Transportation emissions during pandemic: duality of impacts

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Abstract

Through the lens of an electric bicycle (E-bike) sharing program, this paper shows how the impact of the pandemic on transportation emissions can be multifaceted by impacting both (i) modal usage and (ii) trip generation. The pandemic led to a decrease in the number of trips by travelers, but it also induced a modal shift away from shared mobility into personalized modes. As a result, estimates of transportation emissions can present conflicting figures. In this work, we collect data on the travel behavior of users of an E-bike sharing program in Madison, Wisconsin, before and during the pandemic. Observations on trip choices and modal shifts of users provide means to estimate their relative and overall impact on transportation emissions. Results suggest that the influence of the pandemic on transportation behavior and environmental emissions is convoluted. Post-pandemic environmental implications would depend on the extent of recovery between modal shares and trip generations.

1. Introduction

The transportation sector is responsible for 27% of greenhouse gas emissions (GHG) in the United States (US) [1]. With the emergence of the COVID-19 pandemic and its accompanying policy interventions, the transportation sector has seen drastic changes in travel behavior and transportation usage [2–6]. Such changes affected various environmental emissions from the transportation sector across the world. For instance [7], reports changes in air quality and emissions as result of travel restrictions in China [8] shows the carbon emissions during the pandemic in Indonesia [9] looks at urban transportation emissions in Canada [10] reports significant NO2 decline in the U.S..

The reported decrease in environmental emissions of the transportation sector during the pandemic is mainly due to (i) modal usage and (ii) trip generation. For instance, several studies report a change in the mode of transportation used during the pandemic—mainly a migration of users away from public (or shared) modes into private and non-motorized modes [4, 11–14]. On the other hand, some studies note the changes in the frequency of travel, personal vehicle miles traveled, and trip reductions [15, 16]. These two impacts have different implications on transportation emissions. We conjecture that it is critical to monitor how the transportation sector recovers from the pandemic to develop appropriate policy measures. While trip generation might recover as time progresses, the change in travel behavior might persist (or vice versa). Specifically, if the increase in preference for personal vehicles persists, then it is expected that transportation emissions might increase.

As such, this paper is concerned with showing the multifaceted impact of the pandemic on transportation emissions, primarily due to the influence on (i) modal usage and (ii) trip generation. Accordingly, we collect survey data from users of an electric bicycle (E-bike) sharing program in Madison, Wisconsin, called BCycle. Note that this paper is part of a series of works by the authors to analyze E-bike sharing programs and their environmental implications. In a recent paper, we found that E-bikes in a bike sharing program can effectively compete with carbon-intensive modes of transportation (e.g., private vehicles and buses) specifically at short...
distance trips, ultimately reducing the use-phase environmental emissions from the transportation system [17]. Discussion in that paper focused on travel behavior, modal shifts, and environmental implications of users having access to an E-bike compared to before access.

In the present paper, we focus primarily on the environmental implications of the pandemic. Specifically, we aim to highlight how a change in environmental emissions due to the pandemic is a result of two opposing impacts—modal shifts and trip reductions—and what that could signify in a post-pandemic recovery. Our analysis focuses on data collected from a population of E-bike sharing program users. This presents a unique angle to analyze environmental emissions due to the pandemic. Generally, users of E-bike sharing programs could have less reliance on carbon-intensive modes than other travelers [17]. Thus, analyzing the modal shifts by this demographic of transport users allows us to gauge the potential implications of the pandemic on micro-mobility options, often touted as the drivers of sustainable transportation. Specifically, we build a connection between modal shifts of users before and during the pandemic. The environmental impacts are then quantified based on the use-phase life cycle assessment (LCA). We showcase the multi-dimensional environmental impacts of the pandemic as a result of (i) modal shifts and (ii) trip reduction. For brevity, ‘E-bike’ refers to an E-bike through a bike sharing program hereafter, not to be conflated with personally owned E-bikes.

Our analysis of modal distributions before and during the pandemic shows that personal vehicle usage increased the most, while the usage of buses decreased. E-bikes usage decreased but still enjoyed a substantial level of modal share across different types of trips. The usage of the conventional bike remained fairly consistent, while walking increased. The increase in personal vehicle modal share led to an increase in environmental emissions on a per-mile basis. However, the overall decrease in trips triumphed the undesirable trend of modal shifts towards personal vehicles, and ultimately led to a decrease in environmental emissions as compared to the pre-pandemic period. These findings, however, show the convoluted impacts of the pandemic on transportation emissions. Post-pandemic environmental implications would depend on the recovery path and the extent of relative recovery between modal shares and trip generations.

The rest of the paper is organized as follows. Section 2 shows the methods adopted, section 3 discusses the results of the study, and finally, section 4 concludes.

2. Methods

2.1. Survey & data collection
A web-based survey is used to collect data from users of an E-bike sharing program in Madison, Wisconsin, called BCycle [18]. A dataset consisting of 460 respondents was compiled in the months of January and February of 2021. In anticipation of a change in travel behavior due to the pandemic, we asked users how their usage of the E-bike sharing program and other available modes of transportation changed from that before the COVID-19 pandemic. The survey captures a timeline in which lockdowns and of COVID-19 concerns in Madison, Wisconsin, were ongoing.

Specifically, the survey gathered data on the mode of transportation used for different trip types in three main scenarios: (i) before access to an E-bike (that is, before having a membership in the E-bike program BCycle), (ii) after access to an E-bike, and (iii) during the pandemic. Respondents also provided the distance traveled for each of their trips reported. Modes of transportation analyzed were all available modes in the city of Madison: personal vehicles, public transportation (bus), ride-hailing, conventional bicycle, walking, and E-bike. Additionally, respondents were asked general questions about their attitude towards travel during the pandemic. Readers are referred to the supplementary information (SI) for more details on the survey instrument used, demographics of respondents, and general assumptions.

2.2. Environmental analysis: life cycle assessment
In quantifying the environmental implications of transportation modal usage, we adopt the principles of well to wheel (WTW) LCA. Meaning that emissions from different transportation modes were calculated based on the use-phase cycle, considering the complete fuel cycle (from extraction to usage). Accordingly, the emission factors of different modes of transportation were extracted from the Greenhouse Gases Regulated Emissions and Energy Use in Technologies (GREET) model [19]. GREET model is widely adopted in LCA modeling of different transportation modes. In our analysis, five different emission categories were analyzed to provide a broader analysis of the environmental implications: energy consumption (kJ), greenhouse gas emissions (GHG, kg), particulate matter (PM2.5, mg), SO\(_2\) emissions (mg), and NO\(_x\) emissions (g). We note that emissions due vehicle/bicycles material manufacturing or operations were not considered in the LCA boundary; see the SI for more details.

The environmental analysis revolves around fuel and energy consumption, and thus the modes of conventional bicycle and walking were assumed to have no environmental emissions. Accordingly, the emission
analysis focuses on vehicles (personal vehicles and ride-hailing), buses, and E-bikes. These modes of transportation were modeled inside GREET to depict those available in Madison. Emissions from E-bikes are based on their energy consumption generated from electricity. Thus, to quantify their environmental impacts, we model their emissions based on the electricity generation scheme used in Wisconsin state. We refer readers to the SI for specific details and assumptions on emissions modeling.

Accordingly, we calculate the use-phase environmental impacts of the transportation sector in our study based on two key concepts: (i) based on modal usage distribution, which is a per mile basis (emissions/mile) (equation (1)), and (ii) aggregate emissions based on trip distances and emission factors (equation (2)). Precisely, the environmental impacts \(EI\) of an emission factor \(F\), mode of transportation \(m\in\{1,\ldots,M\}\), and trip \(t\in\{1,\ldots,T\}\) are calculated based on the two concepts as follows:

\[
EI(1) = \sum_{m=1}^{M} \text{modal distribution}^m(\%) \times F^m(\text{emissions/mile}) \tag{1}
\]

\[
EI(2) = \sum_{m=1}^{M} \sum_{t=1}^{T} F^m(\text{emissions/mile}) \times \text{trip distance}^t_m(\text{mile}) \tag{2}
\]

The principal idea of having two quantifying methods is to distinguish between two key impacts of the COVID-19 pandemic on the transportation sector. One is influenced by travel behavior, a shift in modal usage, and the migration of users from one mode to another (i.e., the move from shared transportation into personalized transportation during the pandemic). This is shown through equation (1). Another is influenced by the overall reduction in trips by users during the pandemic, which is influenced by overall trip generation (i.e., pandemic policies, preventative measures, etc) (shown in equation (2)).

3. Results & discussion

3.1. Survey data: attitude towards pandemic transportation

Respondents were asked to rate the risk of traveling with different modes of transportation available in Madison during the COVID-19 pandemic, shown in figure 1. Overwhelmingly, users ascertain a high risk in modes of transportation that have some level of ride-sharing. Specifically, 67.24% of respondents designate a high-risk factor for bus travel and 56% for ride-hail travel (e.g., Uber, Lyft). In contrast, personalized modes of transportation such as personal vehicles, conventional and E-bikes, and walking are identified by respondents as low-risk modes. An interesting observation here is that while E-Bikes are personalized travel modes, E-bikes sharing programs have some level of interaction with other travelers or entities. For instance, users of an E-bikes sharing program must pick up the E-bikes from a dock station. This is reflected by users depicting a slightly higher risk in E-bikes as compared to a conventional bike, walking, or personal vehicles. Specifically, 13% of respondents associate a medium level of risk with E-Bikes as compared to less than 2% for the other three personalized modes. This realization can affect the usage of E-bikes during the pandemic compared to walking, conventional bike, or personal vehicles.
Additionally, we ask participants to rate their degree of change in usage for different modes of transportation, as shown in figure 2. Across the board, transportation modes witnessed a major level decrease in usage. Yet, any level of increase in usage was only seen for the modes that allow for personal travel. This duality of impacts on modal shifts and decrease in usage is explored more in the sections below. However, we note that this question reveals a qualitative assessment by users, which renders it challenging to draw conclusions on transportation emissions. As such, we focus our estimation of transportation emissions on quantitative data on trips and modal shifts.

3.2. Shifts in usage of transportation modes

We explore the modal distributions of E-bike sharing users for different types of trips before and during the pandemic, as shown in table 1. As another baseline for comparison, the modal distribution before having access to E-bike sharing is also provided. Exploring modal distributions allows us to gain insights into the modal shifts triggered by the pandemic. First, in comparing the cases ‘before E-bike’ to ‘after E-bike’, we notice a migration of users towards E-bikes. In fact, as mentioned previously, an analysis on the E-bike’s ability to capture users and their underlying travel behavior is part of a different work by the authors [17], and thus will not be the focus of discussion here, readers are referred to that paper for a comprehensive analysis on E-bike sharing programs. The main focus here is the modal distribution in comparison to the ‘pandemic’ case. For better visualization, we further plot the increase/decrease in modal shares between ‘pandemic’ and ‘after E-bike’, as shown in figure 3. This allows us to see some migration trends of users.

Most notably, it is evident that there is a consistent decrease in usage of the bus as a mode of transportation during the pandemic. On the contrary, we see a consistent usage and increase in the modal distribution oriented towards personal vehicles. In fact, the modal usage of personal vehicles increased to the ‘before E-bike’ values. The modal share of E-bikes decreased, though it still maintained some level of usage during the pandemic (10%–20%). In recreational and educational trips, where E-bikes had the highest modal share before the pandemic, its share decreased as opposed to personal vehicles or walking. Additionally, E-bikes modal share decreased the most in restaurant trips. Conventional bike usage remained relatively similar while that of walking increased.

Note that the modal distributions depicted in table 1 consider only the trips that are done. Thus by looking at table 1, we get a sense of travel behavior and modal shifts during the pandemic. This revealed that modal shifts during the pandemic were mostly oriented towards personal vehicles, which signifies a setback for movement towards sustainable transportation. However, it is important to note that during the pandemic there was a notable elimination in trips. For instance, there was a 33% reduction in the total number of commuting to workplace trips, 28% in trips to education centers, and 51% in trips to different transportation facilities. On the contrary, shopping, market, and recreational trips experienced less than 5% of trip loss. Thus, the overall environmental impacts during the pandemic are not straightforward and need a more careful examination.
Table 1. Modal distribution for different trip types: (i) before E-bike, (ii) after E-bike, (iii) during pandemic.

| Modal distribution (%) | Bike | E-Bike | Personal vehicle | Bus | Ridehail | Walking |
|------------------------|------|--------|------------------|-----|----------|---------|
| Workplace              |      |        |                  |     |          |         |
| Before E-bike          | 17.6 | 0      | 42.3             | 17.88 | 0.5 | 21.66 |
| After E-bike           | 14.20| 21.50  | 35.33            | 9.77 | 0.25 | 18.79 |
| Pandemic               | 11.20| 13.50  | 49.80            | 1.50 | 0.74 | 22.80 |
| Shopping/Market        |      |        |                  |     |          |         |
| Before E-bike          | 9.01 | 0.00   | 57.80            | 7.03 | 1.31 | 24.85 |
| After E-bike           | 7.98 | 16.85  | 50.11            | 3.32 | 0.87 | 20.80 |
| Pandemic               | 6.96 | 10.33  | 56.47            | 2.02 | 2.02 | 22.02 |
| Restaurants            |      |        |                  |     |          |         |
| Before E-bike          | 9.82 | 0.00   | 40.82            | 2.67 | 4.24 | 42.40 |
| After E-bike           | 5.84 | 26.74  | 32.13            | 1.34 | 1.02 | 31.91 |
| Pandemic               | 5.55 | 11.55  | 42.40            | 0.44 | 1.11 | 38.88 |
| Recreational           |      |        |                  |     |          |         |
| Before E-bike          | 16.10| 0.00   | 34.67            | 3.36 | 1.11 | 44.74 |
| After E-bike           | 11.03| 31.08  | 26.80            | 0.90 | 0.68 | 29.50 |
| Pandemic               | 9.70 | 19.66  | 31.99            | 0.47 | 0.24 | 37.90 |
| Education              |      |        |                  |     |          |         |
| Before E-bike          | 19.10| 0.00   | 31.90            | 15.22| 0.10 | 33.63 |
| After E-bike           | 13.59| 29.00  | 26.88            | 6.04 | 1.20 | 23.27 |
| Pandemic               | 10.50| 20.50  | 31.50            | 2.10 | 1.00 | 34.29 |
| Transport facilities   |      |        |                  |     |          |         |
| Before E-bike          | 3.90 | 0.00   | 14.75            | 2.71 | 0.90 | 77.70 |
| After E-bike           | 2.50 | 8.20   | 22.55            | 2.73 | 4.78 | 59.22 |
| Pandemic               | 3.75 | 7.51   | 23.00            | 0.93 | 0.47 | 64.30 |
| Hospitals              |      |        |                  |     |          |         |
| Before E-bike          | 11.40| 0.00   | 60.36            | 11.91| 4.12 | 12.76 |
| After E-bike           | 7.02 | 13.24  | 55.60            | 6.75 | 5.10 | 11.62 |
| Pandemic               | 8.15 | 7.25   | 66.76            | 3.23 | 2.70 | 11.10 |
| Others                 |      |        |                  |     |          |         |
| Before E-bike          | 15.20| 0.00   | 49.66            | 5.10 | 2.70 | 24.60 |
| After E-bike           | 8.97 | 32.36  | 38.18            | 3.27 | 1.81 | 15.41 |
| Pandemic               | 8.00 | 21.36  | 45.30            | 0.43 | 2.14 | 21.79 |

Figure 3. Increase/decrease in modal share between ‘pandemic’ and ‘after E-bike’ scenarios seen in table 1.

This duality of impacts on modal shifts and trip generation is the primary motivation behind this work. More specifically, the main focus is what such changes imply in terms of environmental emissions. This is discussed further in section 3.3.

3.3. Environmental emissions

In previous work, we have analyzed how E-bikes enjoy a level of user attractiveness allowing them to capture a sizable market share (see the modal shares for ‘after E-bike’ in table 1). By itself, the migration of users away from carbon-intensive modes of transportation is environmentally desirable. However, the pandemic disrupted travel behavior and modal distribution significantly—more precisely, increasing the modal share of personal vehicles at the expense of buses and E-bikes, as well as decreasing the number of trips done. An interesting question arises here: what are the environmental implications of such disruption brought about by
3.3.1. Environmental impacts as a function of modal shares

Figure 4 presents the environmental impacts calculated based on equation (1) (i.e., based on shifts in modal distributions). Note that here the modal distributions are based on all trips combined. Comparing ‘before E-bike’ (red) to ‘after E-bike’ (green), we see a decrease in environmental impacts, triggered by E-bike’s ability to capture rider-share away from carbon-intensive modes of transportation (this behavior is analyzed thoroughly in a complementary paper by the authors, see). However, the pandemic’s influence in shifting travel towards personal vehicles retracts the environmental benefits (‘during pandemic’ (blue)). In some cases, such as particulate matter (PM2.5) and SOx emissions, we see a slight increase in emissions compared to the original (red) case. This behavior is expected as travelers with access to personal vehicles perceived much less risk and increased utility in using their vehicles during the pandemic as compared to other modes. In general, the trends observed here are consistent with the findings in table 1, where modal shares are oriented toward personal vehicles as in the ‘before E-bikes’ case.
3.3.2. Environmental impacts as a function of trips

The above environmental analysis is based on the modal distributions during the pandemic, without considering the decrease in trips. Accordingly, figure 5 quantifies environmental impacts based on equation (2), which considers aggregate trip distances. Interestingly, we see that the aggregate environmental emissions from our surveyed population decreased beyond those seen in ‘before E-bikes’ or ‘after E-bikes’. This suggests that the decrease in trips due to the pandemic triumphed the increase in modal shares for personal vehicles, leading to an overall decrease in the environmental impacts.

4. Conclusions

The COVID-19 pandemic has disrupted the transportation sector, influencing its environmental emissions. In this study, we consider a micro-mobility mode of transportation, E-bike sharing, to analyze how the pandemic changed: (i) modal shares, (ii) trip characteristics, and (iii) environmental impacts. A survey was conducted for users of an E-bike sharing program (BCycle) in the city of Madison, Wisconsin to collect data on modal preference and usage. Comparing the modal preferences before access to E-bike, after access to E-bike, and during the pandemic, allows for unique perspectives on the pandemic’s influence on micro-mobility users. Accordingly, an LCA analysis through the WTW model was used to quantify the environmental impacts. These impacts were based on two complementary concepts: (i) environmental impacts based on modal shifts, and (ii) environmental impacts based on trips.

4.1. Study implications

Results from sections 3.3.1 & 3.3.2, reveal the duality of impacts of the pandemic on transportation emissions. On the one hand, the significant reduction in trips led to an overall decrease in observed emissions. On the other hand, migration towards personal vehicles, which speaks to a change in user preference, increased the emissions on a per-mile basis. This duality casts a shadow on how transportation emissions would recover post-pandemic and implications for future sustainability efforts. For instance, it is possible that some trips will not fully recover post-pandemic (e.g., some will permanently telecommute). Conversely, it is also possible that modal shifts and preferences would not roll back to the pre-pandemic state, suggesting a lasting travel behavior change. Thus, post-pandemic environmental impacts would depend on the extent of relative recovery of these scenarios. Our findings underscore the importance of monitoring the recovery path of the transportation sector post-pandemic, as this will be the key driver of sustainability efforts in the transportation sector. This entails periodically collecting data on (i) demand on different modes of transportation (e.g., number of trips done by each mode, travel diaries, frequency of usage), and (ii) trip properties of each mode (miles traveled, trip purpose, origin-destination data, etc). Through this, we hope to track whether the induced travel behavior impacted by the pandemic is permanent or temporary.

4.2. Limitations & future needs

While this study highlighted how emissions from the transportation sector are set to be influenced by the pandemic, several research directions are needed to complement this work. A major limitation of this study is that the analysis remains myopic and is in need of longitudinal data collection (during and post-pandemic) to see how modal shifts and travel behavior change over time. Our survey captured a moment of time during the pandemic; however, the influence of the pandemic on travel behavior was dynamically changing as the pandemic progressed (e.g., change in mask mandates, availability of vaccines, the emergence of variants, etc). All these factors can have significant implications and must be studied broadly. Additionally, the studied population here is limiting as it only covers E-bike members in the city of Madison. This population limitation can induce compounding factor bias for modal shares observed in the data since travelers who choose to get an E-bike membership might have an underlying willingness to use this mode of transportation. While this bias is more relevant to the ‘before E-bike’ versus ‘after E-bike’ case, it is valuable to point out.

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Data availability statement

The data generated and/or analysed during the current study are not publicly available for legal/ethical reasons but are available from the corresponding author on reasonable request.

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