ENVIRONMENTAL RESEARCH
LETTERS

PURPOSE-LED PUBLISHING™
Celebrating the 20th anniversary of Environmental Research Letters

LETTER • **OPEN ACCESS**

Are e-scooters polluters? The environmental impacts of shared dockless electric scooters

To cite this article: Joseph Hollingsworth *et al* 2019 *Environ. Res. Lett.* **14** 084031

View the article online for updates and enhancements.

You may also like

- Electric bicycles sharing: opportunities and environmental impacts
Wissam Kontar, Soyoung Ahn and Andrea Hicks
- Evaluation of mitigation effects on air pollutants for electric scooters in Taiwan with the energy flow analysis and system dynamics approach
P Y Hsieh, L F W Chang, T Y Yu et al.
- Electric Vehicles and Renewable Energy
Hasan Aydogan

Environmental Research Letters

LETTER

Are e-scooters polluters? The environmental impacts of shared dockless electric scooters

Joseph Hollingsworth, Brenna Copeland and Jeremiah X Johnson[1]

Department of Civil, Construction, and Environmental Engineering, North Carolina State University, United States of America
[1] Author to whom any correspondence should be addressed.

E-mail: jjohns24@ncsu.edu

Keywords: electric scooter, life cycle assessment, transportation, environmental impacts

Supplementary material for this article is available online

OPEN ACCESS

RECEIVED
1 May 2019

REVISED
26 June 2019

ACCEPTED FOR PUBLICATION
28 June 2019

PUBLISHED
2 August 2019

Original content from this work may be used under the terms of the Creative Commons Attribution 3.0 licence.

Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.

Abstract

Shared stand-up electric scooters are now offered in many cities as an option for short-term rental, and marketed for short-distance travel. Using life cycle assessment, we quantify the total environmental impacts of this mobility option associated with global warming, acidification, eutrophication, and respiratory impacts. We find that environmental burdens associated with charging the e-scooter are small relative to materials and manufacturing burdens of the e-scooters and the impacts associated with transporting the scooters to overnight charging stations. The results of a Monte Carlo analysis show an average value of life cycle global warming impacts of 202 g CO_2-eq/passenger-mile, driven by materials and manufacturing (50%), followed by daily collection for charging (43% of impact). We illustrate the potential to reduce life cycle global warming impacts through improved scooter collection and charging approaches, including the use of fuel-efficient vehicles for collection (yielding 177 g CO_2-eq/passenger-mile), limiting scooter collection to those with a low battery state of charge (164 g CO_2-eq/passenger-mile), and reducing the driving distance per scooter for e-scooter collection and distribution (147 g CO_2-eq/passenger-mile). The results prove to be highly sensitive to e-scooter lifetime; ensuring that the shared e-scooters are used for two years decreases the average life cycle emissions to 141 g CO_2-eq/passenger-mile. Under our Base Case assumptions, we find that the life cycle greenhouse gas emissions associated with e-scooter use is higher in 65% of our Monte Carlo simulations than the suite of modes of transportation that are displaced. This likelihood drops to 35%–50% under our improved and efficient e-scooter collection processes and only 4% when we assume two-year e-scooter lifetimes. When e-scooter usage replaces average personal automobile travel, we nearly universally realize a net reduction in environmental impacts.

1. Introduction

With a small electric motor and a deck on which a single rider stands, stand-up scooters are designed to transport riders short distances around urban settings. Ride share companies are introducing fleets of these vehicles into urban areas, allowing participants to rent the scooters for short periods of time. Dockless ride sharing allows the scooters to be left at a final destination of the user, ultimately to be retrieved by the next user or picked up for charging.

Dockless shared e-scooters are touted as a solution to the *last-mile problem*, a means to reduce traffic congestion, and an environmentally preferable mode of transportation [1, 2]. While these e-scooters have no tailpipe emissions, full consideration of the life cycle impacts is required to properly understand their environmental impacts. In this study, we use life cycle assessment (LCA) to quantify the total global warming, acidification, eutrophication, and respiratory impacts of shared dockless electric scooters. The goal of this study is to identify the key drivers for adverse environmental impacts, to offer recommendations on policies or practices that would reduce these impacts, and to compare the overall impacts to other modes of transportation.

© 2019 The Author(s). Published by IOP Publishing Ltd

To the best of our knowledge, this is the first peer reviewed study that comprehensively examines the environmental life cycle impacts of shared e-scooters. Life cycle approaches have been used extensively to address comparable questions for other transportation technologies. For example, other studies have examined alternative transportation options, including electric vehicles [3, 4], car-sharing programs [5], autonomous vehicles [6], and electric bicycles [7, 8], as well as full urban transportation systems [9] and comparisons across two-wheel vehicles [10, 11].

Although it is not peer reviewed, Chester published the results of an LCA on shared dockless e-scooters that is most relevant to our analysis [12]. This study included impacts from materials and manufacturing, collection and distribution, charging, and disposal of e-scooters. Results show that manufacturing and materials are responsible for the most life-cycle CO_2 emissions, followed by collection and distribution and charging of the scooter, for a total of 320 g CO_2/mile in the best-case scenario. While similar to our study's goal, our analysis extends this work by collecting detailed primary data for the materials inventory, daily e-scooter usage, and survey data on transportation modes being displaced, among other differences.

Compared to e-scooters, far more research has been conducted on the environmental impacts of bicycles, electric bicycles, mopeds, and motorcycles. In 2001, Zhang *et al* quantified the life cycle environmental impacts of electric bike applications in Shanghai and found that electrification improved the environmental performance of many, but not all, impact categories relative to gasoline-powered motorbikes [7]. Cherry studied life cycle environmental impacts of personal electric two-wheelers (moped scooters) on the transportation system in China [8], finding that the materials burdens far outweighed the impacts from assembly, that there were considerable emissions attributable to charging, and that the adverse impacts from the lead batteries was high. (For modern e-scooters, lead batteries have been replaced with lithium-ion batteries.) These e-bikes were found to have lower life cycle emissions than cars per mile traveled across all pollutants examined, with most life-cycle impacts not from local pollutants, but incurred during the production process, introducing environmental externalities into other regions [8].

Luo *et al* used a life cycle approach to compare station-based and dockless bike sharing programs in the US [13]. They found that rebalancing (collection and distribution) of shared bicycles was the main source of life-cycle emissions in dockless bicycles, while the docking infrastructure was a major source of impacts in station-based bicycles. Consistent with Cherry [8], Luo *et al* note that car displacement is the most important factor in reducing emissions, with at least 34% of bike sharing trips needed to replace car usage in order to realize net impact reductions [13]. Similarly, Weiss *et al*, Sheng *et al*, and Rose studied the impacts of personal electric motorcycles and e-bicycles on the environment and transportation system, each noting the importance of the modes of transportation being displaced [11, 14, 15].

In addition to these studies, Hsieh *et al* used a system dynamics approach to examine the air pollution mitigation potential of seated electric scooters in Taiwan, but limited the scope to use phase impacts [16]. Sheng *et al* [14] compared electric motorcycles to gasoline-powered motorcycles on urban noise, finding that electrification can reduce noise pollution. Additionally, Bishop *et al* examined the use phase environmental performance of seated electric scooters in the United Kingdom, while Leuenberger and Frischknect conducted a full comparative LCA for two wheeled vehicles including seated electric scooters [10, 17].

Our study differs from previous research by conducting a full LCA to address the environmental impacts associated with the materials, manufacturing, transportation, charging, and end-of-life for shared dockless standing e-scooters. Conducting an LCA on an emerging technology offers a greater ability to inform policy makers and consumers, as regulations and market behavior are still developing [18]. Wender *et al* [19] describes approaches to early stage LCA, including the use of scenario development (e.g. [20]) to explore the range of possible outcomes. Although e-scooter technology is not in an early stage of development, the business model of shared, dockless e-scooters has emerged quickly in 2018 and is still evolving. Our study utilizes scenario analysis to better understand the ability to reduce the environmental impacts based on this model of shared dockless e-scooters. In this study, we collect primary data on e-scooter materials and use, coupled with scenarios and a Monte Carlo analysis to explore the magnitude and drivers for environmental impacts. In section 2, we describe our data sources and methods. In sections 3 and 4, we present our results and discussion.

2. Methods

In accordance with the ISO standards, our LCA includes goal and scope, inventory analysis, impact assessment, and interpretation. Figure 1 shows our system boundary diagram, which includes materials, manufacturing, e-scooter transport, use and charging, and end-of-life. Due to a lack of data availability and short scooter lifetime, we exclude routine maintenance such as replacing tires or parts during the lifetime of the scooters.

The functional unit for our study is one passenger-mile traveled. Our Base Case assumptions for daily

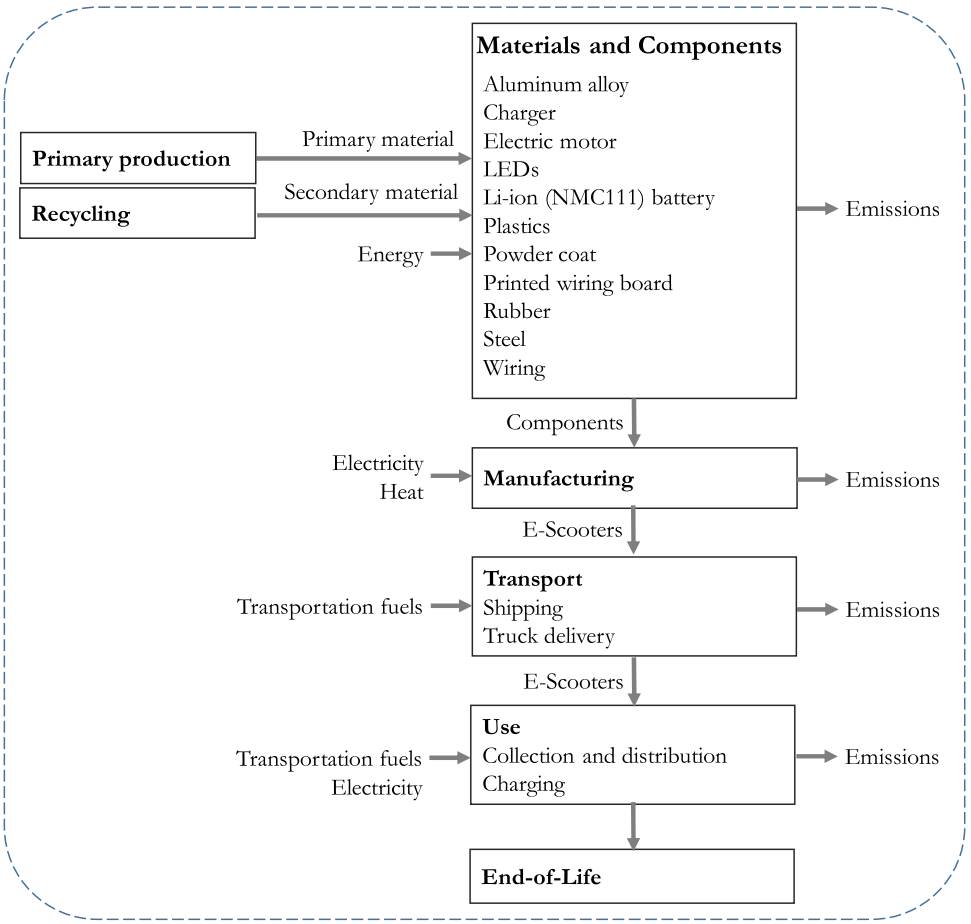


Figure 1. System boundary diagram for a life cycle assessment on shared dockless electric scooters.

scooter usage and collection requirements are consistent with assumptions for Raleigh, North Carolina. We test a range of parameter values to assess each input's sensitivity and ensure broad applicability of results. Equation (1) describes the generalized calculation for impact per passenger-mile for each impact category

$$I = \frac{M + T + \sum_0^d (MPS_d \times EF_{auto}) + \sum_0^d \sum_0^i (E_{grid,\,i,d} \times EF_{grid,i,d})}{\sum_0^d D_d} \quad (1)$$

I represents the life cycle impacts for a given impact category (kg-eq/passenger-mile). M represents the burdens associated with the materials and manufacturing of the scooter (kg-eq/scooter) and T is the burden associated with transportation of the scooter from shipping and trucking (kg-eq/scooter). MPS_d is the auto-miles traveled per day (d) for collection and distribution of scooters (auto-miles/scooter-day) and EF_{auto} is the emissions factor for the vehicle used to collect the scooters (kg-eq/auto-mile). $E_{grid,i,d}$ is the electricity used for charging in hour i, day d (MWh/scooter). $EF_{grid,i,d}$ represents the emission factor associated with the specific grid region where the scooter is being charged (kg-eq/MWh). D_d represents the scooter distance traveled on day d. We use TRACI v 2.1 characterization factors to convert inventory results to environmental impacts [21].

2.1. Materials and manufacturing

To create an accurate materials inventory for an electric scooter, we disassembled a Xiaomi M365 scooter, representative of the model that shared scooter companies including Bird and Lyft currently deploy [22]. Table S1 is available online at stacks.iop.org/ERL/14/084031/mmedia in the supporting information provides the data for the materials inventory and the ecoinvent v3.3 process. The materials characterization was informed by the documentation provided by the manufacturer and the material codes imprinted directly on the components. The mass of each component was recorded to the nearest gram. The ecoinvent material for production of aluminum alloy was used for the frame, representing the best ecoinvent material for 'aerospace grade' aluminum alloy, as described by the manufacturer.

The major materials and components of the e-scooter include an aluminum frame (6.0 kg), steel parts (1.4 kg), a lithium ion battery (1.2 kg), an electric motor (1.2 kg), and tires with tubing (0.83 kg), which in total account for 89% of the total scooter mass. The lithium-ion battery has a cathode material $LiNi_{1/3}Mn_{1/3}Co_{1/3}O_2$ (NMC 111), as indicated by the battery manufacturer. We use the methods detailed by Ellingsen *et al* [23] and Ciez and Whitacre [24] to determine the environmental impacts of battery production and recycling. Manufacturing burdens are estimated from the ecoinvent process electric bicycle production, which is used as a proxy for the energy requirements to manufacture and assemble the scooter from components. We use a recycled content approach; our Base Case assumes 24% recycled content for aluminum, consistent with Chinese aluminum in 2017 [25].

2.2. Transportation to United States

We assume the scooter and battery are assembled in Shenzen, China, as indicated by the manufacturer [26]. The total mass of the scooter, packaging, and accessories is 17.5 kg. We calculate the transportation burdens based on freight shipping to Los Angeles, California (estimated at 11 800 km) and trucking from Los Angeles to Raleigh, North Carolina (estimated at 4000 km), resulting in 207 ton-km and 70 ton-km for shipping and trucking, respectively, per scooter.

2.3. Use phase

The use phase impacts are influenced by the daily distance traveled on each e-scooter, the method of scooter pick-up for charging, the frequency of charging, and the time of day and location of charging. The electricity impacts of charging use seasonal marginal emissions factors from Azevedo *et al* [27], at an eGRID spatial resolution, which employs a statistical relationship between power plant emissions and the hourly generation from fossil fuel generators for a region [28, 29]. We assume a charging rate of 84 W and a full battery charge of 0.335 kWh based on the manufacturer's specifications.

E-scooter employees (chargers) can collect any scooters at any location in the city once the scooters become available for collection, without specified collection routes, areas for pick-up, or specified scooters. Matching current policy in Raleigh, we assume that the e-scooters are picked up each evening to be charged, regardless of the batteries' state of charge. To determine the distribution of the battery state of charge at pick-up, we collected end of day (8 pm–10 pm) data on 800 scooters through the Bird rider application. We found that 4.6% of scooters were fully charged (i.e. unused that day), as shown in figure S1.

We assume that the distribution of personal vehicles in Wake County, North Carolina is representative of the vehicles used for collection and distribution. Using the EPA Motor Vehicle Emission Simulator (MOVES) version 2014a, we determine a global warming (kg CO_2-eq/mile) distribution of passenger car and truck emissions for both gasoline and diesel vehicles. For respiratory effects (kg $PM_{2.5}$-eq/mile), acidification (kg SO_2-eq/mile), and eutrophication (kg N-eq/mile), we use a lognormal distribution with small passenger vehicle (EURO4) in ecoinvent 3.3. To bound the parameters in our analysis, we collected data from several employees of shared scooter companies on how many scooters are picked up per trip and the distance traveled for collection and distribution of scooters, finding a range of 0.6–2.5 miles per scooter for collection and distribution.

Given that shared dockless e-scooters are a recent phenomenon, comprehensive data do not yet exist for the distribution of lifetimes for these products under these usage conditions. In our analysis, we test a wide range of plausible scooter lifetimes (0.5–2 years), informed by battery lifetimes, the manufacturer warranty, and reports of damage under shared usage programs [26, 30]. A 500 cycle lifespan for NMC 111 batteries, as specified by the manufacturer, would result in a scooter lifetime of 18 months under a high-usage approach. For the sale of these scooters to individuals, the manufacturer provides a warranty of 12 months on the main body and 6 months for the accessories [26]. Shared e-scooters may have much shorter lifetimes, however, due to mistreatment or scooters may last longer under lower usage scenarios. Recent reports have suggested that many scooters may be damaged by e-scooter users or citizens, and recent reports suggest that e-scooters may have far shorter lifetimes [30].

To better understand the net impacts of e-scooter usage, we compare our results to alternative modes of transportation. To properly bound this comparison, we conducted a survey of 61 riders and use another published survey [31] to gain insights into the mode of transportation that e-scooters are replacing (e.g. walking, personal automobile). See tables S6 and S7.

2.4. Monte Carlo analysis and scenarios

To investigate the inherent variability and uncertainty of several of the parameters used in this study, we conduct a Monte Carlo analysis with assumed distributions for relevant parameters to determine the overall distribution of life cycle impacts, as shown in table 1. Then, using the Base Case assumptions, we test the sensitivity of the results to each parameter in isolation to determine which parameters have the greatest impact on the results.

In addition to the Base Case, we examine three scenarios relating to the e-scooter collection for charging and one additional scenario related to e-scooter lifetime. In 'Low Collection Distance,' we assume that the retrieval and distribution distance of e-scooters is reduced, resulting in 0.6 miles driven per scooter by

Table 1. Inputs for Monte Carlo simulations.

Parameters for each impact category		Range or (scale, shape factors)	Distribution	Reference/method
Materials and manufacturing[a]	(kg CO_2-eq/scooter)	(200, 17.7)	lognormal	
	(kg $PM_{2.5}$-eq/scooter)	(0.303, 0.0276)	lognormal	Scooter disassembly, Ecoinvent 3.3
	(kg SO_2-eq/scooter)	(1.74, 0.107)	lognormal	
	(kg N_{eq}/scooter)	(1.31, 0.053)	lognormal	
Collection and distribution emissions[b]	(kg CO_2-eq/mile)	(0.366, 0.798)	lognormal	EPA MOVES 2014b model
	(kg $PM_{2.5}$-eq/mile)	(2.45×10^{-4}, 1.21×10^{-5})	lognormal	Ecoinvent 3.3
	(kg SO_2-eq/mile)	(1.33×10^{-3}, 6.55×10^{-5})	lognormal	Ecoinvent 3.3
	(kg N-eq/mile)	(8.21×10^{-4}, 4.05×10^{-5})	lognormal	Ecoinvent 3.3
Transportation to the US[c]	(kg CO_2-eq/scooter)	(9.54, 3.44)	lognormal	
	(kg $PM_{2.5}$-eq/scooter)	(0.00893, 0.00256)	lognormal	Distance to ship and truck to Raleigh, Ecoinvent 3.3.
	(kg SO_2-eq/scooter)	(0.0980, 0.0290)	lognormal	
	(kg N-eq/scooter)	(0.0130, 0.00397)	lognormal	
Scooter use and maintenance[c]	Collection and distribution distance (miles/scooter)	0.6–2.5	uniform	Survey of Raleigh chargers
	End of day battery charge (%)	(0.66, 0.18)	lognormal	Data collection from Bird application
	Scooter lifetime (years)	0.5–2.0	uniform	LG specifications for NMC Battery, [20]
	Time to begin charging (h)	21:00–23:00	uniform	Survey, collection schedule

Static variable	Value	Reference
Scooter distance potential (miles)	18	
Energy per full charge (kWh)	0.335	Battery specific values are drawn from Xiaomi's specifications for the m365 scooter
Time to fully charge (h)	4	
Power required to charge (kW)	0.08375	

[a] Manufacturing burdens represent a range of 0% to 48% recycled content of aluminum for e-scooter production.

.[b] Tailpipe emission distribution for CO_2-eq/mile are drawn from MOVES 2014a and modeled in Wake County, NC for passenger cars and trucks. Other impact categories include a distribution range from Ecoinvent passenger vehicles (EURO 4).

[c] Emissions associated with transport to the US are drawn from Ecoinvent processes transport freight by sea and transporting freight by trucking.

[d] 4.6% of scooters are picked up with a full state of charge. The remaining scooters were fit to a lognormal distribution. See SI figure S1.

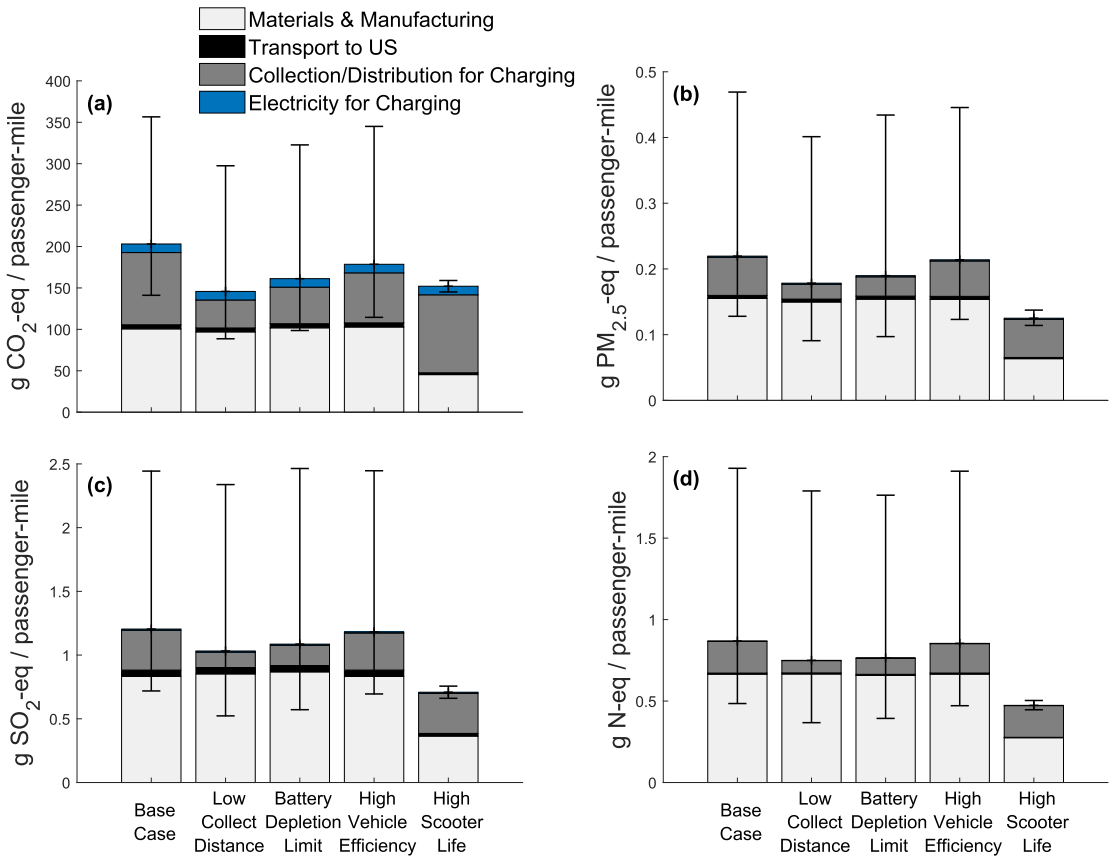


Figure 2. Life cycle environmental impacts for shared electric scooters under Base Case and alternative collection scenarios for (a) global warming, (b) respiratory effects, (c) acidification, and (d) eutrophication. Error bars represent 95% of the Monte Carlo simulations.

the collector. In 'Battery Depletion Limit,' e-scooters are only retrieved and charged when their battery's state of charge drops below 50%. In 'High Vehicle Efficiency,' the vehicles used for collection have a fuel efficiency of 35 miles per gallon (i.e. 235 g CO_2-eq/mile). In 'High Scooter Life,' we assume that the scooters' lifetime is fixed at two years.

3. Results

Figure 2 shows the life cycle environmental impacts per passenger-mile traveled for each scenario. In the Base Case, the average global warming impact is 202 g CO_2-eq/passenger-mile, with 50% from materials and manufacturing and 43% of impacts coming from collection and distribution. The burdens from the electricity used to charge the scooter contribute only 4.7% of the total, while the transportation from the manufacturer proves to be trivial. The error bars in figure 2 represent the range in which 95% of the Monte Carlo results fall.

As shown in figures 2(b)–(d), respiratory effects, acidification, and eutrophication are also driven by a combination of the e-scooter materials and manufacturing and daily collection of the scooters. Using the recycled content approach with 24% recycled content of aluminum, the aluminum frame and lithium-ion battery make up 53%–73% of impacts in manufacturing and materials across all impact categories. The aluminum frame is found to be the highest impact driver of respiratory effects, accounting for 46% of the $PM_{2.5}$-eq from materials and manufacturing, and the battery pack is found to be the highest driver of acidification, accounting for 46% of SO_2-eq. Given that the e-scooters are manufactured in China and much of the primary materials are not sourced from the United States, these environmental harms are consequently not borne by the end users' community in our study.

Alternative approaches to collect and distribute e-scooters can greatly reduce the adverse environmental impacts. Reducing the average driving distance for collection and distribution to 0.6 miles per scooter reduces the average life cycle global warming impacts by 27%, while the exclusive use of fuel-efficient vehicles for collection results in a 12% reduction. Limiting scooters collection to those with a low battery state of charge would require a change in policy to allow scooters to remain in public spaces overnight, but could yield a net reduction in global warming impacts of 19%.

Figure 3 shows the distribution of the results for scenarios that may reduce global warming impacts. In all scenarios except High Scooter Life, we observe a wide range of outcomes which are driven primarily by

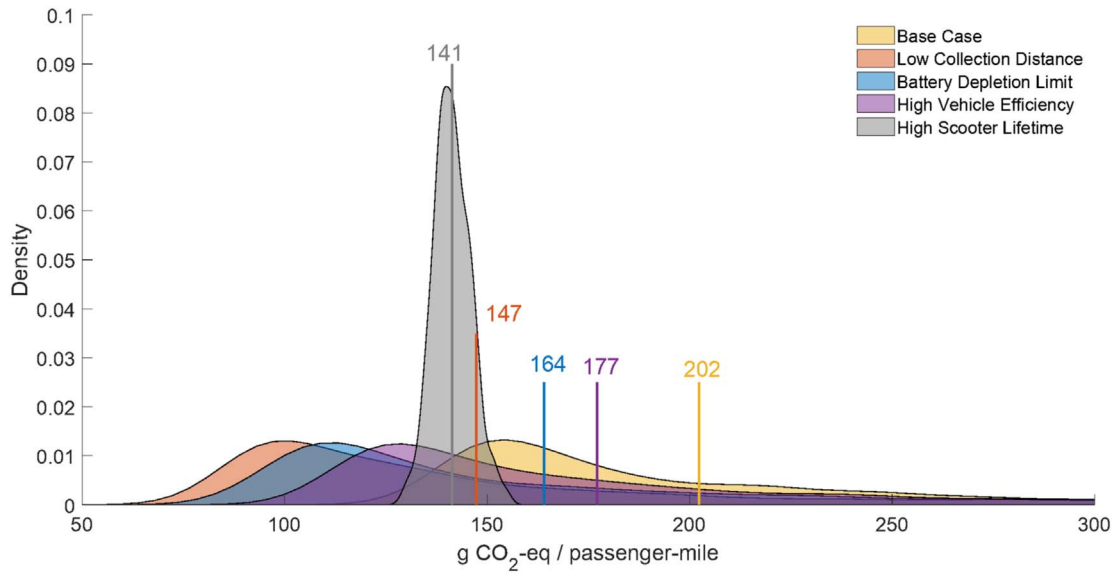


Figure 3. Shared e-scooter Monte Carlo analysis of global warming impact. Kernal density functions show the Base Case and four alternative collection and distribution scenarios: low collection distance, battery depletion limit, high vehicle efficiency, and high scooter lifetime. Colored vertical lines indicate the mean value for each scenario.

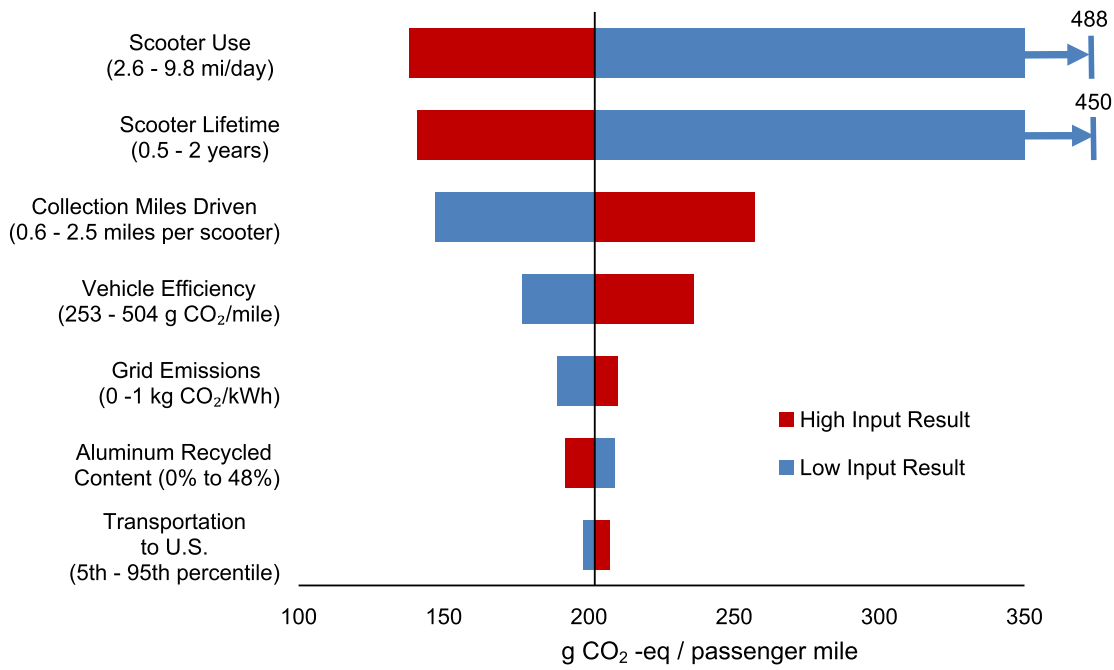


Figure 4. Sensitivity analysis of global warming potential for various shared e-scooter scenarios. This sensitivity uses the average value from the base case scenario as seen previously in figure 3, but applies a static low and high value to the input parameter of interest shown in parentheses along the y axis.

the range of scooter lifetimes. The average values for each scenario, shown by vertical lines in figure 3, are further right than the mode value of each scenario due to short scooter lifetimes which yield a long rightward tail. Although figure 3 is truncated to more clearly display the mean values as vertical lines, the results extend as high as 514 g CO_2-eq/passenger-mile. Table S5 in the supporting information provides the median values for the Monte Carlo results. Due to the long tail of high values for the Base Case, Low Collection Distance, Battery Depletion Limit, and High Vehicle Efficiency scenarios, the median results are 13% to 19% lower than the average results. Comparable results for respiratory impacts, acidification, and eutrophication are shown in the SI, Figures S2–S4.

Figure 4 shows the results of the sensitivity analysis on global warming impacts. We see that the global warming impacts are most sensitive to the daily usage of the scooter, scooter lifetime, distance driven for collection, and vehicle fuel efficiency. Both low daily

Table 2. Likelihood that the e-scooter life cycle global warming impacts per passenger-mile traveled exceeds the impacts associated with alternative modes of transportation.

	Base case	Low collection distance	Battery depletion limit	High vehicle efficiency	High scooter lifetime
Personal automobile[a] (414 g CO_2/mi)	1.7%	0.3%	0.7%	1.0%	0.0%
Shared dockless bicycle[b] (190 g CO_2/mi)	33.2%	20.9%	23.6%	30.0%	0.0%
Benchmark Displacement[c] (150 g CO_2/mi)	65.0%	34.8%	39.9%	50.0%	4.0%
Electric moped[d] (119 gCO_2/mi)	100.0%	54.2%	66.9%	89.5%	100.0%
Bus with high ridership[e] (82 g CO_2/mi)	100.0%	99.6%	100.0%	100.0%	100.0%
Electric bicycle[d] (40 g CO_2/mi)	100.0%	100.0%	100.0%	100.0%	100.0%
Bicycle[d] (8 g CO_2/mi)	100.0%	100.0%	100.0%	100.0%	100.0%

Values drawn from

[a] Argonne National Lab GREET 2 model.

[b] Reference [13].

[c] Benchmark Displacement assumes 1 e-scooter passenger-mile displaces 0.34 miles of personal automobile travel, 0.11 miles of bus travel, and 0.08 miles of bicycle travel.

[d] Reference [11].

[e] Reference [12].

usage of the scooter and low scooter lifetimes show very high global warming impacts driven from the manufacturing and materials burdens, which are spread across a smaller number of passenger-miles traveled over the e-scooter lifetime. Figure 4 also shows that the results are insensitive to the distance for transporting the scooter from the manufacturer to the point of use and the grid emissions.

While this study was conducted with parameters specific to Raleigh, North Carolina, the results can be interpreted and used for a wide range of locations. We found that the environmental impacts of the transportation of the scooter from the manufacturer to the end use location is trivial and the potential differences in grid emissions for charging the e-scooter yield small changes in the overall results. Relative to emissions from charging in Raleigh, charging with a 0 kg CO_2/kWh power source (to approximate wind, solar, or nuclear) would decrease life cycle emissions by 6%, while charging with a 1 kg CO_2/kWh power source (to approximate coal generation) would increase life cycle emissions by 4%. The most important parameter that would vary across locations is the collection miles driven per scooter mile. Densely populated metropolitan areas may enable higher densities of e-scooters and lower collection driving distances per scooter. Conversely, sparsely populated or sprawling areas would likely necessitate higher collection miles driven. Our sensitivity analysis shows that reduced collection distances of 0.6 miles per scooter reduce the life cycle CO_2 emissions by 27%, while longer driving distances of 2.5 miles per scooter increase life cycle CO_2 emissions by 27%.

To better understand the net impacts of shared e-scooter use, we consider the modes of transportation that are being displaced. In our survey of e-scooter riders, 7% of users reported that they would not have taken the trip otherwise, 49% would have biked or walked, 34% would have used a personal automobile or ride-share service, and 11% would have taken a public bus (table S7). These results are consistent with a survey conducted in Portland, Oregon, which shows 8% would not have taken the trip, 45% would have biked or walked, 36% would have used an automobile, and 10% would have used a bus or streetcar [31]. To estimate the displaced burdens from e-scooter usage, we assume that each passenger-mile on an e-scooter displaces 0.34 passenger-miles in a personal car, 0.11 passenger-miles on a public bus, and 0.08 miles on a bicycle. We also assume the life cycle global warming impacts of personal car use is 414 g CO_2-eq/passenger-mile, using Argonne National Laboratory's GREET 2 model with US average petroleum mix, vehicle model year 2012, 26 miles per gallon efficiency, and one passenger [32]. We assume impacts from bus ridership is 82 g CO_2-eq/passenger-mile [33], consistent with the well-to-wheels calculation for urban diesel bus use during peak hours from Chester and Horvath, 2009, with the important caveat that emissions from buses do not decrease proportionally with the loss of one rider. We assume that the use of a personal bicycle results in 8 g CO_2-eq /passenger-mile [11]. Using these assumptions, we calculate that the avoided life cycle emissions from car and bus use is 150 g CO_2/passenger-mile, which we term the 'Benchmark Displacement.' This Benchmark Displacement rate is 26% lower than the average Base Case impacts associated with the use of shared e-scooters and very near the High Scooter Life and Low Collection Distance scenarios.

In table 2, we present the likelihood that the e-scooter life cycle global warming impacts per passenger-mile traveled exceeds the impacts associated with the Benchmark Displacement and alternative single modes of transportation. For this assessment, we use representative life cycle emissions values for these alternatives and report the share of e-scooter Monte Carlo analysis results that exceed those values.

The personal automobile, bus with high ridership, and bicycle emissions match those previously described in the calculation of the Benchmark Displacement. The shared dockless bicycles represent non-electric bikes that require 'rebalancing' [13]. The electric moped, electric bicycle, and bicycle values represent personal ownership, which do not require rebalancing [11].

These results show that dockless e-scooters consistently result in higher life cycle global warming impacts relative to the use of a bus with high ridership, an electric bicycle, or a bicycle per passenger-mile traveled. However, choosing an e-scooter over driving a personal automobile with a fuel efficiency of 26 miles per gallon results in a near universal decrease in global warming impacts. The use of dockless e-scooters are often preferable to dockless bicycles, yielding lower life cycle emissions 67% to 100% of the time across the scenarios. When compared to the Benchmark Displacement CO_2 emissions, our Base Case shows a 65% chance that the life cycle e-scooter emissions will be higher. This likelihood is reduced, but nontrivial, for our Low Collection Distance (35%), Battery Depletion Limit (40%), High Vehicle Efficiency (50%), and High Scooter Lifetime (4%) scenarios. These results underscore the importance of ensuring long lifetimes for e-scooters in reducing life cycle emissions.

4. Discussion

In this study, we found that the global warming impacts associated with the use of shared e-scooters are dominated by materials, manufacturing, and automotive use for e-scooter collection for charging. Increasing scooter lifetimes, reducing collection and distribution distance, using more efficient vehicles, and less frequent charging strategies can reduce adverse environmental impacts significantly. Without these efforts, our Base Case calculations for life cycle emissions show a net increase in global warming impact when compared to the transportation methods offset in 65% of our simulations. Taken as a whole, these results suggest that, while e-scooters may be an effective solution to urban congestion and last-mile problem, they do not necessarily reduce environmental impacts from the transportation system.

Cities that seek to integrate e-scooters into their transportation system have several policy options available to reduce the life cycle environmental burdens associated with their use. Allowing e-scooters to remain in public areas overnight would decrease the automobile burdens associated with picking up fully charged or nearly fully charged e-scooters. Requiring central management or improved e-scooter collection processes could reduce the auto-miles traveled for collection and distribution. Additionally, cities could enact or enforce anti-vandalism policies to reduce e-scooter misuse or mistreatment which can result in short lifetimes (and thus high materials and manufacturing burdens per passenger-mile traveled).

The scooter companies also can take meaningful action to reduce the life cycle burdens of their products. They can reduce collection and distribution burdens by incentivizing or requiring the use of efficient automobiles. In addition, they could reduce vehicle miles traveled for collection and distribution through centralized management or by allowing chargers to 'claim' e-scooters to eliminate unnecessary and competitive driving during daily collection.

This study clearly demonstrates that there is the potential for e-scooters to increase life cycle emissions relative to the transportation modes that they displace. Although we use a Monte Carlo analysis with informed ranges for input parameters such as scooter lifetime, collection distance, and vehicle efficiency, cities and e-scooter companies alike can use this study to further explore life cycle impacts of e-scooters with a higher level of detail in the future. Claims of environmental benefits from their use should be met with skepticism unless longer product lifetimes, reduced materials burdens, and reduced e-scooter collection and distribution impacts are achieved.

Acknowledgments

The authors would like to thank Dr Andrew Grieshop, Dr Joseph DeCarolis, Dr Jarod Kelly, and Aditya Sinha for their valuable insights. This work was conducted with financial support from the North Carolina State University Department of Civil, Construction, and Environmental Engineering Research Experience for Undergraduates Program.

References

[1] Sipe N and Pojani D 2018 Can E-Scooters Solve the 'Last Mile' Problem? They'll Need to Avoid the Fate of Dockless Bikes. The Conversation September 2018. (https://theconversation.com/can-e-scooters-solve-the-last-mile-problem-theyll-need-to-avoid-the-fate-of-dockless-bikes-102633)

[2] Smith C S and Joseph P S 2018 E-scooter scenarios: evaluating the potential mobility benefits of shared dockless scooters in Chicago *Chaddick Institute Policy Series* (Chicago, IL: DePaul University)

[3] Hawkins T R *et al* 2013 Comparative environmental life cycle assessment of conventional and electric vehicles *J. Ind. Ecol.* **17** 53–64

[4] Michalek J J *et al* 2011 Valuation of plug-in vehicle life-cycle air emissions and oil displacement benefits *Proc. Natl Acad. Sci.* **108** 16554–8

[5] Chen T D and Kockelman K M 2016 Carsharing's life-cycle impacts on energy use and greenhouse gas emissions *Transp. Res.* D **47** 276–84

[6] Gawron J H, Keoleian G A, De Kleine R D, Wallington T J and Kim H C 2018 Life cycle assessment of connected and automated vehicles: sensing and computing subsystem and vehicle level effects *Environ. Sci. Technol.* **52** 3249–56

[7] Zhang C, Wang C, Sullivan J, Han W and Schuetzle D 2001 Life cycle assessment of electric bike application in Shanghai *SAE Technical Paper* 2001-01-3727 SAE International (https://doi.org/10.4271/2001-01-3727)

[8] Cherry C R 2007 Electric two-wheelers in China: analysis of environmental, safety, and mobility impacts *Diss. Institute of Transportation Studies* (Berkeley, CA : University of California Press)
[9] Chester M V, Horvath A and Madanat S 2010 Comparison of life-cycle energy and emissions footprints of passenger transportation in metropolitan regions *Atmos. Environ.* **44** 1071–9
[10] Leuenberger M and Frischknecht R 2010 *Life Cycle Assessment of Two Wheel Vehicles* (Uster: ESU-Service Ltd)
[11] Weiss M, Dekker P, Moro A, Scholz H and Patel M K 2015 On the electrification of road transportation–a review of the environmental, economic, and social performance of electric two-wheelers *Transp. Res.* D **41** 348–66
[12] Chester M 2019 It is a Bird…It is a Lime…It is Dockless Scooters! But Can These Electric-Powered Mobility Options Be Considered Sustainable Using Life-Cycle Analysis? (https://chesterenergyandpolicy.com/2019/01/28/its-a-bird-its-a-lime-its-dockless-scooters-but-can-these-electric-powered-mobility-options-be-considered-sustainable-using-life-cycle-analysis/)
[13] Luo H, Kou Z, Zhao F and Cai H 2019 Comparative life cycle assessment of station-based and dock-less bike sharing systems *Res. Conservation Recycling* **146** 180–9
[14] Sheng N, Zhou X and Zhou Y 2016 Environmental impact of electric motorcycles: evidence from traffic noise assessment by a building-based data mining technique *Sci. Total Environ.* **554** 73–82
[15] Rose G 2012 E-bikes and urban transportation: emerging issues and unresolved questions *Transportation* **39** 81–96
[16] Hsieh P Y, Chang L F W, Yu T Y and Wu K C 2018 Evaluation of mitigation effects on air pollutants for electric scooters in Taiwan with the energy flow analysis and system dynamics approach *IOP Conf. Ser.: Earth Environ. Sci.* **191** 012136
[17] Bishop J D, Doucette R T, Robinson D, Mills B and McCulloch M D 2011 Investigating the technical, economic and environmental performance of electric vehicles in the real-world: a case study using electric scooters *J. Power Sources* **196** 10094–104
[18] Miller S A and Keoleian G A 2015 Framework for analyzing transformative technologies in life cycle assessment *Environ. Sci. Technol.* **49** 3067–75
[19] Wender B A, Foley R W, Hottle T A, Sadowski J, Prado-Lopez V, Eisenberg D A, Laurin L and Seager T P 2014 Anticipatory life-cycle assessment for responsible research and innovation *J. Responsible Innov.* **1** 200–7
[20] Eckelman M J, Mauter M S, Isaacs J A and Elimelech M 2012 New perspectives on nanomaterial aquatic ecotoxicity: production impacts exceed direct exposure impacts for carbon nanotoubes *Environ. Sci. Technol.* **46** 2902–10
[21] Bare J C 2012 Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI), Version 2.1 - User's Manual; EPA/600/R-12/554 2012
[22] Whittaker Z 2018 Xiaomi Does not Want Lyft Using Its Electric Scooters. Tech Crunch. October 2018 (https://techcrunch.com/2018/10/31/xiaomi-doesnt-want-lyft-using-its-electric-scooters/)
[23] Ellingsen L A W, Majeau-Bettez G, Singh B, Srivastava A K, Valøen L O and Strømman A H 2014 Life cycle assessment of a lithium-ion battery vehicle pack *J. Ind. Ecol.* **18** 113–24
[24] Ciez R E and Whitacre J F 2019 Examining different recycling processes for lithium-ion batteries *Nat. Sustainability* **2** 148
[25] Bertram M, Ramkumar S, Rechberger H, Rombach G, Bayliss C, Martchek K J, Müller D B and Liu G 2017 A regionally-linked, dynamic material flow modelling tool for rolled, extruded and cast aluminium products *Res. Conservation Recycling* **125** 48–69
[26] Xiaomi United States 2019 (https://mi.com/us/mi-electric-scooter/specs/) (Accessed: 02 July 2019)
[27] Azevedo I L, Horner N C, Siler-Evans K and Vaishnav P T 2017 *Electricity Marginal Factor Estimates. Center For Climate and Energy Decision Making* (Pittsburgh: Carnegie Mellon University)
[28] Siler-Evans K, Azevedo I L and Morgan M G 2012 Marginal emissions factors for the US electricity system *Environ. Sci. Technol.* **46** 4742–8
[29] Siler-Evans K, Azevedo I L, Morgan M G and Apt J 2013 Regional variations in the health, environmental, and climate benefits from wind and solar generation *Proc. Natl Acad. Sci.* **110** 11768–73
[30] Newberry L 2018 Fed-up Locals Are Setting Electric Scooters on Fire and Burying Them at Sea. Los Angeles Times, August 10, 2018.
[31] Portland Bureau of Transportation 2018 2018 E-Scooter Pilot User Survey Results (https://www.portlandoregon.gov/transportation/article/700916)
[32] Argonne National Laboratory, The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model (GREET), GREET2, 2018
[33] Chester M V and Horvath A 2009 Environmental assessment of passenger transportation should include infrastructure and supply chains *Environ. Res. Lett.* **4** 024008