TRB Annual Meeting

EXPLORING THE POTENTIAL OF SHARED E-SCOOTERS AS A LAST-MILE COMPLEMENT TO PUBLIC TRANSIT

--Manuscript Draft--

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Manuscript Classifications:	Planning and Analysis; Travel Survey Methods AEP25; Micropowered Devices Data (electrical scooters, e-bikes, etc.); Travel Surveys; Traveler Behavior and Values AEP30; Preference Survey Data Analysis; Public Transportation; Innovative Public Transportation Services and Technologies AP020; Scooters; Transit
Manuscript Number:	TRBAM-22-03738
Article Type:	Presentation
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Additional Information:	
Question	**Response**
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Word Count: 5548 words + 4 table(s) × 250 = 6548 words

Submission Date: August 1, 2021

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ABSTRACT

As shared e-scooters grow in popularity, they become an increasingly important component of the transportation system. A main policy question is if and to what extend shared e-scooters can serve as a last-mile complement to public transit. To investigate the potential for shared micromobility and public transit integration, we conducted a survey in Washington D.C. and collected 271 complete responses. Based on the survey results, we find that almost 60% of the e-scooter users have used e-scooters to connect with public transit. For about one fifth of the e-scooter users, over a quarter of their e-scooter trips were feeder trips. We have further fit discrete choice models to investigate which factors shape travelers' mode choice. Unsurprisingly, both travel time and cost are significant factors, and people value out-of-vehicle time more than in-vehicle travel time. Somewhat surprisingly, non-White and low-income respondents indicate a stronger tendency to choose the e-scooter and "E-scooter + transit" options than Whites and higher-income travelers. E-scooter users have a stronger preference for the "E-scooter + transit" option than non-users. Finally, we find significant preference heterogeneity for travel modes and response heterogeneity to travel time and costs. Major strategies to promote shared e-scooters as a last-mile complement to transit include bundled pricing, fare payment and app integration, providing more e-scooter and enhancing bike infrastructure surrounding transit stops. To encourage modal shift from driving to integrated transit and e-scooter trips, policymakers should not only consider transit improvements but also coupling strategies such as road and parking charges.

Keywords: Public transit, e-scooter, mode choice, stated preference, bundled pricing

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INTRODUCTION

In recent years, shared micromobility options including station-based bikesharing, shared e-scooters, and shared e-bikes have become increasingly popular. Most impressive is the growth of shared e-scooter trips: just two years after shared e-scooters first appeared in North America, the number of e-scooter trips (86 million) was more than double that of station-based bikesharing trips (40 million) in 2019 (*1*). When the COVID-19 pandemic began in March 2020, e-scooter ridership plummeted but has quickly rebounded since summer 2020 (*2*). During such a health crisis when transit becomes a less preferable option to many (*3*), e-scooters have likely filled major gaps in the transportation networks and played a vital role in helping people get around. In addition to serving as a short-term alternative to transit during COVID-19, shared e-scooters benefited public transit in the long run by preventing some individuals from purchasing personal cars.

As cities gradually recover from COVID-19, transportation officials should consider ways that can make shared e-scooters contribute to long-term transportation goals such as accessibility, equity, and safety. While some critics have argued for a complete ban of e-scooters on the basis of safety concerns and parking violations, both the pre-COVID and emerging trends suggest that the popularity of e-scooters is not likely to dwindle in any time soon (*1, 2*). To make shared e-scooters as an essential component of public transportation systems, a main strategy can be to promote shared e-scooters as a last-mile complement to public transit. It is widely known that a major challenge to public transit is the “first-/last-mile" problem, which refers to the difficulty of buses and trains to transport people to and from the doorsteps of their trip origins and destinations. Accessible and affordable shared e-scooter services offer a possible solution to this last-mile problem, and integrated transit and e-scooter use can promote transit recovery by expanding the service radius of transit stops and by enhancing rider experience.

The focus of this study is to explore the potential of shared e-scooters as a last-mile complement to public transit. Although the popularity of e-scooters has drawn significant research interest in recent years, this topic has not been thoroughly investigated. Specifically, we will address the following research questions:

- Which population groups are more likely to use e-scooter as a first-mile and last-mile connection to public transit?
- How do different trip attributes such as travel cost and time affect individuals’ choice of travel modes, especially the option of combined transit and e-scooter use?
- What policy interventions are effective to promote combined “e-scooter + transit" (“Es + T") trips?

LITERATURE REVIEW

In recent years, shared e-scooter programs have been deployed in hundreds of cities around the world. A growing number of studies are published to shed light on the user profile of e-scooters, the spatiotemporal patterns of e-scooter trips, and how e-scooters interact with other travel modes. Here we summarize the main findings.

Compared to the populations of the cities where shared e-scooters operate in, e-scooter riders are disproportionately young (particularly age below 44), White, male, have higher levels of household income, and have higher levels of education (*4–7*). While some have suggested that e-scooters have the potential to enhance mobility for Black and other minority neighborhoods, these findings suggest that this potential has yet become a reality. Interestingly, however, the North American Bikeshare Association found that people in the lowest-income bracket were proportion-

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ately represented in the e-scooter rider profile (*4*). This suggests that the equity programs implemented in some cities have promote e-scooter use among the low-income travelers; these programs require e-scooter operators to place a certain percentage of e-scooters in predefined equity zones and/or to provide discount fares for low-income individuals (*8*).

Regarding e-scooter trip patterns, analysts have in generally focused on trip purpose, trip distance, trip duration, trip costs, and mode shift. Studies showed that travelers used e-scooters both for leisure and recreation and for utilitarian purposes such as commuting, shopping, running errands, and attending social activities (*4*). The land-use contexts (e.g., college campus, downtown, or tourist attractions) where most e-scooters were placed can be a main factor shaping trip purposes. E-scooter trips were quite short in general, and most studies found that the average trip length was between 1-1.5 miles and the average duration was 12-20 minutes (*1, 4*). The average e-scooter trip cost was between \$2.8 and \$4.5 in 2019, but the price has increased recently (*9*). Finally, e-scooters were found to mostly replace walking, driving, taxi or ridehail, and transit trips (*4–6, 10, 11*); the order of most replaced modes may differ across cities but the general patterns were similar.

Several studies have examined the spatiotemporal patterns of e-scooter services in relation to existing public mobility services especially station-based bikesharing and public transit. An early study by Grant McKenzie suggested that the Capital Bikeshare program and the dockless vehicle pilot in Washington D.C. were largely complementary to each other (*12*). The study found that while bikesharing trips taken by nonmembers and e-scooter trips had a similar spatial distribution, their temporal patterns differed substantially; and bikesharing use by members differed from e-scooter use both spatially and temporally. Another study on Washington D.C. reached the same conclusion that patterns of e-scooter trips differed from those of bikesharing trips (*13*). Moreover, researchers who studied the micromobility systems in Singapore found that e-scooter trips was more spatially concentrated than bikesharing trips (*14*). Finally, a recent study examined the spatiotemporal patterns of e-scooter availability and use in relation to public transit and bikesharing (*15*). The authors found that e-scooters had both complementary and substituting effects on public transit and bikesharing. E-scooters services were mostly supplied at locations where transit and bikesharing services available, which indicates a strong competitive relationship; however, a decent percentage (over 10%) of e-scooter trips were identified as last-mile feeder trips to public transit.

Preliminary results are available from existing research regarding how shared e-scooters can be integrated with public transit. Some survey studies showed that about a fifth to a third of e-scooter users had used e-scooters to connect with public transit (*6, 7*). Even though the frequency of such combined e-scooter and transit use is unknown, these results indicate a general willingness toward combined transit and e-scooter use. Also, several studies have found a strong correlation between transit stops and e-scooter trips (*16, 17*), which may indicate the use of e-scooters for first-/last-mile transit connection. Moreover, some findings from previous studies that focus on the interactions between bikeharing and public transit can be applicable to e-scooters. For instance, Martens (*18*) found that it is more common for a rail trip than a bus trip that travelers use the bicycle as a feeder mode. Martin and Shaheen (*19*) further suggested that chances of bikesharing serving as a first-/last-mile feeder are higher in areas with less intensive transit network. These findings shed light on the transportation and land-use contexts where micromobility is more likely used as a feeder mode. Finally, a recent study has examined stated preferences for using shared e-scooters as a last-mile feeder mode to transit and found significant preference heterogeneity among Korean travelers Baek et al. (*20*).

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Despite these early findings, our overall knowledge regarding the potential for shared e-scooters to serve as a last-mile complement to public transit is limited (*21*). Specifically, little is known regarding who are more likely to use e-scooter as a feeder mode to transit and how different trip attributes (e.g., time and cost) affect people's choice of travel options such as driving and integrated "transit + e-scooter" use. Without such knowledge, transportation officials are uncertain what policy interventions can be more effective to promote the integration of shared micromobility with public transit. This study addresses these research gaps by conducting a survey study in Washington DC.

DATA AND APPROACH

Study area

Our study area is Washington DC, an early adopter of dockless micromobility. The District Department of Transportation (DDOT) started a shared e-scooter pilot in September 2017, permitting eight operators to deploy a total of 3,200 vehicles (up to 400 vehicles) in total. A follow-up evaluation of the pilot program found that much of the public reaction to the pilot program was positive (*22*), prompting the District to continue and expand the dockless micromobility program. In 2021, more than 10,000 e-scooters have been allowed to be operated on D.C. streets, and two companies have been issued permits to operate a total of 3,970 e-bikes. DDOT has established detailed terms and conditions for e-scooter operations, covering a range of topics such as fleet management, parking, data reporting, and payment options. However, unlike the Capital Bikeshare system which has an emphasis on its integration with the transit network,[1] no formal public-private partnerships have yet been established to promote the combined use of transit and dockless micromobility.

Survey

We designed a web-based survey that contains three components. The survey was piloted among a small group of individuals, including travel-behavior researchers and individuals who are familiar with the transportation systems in Washington DC, whose feedback was incorporated to develop the final version of the survey. The first set of questions asked the use of different travel modes (personal vehicle, walking, public transit, biking, e-scooter, scooter or moped, for-hire vehicle (FHV) including ridehail and taxi, and carsharing) in the last 30 days, expected use of mode choice after COVID-19, and travel attitudes and preferences related to public transit and e-scooters. Transit users were asked additional questions related to the last-mile access problem, and e-scooter users were asked questions regarding trip purpose, use of e-scooters to connect with transit, and barriers to combined use of e-scooters and public transit. The second set of questions collected information on individual demographic and socioeconomic characteristics.

The third set of questions sought to elicit traveler responses to bundled "transit + e-scooter" pricing schemes, that is, to evaluate how lower pricing can make individuals shift from using other travel modes to combined use of transit and e-scooters. Since bundled pricing of transit and e-scooters is not implemented in practice yet, we used the commonly adopted method of stated choice experiments (*23*). To design realistic stated choice experiments that can effectively elicit traveler responses, we applied orthogonal main-effects experimental design to obtain nine stated choice experiments based on the following trip attributes and attribute levels: e-scooter travel speed (6 mph, 9 mph, 12 mph), e-scooter pricing (one dollar to unlock and 32 cents per minute use, and

[1] See the 2015 District of Columbia Capital Bikeshare Development Plan available at https://parkviewdc.files.wordpress.com/2015/10/draft-ddot-bikeshare-development-final-reduced.pdf.

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one dollar to unlock and 40 cents per minute use), bundled “transit + e-scooter" pricing discount (waive of e-scooter unlock fee, 25% off e-scooter trip costs, and 50% off e-scooter trip costs), and transit type (bus and rail). The attribute levels were determined based on empirical values derived from the study area. Table 1 shows the respective trip attribute levels for the nine stated choice experiments.

TABLE 1: Profiles of the nine stated choice experiments

Experiment	E-scooter speed	E-scooter pricing	Transit type[1]	incentive
1	12 mph	\$1 to unlock, ¢32 per min	Rail	Waiver of unlock fee
2	6 mph	\$1 to unlock, ¢32 per min	Bus	Waiver of unlock fee
3	9 mph	\$1 to unlock, ¢32 per min	Rail	50% off e-scooter fare
4	12 mph	\$1 to unlock, ¢32 per min	Bus	25% off e-scooter fare
5	9 mph	\$1 to unlock, ¢32 per min	Bus	25% off e-scooter fare
6	9 mph	\$1 to unlock, ¢40 per min	Bus	Waiver of unlock fee
7	6 mph	\$1 to unlock, ¢32 per min	Bus	50% off e-scooter fare
8	12 mph	\$1 to unlock, ¢40 per min	Bus	50% off e-scooter fare
9	6 mph	\$1 to unlock, ¢40 per min	Rail	25% off e-scooter fare

[1]Note: For bus, the travel speed is set as 10 mph and the transit fare is set as \$2; for rail, the travel speed is set as 35 mph and the transit fare is set as \$3.

To improve the realism of the stated choice experiments, each respondent was presented with individual-specific choice scenarios tailored to their prior trip experiences. Specifically, we asked respondents to report the trip attributes of a one-way trip that they regularly make before COVID-19 and then constructed the stated choice experiments by pivoting around these self-reported trip attributes. Trip attributes that we asked each respondent to report include trip purpose (work or nonwork), travel mode used (limited to four options, including personal vehicle, walking, transit with walking as the access/egress mode, or for-hire vehicle), trip length, trip cost, and components of travel time (e.g., for a transit trip, individuals are asked to estimate the waling to and from transit stops, wait time, and riding time). In each stated choice experiment, respondents were asked which of the three travel options they would choose for the one-way trip that they described: the travel mode currently used, e-scooter, or the “e-scooter + transit" (“Es + T") option. Figure 1 is an illustration of the stated choice experiments. The choice among the three options is likely to differ as trip attributes for the e-scooter and the “Es + T" options vary across stated choice experiments. Finally, to reduce the cognitive burden for each survey respondent, we presented a random subset (five) of the nine stated choice experiments to each respondent. Previous research has shown that the validity of responses to stated choice experiments decreases if respondents are overburdened (*23*).

We administrated the survey to adults who live, work, or frequently visit Washington D.C. through a variety of means, including personal social networks, email lists and newsletters of advisory neighborhood commissions (some commissioners that we reached out kindly agreed to help promote the survey), and social media platforms such as Facebook groups, Twitter, and Linkedin. Moreover, the e-scooter company Spin helped distribute the survey to its users in the D.C. region. No cash incentive was offered to survey respondents, but they can get a promo code which can be used to redeem for \$5 Spin rider credits. Respondents were offered an option to opt out the

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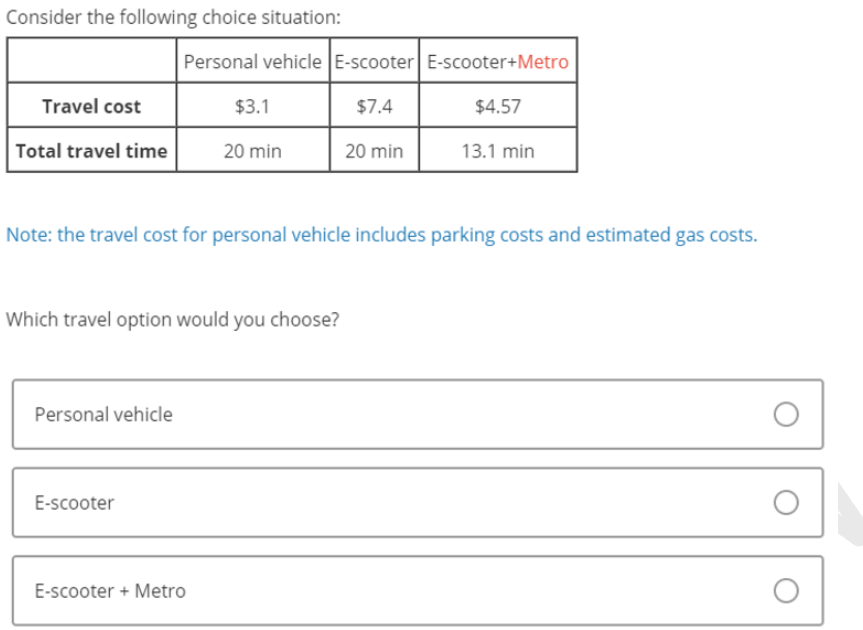
Consider the following choice situation:

	Personal vehicle	E-scooter	E-scooter+Metro
Travel cost	$3.1	$7.4	$4.57
Total travel time	20 min	20 min	13.1 min

Note: the travel cost for personal vehicle includes parking costs and estimated gas costs.

Which travel option would you choose?

Personal vehicle

E-scooter

E-scooter + Metro

FIGURE 1: An example of the stated choice experiments

stated choice experiments, in which case they will get a promote code worthy of $3 Spin rider credits (only 17 respondents did so). In the end, 357 individuals in the D.C. region responded the survey. After a data cleaning process, we kept a total of valid 271 responses,[2] among which 238 individuals provided completed responses for the stated choice experiments that were further used for mode-choice modeling.

Socioeconomic characteristics of survey sample

Table 2 presents the socioeconomic profile of the survey respondents. The results show that 53% of survey respondents used an e-scooter at least once in the past 30 days and 45% of them used transit. Both e-scooter and transit users are most likely oversampled here. Given that the survey focuses on the two modes, it is natural for their users to be more willing to participate in the survey. According to a 2019 survey conducted by the Washington Post and George Mason University, 16% of the D.C. residents took an e-scooter in the past year and more than 70% of them used public transit; since then, we expect that the share of e-scooter users has increased due to greater market penetration and that the share of transit users has dropped due to COVID-19.

The percentage of respondents who were males and Whites were close to 60% and 70%, respectively. A disproportionately high percentage (above 85%) of respondents were below 50 years old. Moreover, most survey respondents (over two thirds) had a household income above $75,000, and only 6% of respondents had a household income below $25,000. Compared to the overall population in D.C., males, Whites, younger adults, and higher-income people were over sampled. As shown in previous survey findings(*4*), a disproportionate percentage of e-scooter users also come from these population groups. On the other hand, the percentages of survey respondents who were students (11%) and who had access to a personal vehicle (64%) were close

[2]Responses were removed if the respondent progressed 50% or less of the survey or if the respondent spent three minute or less answering the survey.

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TABLE 2: Socioeconomic profile of survey respondents

	Respondent Count	Sample Percentage	City Percentage
Sample size	257	100.0%	
E-scooter user[1]	137	53.3%	
Transit user[1]	115	44.7%	
Gender			
Female	105	40.9%	52.6%
Male	152	59.1%	47.4%
Race/ethnicity			
Hispanic	7	2.7%	11.3%
White	177	68.9%	46.0%
Black	28	10.9%	46.0%
Have a college degree	224	87.2%	59.7%
Age			
18-24	27	10.5%	12.6%
25-29	62	24.1%	14.3%
30-39	90	35.0%	24.8%
40-49	44	17.1%	14.9%
50-59	17	6.6%	12.7%
60-69	9	3.5%	11.0%
70 or over	8	3.1%	9.8%
Household income			
Less than $25,000	14	5.8%	16.2%
$25,000-$49,999	27	11.3%	13.1%
$50,000-$74,999	34	14.2%	12.1%
$75,000-$99,999	44	18.3%	11.0%
$100,000-$149,999	53	22.1%	16.2 %
$150,000 or more	68	28.3%	31.3%
Student	29	11.3%	12.6%
Own a vehicle	165	64.2%	65.1%
Have no smartphone	256	100.0%	
Have no mobile data plan	255	99.6%	
Have no internet access	256	100.0%	
Have no disability	251	98.0%	

[1]E-scooter users and transit users are defined as individuals who have used the corresponding mode at least once in the past 30 days.

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to the city percentages. Finally, we asked about potential technological and physical barriers to using e-scooters, and we found that only six (2%) of the survey respondents faced barriers such as lack access to a mobile data plan or having a disability.

DESCRIPTIVE ANALYSIS

To evaluate the potential for promoting the use of “Es + T" trips, in the survey we asked several questions related to last-mile connection to public transit. Figure 2 shows the survey responses for these questions. Specifically, Figure 2(a) reveals to what extend the last-mile problem is a main reason for people not to use transit for their trips. The question asked transit users: “when you considered using public transit transit for your trips but ended up using a different mode, was the distance to the nearest transit stop too far away an important factor in these decisions?" The results suggested that the issue of last-mile access deterred transit use among about three quarters of survey respondents. We also asked e-scooter users if and how frequent they had ridden e-scooters to connect with public transit. Results presented in Figure 2(b) showed that almost 60% of e-scooter users had used e-scooters as a feeder mode to public transit; and for a sizeable percentage (over one fifth) of respondents, over a quarter of the e-scooter trips were made to connect with transit.

Moreover, we asked respondents what changes would make them increase the use of public transit and increase the use of e-scooters to connect with transit. As shown in Figure 2(c), “Transit stops closer to home/workplace and key destinations" was an option chosen by about 34% of respondents, which indicates a great potential for transit ridership to grow if last-mile transit connectivity is enhanced. Note that this potential improvement even ranked higher (i.e., selected by more respondents) than the option of “lower fare." These results indicate that, for many transit users, enhancing last-mile connectivity to transit stops can be more important than making transit cheaper. Finally, Figure 2(d) presents what changes can potentially promote more “Es + T” trips. Discounted e-scooter fares (from bundled “Es + T" pricing) was the top choice selected by respondents, but app and payment integration and physical infrastructure (e.g., parking space) at and connecting to transit stops were also essential.

MODE CHOICE MODELING

We further examine how travelers with different modal preferences and socioeconomic characteristics made trade-offs among various trip attributes such as travel time and cost in their travel mode choice. As discussed above, we constructed individual-specific stated choice experiments based off attributes of a self-reported trip. Among the 238 individuals who participated in the stated choice experiments, 139 of them reported a work trip and others reported a nonwork trip. For all the reported trips, 106 were made by public transit, 61 by personal vehicle, 61 by walking, and 30 by for-hire vehicle. The median trip length for FHV trips, personal vehicle trips, transit trips, and walking trips were 4.0 miles, 3.6 miles, 3.0 miles, and 1.3 miles, respectively; and the median (estimated) trip cost for FHV trips, personal vehicle trips, and transit trips were \$12, \$0.93, and \$2.25, respectively.[3]

Multinomial logit

After setting up the datasets for discrete choice modeling, we first fit a multinomial logit (MNL) model. Following a bottom-up model-building approach (i.e., gradually adding parameters into the model), we tested a variety of specifications before deciding on the final model. Its functional

[3]The costs for personal vehicles include two components, gas costs and parking costs. We did not include vehicle maintenance or ownership costs because the choice of vehicle ownership is already made before the choice of travel modes examined here. The gas costs was assumed to be \$0.2 per mile. Most travelers who reported a personal vehicle trip did not pay for parking.

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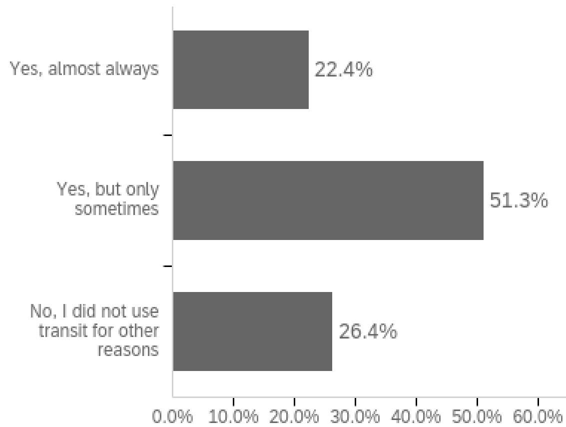
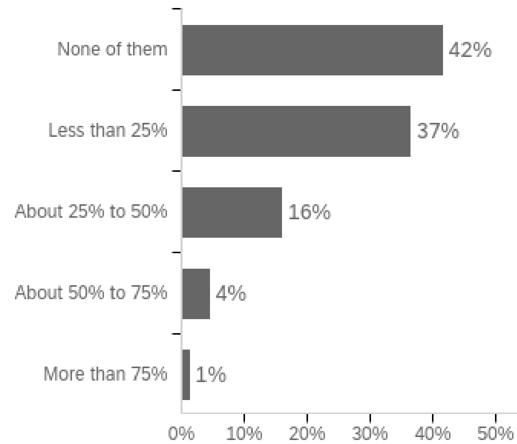
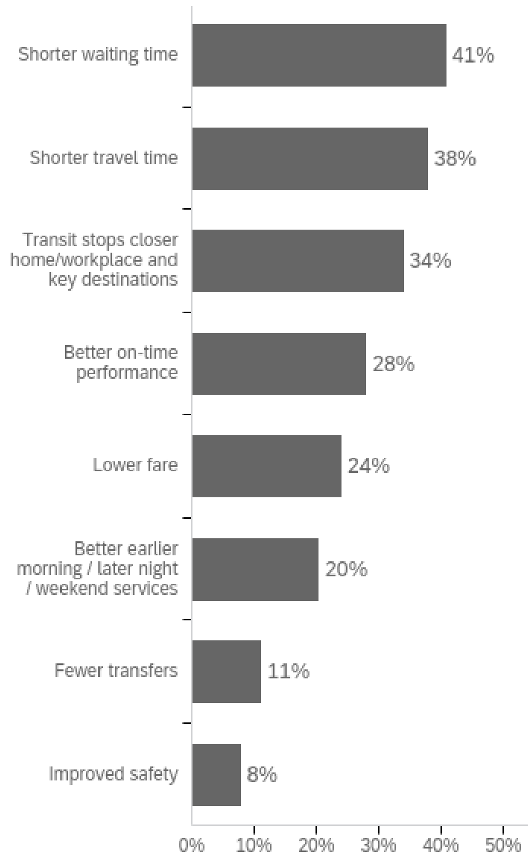


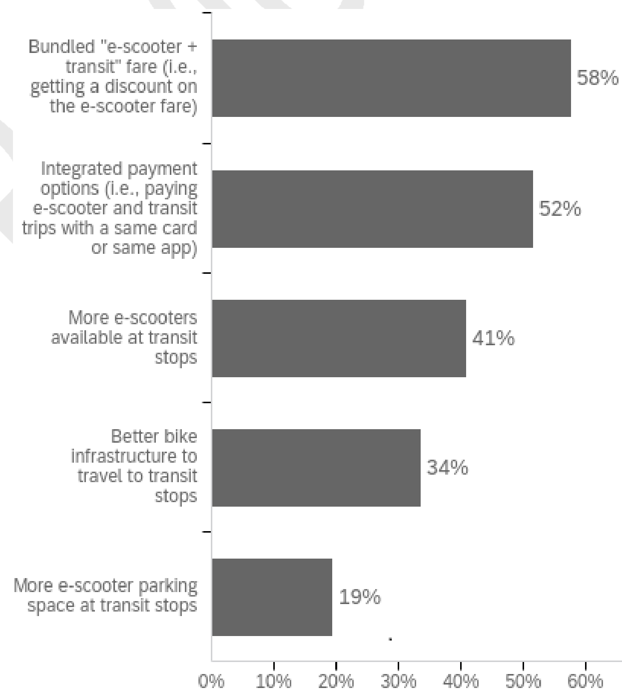
(a) If the last-mile problem a main reason for not using public transit (N=278)



(b) Percentage of e-scooter trips serving as feeder trips to public transit (N=157)



(c) Improvements that will increase use of public transit (N=269)



(d) Changes that can increase use of e-scooters to connect with public transit (N=150)

FIGURE 2: Survey responses related to the last-mile connection to public transit

form is shown in Equation (1). We computed the variance inflation factor (VIF) value for all independent variables and found that all the variables had a value of smaller than 5, which indicates little concerns for multicollinearity.

$$
\begin{aligned}
&U_{Car} = ivtt * IVTT + ivtt * OVTTDIST + ovttdist * OVTTDIST + costinc * COSTINC\\
&U_{Walk} = ASC_{Walk} + ivtt * OVTTDIST + ovttdist * OVTTDIST\\
&U_{Transit} = ASC_{Transit} + ivtt * IVTT + ivtt * OVTTDIST + ovttdist * OVTTDIST + costinc * COSTINC\\
&U_{FHV} = ASC_{FHV} + ivtt * IVTT + ivtt * OVTTDIST + ovttdist * OVTTDIST + costinc * COSTINC\\
&U_{Es} = ASC_{Es} + ivtt * OVTTDIST + ovttdist * OVTTDIST + costinc * COSTINC\\
&+ Esuser_{Es} * ESCOOTERUSER + AgeBelow40_{Es} * AGEBELOW40 + white_{Es} * WHITE + male_{Es} * MALE\\
&U_{Es+T} = ASC_{Es+T} + ivtt * IVTT + ivtt * OVTTDIST + ovttdist * OVTTDIST + costinc * COSTINC\\
&+ esuser_{Es+T} * ESCOOTERUSER + transituser_{Es+T} * TRANSITUSER + lowincome_{Es+T} * LOWINCOME\\
&+ AgeBelow40_{Es+T} * AGEBELOW40 + white_{Es+T} * WHITE,
\end{aligned}
\tag{1}
$$

where ASC refers to alternative-specific constant, IVTT refers to in-vehicle travel time (IVTT), OVTTDIST refers to out-of-vehicle time (OVTT) divided by trip distance, and COSTINC refers to trip cost divided by household income. The IVTT includes riding time on the bus and in the FHV, and we treated the riding time on e-scooters as OVTT. OVTT also includes walking time and waiting time (for the FHV and the bus). Here we divided OVTT by trip distance and trip cost by household income because of two considerations. One is that individuals tend to become less sensitive to OVTT when the trip distance is longer and that higher-income people tend to be less sensitive to trip costs; the other is to reduce the degree of correlation between trip cost and travel-time variables. All other variables codes and their corresponding coefficients should be self-explanatory. By omitting the ASC for the driving alternative, we have set driving as the reference alternative. *ivtt*, *ovttdist*, and *costinc* were generic coefficients, and other coefficients were alternative specific; the subscripts indicate the alternative that each coefficient is associated with.

Results of the MNL logit are presented in Table 3. The adjusted McFadden pseudo R-square was 0.24, which indicated satisfactory model fit. The ASC for walking was positive and statistically significant at the 0.05, which means that respondents, on average, prefer walking over driving a personal vehicle when travel costs and time are controlled for. The ASCs for other modes (transit, FHV, e-scooter, “Es + T") were all negative, but the coefficient for the transit alternative was insignificant. As expected, all level-of-service variables (i.e., time and cost variables) were all negative and highly significant (at the 0.01 level). Consistent with the literature, we found that respondents tend to value OVTT more than IVTT (*24*). For instance, for a 3-mile trip, the MNL model estimated that the travelers valued one min of OVTT 2.27 times as much as they valued IVTT.

We found that the socioeconomic characteristics of travelers who indicate a stronger preference for e-scooters and “Es + T" options appeared to be different from those who currently use e-scooters. The MNL model suggested that non-White travelers had a stronger preference for choosing the e-scooter and “Es + T" options than White travelers. Though somewhat surprisingly, this finding was consistent from an earlier study which showed that non-White travelers were more likely to intend to try e-scooters (*25*). It is also worthwhile to mention that stated intentions may not always translate into actual use Buehler et al. (*26*). Moreover, low-income travelers had a stronger tendency to choose “Es + T" than others. This means that when lower-income travelers are found to use shared e-scooters less frequently than higher-income travelers, it is largely due to

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TABLE 3: Model outputs

Variable	Alternatives	Multinomial logit		Mixed logit	
		Coeff.	z value	Coeff.	z value
Constants					
Walk	Walk	0.973**	2.40	-0.131	-0.21
Transit	Transit	-0.014	-0.06	-1.150	-1.14
For-hire vehicle	For-hire vehicle	-0.747**	-2.37	0.196	0.23
E-scooter	E-scooter	-1.686***	-5.40	-2.294	-1.31
E-scooter+transit	E-scooter+transit	-1.486***	5.37	-3.980	-1.33
level of service variables					
In-vehicle travel time	All modes	-0.052***	-6.60	-0.189***	-6.64
Out-of-vehicle travel time (divided by trips distance)	All modes	-0.198***	-6.86	-0.638***	-6.38
Trip cost (divided by household income)	All modes	-0.333***	-5.48	-2.862***	-6.93
Random parameter standard deviations					
Walk	Walk			1.091***	3.74
Transit	Transit			1.131**	2.54
For-hire vehicle	For-hire vehicle			0.605**	2.11
E-scooter	E-scooter			0.815**	2.35
E-scooter+transit	E-scooter+transit			1.121**	1.99
In-vehicle travel time	All modes			0.189**	6.64
Out-of-vehicle travel time (divided by trips distance)	All modes			0.638***	6.38
Trip cost (divided by household income)	All modes			2.862***	6.93
Sociodemographic variables					
Male	E-scooter	0.079	0.42	-0.019	-0.03
	E-scooter+transit	0.029	0.15	-0.465	-0.99
Age below 40	E-scooter	0.368*	1.94	0.757	1.12
	E-scooter+transit	0.022	0.10	0.314	0.53
White	E-scooter	-0.642***	-3.13	-1.153*	-1.65
	E-scooter+transit	-1.095***	-5.37	-1.941***	-3.30
Household income <$25,000	E-scooter+transit	0.591**	2.56	0.620	1.05
E-scooter user	E-scooter	1.013***	5.37	1.221*	1.93
	E-scooter+transit	0.339*	1.73	0.292	0.53
Transit user	E-scooter+transit	0.198	1.06	0.444	1.03
Number of observations		238		1190	
Log likelihood at convergence		-773.34		-568.04	
Log likelihood at NULL		-1021.65		-1021.65	
McFadden Pseudo R2		0.24		0.44	

***, **, * ==> Significance at %1, %5, %10 level.

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availability or affordability issues rather than preference differences. Furthermore, we found that traveler preferences for e-scooters and “Es + T" options did not vary by gender or age. These results are consistent with another recent study that examines travelers’ stated preferences for using shared e-scooters as a last-mile travel mode Baek et al. (*20*). In addition, preferences of transit users for “Es + T" did not differ from non-users. Finally, e-scooter users had a stronger preference for both the e-scooter and "Es + T" options.

Mixed logit

The MNL model did not account for the issue of serial correlation, which results from the fact that the same individuals responded to multiple choice experiments. Hence, we further fit a mixed logit (ML) model to address this issue. The ML model also allowed us to examine individuals’ preference heterogeneity for different alternatives and their response heterogeneity for trip attributes. In the ML model, we specified random effects for all alternative-specific constants (assessed as normal distributions) and for all level-of-service attributes (assessed as triangular distributions). Here we adopted the common practice of testing a variety of random parameters and keeping those whose standard deviations are significant at the 0.05 level. To estimate the ML model, we used 2000 Halton draws from the mixing distribution to perform the integration. The model outputs are presented in Table 3. The adjusted McFadden’s pseudo R-square value for this model was 0.44, a significant improvement compared to the MNL model.

The standard deviations of all ASCs were statistically significant at the 0.05 level, which indicates significant preference heterogeneity for different travel modes among the respondents. This finding is consistent with another study that surveyed travelers in Seoul, South Korea (*27*). Similar to the MNL model, the mean estimates of the ASCs for the e-scooter and “Es + T" alternatives were negative and significant. However, unlike the MNL model, the mean estimate of the ASC for walking was negative but it was not significantly different from zero; this means that the average respondent value walking and driving about the same after individual preference heterogeneity is accounted for. The mean estimates of the ASCs for FHV and e-scooters were not statistically significant. Also, all level-of-service variables were negative and statistically significant. It appears that the response heterogeneity for OVTT was larger than that for IVTT and that the response heterogeneity for travel cost was much large than that for the two time variables. Regarding the socioeconomic characteristics and travel-behavior variables, the coefficient estimates from the ML model were largely consistent with those from the MNL model. The main difference was that in the ML model, several coefficients (i.e., household income and e-scooter user) became statistically insignificant. This is mainly because the preference differences between low-income respondents and higher-income respondents and between e-scooter users and non-users have been captured by the individual-specific ASCs or level-of-service variables.

POLICY SIMULATIONS

We further applied the model results to simulate market shares of each travel mode under different “Es + T" bundled pricing schemes. The one-way trips reported by the 238 survey respondents, which was used for constructed the stated choice experiments, were used as the input data for these simulations. Note that the main purpose here is to evaluate the relative effectiveness of plausible “Es + T" bundled pricing schemes rather than to have a precise prediction of future modal split. The latter is unrealistic considering that the sample size was both relatively small, that sample was not representative of the general population, and that the one-way trips reported by respondents

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TABLE 4: Market share of “Es + T" use under different bundled pricing incentives

Bundled pricing incentive	Car	Walk	Transit	FHV	E-scooter	“Es + T"	Market share gains
Baseline	18.4%	16.9%	28.8%	6.7%	18.3%	10.9%	
25% off e-scooter fare	18.3%	16.8%	28.6%	6.6%	18.1%	11.6%	**0.7%**
50% off e-scooter fare	18.2%	16.8%	28.3%	6.5%	17.9%	12.3%	**1.4%**
$1 off e-scooter fare	18.3%	16.8%	28.5%	6.6%	18.1%	11.7%	**0.8%**
$3 off e-scooter fare	17.8%	16.5%	27.5%	6.3%	17.1%	14.7%	**3.8%**

were not representative of the trips taken by D.C. travelers. One could also argue that, as travel trends constantly shift during COVID-19, performing travel demand forecasting based on existing data is extremely challenging, if not impossible.

We tested the following “Es + T" bundled pricing incentives: 25% off e-scooter fare, 50% off e-scooter fare, $1 off e-scooter fare (i.e., waiver of e-scooter unlock fee), and $3 off e-scooter fare. These options are what we believe to be plausible discounts that future public-private partnerships between transit agencies and micromobility operators can lead to. There have been ongoing conversations on developing such partnerships to our knowledge, and time-limited, small-scale partnerships have already happened in some places (e.g., the 2020 Miami-Dade County multi-modal rewards program). When estimating the market share among the six travel modes that we modeled, we made the following assumptions: 1) for the travel modes that people currently use (i.e., personal vehicle, walking, transit, and FHV), their trip attributes were respondents' own estimates. 2) for e-scooters, the e-scooter fare was assumed to be “one dollar to unlock, and $32 cents per min use", and the e-scooter speed was set at 9 mph (DC's micromobility policy allows e-scooters to operate at a maximum speed of 10 mph); 3) for the “Es + T" option, the e-scooter speed was set at 9mph and the baseline pricing was “one dollar to unlock, and $32 cents per min use." The e-scooter leg of the trip was assumed to be one mile. We also assumed that travelers may take an e-scooter to either connect with the bus or the Metro (the two transit types were randomly assigned to trip scenarios).

Table 4 shows the simulation results, and the last column shows the market share gains for the “Es + T" option if bundled pricing was implemented. Note that although the market-share gains are only a few percentage points, they can be substantive in absolute numbers due to the large volume of trips happening in Washington D.C.. The results suggested that offering a $3 e-scooter credit would be the most effective pricing strategy, followed by a half price discount. In the case of a feeder trip to public transit, a $3 discount is usually great than a half price discount. Somewhat disappointingly, the modal shift would mainly come from existing e-scooter or transit trips rather than from driving trips such as personal vehicle or FHV trips. Regardless, the results represent positive transportation outcomes because transit and e-scooter users benefit from savings in travel time and cost when they switch to the “Es + T" option. Moreover, considering the significant price increases in Uber and Lyft rides since 2021 (*28*), more people who took FHV trips are likely to switch to the “Es + T" option than estimated here if the FHV trip prices do not drop in the future. Finally, individuals who own a car and can enjoy free parking are not likely to switch modes; this confirms previous research findings which suggest that in addition to transit improvements, road and parking pricing are integral to promoting the use of public transit (*29*).

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CONCLUSION

With shared e-scooter programs continuing to expand to more cities, e-scooters are becoming an increasingly visible and indispensable component of city transportation systems. This study evaluates the potential for shared e-scooters to function as a last-mile complement to public transit. We conducted a survey in Washington D.C., which resulted in 271 complete responses. Almost half of the respondents used transit between January 2021 to May 2021, many of who are also e-scooter users. We found that almost 60% of the e-scooter users had used e-scooters to connect with public transit; and for about one fifth of them, over a quarter of their e-scooter trips were feeder trips to transit. Discrete choice models further revealed that both travel time and cost were significant factors shaping travelers' choice of travel modes. Consistent with some previous studies on stated intentions, we found that non-White and low-income travelers indicated a stronger tendency to use the e-scooters and "E-scooter + transit" options than Whites and higher-income travelers. Furthermore, e-scooter users were found to have a stronger preference for the "Es + T" option than non-users. Finally, the mixed logit model revealed significant preference heterogeneity for different travel modes and response heterogeneity to travel time and costs.

Overall, the study results suggest a potential for transit and e-scooter operators to collaborate together to enhance trip experiences for public and shared mobility users. Major strategies to promote micromobility as a last-mile complement to transit include the following: "Es + T" bundled pricing, fare payment and app integration between transit and e-scooters, providing more e-scooter and enhancing bike infrastructure surrounding transit stops. Moreover, our simulation analysis suggests that providing a \$3 fare discount to e-scooter trips can lead to significant increases in "Es + T," but the modal shift would most likely come from non-driving modes. Other strategies such as road and parking charges should be coupled with transit improvements to effectively promote a shift from driving trips to transit trips.

The study focuses on Washington DC, a city with a robust transit system which has few service gaps. The complementarity effects of shared e-scooters and other micromobility options on public transit can be even greater in many other U.S. cities where the last-mile transit-access problem is more common and more serious (*30*). If functioning as a widely used feeder mode, shared e-scooters can effectively expand the service coverage areas of transit stops. To empirically test this hypothesis, future studies may examine other land-use and transportation contexts. Moreover, future research may investigate under what trip situations are travelers more likely to use shared micromobility to connect with transit, at which transit stops more "Es + T" trips are happening, and what are the underlying contributing factors.

AUTHOR CONTRIBUTIONS

Study conception and design: Yan, Zhao, Broaddus; data collection: Yan, Zhao, Broaddus, and Johnson; analysis and interpretation of results: Yan, Zhao, Broaddus, and Srinivasan; draft manuscript preparation: Yan, Zhao, Broaddus, Johnson, and Srinivasan.

ACKNOWLEDGEMENTS

This research was supported by the U.S. Department of Transportation through the Southeastern Transportation Research, Innovation, Development and Education (STRIDE) Region 4 University Transportation Center (Grant No. 69A3551747104). We appreciate the micromobility company Spin for helping promote the survey and for providing rider credits to incentivize survey participation.

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