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The E-Bike Potential: Estimating regional e-bike impacts on greenhouse gas emissions

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ABSTRACT

Electric bicycles (e-bikes) have been found to offer a promising solution to reduce the greenhouse gas (GHG) impact of a region's passenger transportation system. Using data from a North American survey of e-bike owners, a mode replacement model was adapted and augmented to consider the case of Portland, OR for various levels of e-bike person miles traveled (PMT) mode share penetration. It was estimated that for a 15% e-bike PMT mode share, car trip mode share could be reduced from 84.7% to 74.8%. Total car PMT per day could be reduced from 28.9 million to 25.5 million. Furthermore, carbon dioxide (CO_2) emissions from passenger transportation could be reduced by 12% after accounting for e-bike emissions from electricity generation and induced e-bike trips. An individual e-bike could provide an average reduction of 225 kg CO_2 per year. These estimates show that e-bikes have the potential to help cities and regions achieve their climate goals. Additionally, this research can be used to support policies and programs necessary to facilitate the growth of this emerging mode to realize carbon reduction impacts.

1. Introduction

Many cities have goals for reducing automotive vehicle miles travelled (VMT) in order to reduce tailpipe emissions and congestion. Conventional cycling is a good solution, though its uptake has been slow in the U.S., despite the implementation of bike infrastructure, bike share, and outreach programs in several cities (Anderson and McLeod, 2017). Electric bicycles (e-bikes) could be an effective new solution to accelerate mode shift transitions toward greener travel.

The e-bike is a recently introduced mode that is rapidly gaining in popularity throughout the U.S. E-bikes can offer a cheaper alternative to car travel (Popovich et al., 2014) and can provide users with an adequate level of physical activity intensity necessary to enhance health (Castro et al., 2019; Fishman and Cherry, 2016). In the U.S., several states define e-bikes using a three-tier classification system based on maximum speed and motor power, allowing their usage to be regulated as a bicycle. Yet, in states where there is no formal definition for e-bikes, licensure and registration are sometimes required to operate them (State Electric Bicycle Laws: A Legislative Primer, 2020). Riding an e-bike is rewarding and fun for many users, is freeing for users with limited ability and mobility, and can even lead to a car-free household (Jones et al., 2016; Ling et al., 2017; MacArthur et al., 2018b, 2017; Popovich et al., 2014). E-bikes can be useful tools for reducing CO_2 emissions, urban noise, and inner city traffic (Weiss et al., 2015).

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Lastly, e-bikes encourage users to cycle farther and more often than conventional bicycles (Castro et al., 2019; Fyhri et al., 2016; Fyhri and Fearnley, 2015; MacArthur et al., 2018b), meaning that e-bikes offer the opportunity to multiply the benefits already available through conventional cycling.

The purpose of this study was to quantify the potential impact that an increased e-bike mode share could have on a region's CO_2 emissions from passenger transportation. To this end, we made use of data from the MacArthur et al. (2018b) North American study of e-bike uses. Our findings provide novel insight into to the potential for e-bikes to reduce GHG emissions due to mode shift away from polluting modes, which was not considered in the original study. We accomplished this by estimating net changes in aggregate person miles traveled (PMT) by mode and total greenhouse gas (GHG) emissions in terms of CO_2 for various levels of e-bike mode share, based on naturalistic mode substitution ratios from the survey. To simplify the analysis, we decided to perform our estimates using PMT instead of VMT. This is because it was more useful to normalize and compare the carbon emissions rates of modes on a per capita basis, as the majority of e-bikes carry a single rider at a time.

We calculated the share of PMT of other modes that was replaced by e-bike based on self-reported mode replacement information of survey respondents' last three e-bike trips. This method is narrower in scope compared to the longitudinal approach of Sun et al. (2020) that used three-day travel behavior of respondents across different years as part of the Netherlands Mobility Panel, but is similar to that used by Winslott Hiselius and Svensson (2017) and Fyhri et al. (2016).

Of the existing studies that assess e-bike mode shift of users, few estimate CO_2 reduction impacts. Our CO_2 emission calculations are similar to those of Winslott Hiselius and Svensson (2017) in that they incorporate automobile emissions avoided. Fyhri et al. (2016) considered the emissions of cars and transit when performing their calculations. We expand on this by also including the additional source of CO_2 emissions from the upstream electricity generation required to charge the e-bikes themselves. The model we created for North America is applicable to specific regions by using locale-specific trip generation and emissions profiles, unlike the worldwide estimates of Mason et al. (2015).

The present study is additionally distinct from past research in that it uses mode shift ratios based on data from a large sample of existing e-bike users (n = 1,796), an improvement on the sample sizes of Winslott Hiselius and Svensson (2017) (n = 321) and Sun et al. (2020) (n = 107). It captures naturalistic use and mode shift, as respondents already possessed an e-bike that they had purchased themselves. This is a different approach from Cairns et al. (2017), Fyhri and Fearnley (2015), and (MacArthur et al., 2017), who studied the behavior of participants that were provided with an e-bike for a limited time. It is also a change from other studies, such as Fyhri et al. (2016) and de Kruijif et al. (2018), who observed the behavior of e-bike users that purchased an e-bike through an incentive program. To our knowledge, this study is the first to assess e-bike mode shift and GHG reduction potential in North America, as existing literature tends to favor European contexts.

The simple estimation model that we created for quantifying this PMT shift and GHG reduction can be used by North American regions to perform an impact analysis. It only requires local information about population, trip generation by mode, trip length by mode, auto occupancy, auto fuel economy, transit fuel economy by person mile, and e-bike emissions rate as inputs. E-bike mode shift ratios calculated from the MacArthur et al. (2018b) survey are then applied to provide an estimated range of CO_2 emission reductions based on the expected percent of mode shift to e-bikes. As 20% of the respondents to the MacArthur et al. (2018b) survey used e-bikes with top speeds of 28 mph, commonly referred to as "speed-pedelecs," we consider the model to apply to a mix of class 1, class 2, and class 3 e-bikes (PeopleforBikes, n.d.).

Though the model provides CO_2 reduction potential for a range of e-bike mode shares, it is left to the user to consider the realistic expected target of e-bike mode shift given their regional context. This context includes local land use and density, bike infrastructure, climate, and the financial resources required to promote e-bikes through incentive programs or other outreach.

We used Portland, OR as a case study because of the availability of regional transportation data and the extensiveness of the city's bike network that lends itself to e-bike uptake. In this case, we found that a 15% e-bike mode share by PMT could result in a 12% reduction in transportation CO_2 emissions, with an average CO_2 savings of 225 kg per e-bike per year. We selected the 15% mode share arbitrarily as the optimistic maximum of a range of potential e-bike regional mode share values. This is in line with the hypothetical Global High Shift Scenario, suggested by Mason et al. (2015), of 14% of worldwide combined cycling and e-bike person miles travelled accomplished by 2050 through an aggressive set of pro-cycling policies.

2. Literature review

E-bikes offer promising potential to reduce carbon emissions from the transportation sector. A comprehensive metric that can be used to demonstrate this is a mode's lifecycle CO_2 emission rate, which takes into account emissions from manufacturing and disposal as well as usage. The literature shows that despite having slightly higher lifecycle emissions than conventional bicycles, privately owned e-bikes emit far less than other motorized modes. We specify *privately owned* because shared systems may have significantly higher life cycle emissions due to rebalancing (Hollingsworth et al., 2019; Kou et al., 2020; Luo, 2007). Cherry (2007) estimated lifecycle emissions for conventional bicycles at 4.7 g, e-bikes at 22 g, buses at 48.4 g, and cars at 306 g lifecycle CO_2 per person kilometer in China. The European Cyclists' Federation found that bicycles emit 21 g, e-bikes emit 22 g, buses emit 101 g, cars emit 271 g lifecycle CO_2e per person kilometer in Europe (Blondel et al., 2011). Additionally, according to the European lifecycle emission estimates of Weiss et al. (2015), bicycles emit 5 g, e-bikes emit 25 g, buses emit 110 g, and cars emit 240 g CO_2e per person kilometer. Clearly, e-bikes emit little more than conventional bicycles and far less than cars and buses, even when considering manufacturing, use, and disposal.

A recent study considered the effect that pedelec type e-bikes limited to 15.5 mph (25 km/hr) could have on GHG emissions in Europe, using the Assessment of Transport Strategies (ASTRA) model (Astegiano et al., 2019). This multidimensional model accounted for the interdependencies of trip characteristics, vehicle fleets, population demographics, economics, and the environment when determining potential e-bike mode share and the effects on emissions. It found that an e-bike mode share by trips of 2.9% could be achieved by 2050 using a cordon congestion pricing policy program only to incentivize the replacement of car trips with trips using other modes. Compared to the baseline scenario, the policy change was calculated to influence a total 0.2% CO_2 emissions change by 2050 attributable to e-bikes. This impact seems minute, however only one transportation policy measure was analyzed, leaving out other policies and market forces that could more directly improve e-bike mode share.

The Global High Shift Scenario project modeled transportation emission trends country-by-country through 2050, including both business-as-usual and high-mode shift scenarios (Replogle and Fulton, 2014). This initial study was augmented the following year to include more aggressive contributions from cycling and e-cycling as utilitarian modes of transport (Mason et al., 2015). The study presented optimistic outcomes, finding that a world that achieves a scenario of 14% combined bicycle and e-bike mode share by person kilometers traveled could see a 10% reduction in transportation emissions. This was attributable to the immense energy required per person kilometer for light-duty passenger vehicles compared to e-bikes and bicycles. The 14% mode share increase would be obtained by a combination of policies not limited to congestion pricing, including bike lane network build out, bike share programs, implementation of laws that increase cyclist safety, transit investment, land use and transportation planning improvements, elimination of parking and fuel subsidies, and new government funding streams for active transportation investment. It should be noted that the estimation method used by Mason et al. was "technology neutral," that is, it did not specify the individual contributions of different types of e-bikes. As such, their results included modeled effects of a global e-bike fleet including pedelecs and non-pedaled electric two wheelers. Yet, the report describes these vehicles to be speed-limited, thereby seemingly excluding electric mopeds.

Winslott Hiselius and Svensson (2017) also found promising GHG reductions in observed e-bike use. They estimated that, on a weekly basis, Swedes saved an average of 7.74 kg/km ($sd = 8.16$ kg/km) in urban areas and 8.62 kg/km ($sd = 10.79$ kg/km) in rural areas when using pedelec type e-bikes limited to 15.5 mph (25 km/hr). This sums to an average total of between 272 kg and 394 kg CO_2 avoided per year, per person, depending on the number of cycling weeks that are assumed in Sweden due to seasonal weather patterns. Overall, this represents a 14%-20% reduction in the average total CO_2 emitted per person from transportation.

Even with this potential to reduce emissions, does that mean that people will actually choose to use e-bikes to replace trips taken by more carbon intensive modes? A study in Brighton, United Kingdom found that a trial group of 80 participants that were loaned pedelec type e-bikes limited to 15.5 mph (25 km/hr) reduced their number of miles driven by 20% (Cairns et al., 2017). Users traveled a weekly average of 15–20 miles by e-bike, with commuting coming out as the dominant trip purpose. In addition, 43% of participants reported that they travelled less as a car driver. A Norwegian study observed the actual travel behavior and GHG emission reductions of participants in an e-bike incentive program in Oslo using surveys and an app that tracked travel behavior (Fyhri et al., 2016). The sample consisted of 619 people, of which 153 people were e-bike users. Those who obtained an e-bike through the program increased their cycling mode share by kilometers traveled from 17% to 52%. It was found that each e-bike user, compared to the control group, saved between 87 and 144 kg of CO_2 emissions per year. This study also limited participation to those with pedelec type e-bikes limited to 15.5 mph (25 km/hr).

Outside of structured loan and incentive programs, naturalistic e-bike use and mode shift has also been studied. The Swedish study found that e-bikes saved users an average of 55 km per week of driving in urban areas and 62 km per week of driving in rural areas (Winslott Hiselius and Svensson, 2017). E-bike trips were also found to predominantly replace car trips compared to other modes. The Dutch study made use of the longitudinal Netherlands Mobility Panel dataset to understand the demographics and environments of those that obtained access to an e-bike across several years (Sun et al., 2020). The study assessed the effective mode shift potential of e-bikes by comparing each individual's distance mode share before and after obtaining an e-bike. The results indicated that new e-bike users significantly reduced their car driving, walking, public transit, and conventional cycling mode share of total distance traveled in exchange for an increased level of e-bike mode share. Additionally, users aged 25–49 and 60–69 and those in non-urbanized areas were found to significantly decrease their car use in particular after obtaining an e-bike. It is unclear what types of e-bikes were observed in this study. The North American survey of e-bike owners found that 62% of e-bike trips replaced trips that otherwise would have been taken by car (MacArthur et al., 2018b). Of the trips previously taken by car, 45.8% were commute trips to work or school, 44.7% were other utilitarian trips (entertainment, personal errands, visiting friends and family, or other), and 9.4% were recreation or exercise trips. The average length of trips otherwise taken by car was 9.3 miles.

The model presented in this study employs e-bike PMT mode shift ratios based on e-bike usage data uncovered by the North American survey (MacArthur et al., 2018b). In order to perform a case study of Portland, we obtained baseline transportation usage and emissions conditions for the region from the Oregon Metro Regional Transportation Plan appendices, Oregon Household Activity Survey, U.S. Energy Information Administration, U.S. Environmental Protection Agency eGrid data, and the Federal Transit Administration.

3. Data and methods

In this section, we develop the process we used to estimate CO_2 reduction potential due to e-bike mode shift in Portland, OR. We explain the foundations of our model, provide the input parameters, and describe the calculation method.

In order to apply the information of e-bike mode replacement trends gleaned in the North American Survey (MacArthur et al., 2018b) and to create a smaller scale estimation in the style of the 2015 High Shift Cycling Scenario report (Mason et al., 2015) for Portland, OR, we needed a tool to model PMT and GHG reduction potential due to e-bike mode share increase. We initially chose to perform our analysis using a modified version of a Microsoft Excel tool developed by researchers at the Hamburg University of

Technology (TUHH) Institute for Transport Planning and Logistics in conjunction with the Mobile 2020 Project (Fawzy et al., 2014), co-funded by the Intelligent Energy Europe Programme of the European Union. This tool was designed to assess the CO_2 reduction potential of mode shift from conventional cycling only. It calculated PMT and carbon footprint impacts resulting from conventional bicycle mode share variations but did not account for e-bikes. We augmented the tool to accommodate English units, calculate average carbon footprint per person mile for public transit, calculate total e-bike emissions, and account for reductions in trips and distance traveled of other modes given a specified increase in e-bike mode share by PMT.

Our adapted model reduced the distance traveled by other modes proportional to the ratios of PMT replaced by e-bikes from the North American survey (MacArthur et al., 2018b). In the survey, mode replacement information was obtained by asking the respondent to note the trip purpose and distance of their last three trips by e-bike. The respondents then identified the mode that would have been taken had the e-bike not been available, or indicated that they would not have otherwise taken the trip. The overall impact of "induced trips" is later quantified in the sensitivity analysis section. Of all of the e-bike trips observed by the survey, 80% were utilitarian, which includes trips that were made for commuting, running personal errands, visiting friends and family, and visiting entertainment facilities. Of the utilitarian e-bike trips, 67.9% would have been made by car, 12.8% by conventional cycling, 12.7% by public transit, and 6.6% by walking. Of the utilitarian PMT made by e-bikes instead of by other modes, 72.4% would have been traveled by car, 12.2% by conventional cycling, 13.2% by public transit, and 2.2% by walking, assuming route choice was held constant. We initially excluded non-utilitarian trips made for recreation and exercise purposes, which also tended to be induced trips. However, the additional impact of these trips was considered and is quantified later in the sensitivity analysis section.

Because the augmented Excel model only provided results for one e-bike mode share increase test value at a time, a companion code in R was developed to create visualizations for a range of e-bike mode share values, the results of which are presented below. The R tool can be used to estimate PMT shift and GHG reductions for any region as long as all required input data is available. The input data values and sources that we used are found in Table 1. For the Portland, OR, case study, we assumed that bicycles and walking modes emit 0 g CO_2, e-bikes emit 4.9 g CO_2, public transit emits 140 g CO_2 (calculated from a weighted average of Portland-area bus, streetcar, light rail, and hybrid rail emissions), and cars emit 268 g CO_2 per passenger mile (accounting for Portland-area average fuel economy and car occupancy).

3.1. Calculation method

In this section, we summarize the model calculation method used by the R code.

First, calculate the daily total PMT for each mode.

$$l_n = t_n * \bar{l_n}$$

Where t_n is the total trips in the region for mode n, $\bar{l_n}$ is the average trip length for mode n, and l_n is the average total daily PMT for mode n.

Next, calculate the new total PMT for each mode after subtracting the miles replaced by e-bikes.

$$l_n^{'} = l_n - \%PMT_e * \sum_{i=1}^{n} (l_i) * \%r_{PMTn}$$

Where $\%PMT_e$ is the mode share by PMT of e-bikes being assessed, $\sum_{i=1}^{n} l_i$is the average total daily PMT for all modes in the region, $\%r_{PMTn}$ is the PMT replacement ratio of e-bikes for mode n, and $l_n^{'}$ is the new PMT for mode n after miles replaced by e-bike have been subtracted.

Finally, calculate and sum the emissions generated by each mode (if applicable).

$$C = \sum_{i=1}^{n} (l_i^{'} * \bar{c_i})$$

Where C is the total carbon emissions from all modes that is the sum of the product of the new PMT for each mode $l_i^{'}$ and the average carbon emissions per person mile for each mode, $\bar{c_i}$.

4. Results

This section presents findings from the model on the potential PMT and CO_2 emission impacts of e-bike mode shift.

4.1. Mode share and PMT

Using the mode replacement ratios found by the North American survey (MacArthur et al., 2018b), we calculated the resulting mode shares for a given e-bike mode share and display them in Fig. 1. There is no data to separate out e-bikes from current Portland cycling (bike) mode share figures, so an initial value of 0 region-wide PMT for e-bikes is assumed since e-bikes are currently in the early adopter phase. At a maximum of 15% e-bike mode share penetration, conventional bike trips accounted for 0.9% of trips, car trips accounted for 74.8% of trips, transit trips accounted for 1.7% of trips, and walking trips accounted for 5.8% of trips.

We also observed changes in the resulting daily person miles traveled for each mode. At a maximum of 15% e-bike mode share penetration, e-bike trips accounted for 4.6 million person miles, bike trips accounted for 177,000 person miles, car trips accounted for

Table 1
Tool input values.

Tool input values, Portland, OR (excluding Clark County, WA)				
Type	Measure	Value	Unit	Source
City Information	Population	1,605,672	People	Oregon Metro Regional Transit Plan Appendix I
	Average trips per day per person	3.87	Trips per person	Oregon Metro Regional Transit Plan Appendix I
Car Information	CO_2 emissions	8572	g CO_2/gallon	U.S. Energy Information Administration
	Average fuel economy	23	Miles per gallon	Environmental and Equity Scenarios… (MacArthur et al., 2018a)
	Average vehicle occupancy rate	1.36	People/vehicle	Oregon Metro Regional Transit Plan Appendix I
	Average person fuel economy	31.26	Person miles per gallon	Calculated
Public Transit Information	Average emissions per passenger mile	140	g CO_2 / person mile	Calculated from data supplied by the Federal Transit Administration and U.S. Energy Information Administration
E-Bike Information	Average emissions per passenger mile	4.90	g CO_2/mile	(USEPA, 2020) and calculations
Initial (current) modal split by number of trips	Car	84.70%	Percentage mode split	Oregon Metro Regional Transit Plan Appendix I
	Cycling	3.70%	Percentage mode split	Oregon Metro Regional Transit Plan Appendix I
	Public transit	4.20%	Percentage mode split	Oregon Metro Regional Transit Plan Appendix I
	Walking	7.40%	Percentage mode split	Oregon Metro Regional Transit Plan Appendix I
	E-bike	0.00%	Percentage mode split	Oregon Metro Regional Transit Plan Appendix I
Average trip length by mode	Car	5.49	Miles	Oregon Metro Regional Transit Plan Appendix I
	Cycling	3.23	Miles	Oregon Metro Regional Transit Plan Appendix I
	Public transit	3.93	Miles	Oregon Household Activity Survey
	Walking	1.00	Mile	Oregon Household Activity Survey
	E-bike	4.65	Miles	North American Survey (MacArthur et al., 2018b)
E-bike replacement by miles traveled	Car	72.40%	Percentage distance traveled replacement split	North American Survey (MacArthur et al., 2018b)
	Cycling	12.20%	Percentage distance traveled replacement split	North American Survey (MacArthur et al., 2018b)
	Public transit	13.20%	Percentage distance traveled replacement split	North American Survey (MacArthur et al., 2018b)
	Walking	2.20%	Percentage distance traveled replacement split	North American Survey (MacArthur et al., 2018b)

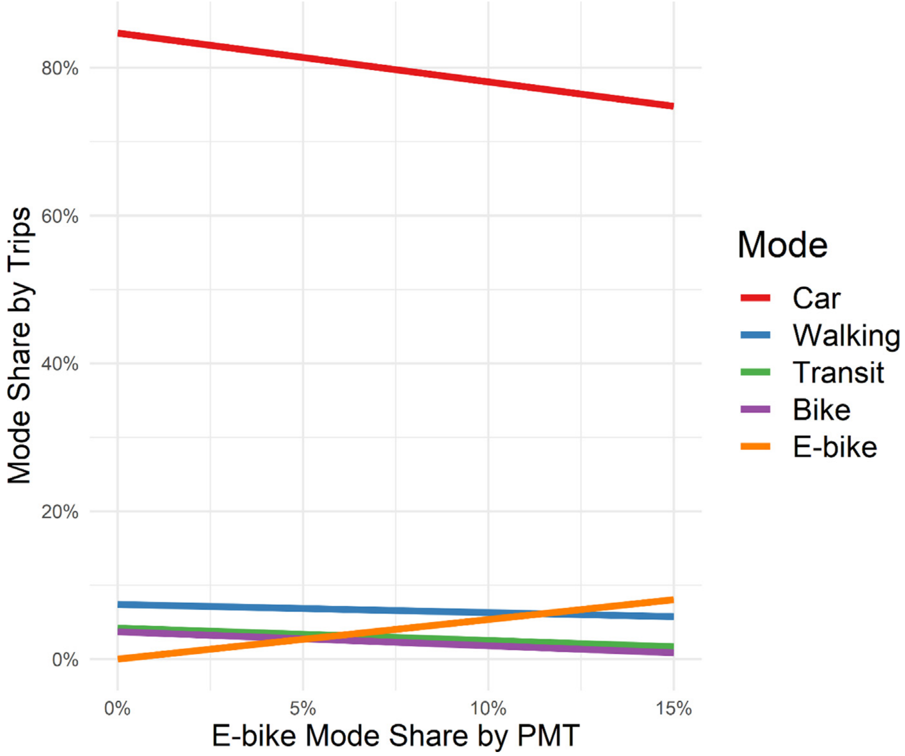

Fig. 1. Impact of e-bike mode share increases on the mode share by trips of other modes.

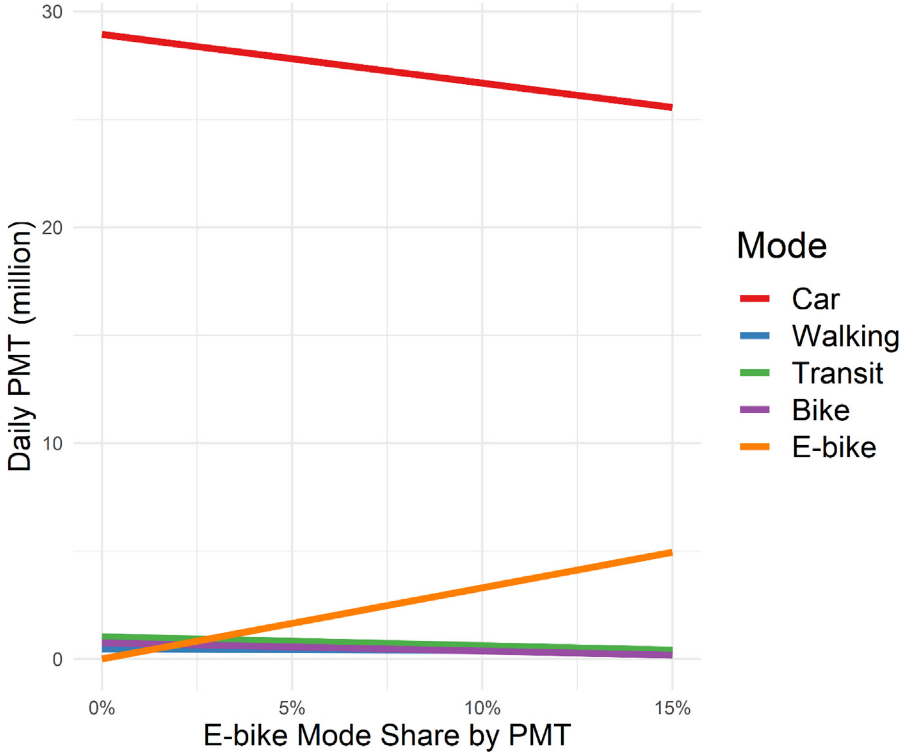

Fig. 2. Impact of e-bike mode share increases on daily person miles traveled (PMT) by mode.

Table 2
Impact of e-bike mode share increases on daily passenger transportation CO_2 emissions in Portland.

Portland Daily Transportation CO_2 Emissions (metric tons)			
E-bike Mode Share	No Induced Trips	Induced Utilitarian Trips	Induced Utilitarian and Recreational Trips
0%*	8080	8080	8080
5%	7749	7749	7754
10%	7418	7419	7429
15%	7088	7089	7103

* baseline case.

25.6 million person miles, transit trips accounted for 414,000 person miles, and walking trips accounted for 358,000 person miles. These results are displayed in Fig. 2.

4.2. Carbon emissions

From a GHG perspective, we found that, according to the model, a 15% e-bike mode share penetration resulted in a 12% decrease in CO_2 emissions, from 8,079 metric tons per day to 7,088 metric tons per day. Total emissions represented here were the sum of emissions from cars, transit (all vehicle types), and e-bike charging. Notably, car emissions accounted for a large majority of this total (98.9% of emissions were attributed to cars at the 15% e-bike mode share case). The results for various levels of e-bike mode share by PMT are displayed in the “No Induced Trips” column in Table 2.

4.3. Sensitivity analysis

On average, if an individual replaced 15% of their PMT by e-bike according to the mode replacement ratios in the North American survey (MacArthur et al., 2018b), they could reduce their individual transportation carbon footprint by 225 kg CO_2 per year. This estimate was fairly conservative because it was solely based on the Portland average regional values for average mode trip length. As seen in the survey (MacArthur et al., 2018b), e-bike users across North America replaced utilitarian automobile trips with a mean length of 7.80 miles and a standard deviation of 6.79 miles, whereas the Portland mean automobile trip length was only 5.49 miles. This implies that for people with a similar transportation mode profile to the national survey respondents, marginal emission reductions per person per year could range between 53 kg CO_2 and 575 kg CO_2 just by varying that person’s average car trip length between the survey car trip length mean +/- the standard deviation. This was calculated while maintaining the same e-bike PMT replacement ratios.

Despite zero tailpipe emissions, an e-bike’s carbon impact is still dependent on the emissions profile of electricity generated within the operating region. This value ranges from 3.778 g CO_2 / e-bike mile within the AKMS electricity generation subgrid, containing parts of Alaska, to 12.568 g CO_2 / e-bike mile within the MROE electricity generation subgrid, containing parts of Wisconsin and Michigan. Portland falls towards the cleaner end of the spectrum at 4.905 g CO_2 / mile within the NWPP electricity generation subgrid. Holding all other variables constant, setting the e-bike emissions per mile rate highest value found in the United States (MROE) had a negligible effect on total e-bike charging emissions, leaving the 12% decrease in CO_2 emissions for a 15% e-bike mode share by trips use case virtually unchanged. Thus, transportation emission reduction benefits due to e-bike charging were inelastic to differences in electricity generation emission profiles within the United States.

E-bikes may also have the potential to induce new PMT, that is, generate new e-bike trips that otherwise would not have been taken. In the North American Survey (MacArthur et al., 2018b), 24.7% of all e-bike trips recorded by survey respondents, both utilitarian and recreational, were induced. Of these induced trips, 11.3% of trips were utilitarian. In terms of PMT, 32.7% of reported e-bike miles were induced. Of this induced mileage, 8.3% was for utilitarian trips. This means that the majority of induced e-bike PMT (91.7%) was for recreational purposes. We performed a sensitivity analysis to understand the impact of these induced e-bike miles on CO_2 emissions and found that including the induced utilitarian trips led to a 0.018% increase in CO_2 emissions at the 15% mode share case. Including both utilitarian and recreational trips led to a 0.219% increase in CO_2 emissions at the 15% mode share case. These marginal emission increases left the net CO_2 reduction virtually unchanged. This means that despite the potential for e-bikes to generate induced PMT, the resulting impact on CO_2 emissions is negligible. Furthermore, the overall public health benefit of increased physical activity for riders should also be taken into consideration as a positive side effect of an increase in e-bike PMT, something that this analysis does not capture. Fortunately, the emission increases are minimal and thus should not require this tradeoff to be examined too intensely in practice. Table 2 summarizes these results, for the three calculation methods: excluding induced trips, including induced utilitarian only trips, and including induced utilitarian and recreational trips.

5. Discussion

This study used the mode replacement behavior from a set of respondents across North America and applied it to a single region, Portland, OR. However, it is likely that mode replacement behavior exhibits heterogeneities in different regional contexts. For example, different land use density, low-stress bicycle network maturity level, and climate could all impact the maximum expected

PMT mode shift to e-bike. Building out the bicycle network of Lisbon led to a 3.5-fold increase in volume and implementing e-bike share led to an additional 2.5-fold increase (Félix et al., 2020). E-bikes had a greater propensity to replace car trips in rural areas than in urban areas in a Swedish study (Winslott Hiselius and Svensson, 2017). The opposite could be true in the U.S. due to large travel distances and inadequate infrastructure in less dense areas, yet e-bikes in a suburban setting have been shown to be effective in promoting utilitarian cycling and reducing car use (MacArthur et al., 2017). Adverse weather conditions could also severely impact cyclists (Zhao et al., 2019). In particular, high temperature could impact e-bike riders less than conventional cyclists, however rain impacts both in a similar, negative way (Campbell et al., 2016). Considering these impacts, demographic makeup of a regional population may not play as important of a role in mediating e-bike uptake, as e-bikes have been shown to reduce barriers for riders with disabilities and mobility issues, older riders, and female riders compared to conventional bicycles (MacArthur et al., 2018b). Regions should consider all of these factors before setting e-bike mode shift goals and estimating the total GHG impact of policies that encourage shifting to e-bike.

In an attempt to understand heterogeneities between the Portland region and the larger context of the survey, we filtered the North American survey respondents to just respondents in the Portland metro area. We found that users replaced car trips and transit trips with similar mean lengths compared to those across the entire data set: for car, 9.86 mi (Portland) and 9.06 mi (North America); for transit, 9.68 mi (Portland) and 9.38 mi (North America). T-tests revealed that these average trip length distances were not significantly different from each other: for car, $t = 0.138$, *ns*; for transit, $t = -0.424$, *ns*. Additionally, chi-square tests revealed that the wider dataset did have a significantly higher percentage of induced trips (24.7%) and miles (32.7%) compared to the Portland region's percentage of induced trips (13.3%) and miles (16.2%), $\chi^2 = 37.57, p < .001$, and $\chi^2 = 587.31, p < .001$. This means that since the higher induced trip and mileage rates were used, the induced trip sensitivity analysis results were conservative.

Secondly, VMT was not recalculated from PMT. As a result, the emissions calculations were simplified by assuming that car and transit occupancy rates remain constant, preserving CO2 per person mile emission rates as e-bike mode share increased. In reality, if a transit agency does not adjust route schedules and number of vehicles on a transit line to accommodate lower ridership, occupancy rates would decrease, leading to an increase in average CO_2 emissions per person mile for transit riders. However, transit makes up such a small percent of person miles traveled that the effect on total emissions would be minimal. For instance, if average CO_2 per transit person mile doubled due to decreased ridership and minimal route and fleet adjustments, total CO_2 emissions for the region would only increase by 1.8%. Additionally, reductions in transit trips may occur to a greater extent in cities with denser transit systems compared to cities where transit service is sparse. Research may be necessary to further inform modeling the effects of lower transit ridership on emissions per transit person mile. It is also possible that cities with fewer transit trips could see a higher e-bike PMT replacement rate of other modes instead, however local research would be required to estimate this effect.

Along these lines, it is possible that mode shift towards e-bikes does not occur in a linear fashion, as is suggested by this model. Attitudinal and built environment factors are not accounted for in this model, and thus the e-bike mode shift ratios could change at different levels of e-bike mode share. It could be that mode shift occurs in an asymptotic fashion because it takes more effort and resources to "switch" travelers to using an e-bike, or even bicycle, as the overall regional mode share increases. Further research is needed to study observed aggregate mode shift behavior.

Next, this study used stated information from survey respondents, which may have led to imprecisions in the final mode replacement ratios. This limitation will be addressed during the next phase of this research, as the model will be updated to include findings from the Mobility by E-Bike (ME-Bike) study, led by the present authors. This effort will passively collect GPS trip data of naturalistic e-bike use, and will provide a data source that will be useful to overcome intrinsic shortcomings of recall surveys. In addition, it will provide the opportunity to observe e-bike use and mode shift trends over a larger period of time.

Finally, we focused primarily on "use-phase" emissions and left upstream (manufacturing) and downstream (disposal and recycling) emissions out of this study's scope. E-bikes, like all other vehicles, are responsible for greenhouse gas emissions during their manufacturing, transportation to the end user, and final disposal. However, it is unlikely that including lifecycle emissions for all vehicles would have drastically changed the main findings of this research, as lifecycle emissions for other transportation vehicles have been found to be dramatically higher than the lifecycle emissions for e-bikes (Blondel et al., 2011; Hollingsworth et al., 2019). Privately owned e-bikes could even have a lower lifecycle emissions impact than bike share and scooter share vehicles, due to rebalancing considerations (Hollingsworth et al., 2019; Kou et al., 2020; Luo, 2007).

6. Conclusions

Through applying e-bike PMT distance replacement ratios to Portland's existing mode share and emissions profiles, we estimated that total transportation emissions could be substantially reduced as e-bike mode share increases. This is on the order of a reduction in CO_2 emissions of 1,000 metric tons per day for a 15% e-bike mode share by PMT, down 12% from Portland's current CO_2 emissions of 8,000 metric tons per day. A single e-bike could save 225 kg CO_2 per year, on average. This was estimated while holding total person miles and trips constant. They are consistent with the 10% reduction in CO_2 emissions found to correspond with a 14% combined bicycle and e-bike mode share in the Global High Shift Scenario (Mason et al., 2015). Our results at the 15% mode share level of a 225 kg CO_2 per capita savings per year are of the same order of magnitude of the findings of Winslott Hiselius (2017) at between 272 and 394 kg CO_2 per year and Fyhri et al. (2016) at between 87 and 144 kg CO_2 per year. As demonstrated in the sensitivity analysis, this 12% reduction in CO_2 emissions was also maintained even when using the "dirtiest" electricity generation profile in the U.S. and after accounting for induced e-bike trips. The strategy of increasing e-bike mode share within a given region could therefore be used confidently as a tool to help meet a region's carbon emission reduction goals, as it is inelastic to induced trips and power generation profile.

The question arises, however, about how a region could realize the necessary e-bike mode share to meet carbon reduction goals. Implementing e-bike subsidy or incentive programs could help boost e-bike uptake (Fyhri et al., 2016; Haubold, 2016; McQueen et al., 2019; Winslott Hiselius and Svensson, 2017). Infrastructure for e-bike riding, charging, and parking could also be an effective approach (Haubold, 2016; Jones et al., 2016; Weiss et al., 2015). Reducing the speeds and volumes of motor vehicles and building separated bike lanes or "superhighways" could also help to increase e-cycling (Buehler et al., 2016; Yanocha and Allan, 2019). The implementation of electrified public bike share systems could encourage use, however the environmental impacts of rebalancing would also need to be considered (Kou et al., 2020; Luo et al., 2019). Lastly, nation-wide incongruities in how e-bikes are defined should be addressed, as in some regions these inconsistencies reinforce regulatory barriers such as licensure, registration, and prohibited use outside of roadways and bike lanes (MacArthur and Kobel, 2014; State Electric Bicycle Laws: A Legislative Primer, 2020).

More research regarding the sustainability impacts of e-bikes is needed, especially when it comes to the naturalistic use of e-bikes. More studies are needed to understand how e-bikes are used outside of an organized loan program, where users may only have access to an e-bike for a limited time (Cairns et al., 2017; Fyhri et al., 2016). There are two such frameworks that can be used to design studies of naturalistic e-bike use. Sun et al. (2020) and the present study approach e-bike sustainability contributions through a total mode shift lens, where mode share is aggregated and compared before and after the introduction of e-bikes. Other studies, such as Winslott Hiselius and Svensson (2017), describe e-bike contributions by understanding mode substitution on a trip-by-trip basis and estimating the GHG emissions that were avoided from the use of an alternative mode. Similarly, forthcoming research by the present authors will use a trip-level mode substitution approach to understand e-bike sustainability contributions. Studies within both frameworks are necessary to paint a realistic picture of the potential of e-bikes to create a net reduction in GHG emissions within the transportation system.

E-bikes offer regions a solution to accelerate the uptake of cycling as an alternative to the automobile for taking utilitarian trips. By making e-bikes an integral part of the local mode share, regions can substantially decrease greenhouse gas emissions and automotive PMT. As was estimated in Portland, OR, this could be a reduction on the order of 1,000 metric tons CO_2 per day or 225 kg CO_2 per e-bike per year, on average, at the 15% PMT mode share case. Significant political will and effort may be required, however, to seize this opportunity. The model presented here is useful for helping regional stakeholders see this potential so that an informed decision can be made to include e-bike promotion as part of a larger suite of carbon emission reduction initiatives.

Author Contributions

The authors confirm contribution to the paper as follows: study conception and design: McQueen, MacArthur and Cherry; analysis and interpretation of results: McQueen and MacArthur; draft manuscript preparation: McQueen and MacArthur. All authors reviewed the results and approved the final version of the manuscript.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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