.7 daily trips per bike to 3.28 daily trips per bike. Thus, ridership would need to increase 1.8 times. In contrast, there is evidence that smart bike systems have less ridership per bike than smart dock systems. In the United States, smart bike systems averaged 0.3 rides per bike per day, whereas smart dock systems averaged 1.7 rides per bike per day in 2017 (National Association of City Transportation Officials, 2017).
FIGURE 2  Impact per kilometer biked for private bicycle, smart dock, and smart bicycle BSS
### TABLE 5  Summary of BSS arrangement environmental and system characteristics

| Topic                        | Smart bike system                                                                 | Smart dock system                                                                 |
|------------------------------|-----------------------------------------------------------------------------------|-----------------------------------------------------------------------------------|
| Production phase             | Production phase environmental impact per bicycle is high due to amount of electronics fitted per bike. GHG: 1.460 kg CO₂ Endpoint total: 148 Pts | Centralized electronic system reduces the environmental impact per bike relative to smart bike. GHG: 479 kg CO₂ Endpoint total: 55 Pts |
| Complete lifecycle           | Ridership would need to increase by 1.8 for a smart dock system or vehicle substitution rate of 71%. GHG: 1.3 x 10⁻¹ kg CO₂/km Endpoint total: 1.3 x 10⁻² Pts/km | Lower environmental impact per kilometer ridden than smart bike. Requires vehicle substitution rate of 38%. GHG: 6.9 x 10⁻² kg CO₂/km Endpoint total: 7.2 x 10⁻³ Pts/km |
| environmental impact per     |                                                                                   |                                                                                   |
| kilometer biked              |                                                                                   |                                                                                   |
| Station density or           | Impact per bike is consistent when varying the number of bikes per docking station. Should be considered when less than five bikes are fitted per docking station area or for cities with fewer than 3,000 residents/km². | Results suggest that the smart dock system provides an environmental benefit when having 5 or more bicycles per docking station area. Should be considered for cities with more than 1,000 residents/km². |
| number of bikes per          |                                                                                   |                                                                                   |
| station                      |                                                                                   |                                                                                   |
| Bicycle rebalancing         | The rebalancing operation is a significant source of environmental impact on both BSS arrangements. Regardless of the BSS arrangement, it is recommended to adopt low-emission or even zero-emissions rebalancing procedures. GHG: 3.6 x 10⁻² kg CO₂/km Endpoint total: 3.4 x 10⁻³ Pts/km |                                                                                   |
| Electronic components       | The LCA results show the solar panel has the highest environmental impact at 7,453 kg CO₂/m², followed by the PCB at 14 kg CO₂/kg and finally the battery at 1 kg CO₂/kg. The solar panel impact could be reduced by improving solar panel technology or minimizing the required electrical loading of the battery. |                                                                                   |

#### 4.4 Sensitivity analysis

We performed two sensitivity analyses, one testing the assumptions of rebalancing and a second testing the vehicle substitution rate. For rebalancing, we tested the sensitivity of breakeven ridership levels to the assumption that the rebalancing requirement is the same for smart dock and smart bike systems. We evaluated a smart bikes best-case scenario of a 90% reduction in rebalancing requirements for City X, yielding 10,558 km rebalancing for smart bike and 105,582 km rebalancing for smart dock. Smart bikes still have a higher impact of 0.0912 kg CO₂ per day to result in equal impact.

To test vehicle substitution rates, we tested scenarios with the highest observed vehicle substitution rate (79%) for the smart bike and the lowest reported vehicle substitution rate (1%) for the smart dock. In this best case for smart bikes scenario, smart bikes resulted in more CO₂ savings, −0.0665 versus −0.02122 kg CO₂ Eq./km traveled. For equivalent net impact, the smart bike requires a 35% higher substitution rate than smart bike. This result supports earlier evidence for the importance of a high vehicle substitution rate for overall BSS sustainability.

To ensure the parameters of City X did not drive the final results, the analysis was repeated with the reported parameters for Melbourne, Washington, DC, and Minnesota. The smart bike impact ranged from 2.2 to 3.6 times larger than the smart dock impact for those cities, consistent with the results for City X. Assuming similar ridership levels for smart dock and smart bike systems may provide a conservative estimate. Although 44% of the U.S. BSS bicycles in 2017 are smart bike, they only accounted for 4% of the trips taken (National Association of City Transportation Officials, 2017).

Table 5 summarizes the key findings of this study with respect to the environmental impact for both BSS arrangements. It provides the key characteristics of each systems and their strengths and weaknesses.

#### 5 CONCLUSION

This study evaluated the environmental tradeoffs of increasing use of electronics of smart bike BSS relative to smart dock BSS. This was accomplished with a comparative LCA of the production, disposal, and use phases of a smart bike BSS, a smart dock BSS, and private bikes. This study is the first to the author’s knowledge containing LCI data for smart bike systems.

Shifting to smart bike in our analysis requires an increase in ridership by a factor of 1.8 to overcome the increased environmental impact of electronics in smart bikes. We identified that smart bike is the preferred configuration when there are less than five docks per station. Smart bikes are appropriate for cities with lower population density, less than 1,000 residents/km² if the city is bike friendly and less than 3,000 residents/km² if the city is less bike friendly. Otherwise, smart docks are more environmentally preferable. Future technology development efforts should reduce...
environmental impact of smart bike BSS by focusing on the solar panel and PCB. Using lower impact solar technologies and reduce the power requirements are two viable methods.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

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