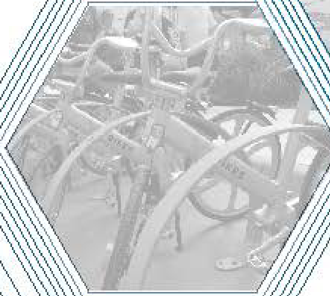
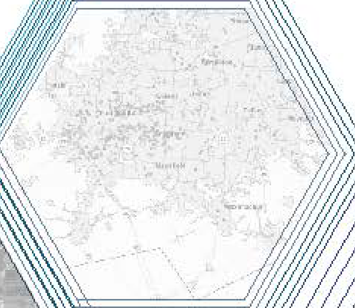


Electric Bike Sharing Environmental and Travel Insights: A Case Study in Madison

Andrea Hicks
Soyoung Ahn
Wissam Kontar



FINAL REPORT

Center for Transportation Equity, Decisions & Dollars

E-BIKE SHARING AND THE INFRASTRUCTURE IMPLICATIONS AND ENVIRONMENTAL IMPACTS OF NEW TECHNOLOGY IN TRANSPORTATION SYSTEMS

FINAL PROJECT REPORT

By:

Andrea Hicks
Soyoung Ahn
Wissam Kontar

University of Wisconsin-Madison, Department of Civil and Environmental Engineering

Sponsorship:
CTEDD

For:
Center for Transportation, Equity, Decisions and Dollars **(CTEDD)**
USDOT University Transportation Center
The University of Texas at Arlington
Woolf Hall, Suite 325
Arlington TX 76019 United States
Phone: 817-272-5138 | Email: c-tedd@uta.edu

Acknowledgments

This work was supported by a grant from the Center for Transportation Equity, Decisions, and Dollars (CTEDD) funded by U.S. Department of Transportation Research and Innovative Technology Administration (OST-R) and housed at The University of Texas at Arlington.

Disclaimer

Technical Report Documentation Page

1. Report No. CTEDD 020-04	**2. Government Accession No.**	**3. Recipient's Catalog No.**

4. Title and Subtitle

E-BIKE SHARING AND THE INFRASTRUCTURE IMPLICATIONS AND ENVIRONMENTAL IMPACTS OF NEW TECHNOLOGY IN TRANSPORTATION SYSTEMS

5. Report Date January 28, 2022

6. Performing Organization Code

7. Author(s)

Andrea Hicks 0000-0002-6426-9717
Soyoung Ahn 0000-0001-8038-4806

8. Performing Organization Report No.

9. Performing Organization Name and Address

University of Wisconsin-Madison, Department of Civil and Environmental Engineering, 1415 Engineering Drive, Madison, WI 53706

10. Work Unit No. (TRAIS)

11. Contract or Grant No.

USDOT - 69A3551747134

12. Sponsoring Organization Name and Address

Center for Transportation, Equity, Decisions and Dollars (CTEDD)
USDOT University Transportation Center
The University of Texas at Arlington
Woolf Hall, Suite 325
Arlington TX 76019 United States

13. Type of Report and Period Covered

Final Report

14. Sponsoring Agency Code

15. Supplementary Notes

Additional project information is available at https://ctedd.uta.edu/research-projects/e-bike-sharing-and-the-infrastructure-implications-and-environmental-impacts-of-new-technology-in-transportation-systems/ for this project. Project performed under a grant from the U.S. Department of Transportation's University Transportation Centers (UTC) Program.

16. Abstract

This work investigates the opportunities and environmental impacts brought about Electric bicycles (E-bikes) sharing program. Electric bicycles (E-bikes) are an emerging transportation technology with the potential of replacing other available modes. In this work, we investigate the ability of E-bike sharing to compete with different modes of transportation and the resulting use phase environmental impacts. An empirical approach is taken to build mode choice models informed through a survey study in Madison, Wisconsin. The resulting model reveals potential users of this technology and the underlying modal shifts triggered by its usage. A life cycle analysis (LCA) based on Well-to-Wheel (WTW) model is then adopted to quantify the use-phase environmental impacts of E-bikes. The analysis reveals the attractiveness of E-bikes as a mode of transportation, ultimately replacing other available modes. This directly translates into environmental impacts across five studied categories: energy consumption, greenhouse gas emission, particulate matter, sulfate and nitrate emissions. The electricity generation scheme is further analyzed to showcase the dependency between environmental benefits of E-bikes and the energy infrastructure used. Additionally, we look at how the E-bikes sharing program performed in comparison to other available modes during the pandemic.

17. Key Words

Electric bicycles; Bike sharing; Life cycle assessment; Environmental impacts; Travel behavior

18. Distribution Statement

		No restrictions. This document is available to the public through the Transport Research International Documentation (TRID) repository.	
19. Security Classification (of this report)	**20. Security Classification (of this page)**	**21. No. of Pages**	**22. Price**
Unclassified.	Unclassified.	32	N/A

Contents

Abstract 2
Chapter I: Introduction 3
  Madison City 4
  BCycle 5
  Environmental Impacts of Transportation 5
Chapter II: Methodology 6
  Survey 6
    Survey Design 6
  Mode Choice Modeling 8
    Mathematical Framework 8
  Environmental Impact Assessment 9
    The GREET Model 10
Chapter III: Results and Discussion 11
  Mode Choice Modeling Results 11
  Impact of Travel Distance: Prediction and Scenarios 12
  Environmental Impacts 14
  Impact of Electricity Generation Mix 16
  Performance of E-bikes During the Pandemic 17
Chapter IV: Conclusions 19
Works Cited 20

List of Tables

Table 1. Average trip length for modes as seen from survey data ... 12
Table 2. Environmental impacts as a result of modal shifts before and after E-bikes ... 15

List of Figures

Figure 1. LCA boundaries ... 9
Figure 2. Modal splits for different scenarios. Note that the bracketed values in the x-axis represent the lower and upper bound, respectively, of the trip length in the simulation experiment ... 13
Figure 3. Environmental impacts before and after E-bike. Red line represents the total environmental impacts: sum of impacts from each mode ... 14
Figure 4. Environmental impacts for simulated scenarios based on trip length. Red line represents the total environmnetal impacts. The black line shows the total environmental impact in a simulation scenario before users had E-bike sharing access ... 16
Figure 5. Impact of electricity mix distribution for different states on observed benefits ... 17
Figure 6. Risk of travel for different modes of transportation during the COVID-19 pandemic ... 18
Figure 7. Change in usage of different modes of transportation during the COVID-19 pandemic as compared to before the pandemic ... 18

Abstract

This work investigates the opportunities and environmental impacts brought about Electric bicycles (E-bikes) sharing program. Electric bicycles (E-bikes) are an emerging transportation technology with the potential of replacing other available modes. In this work, we investigate the ability of E-bike sharing to compete with different modes of transportation and the resulting use phase environmental impacts. An empirical approach is taken to build mode choice models informed through a survey study in Madison, Wisconsin. The resulting model reveals potential users of this technology and the underlying modal shifts triggered by its usage. A life cycle analysis (LCA) based on Well-to-Wheel (WTW) model is then adopted to quantify the use-phase environmental impacts of E-bikes. The analysis reveals the attractiveness of E-bikes as a mode of transportation, ultimately replacing other available modes. This directly translates into environmental impacts across five studied categories: energy consumption, greenhouse gas emission, particulate matter, sulfate and nitrate emissions. The electricity generation scheme is further analyzed to showcase the dependency between environmental benefits of E-bikes and the energy infrastructure used. Additionally, we look at the E-bikes sharing program performed in comparison to other available modes during the pandemic.

Chapter I: Introduction

The search for alternative modes of transportation has seen a spike in interest with the growing concern about various environmental impacts of the transportation system. It is estimated that 28% of the greenhouse gas emissions (GHG) in the United States (US) comes from the transportation system [1]. This significant contribution from transport emissions presents an urgent need to reduce overall GHG emissions in the US by adopting environmentally friendly modes of transportation. Indeed, over the past decade travelers have witnessed a growing number of such transportation modes, with electric options surging the market (electric vehicles, hybrid vehicles, e-scooters, e-bikes, etc.) [2]. With the presence of different modes of transportation, comes an intricate web of choices that can alter transportation demand and in turn, have potential environmental implications. The change in travel demand, more specifically the change in mode choice, is important in reforming the environmental blueprint of the transportation systems. For instance, shifting travelers from carbon-intensive modes (e.g., vehicles) into much less intensive modes (bicycles, or E-Bikes) can have drastic impacts. Such shift has already been set in action with increasing popularity of biking as an alternative mode of transportation and has been brought to life through the usage of bike sharing programs [3] [4] [5] [6]. In fact, between 2018 and 2019, the US has witnessed a 60% increase in shared micro-mobility trips (shared bikes and scooters). Specifically, the electric bicycle has been a major influence on bike share popularity as it requires less effort than its predecessor; the bicycle [7]. Accordingly, this work presents an analysis into the nature of use phase environmental impacts resulting from the adoption of E-bikes and its effectiveness in replacing other modes of transportation (e.g., car, bus, bicycle, and walking). Additionally, Recent findings suggest a change in travel behavior and mode choices after the COVID-19 pandemic. Particularly, there was shift away from shared mobility (public transportation, shared vehicles, etc...) towards more personalized modes. While micro-mobility modes such as E-bikes sharing programs have been on upward trend, especially in urban cities, few insights are known on how they performed during the COVID-19 pandemic [8] [9] [10] [11]. We further provide insights on three main questions: (i) How did E-bikes sharing fare in comparison to available modes, (ii) How users rate the risk associated with different transportation modes and (iii) What are some characteristics on E-bikes users during the pandemic.

Socially, and from a transportation mobility perspective, e-bikes have many advantages over conventional bikes, in enabling people who could not complete the trips with a conventional bike to continue riding [12] [13] [14] [15] [16] [17]. These benefits allow the users to maintain some level of physical activity (some models provide an electric assist but still require the user to pedal), increasing the number of trips made by bike, utilize e-bikes as part of multimodal trips, carry more cargo with them, and ride to destinations farther away than otherwise possible [12] [18] [19] [20]. From an equity perspective, e-bike sharing may allow people who are not well served by the current transportation system greater mobility due to the relatively low cost compared to other transportation alternatives, and that the e-bikes may be accessed 24 hours per day which is ideal for commuters working non-traditional schedules.

Environmentally and economically, e-bikes present an advantage compared to other modes of travel. Previous work, focusing on China and Europe, has found completing trips with-bikes to have a lower environmental impact than mopeds, busses, and automobiles (both conventional fossil combustion and electric) [21] [22] [23] [24]. Suggesting that mode shifting to e-bikes has the potential to reduce the environmental impacts of the transportation system. The environmental impact of producing an e-bike is only 12% higher than a conventional bike, and largely due to the battery) [21]. The economic advantages are well documented in ownership systems, due to the much lower purchase price and use cost than an automobile [25] [26]. Literature suggests that e-bikes while, replacing some bike trips, largely replace trips that would have been completed by car or on public transit, based on a small body of research [13] [17] [18]. However, the current body of work has focused only on e-bike ownership, and not sharing programs, which are likely to broaden participation. Their potential to substitute for cars in the urban environment, and as part of multi-modal trips is a critical consideration for future sustainable transportation planning [20]. Current mode choice models addressing e-bikes are very limited, due to limited data set, as they present a relatively small market share, and have only focused on ownership models and not bike sharing. Essentially due to the low levels of market adoption of e-bikes, there isn't a large enough dataset to accurately model them. This is a major gap in the current literature, which could be addressed by focusing on an area with a higher density of e-bikes, particularly access to them through sharing programs. Studying a geographic area with an e-bike sharing program would facilitate collection of data sufficient to generate a mode choice model, due to sufficient usage and adoption of the e-bike mode of transportation, such as a case study in Madison, Wisconsin with the BCycle e-bike sharing program. Eventually this work will generate insight for other communities who introduce emerging e-bike sharing programs and give an indication of potential mode shift for planning purposes.

This research relates to multiple facets of the C-TEDD objectives regarding transportation policy research and fits with Focus Area 1"Creative Use of Existing Infrastructure for Future Needs" and Focus Area 5 "Ensuring Transportation System Vitality through Performance Management and Monitoring System". First, E-bikes usability and impacts on mode shift will be quantified and assessed. Second, the environmental impacts of shifting modes of transportation will be modeled. Third, the impact of the energy infrastructure is further assessed to see how it relates with E-bikes emissions. And fourth, policy implications of this emerging transportation modes are highlighted. This research seeks to assist in preparing the infrastructure of the future and motivate the use of sustainable transportation modes in urban cities. At the same time, seek to unveil what environmental and travel implication can be seen with adoption of E-bikes.

Madison City

Madison is a midsized midwestern city located in the state of Wisconsin. It has a population of 258,054 people in the city itself, and 634,000 people in the metropolitan statistical area [27] [28]. Madison is the capital of Wisconsin and home to the University of Wisconsin-Madison (UW-Madison), the flagship campus of the University of Wisconsin system. UW-Madison employs over 22,000 faculty and staff, has a total student body of 45,000 students, making it a significant portion of the population of the city of Madison [29]. Major private employers in the area include Epic systems, UW Hospital and Clinics, American Family Insurance, Dean Health System, and WPS Health Insurance [30].

BCycle

Bcycle part of Trek Bicycles is a bike-sharing program with an all-electric-bike fleet (peddle-assisted) with a location in Madison city. The bike sharing program allows users to check out an E-bike and return at various stations located throughout the city, to serve their travel needs. Since the transition from renting conventional bikes to E-bikes earlier in 2019 ridership has tripled. E-bikes are expensive to purchase, compared to conventional bikes, retailing for $1,500 or more. Sharing programs, such as BCycle allow users to pay a fee to rent the bike of $5 for a 30-minute ride, weekly passes for $16, monthly passes for $20 or an annual pass for $100.

Environmental Impacts of Transportation

The environmental impact of transportation varies as a function of mode. The greatest impact during the lifecycle of an automobile occurs during its usage phase, when the automobile is in service [31]. The same is true for buses across multiple fuel types, including diesel, hybrid, and compressed natural gas [32]. The environmental impact in greenhouse gas emissions per person-mile is greater when traveled as a single passenger in an automobile than on a bus that is operating carrying a large number of passengers. Additionally, modes running on electricity (as E-bikes) will have an environmental impact that is dependent on the electricity consumption and electricity generation schemes. Electricity that is heavily coal-dependent will have different impacts and emission factor from that of solar energy. This work analyzes the environmental impact of the usage phase of the different transportation options, neglecting the raw materials, manufacturing, and end of life.

Chapter II: Methodology

In this work, multiple methods are employed to analyze the challenging task ahead. The methods include a survey, random-utility mode choice modeling, and environmental impact tools. Each method is presented in a subsection in Chapter 2.

Survey

A web-based survey was distributed to members of BCycle in Madison, Wisconsin, through the UW-Madison Qualtrics survey center. BCycle is a bike sharing system with fully electric fleet (peddle assisted E-bikes). This bike sharing system allows its members to check out E-bikes at various dock stations and return them to any stations around the city to serve their specific travel needs. A total of 667 responses were received, of which 450 were used as a final dataset after data filtering.

Survey Design

The survey consisted of three main parts. The first part was designed to gather socio-demographic information of the participants. In the second, participants were asked about general travel behavior and their attitudes towards E-bikes. The third part was specifically designed to gather data on respondents' mode choice preference before and after owning a BCycle membership. Specifically, participants were asked to provide travel attributes (distance and time) of different trip types and state their mode of transportation used. The survey considers six different mode choices: personal vehicle, bus (a public transport system in Madison), ride hailing, bicycle (conventional), E-bike, and walking. We note that respondents were also asked to answer the survey questions considering normal travel behavior before the pandemic and during the lockdown. This was done to gain insights into the impact of the pandemic on travel behavior. Consequently, the collected data will inform a mode choice model that analyzes travel characteristics of E-bike users and the modal shifts triggered by E-bikes.

A brief description of the survey data can be seen in Table 1 below. Further analysis and insights into the data is found following sections.

Table 1. Brief summary from survey data

Usage of E-Bike		Increase E-Bike Usage (%)	No Change (%)	Decrease E-Bike Usage (%)
Age	18-29	53.44	41.59	39.24
	30-44	21.69	18.58	31.01
	45-59	14.29	22.12	19.62
	60+	10.58	17.7	9.49

Gender	Female	51.85	51.33	49.37
	Male	47.09	46.9	48.1
Income	Less than or equal $24,999	11.64	10.62	14.56
	25,000 - 74,999	33.86	30.09	23.42
	75,000 - 124,999	19.05	22.12	29.11
	125,000 - 199,999	15.87	13.27	15.19
	200,000 +	6.88	9.73	8.23
	Prefer not to answer	12.7	14.16	9.49
Degree	High School Graduate	11.64	11.5	8.86
	Bachelor’s degree	40.21	37.17	25.32
	Graduate or Professional Degree	25.93	34.51	42.41
	Some College of Associate Degree	22.22	16.81	23.42
Job Category	Government	8.99	7.96	15.19
	Healthcare Personnel	12.7	14.16	8.86
	Professional, scientific or technical	25.4	24.78	24.68
	Restaurants, food and drink services	8.99	3.54	2.53
	Teacher of Faculty	7.94	8.85	16.46
	Other	23.81	21.24	19.62
Work Status During Pandemic	Regular work	22.22	33.63	10.76
	Work from Home	44.97	38.94	68.99
	Not Working	23.28	19.47	10.76

Mode Choice Modeling

A mode choice model was developed based on the random utility maximization of mode preferences revealed through the survey. Such modeling framework is highly adopted in applications of mode choice models for survey data, as it is able to handle various heterogeneity between populations and sample data.

Mathematical Framework

The principal mathematical formulation for mode choice models can be represented as follows:

$$U(X_i, C_p) = V_{i,p} + \epsilon_{i,p}$$

$$V_{i,p} = V(C_p) + V(X_i) + V(C_p, X_i)$$

Where; U Represents the utility function; i Represents a mode-choice from a set of choices ; X_i is a vector containing various attributes for each mode of transportation (travel time, access time, travel cost, etc.); C_p Is a vector containing commuter specific attributes that influence the decision (income, ownership of a bicycle, housing location, age, etc.) ; $V_{i,p}$ is a portion of utility that can be measured from survey data, including transportation mode attributes (X_i) and commuter specific attributes C_p

Thus, it follows that the probability of choosing an alternative is then

$$P(\epsilon_1 < V_0 - V_1 + \epsilon_0, \dots, \epsilon_i < V_i - V_0 + \epsilon_0)$$

If we Assume the error term ϵ follows the Gumbel distribution whose density function is expressed as

$$f(z) = \frac{1}{\theta} e^{-\frac{z-\mu}{\theta}} e^{-e^{-\frac{z-\mu}{\theta}}}, F(z) = \int_{-\infty}^{z} f(t)dt = e^{-e^{-\frac{z-\mu}{\theta}}}$$

This leads to the conditional probability formulation as below:

$$(P_i \mid \epsilon_i) = \prod_{j \neq 1} e^{-e^{-(V_i - V_j + \epsilon_i)}}$$

$$P_i = \int_{-\infty}^{+\infty} \prod_{j \neq 1} e^{-e^{-(V_i - V_j + \epsilon_i)}} e^{-t} e^{-e^{-t}} dt.$$

The closed formulation is simplified into

$$P_i = \frac{e^{v_i}}{\sum_{j=1}^{J} e^{V_j}}$$

Further, this works uses a random utility model while specifying panel data. This is primarily done to represent different choice experiments by a single respondent more precisely. Doing so allows for analyzing change in choice respondents, through modeling the parameters as random parameters (i.e., they can vary from one respondent to another). Following the random parameter formulation and panel data, we allow $V_{i1} = \beta_i^T x_{i1}$,the closed formulation becomes

$$P_i = \prod_t \prod_j \frac{\sum_j y_{itj} e^{\beta_i x_{itj}}}{\sum_j e^{\beta_i x_{itj}}}$$

Environmental Impact Assessment

In modeling the environmental impacts of modal shifts triggered by E-bike usage, it is essential to have a unified analysis framework that quantifies various environmental impacts of different transportation modes during their use phase. For this, we adopt the principles of well to wheel life cycle assessment (WTW-LCA). In general, LCA analysis has been widely adopted to evaluate different engineering applications and quantify their contribution to different environmental emissions. In transportation systems, use-phase environmental analysis is critical, this entails quantifying emissions of different transportation modes taking into consideration the complete fuel cycle; from extraction until usage. It is important to note here, that transportation system is naturally dynamic and depends on travel behavior and mode choices. When modeling use-phase environmental impacts of E-bikes it is critical to assess how the presence of E-bikes affects the usage of different modes of transportation, which will result in various impacts. The figure below represents an overview of the envisioned environmental impacts framework and system boundary.

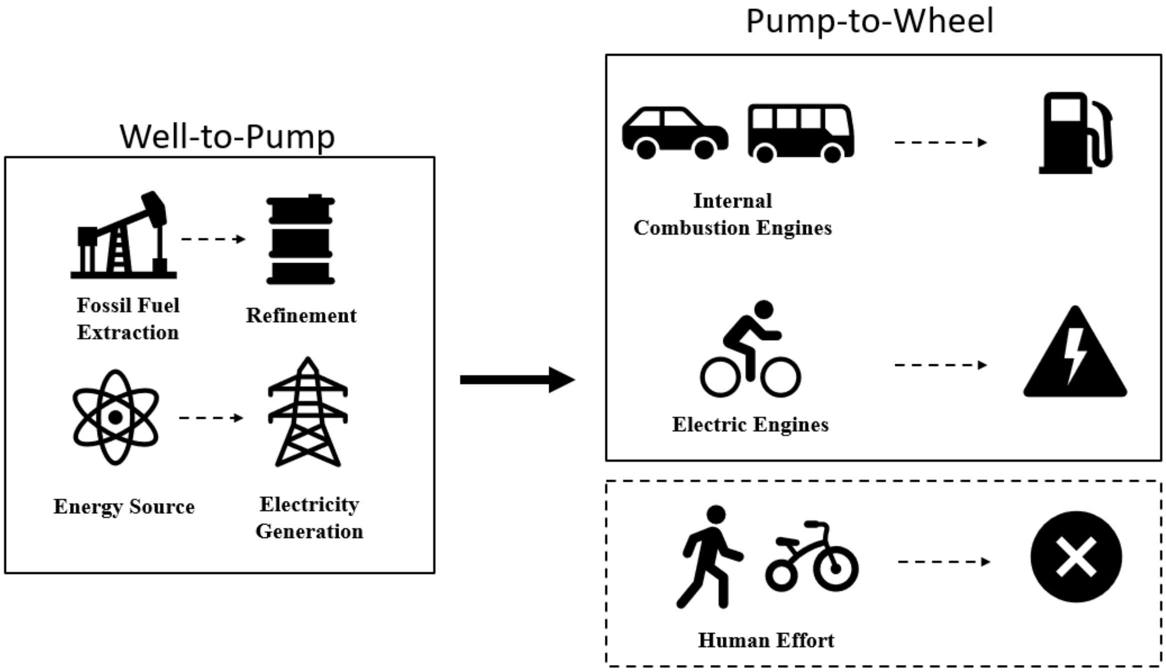


Figure 1. LCA boundaries

The GREET Model

The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model is used to estimate the environmental impact of different transportation modes. GREET uses a life cycle assessment approach, considering well-to-wheel impact of each transportation mode. In our work, there are six different modes of transportation which are of interest; personal vehicle, bus, ride-hailing, E-bike, conventional bike, and walking. Accordingly, we use the GREET model to extract emission factors of these different transportation modes. Note that in our analysis we use the GREET tool to model the transportation modes of interest in a way that closely depicts those available in Madison. For instance, vehicles (personal vehicles and ride hailing vehicles) are modeled as spark ignition (SI) with internal combustion engines running on a mixture of 90% gasoline and 10% ethanol by volume (this specific mix is used as it is widely available in Madison) and assumed to carry only one person. Buses are modeled to depict those available in Madison: they are assumed to be compression ignition direct injection vehicles running on low sulfur diesel and carrying on average 13 people (based on observed ridership data). Conventional bicycles and walking are not considered to have any use phase environmental impacts, as we disregard any impacts due to human effort. However, we note that the impact of conventional bike and walking will be altering the modal shifts. As for E-bikes, their environmental impacts are due to electricity generation and usage. They are assumed to consume an average of 10WH/mile (ref) and are powered with an electricity generated according to the Wisconsin state electricity generation mix. Consequently, four different environmental impact categories are used to gather a deeper insight into the environmental impacts of transportation system. The environmental categories are: energy consumption (kJ), greenhouse gas emissions (GHG, kg), particulate matter (PM2.5, mg), SOx emissions (mg), and NOx emissions (g). The environmental impacts are estimated per passenger mile basis and computed as the product of distributional transportation mode usage (i.e., mode splits) and extracted emission factors from the GREET model.

Chapter III: Results and Discussion

Mode Choice Modeling Results

The mode choice model was developed from survey. It is noted that the distribution of modal splits before joining the BCycle membership were: personal vehicle (42.5 %), ride hailing (1.6 %), bus (14.13%), E-bike (0%), conventional bike (12.76%), and walking (28.94 %). However, after access to an E-bike with BCycle membership, the updated modal splits were: personal vehicle (35.91%), ride hailing (1.96%), bus (10.11%), E-bike (21.83%), conventional bicycle (8.63%) and walking (21.56%).

To gain more insights into the characteristics and travel choices of E-bike users, we analyze the various relationships between mode choice and respondent characteristics, as it reveals potential users of E-bikes. First, we analyze different attributes of E-bikes users. It is noted that those aged between 20-26 were most likely (from a statistical point of view) to travel with E-bike, as well as those aged 40+ were found to have significant likelihood in using the E-bike. In contrast, other age groups were most likely to rely on personal vehicles. This is rather expected as young adults are generally regarded as early adopters of newer technologies. Interestingly, the usage of E-bikes by older generation (40+) was consistent with other studies, which might be attributed to the advantage of E-bike in relieving some of physical requirements of cycling. As for income status, it is found that those with income between $10,000 - $24,000 were most likely to use E-bike. Further, those who do not own a personal vehicle were also more likely to use E-bikes as compared to those who own one. Males were found to be more likely to use an E-bike as compared to females. Such behavior might be traced back to the impact of trip chaining and care giving responsibilities on women's travel patterns and mobility decisions. However, the exact nature of such behavior is in need of further experimental study that focuses mainly on direct comparison of such usage patterns.

Interestingly, those who noted cost effectiveness as their primary motive in using an E-bike were more likely to travel with an E-bike. This is rather interesting as it reveals an economical interest in the adoption of E-bike through a bike sharing program. However, the economic incentives between owning E-bikes versus using an E-bike through bike sharing program remains an interesting topic and in need of further analysis, outside the scope of this work. Additionally, people with governmental jobs and those working in the restaurant and food service industry were more likely to use E-bikes. This can be attributed to the locality of such types of jobs which typically is in the Central Business District, where amenities are close by and travelers do not need to travel far for their typical destinations. Finally, those who identified themselves as being extremely environmentally aware were more likely to use E-bikes. This is an interesting observation in light of the ongoing efforts of individuals and cities to move into more environmentally friendly modes of transportation. However, it is important to note that these observations remain as short-term insights as travel behavior constantly evolve as modes of transportation evolve and new technologies arrive.

It is found that the trip distance is the primary travel attribute factor that impact the modal shifts in presence of E-bikes. This is expected and consistent with previous literature on cycling and E-bikes [15] [6] [14]. The main idea is that travelers are most likely to cycle when distances are relatively short and would adopt other modes of transportation for longer distances. This is particularly interesting as E-bikes are an effective mode of transportation in short distances and have the potential to compete with other modes of transportation that are used for short distances as well, most notably buses and personal vehicles. In doing so, E-bikes can alleviate the environmental impacts of more energy intensive modes by substituting these modes. For instance, Table 2 presents the average trip length for each mode of transportation as observed in the survey. As expected, personalized travel (personal vehicles and ride hailing) are more likely to be used for longer trip distances. Interestingly, E-bikes are more adaptable to longer distances than conventional bicycles, suggesting the potential for competing with modes such as personal vehicles and bus, particularly in urban areas.

Table 2. Average trip length for modes as seen from survey data

Mode of Transportation	Average Trip Length (miles)
Personal Vehicle	10.17
Ride Hailing	6.34
Public Transportation (Bus)	5.24
E-bike	4.12
Conventional Bike	3.29
Walking	1.46

Impact of Travel Distance: Prediction and Scenarios

To better understand the impact of E-bikes in shifting modal splits in urban areas, a simulation experiment was conducted using the mode choice model developed. Specifically, a set of scenarios were designed to depict various trip lengths. In each scenario, an incremental change in trip distance was adopted to preserve the elasticity of predictions, and then a number of randomly generated trip lengths within the desired range were generated. For each generated trip length, the model was run to predict the likelihood of travelers choosing a certain mode of transportation. Consequently, the modal splits were estimated and compared to the survey-based data of before E-bikes (BE) and after E-bikes (AE) as shown in Figure. 2 below.

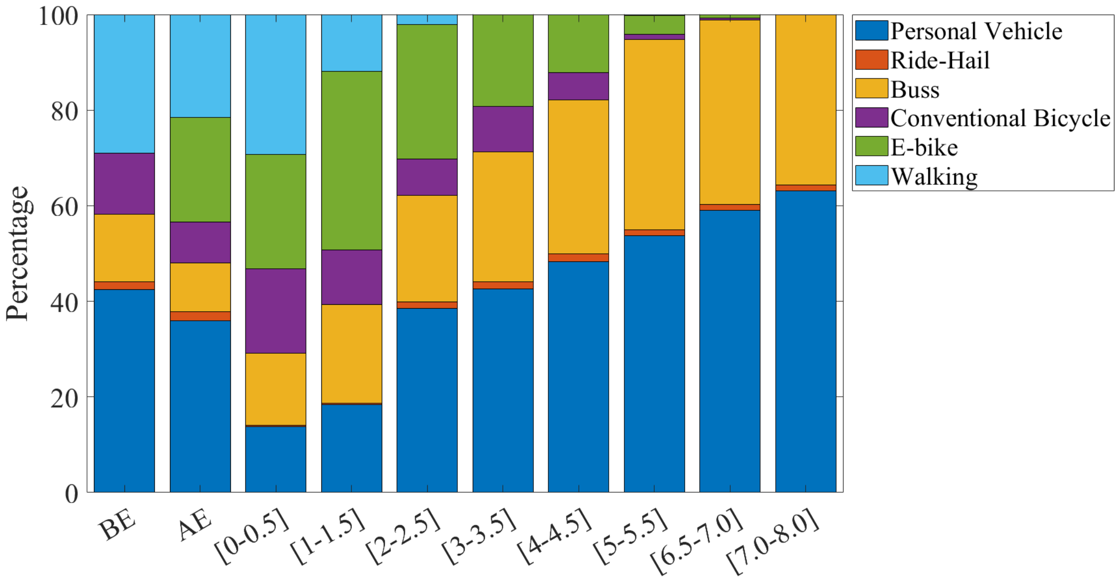


Figure 2. Modal splits for different scenarios. Note that the bracketed values in the x-axis represent the lower and upper bound, respectively, of the trip length in the simulation experiment

Interestingly, one can notice the potential of E-bike in competing with available modes (see green color in Figure 2. A comparison between BE and AE scenarios shows how the presence of E-bikes triggered a migration of travelers away from available modes (with the exception of ride hailing) and towards E-bikes. In fact, the survey data reveals that trips that were previously done by other modes were replaced by an E-bike (after joining BCycle membership): around 30% of them were previously done by personal vehicle, 19% by bus, 16% by bicycle and 33% by walking. Clearly, the migration of travelers away from carbon-intensive modes (i.e., vehicles, buses) into E-bikes is a desirable outcome when it comes to environmental benefits. However, it is critical to note here that the environmental impacts of modal shifts are convoluted. While E-bikes replaced trips done by personal vehicles and buses, it also replaced some of conventional bicycles and walking. Environmental benefits are seen when E-bikes replace the carbon-intensive modes, however an increase in environmental impacts is present when E-bikes replace walking and conventional bicycle. That is due to the fact that E-bikes consume electricity and thus generate emissions, while low, those emissions are still higher than walking/conventional bicycle. Further analysis on environmental impacts will highlight this by presenting the systematic investigation of different environmental impacts

Additionally, Figure 2. reveals that E-bikes are better able to compete with energy intensive modes as compared to walking or conventional bicycle. However, this is most effective for short-to-medium length trips: the increase in trip length (mainly beyond 2 miles) leads travelers away from E-bike and into more energy intensive modes. Although this is expected, the impact of short-to-medium length trips could be significant in medium-sized cities like Madison. Note that ride hailing (denoted as RH in Figure 2.) did not play a significant role in our analysis due to the low number of users recorded in our survey data.

Environmental Impacts

The environmental impacts as a result of modal shifts triggered by E-bike membership with BCycle, is shown in Figure 3. A comparison between the BE and AE cases, shows a decrease in use phase environmental impacts (per passenger mile) across all studied categories. E-bikes are shown to be an attractive mode of transportation that travelers are likely to use. This leads to a migration of modal usage away from carbon-intensive modes towards the environmentally desired E-bikes. However, an important point here is that E-bikes are adding some environmental impacts when they replace trips done by walking or conventional bikes. While these impacts are low, they are still present and are impacting the overall use-phase environmental impacts of the transportation network.

Building on the discussion above, this result is rather expected. E-bikes are shown to be an attractive mode of transportation that travelers are likely to use to serve their trips. This leads to a migration of modal usage away from carbon-intensive modes towards the environmentally desired E-bike. Additionally, one can infer from Figure 2. that conventional bicycles represent a portion of the modal splits and thus are competing for ridership in presence of the other modes. However, E-bikes with a bike sharing platform appear to present a more robust mode that can better compete with personal vehicles and buses. The expected decrease in environmental impacts are summarized in Table 3.

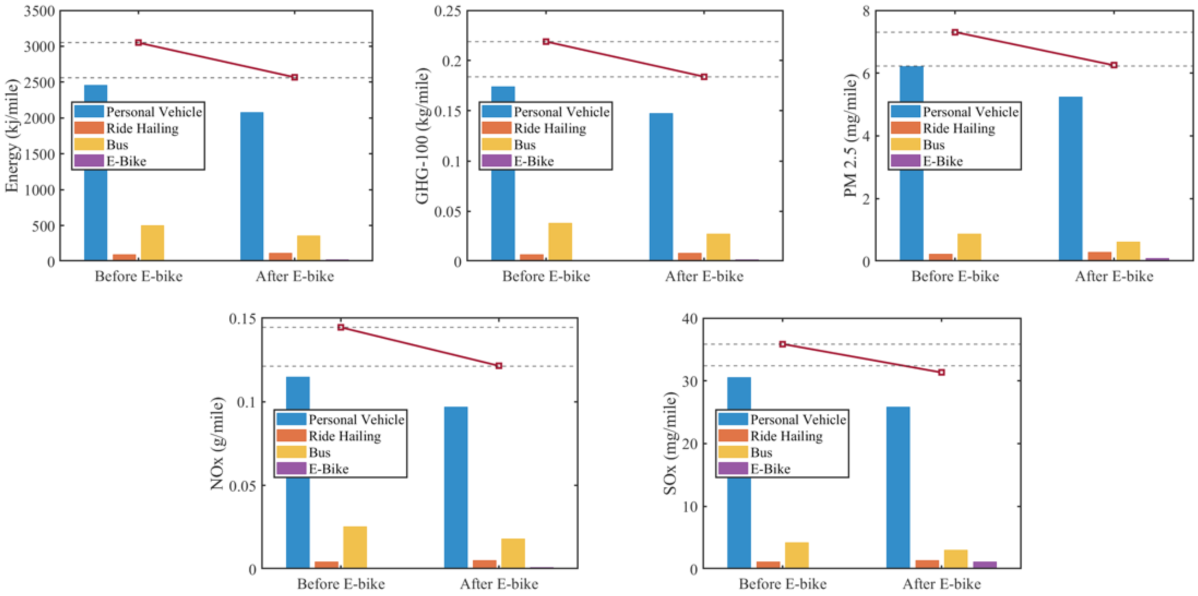


Figure 3. Environmental impacts before and after E-bike. Red line represents the total environmental impacts: sum of impacts from each mode

While the adoption of E-bikes yields use-phase environmental benefits, it is critical to note that these benefits are influenced by the traveler's trip distance. First, in a medium size city like Madison, short-to-medium length trips are common.

Second, bike sharing programs have a distributed network of stations that are strategically located in proximity of users, which could allow users to have close by access to a bike and might decrease the trip distances to their desired destination. Additionally, bike sharing programs operate with an economical membership that ensures some level of viability to users (e.g., annual membership for BCycle users). These factors combined play an important role in increasing the adoption rate of E-bikes.

Table 3. Environmental impacts as a result of modal shifts before and after E-bikes

Environmental Impacts	*Change (%)*
Energy consumption (kj/mile)	-15.78
GHG-100 (kg/mile)	-15.92
PM2.5 (mg/mile)	-14.44
NOx (g/mile)	-15.89
Sox (mg/mile)	-12.61

Figure 4. shows the environmental impacts for various simulated trip lengths. It is noted that in short distance trips (mainly those below 2 miles), E-bikes occupy a heavy share of the modal splits (up to 35%) thus results in lower environmental impacts. That is due to the competing factors E-bikes have with personal vehicles and buses. As discussed before, E-bikes can also take rider away from conventional bicycles and walking, which is undesirable from an environmental perspective. However, we show that the benefit of E-bikes sharing lies in its ability to compete with personal vehicles and buses, better than what conventional bicycles or walking can achieve. To visualize this, we compute the total impacts for the different trip cases, in a scenario where E-bikes are not available (i.e., before users had access to BCycle). This is shown through the black line in Fig. Comparing the black and red line (which represents the total impacts after E-bikes) we see a larger environmental impacts before E-bikes. Conventional bicycles alone might not be able to draw in ridership away from carbon-intensive modes. However, when trip distances start to increase, personal vehicles and buses dominate the commuting shares and thus present a little opportunity for E-bikes to draw in ridership and have significant environmental impacts.

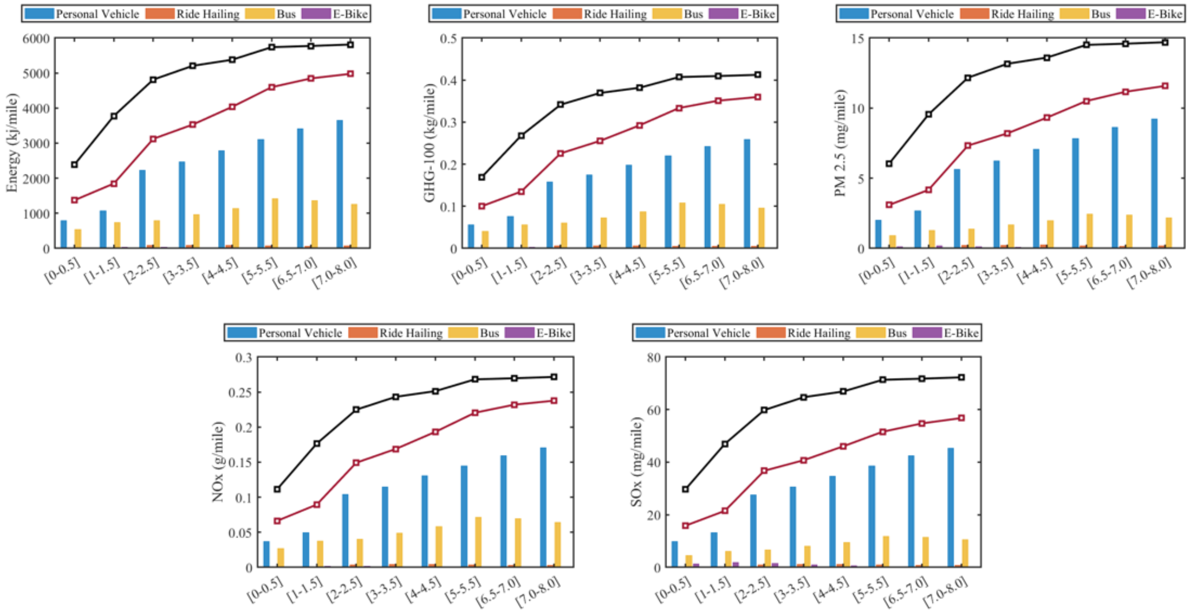


Figure 4. Environmental impacts for simulated scenarios based on trip length. Red line represents the total environmnetal impacts. The black line shows the total environmental impact in a simulation scenario before users had E-bike sharing access

Impact of Electricity Generation Mix

In the discussion of electricity dependent modes of transportation, the impact of the energy infrastructure is often neglected. The way electricity is generated (i.e., distribution of various energy resources) can alter the predicted environmental benefits. In the previous section, we summarize in Table 2. the expected environmental benefits as a result of the E-bike sharing competing for ridership with other modes of transportation. However, the environmental benefits of E-bikes are still dependent on the electricity mix usage to power them. This is of specific interest, as we have seen that E-bikes could also compete with walking/conventional bicycle, which yields an increase in use-phase environmental impacts. Accordingly, in this section we study how the observed environmental benefits would change if the electricity mix used in powering the E-bikes, changes. Figure 5. shows how the change in these impacts for different electricity mixes. The electricity mix scheme used in this study is the one following Wisconsin's resource distribution. A sample of different US states are chosen, and their electricity mix distribution (as summarized by the Energy Information Administration, [33]), is used to simulate the behavior when E-bikes are powered by the corresponding mix. Indeed, the results indicate that the energy infrastructure plays a role in the benefits reaped from adopting an E-bike sharing program. States whose electricity generation mix is dominated by coal (West Virginia (88.4%), Kentucky (68.8)) might experience less benefits. Specifically, when it comes to particulate matter (PM2.5), greenhouse gas and nitrate (N0x) emissions (GHG-100). Others, such as California, Connecticut, Oklahoma, who are more reliant on cleaner energy (as natural gas, solar, wind, etc..) can reap further benefits. An interesting case here is New Hampshire, which has a 59% dependency on nuclear energy and merely (0.8%) on coal energy, might still observe lower benefits in different environmental categories (nitrate and sulfate emissions). This stresses on the importance of analyzing the energy infrastructure systematically while adopting electric powered vehicles

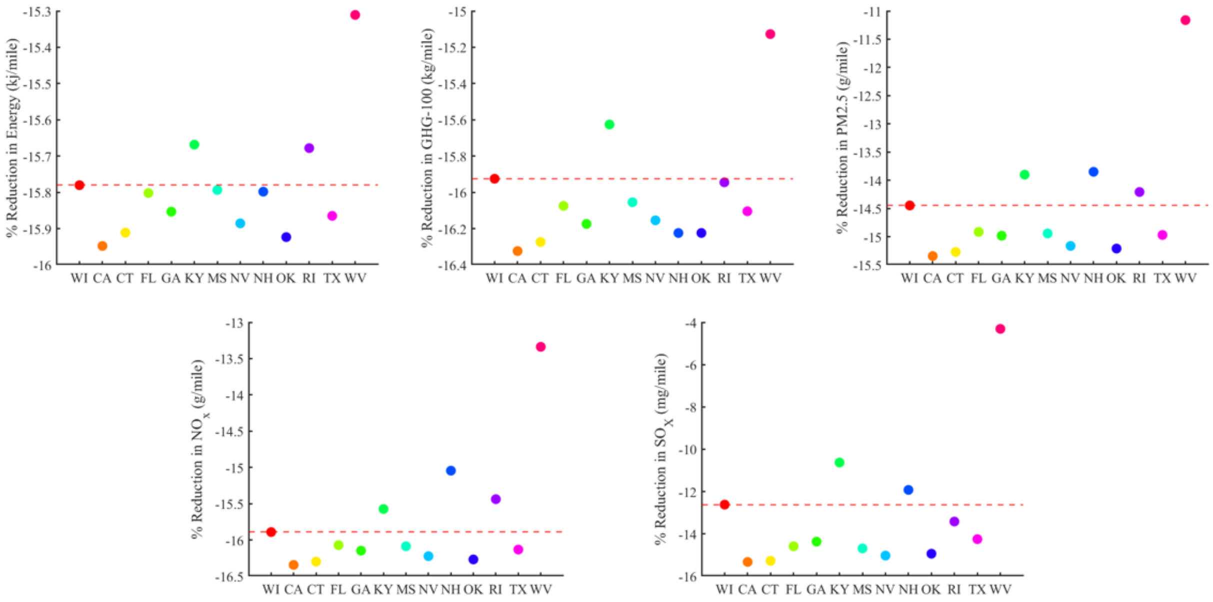


Figure 5. Impact of electricity mix distribution for different states on observed benefits

Performance of E-bikes During the Pandemic

First, we examine how users rate the risk of traveling with different modes of transportation available in Madison, during the COVID-19 pandemic, shown in Figure 6. 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 (i.e., Uber or Lyft services). On the contrast, personalized modes of transportation 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. For instance, users of E-Bike sharing are required to pick up the E-Bike from a dock station. This is reflective on users depicting a slightly higher risk in E-Bikes as compared to conventional buses, walking or personal vehicles. Specifically, 13% of respondents associate a medium level of risk in E-Bikes as compared to less than 3% for the other three personalized modes.

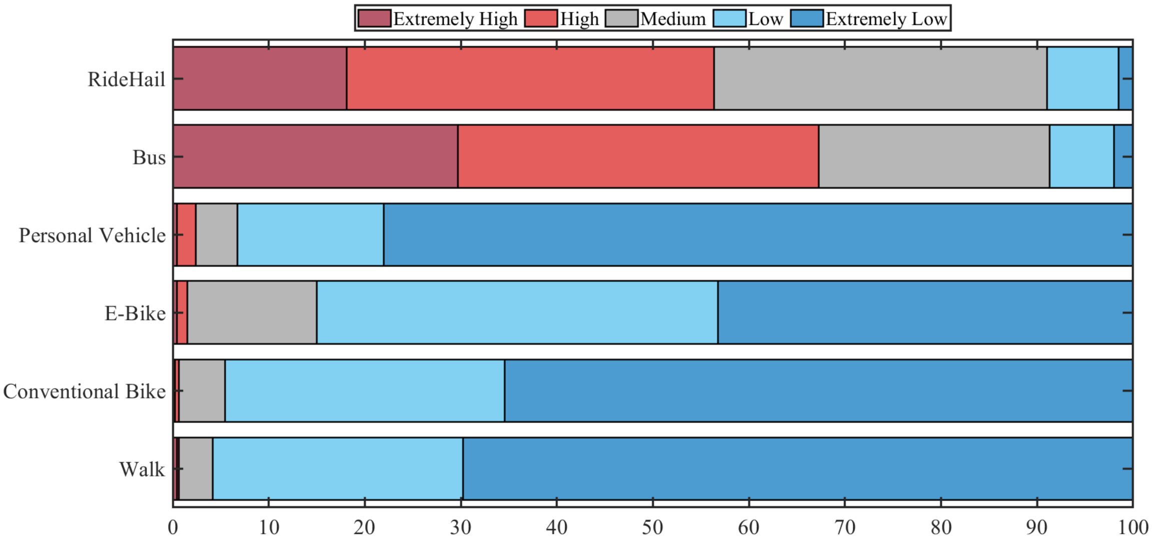


Figure 6. Risk of travel for different modes of transportation during the COVID-19 pandemic

Second, we examine the respondent's change in usage of different modes of transportation during the pandemic, shown in Figure 7. Micro-mobility modes saw a higher level of some increase (i.e., major increase and some increase) in usage during the pandemic as compared to other modes. For instance, 32% of respondents identified that walking as their mode of travel had some level of increase, similarly 24% for conventional bike. However, any increase in usage of personal vehicle, bus or ride hailing was only reported by 13%, 3% and 4% of respondents, respectively. Interestingly, 41% of respondents had some level of increase in E-Bike sharing usage. This highlights a potential for E-bikes sharing to be a reliable transportation mode during a pandemic.

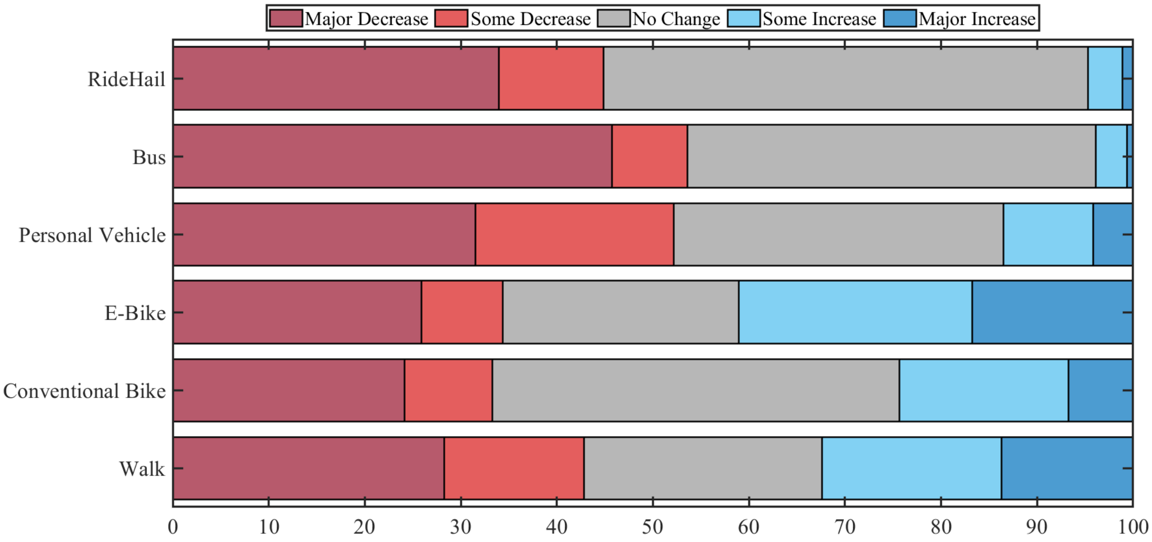


Figure 7. Change in usage of different modes of transportation during the COVID-19 pandemic as compared to before the pandemic

Chapter IV: Conclusions

In this work, the adoption of E-bikes through bike sharing platforms is analyzed and its respective impacts on use phase environmental factors is quantified. A holistic framework is adopted to link E-bikes usage patterns and its potential in altering modal distribution. Accordingly, use phase environmental analysis based on WTW emission factors is used to estimate the environmental benefits. It was found that E-bikes enjoy a level of attractiveness as a viable mode of transportation. This allows it to compete with other energy intensive modes of transportation as personal vehicles and buses, and cause a migration of trips in its interest. Eventually, this was found to a beneficial impact by reducing use phase transportation emissions across five different categories. However, the extent of E-bikes ability to compete with other transportation modes is dependent on trip length. It was shown that in short trip distances, E-bikes can hold its ground against other modes, yet when distances increase their usage rate drops significantly. Additionally, the impact of energy infrastructure on the environmental benefits is explored, it was found that electricity mix distribution can impact the environmental benefits from E-bikes. When it comes to pandemic performance riders perceived considerably less risk in using E-bikes and other personalized travel modes, and some increased their usage of E-bikes during the pandemic as compared to other available modes.

At the current state, E-bikes enjoy rigorous efforts by cities to move into more environmentally friendly modes of transportation and the booming popularity of bike sharing programs. This provides a unique opportunity for stakeholders to introduce environmentally desired modes of transportation, however it is essential to steer their deployment in ways that match travel behavior and trip requirements. This comes with a unique challenge in building an effective, safe, accessible and energy efficient bike sharing platforms with E-bikes as their core. As well as, continuously monitoring the modal shifts and usage patterns to adjust for dynamic travel behavior.

This study serves as a step forward in analyzing E-bikes in the US transportation system, however several research directions and limitations need to be addressed. First, the data explored in this study focused mainly on members of BCycle, however there could be some owners of E-bikes or other users through different means. Thus it is important to generate bigger datasets at a national level or a larger geographical level to gain deeper understanding. Second, travel behavior is dynamically changing and continuous efforts in analyzing commuting trips and modal shift is necessary. For instance, longitudinal data on E-bike usage pattern through an extended period of time is essential in analyzing the seasonal changes and travel behavior. Also, transportation technology is continuously changing and evolving, which can ultimately impact the emission factors of various transportation modes assumed here, thus future studies should integrate these changes.

Works Cited

[1] Environmental Protection Agency, "Fast Facts on Transportation Greenhouse Gas Emissions," 2021.

[2] M. Muratori, M. Alexander, D. Arent, Doug, M. Bazilian, P. Cazzola, E. M Dede, J. Farrell, C. Gearhart and A. Greene, "The Rise of Electric Vehicles - 2020 Status and Future Expectations," *Progress in Energy,* vol. 3, no. 2, 2020.

[3] Z. Kou, X. Wang, S. Chiu, A. Fung and H. Cai, "Quantifying greenhouse gas emissions reduction from bike share systems: a model considering real-world trips and transportation mode choice patterns," *Resources, Conservation and Recycling,* vol. 153, p. 104534, 2020.

[4] W. Li, L. Tian, X. Gao and H. Batool, "Effects of dockless bike-sharing system on public bike system: case study in Nanjing, China," *Energy Procedia,* vol. 158, 2019.

[5] Y. Ouyang, B. Guo, X. Lu, Q. Han, T. Guo and Z. Yu, "Competitive bike: Competitive analysis and popularity prediction of bike-sharing apps using multi-source data," *IEEE Transactions on Mobile Computing,* vol. 18, pp. 1760--1773, 2018.

[6] Z. Kou and H. Cai, "Understanding bike sharing travel patterns: An analysis of trip data from eight cities," *Physica A: Statistical Mechanics and its Application,* vol. 515, pp. 785--797, 2019.

[7] NACTO, "Shared Micromobility in the U.S.: 2019".

[8] R. J. Schneider and H. Schinkowsky, "Reactions to University Campus Commute Mode Shifts During COVID-19," *Findings,* 2021.

[9] A. Thombre and A. Agarwal, "A paradigm shift in urban mobility: policy insights from travel before and after COVID-19 to seize the opportunity," *Transport Policy,* 2021.

[10] M. Abdullah, C. Dias, D. Muley and M. Shahin, "Exploring the impacts of COVID-19 on travel behavior and mode preferences," *Transportation research interdisciplinary perspectives,* vol. 8, 2020.

[11] R. L. Abduljabbar, S. Liyanage and H. Dia, "The role of micro-mobility in shaping sustainable cities: A systematic literature review," *Transportation research part D: transport and environment,* vol. 92, 2021.

[12] S. Kaplan, D. K. Wrzesinska and C. G. Prato, "The role of human needs in the intention to use conventional and electric bicycle sharing in a driving-oriented country," *Transport Policy,* vol. 71, pp. 138--146, 2018.

[13] M. Johnson and G. Rose, "Extending life on the bike: electric bike use by older Australians," *Journal of Transport & Health,* vol. 2, no. 2, pp. 276--283, 2015.

[14] J. MacArthur, J. Dill and M. Person, "Electric bikes in North America: Results of an online survey," *Transportation Research Record,* vol. 2468, 2014.

[15] M. a. R. G. Johnson, "Electric bikes--cycling in the New World City: an investigation of Australian electric bicycle owners and the decision making process for purchase," in *Proceedings of the 2013 Australasian Transport Research Forum*, 2013.

[16] A. Wolf and S. Seebauer, "Technology adoption of electric bicycles: A survey among early adopters," *Transportation Research Part A: Policy and Practice,* vol. 69, 2014.

[17] A. Lee, E. Molin, K. Maat and W. Sierzchula, "Electric bicycle use and mode choice in the Netherlands," *Transportation Research Record,* vol. 2520, 2015.

[18] T. Jones, L. Harms and E. Heinen, "Motives, perceptions and experiences of electric bicycle owners and implications for health, wellbeing and mobility," *Journal of transport geography,* vol. 53, pp. 41-49, 2016.

[19] R. Frischknecht and K. Flury, "Life cycle assessment of electric mobility: answers and challenges," *The International Journal of Life Cycle Assessment,* vol. 16, pp. 691--695, 2011.

[20] N. Popovich, E. Gordon, Z. Shao, Y. Xing, Y. Wang and S. Handy, "Experiences of electric bicycle users in the Sacramento, California area," *Travel Behaviour and Society,* vol. 1, pp. 37-44, 2014.

[21] C. Abagnale, M. Cardone, P. Iodice, S. Strano, M. Terzo and G. Vorraro, "Power requirements and environmental impact of a pedelec. A case study based on real-life applications," *Environmental Impact Assessment Review,* vol. 53, pp. 1--7, 2015.

[22] S. Ji, C. R. Cherry, M. J. Bechle, Y. Wu and J. D. Marshall, "Electric vehicles in China: emissions and health impacts," *Environmental science \& technology,* vol. 46, 2012.

[23] C. R. Cherry, J. X. Weinert and Y. Xinmiao, "Comparative environmental impacts of electric bikes in China," *Transportation Research Part D: Transport and Environment,* vol. 14, no. 5, 2009.

[24] P. Baptista, A. Pina, G. Duarte, C. Rolim, G. Pereira, C. Silva and T. Farias, "From on-road trial evaluation of electric and conventional bicycles to comparison with other urban transport modes: Case study in the city of Lisbon, Portugal," *Energy Conversion and Management,* vol. 92, 2015.

[25] E. Salmeron-Manzano and F. Manzano-Agugliaro, "The electric bicycle: Worldwide research trends," *Energies,* 2018.

[26] M. Weiss, P. Dekker, A. Moro, H. Scholz and M. K. Patel, "On the electrification of road transportation--a review of the environmental, economic, and social performance of electric two-wheelers," *Transportation Research Part D: Transport and Environment,* vol. 41, 2015.

[27] US Census Bureau, "Quick Facts, Madison Wisconsin," 2019. [Online]. Available: https://www.census.gov/quickfacts/fact/table/madisoncitywisconsin/PST045219#PST045219. [Accessed 10 January 2020].

[28] statisticalatlas, "Madison Metropolitan Area," 14 September 2018. [Online]. Available: https://statisticalatlas.com/metro-area/Wisconsin/Madison/Population. [Accessed 10 January 2020].

[29] University of Wisconsin-Madison , "Fact Sheet," 2019. [Online]. Available: https://www.wisc.edu/about/facts/. [Accessed 10 January 2020].

[30] Madison Economic Development, "Major Employers," 2013. [Online]. Available: https://www.madisoneconomicdevelopment.com/region/employers.htm. [Accessed 10 January 2020].

[31] H. L. MacLean and L. B. Lave, "Life cycle assessment of automobile/fuel options," *Environmental science & technology,* pp. 5445-5452, 2003.

[32] E. C. McKenzie and P. L. Durango-Cohen, "Environmental life-cycle assessment of transit buses with alternative fuel technology," *Transportation Research Part D: Transport and Environment,* 2012.

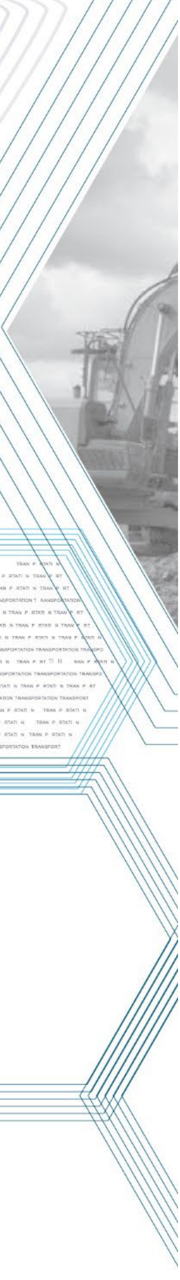
[33] State Electricity Generation Fuel Shares, 2020. [Online]. Available: https://www.nei.org/resources/statistics/state-electricity-generation-fuel-shares.

[34] E. Croft McKenzie and P. L.Durango-Cohen, "Environmental life-cycle assessment of transit buses with alternative fuel technology," *Transportation Research Part D: Transport and Environment ,* vol. 17, no. 1, pp. 39-47, 2012.

[35] S. Dave, "Life cycle assessment of transportation options for commuters," *Massachusetts Institute of Technology,* 2010.

CENTER FOR TRANSPORTATION
EQUITY, DECISIONS & DOLLARS

The **Center for Transportation, Equity, Decisions and Dollars (CTEDD)** is a USDOT University Transportation Center, leading **transportation policy research** that aids in **decision making** and **improves economic development** through **more efficient, and cost-effective use of existing transportation systems,** and offers **better access to jobs and opportunities.** We are leading a larger consortium of universities focused on **providing outreach** and **research to policy makers**, through **innovative methods** and **educating future leaders of the transportation field.**



UNIVERSITY OF TEXAS ARLINGTON

CAL POLY SAN LUIS OBISPO

Georgia Tech

USF UNIVERSITY OF SOUTH FLORIDA

WISCONSIN UNIVERSITY OF WISCONSIN–MADISON

C-TEDD@UTA.EDU
CTEDD.UTA.EDU
@UTACTEDD
@ C__TEDD
@ CENTER FOR TRANSPORTATION, EQUITY, DECISIONS AND DOLLARS
817.272.5138