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Exploratory Analysis of Real-Time E-Scooter Trip Data in Washington, D.C.

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Abstract

The proliferation of micromobility, evolving from station-based to dockless bikeshare programs, has dramatically accelerated since 2017 with an influx of investment from the private sector to a new product, dockless e-scooter share. As an alternative to pedal bikes, e-scooters have become widespread across the U.S.A. owing to the unprecedented convenience they bring to commuters and travelers with electric-power propulsion and freedom from docking stations. In cities like Washington, D.C., e-scooter share can play an important role to support transportation sustainability and boost accessibility in less-connected communities. This study takes advantage of publicly available but not readily accessible e-scooter share data in Washington, D.C. for an initial view of the travel patterns and behaviors related to this new mode. The study adopted an innovative approach to scrape and process general bikeshare feed specification data in real time for e-scooters. Not only locational time series data, but also e-scooter share trip trajectories were generated. The trip trajectory data provide a unique opportunity to examine travel patterns at the street link level—a level of analysis that has not been reached before for e-scooter share to the authors' knowledge. The paper first provides descriptive statistics on e-scooter share trips, followed by an exploratory analysis of trip trajectories conjoined with street link level features. Important insights on e-scooter route choice are derived. Lastly, policy and regulatory implications in relation to e-scooter facility design and safety risks are discussed.

Cycling and scooting have never been more popular in the U.S.A. and across the globe thanks to the proliferation of shared micromobility. In just a few years, several micromobility start-ups have surpassed the valuation of \$1 billion (*1*). Cycling has grown outside of the traditional cyclist community and has become a ubiquitous commute mode for ordinary people. The concept of shared micromobility "encompasses all shared-use fleets of small, fully or partially human-powered vehicles such as bikes, e-bikes, and e-scooters" (*2*). Three types of shared micromobility programs are most widely adopted by cities in the U.S.A.: station-based bikeshare, dockless bikeshare, and dockless e-scooter share. Just within the year of 2018, the number of shared micromobility trips more than doubled (from 35 million to 84 million) in the U.S.A. (*2*). This overwhelming growth was primarily attributed to the emergence of dockless bikeshare and e-scooter share (*2*). Theoretically, the majority of short-distance passenger trips (less than 5 mi) can be accomplished by micromobility (*1*). According to the 2017 National Household Travel Survey summary statistics, almost 60% of all vehicle trips taken in the U.S.A. are within 5 mi (*3*). Even though bikes (and e-scooters) cannot perfectly substitute for cars because of various factors, such as weather, passengers, and luggage, there is still a sizeable urban transportation market for micromobility to compete against the most popular choice of mobility in the country, driving. In addition, just as the benefits associated with bikeshare are well documented in academic literature (*4*), shared micromobility is well received by the public in comparison with its controversial "relative"—ridesourcing.

As one of the most bike-friendly cities in the country and the first U.S. city to implement a citywide bikeshare program, Washington, D.C. introduced dockless bikes and e-scooters in September 2017 (*5*). In less than 2 years,

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Phase I of the demonstration program attracted six vendors to operate in the District of Columbia (Skip, Lime, Jump, Spin, Lyft, and Bird), five of which now (early 2020) operate exclusively with e-scooters. From the public feedback on the demonstration program, most users hope the program will continue thriving in the District with a few areas of improvement, such as parking and safety. In the spirit of the Sustainable DC 2.0 Plan (*6*), in which a major goal is to "expand safe, connected infrastructure for pedestrians and cyclists" and a major target to "increase biking and walking to 25% of all commuter trips in all wards (17.7% as of now)," the District Department of Transportation (DDOT) decided to expand the dockless demonstration program in 2019. In Phase II, DDOT planned to increase the caps on the number of vendors and fleets operated in the District, allowing three additional operators (Bolt, Hopr, and Razor) to join the program (*7*). In its newest plan, effective April 2020, DDOT will cut back the number of dockless vendors to four (Jump, Lyft, Skip, and Spin) but increase each vendor's fleet cap to 2,500 (*8*). Currently, there are 5,235 dockless vehicles operated by eight vendors (*8*).

The rapid expansion of the e-scooter pilot program in the District calls for in-depth analysis of available data to understand better e-scooter travel patterns and behavior, to address safety concerns, and to inform future expansion strategies or applications elsewhere. This paper explores the e-scooter share program by analyzing detailed trip level data from one dockless vendor. The reason for using data from one vendor is twofold: data accuracy and data quality. Trip data was acquired by scraping the vendor's application programming interface (API) in real time at 30-s intervals to maximize the amount of information that could be obtained about an e-scooter trip. The unprecedented level of detail provides a unique opportunity to derive trip trajectory summaries and conduct analyses unavailable in the current literature.

The rest of the paper is organized as follows. The next section presents a literature review on shared dockless micromobility to outline the current state of research and existing research gaps. The next section describes the processes of collection and cleaning of e-scooter trip data. Next, e-scooter trip trajectory data is cross-tabulated with street functionality and traffic volume data to identify priorities in e-scooter management at the street link level. In addition, two research topics are identified—bikeway design and safety—that can be further studied using trip trajectory data. Lastly, based on the preliminary findings, insights are provided into the current state of e-scooter share in the District and policy implications on planning and management of the e-scooter program.

Literature Review

Dockless micromobility was first implemented on a large scale in China. The Chinese dockless bikeshare companies Mobike and Ofo rapidly expanded their business over all major Chinese cities between 2015 and 2017 (*9*). In 2017 dockless bikeshare systems started to emerge in U.S. cities, including Dallas, Seattle, Washington, D.C., and San Diego (*10*). Dockless e-scooter share was introduced to the shared micromobility market around the same time in 2017. Vendors like Bird, Skip, and Lyft operate dockless e-scooters exclusively. Vendors like Lime and Jump operated bikeshare initially and switched to e-scooters recently. Because of its novelty, the literature on e-scooter operations and its interactions with other modes, as well as system-wide impacts, is very limited. In contrast, the literature on station-based bikeshare is relatively well established as bikeshare programs have become ubiquitous across the globe and ridership data are well archived and publicly accessible for the most part (*11*). This literature review will focus primarily on research into dockless micromobility and is separated into two parts: (a) micromobility studies that combine both dockless and station-based data or studies that include both e-scooter and regular bike data, and (b) dockless e-scooter share as a growing subset of micromobility.

Micromobility

Internationally, several research papers were found that compare and contrast station-based and dockless micromobility. Chen et al. (*9*) contrasted user characteristics between station-based bikeshare and dockless (with an equivalent term, "free-floating") bikeshare in HangZhou, China. They found that people used the former for its high service quality at a low cost and the latter for its flexibility. Gu et al. (*12*) overviewed the development of dockless bike systems in Chinese cities, the factors contributing to their popularity, and the challenges faced by these systems in a policy study.

Besides understanding who uses dockless micromobility, researchers have also examined dockless micromobility trip characteristics using vendor data or GPS tracking data. Two studies have analyzed data from dockless bikeshare vendors. Xu et al. (*13*) analyzed the spatiotemporal dynamics of dockless bikeshare trips in Singapore. They found significant variations in weekday early morning trips that can be explained by cycling activeness. Shen et al. (*14*) analyzed the impact of built environment on dockless bikeshare usage in Singapore. They found that access to public transit, bike infrastructure, and several other built environment factors are critical to dockless ridership. Bao et al. (*15*) proposed a data-driven approach to develop bike lane construction plans in Shanghai based on analytical results on trip trajectory data from Mobike.

One recent study offers insights on trip differences between the station-based bikeshare and dockless operations in Washington, D.C. (*16*). Younes et al. (*16*) analyzed the general bikeshare feed specification (GBFS) data from dockless vendors and historical station-based bikeshare data and compared the temporal determinants of micromobility ridership. The study found that dockless users were less sensitive to weather and more sensitive to gas prices than station-based users.

As a sustainable mode of transportation, micromobility receives attention from researchers in environmental studies. Using Euclidean network distance, Zhang and Mi (*17*) translated Mobike trip distances in Shanghai into emission reduction. Luo et al. (*18*) conducted a lifecycle impact analysis on both station-based bikeshare and dockless bikeshare using European and American cities as references. They found that the greenhouse gas emissions from the latter were much higher than the former, because of an excessive number of rebalancing trips in the dockless bikeshare system.

Dockless E-Scooter Share

Researchers, including the authors of the present study, are interested in e-scooters as they are a novel product in the transportation market. Degele et al. (*19*) conducted a market segmentation analysis using clustering techniques to understand which user segments are most important to e-scooter vendors. Four clusters were identified, with a millennial casual user group dominating e-scooter usage. In an early study exclusively on e-scooter share, McKenzie (*20*) collected GBFS data for Lime in Washington, D.C. from June 2018 to October 2018 at 5-min intervals. He defined an e-scooter trip as the difference in time stamps and coordinates between two "snapshots" (i.e., two API scrapes), where an e-scooter appeared and reappeared to be available on the API. McKenzie compared the similarities and differences in the temporal and spatial dynamics between Lime scooter and Capital Bikeshare (CaBi), the citywide station-based bikeshare program. He found that e-scooter share and casual CaBi rides share more similarity than membership CaBi rides. Mathew et al. (*21*) studied the spatial and temporal distribution of e-scooter trips (origins and destinations) in Indianapolis, IN. An interesting finding in the temporal distribution was that e-scooter usage picked up during the mid-day hours and was sustained until 9:00 p.m. during weekdays, with the peak appearing in the early evening.

E-scooter share has brought both convenience and nuisance to cities. On the one hand, e-scooters provide another micromobility option to residents. Mooney et al. (*22*) combined dockless bike location data with the underlying sociodemographic data from Seattle, WA. They found that most neighborhoods had good accessibility to dockless bikes, with a concentration of fleets in well-educated and well-resourced communities. In two separate reports, Populus (*23*, *24*) overviewed the U.S. e-scooter share market and conducted a case study comparing the equitable accessibility to e-scooter share and CaBi in Washington, D.C. Based on survey responses, they found that a majority of people (70%) considered e-scooter a positive product that can expand transportation options, enable a car-free lifestyle, and replace some of the short-distance driving trips (*23*). In addition, the accessibility analysis revealed that residents in D.C. can access e-scooters more easily than CaBi in relation to the walking distance to the nearest available fleet (*24*). On the other hand, e-scooter share is not well received by all. James et al. (*25*) surveyed e-scooter riders and non-riders to understand their perceived safety around e-scooter riders and pedestrians in the greater Washington, D.C. area. In addition, in their observational analysis in the street they found that many e-scooters were not parked properly and a few were blocking the right of way. They also found that e-scooter trips tended to replace ridershare trips (39%). Portland Bureau of Transportation (*26*) assessed its e-scooter pilot program in 2019 and suggested both the potential of using e-scooters to replace driving and ride-hailing and challenges, such as illegal sidewalk riding and incorrect e-scooter parking.

What is unique about this paper is that e-scooter share trip trajectories are studied for the first time, to the authors' knowledge. E-scooter share API were webscraped in real time at 30-s intervals, which allowed accurate trip trajectory inventories to be constructed. Rather than working with e-scooter trip origins and destinations and their connection with underlying social and built environment, this research provides e-scooter travel patterns at the street link level and the analysis is focused on e-scooter traffic management and safety issues at particular streets/corridors. With intensifying public concerns about e-scooter safety, the authors provide insights and possible solutions to the transportation authority so that it can concentrate its efforts on certain corridors, facility types, and time periods where and when e-scooters travel actively. This will aid the District in achieving the "Vision Zero" initiative's objective of reaching zero traffic fatalities and serious injuries through more effective use of data, education, enforcement, and engineering by the year 2024 (https://ddot.dc.gov/page/vision-zero-initiative). It will also aid policymakers and transportation planners in communicating with e-scooter share vendors on safety issues or other issues that the data may reveal.

E-Scooter Share Data

This section concisely describes the data collection and cleaning processes with a focus on the uniqueness of trip trajectories it is possible to describe using real-time API data. It then examines trip summary statistics to take an initial look at the e-scooter mode. Trip trajectories are overlaid with D.C. street links and trips are summarized by street functionality and traffic volume. Last but not least, this section reports the study's findings on a special issue in Washington, D.C. related to e-scooter management within the National Park Service areas.

Data Collection and Cleaning

Web-scraping data has become a popular source in the era of urban data science. DDOT made tremendous efforts to guarantee data sharing from e-scooter vendors that operate in the District, including a requirement that the vendors provide a public API. The APIs can be found at https://ddot.dc.gov/page/dockless-api. These APIs provide information in accordance to the GBFS standard, an open data standard for bike share system availability (*27*). GBFS is a specification for real-time or semi-real-time data. In this study, several scraping intervals were tested, ranging from 30 s to 15 min for each vendor's API, and finally a 30-s scraping interval was specified for one vendor's API. By scraping at a high frequency, it is possible to retrieve high-resolution locational information on each e-scooter in the system. Two major considerations led to the exclusion of other vendors' data from the analysis:

- Two vendors randomized bike-ID to prevent third-party trip tracking.
- Five vendors only provide the locations where an e-scooter appears available in the system, which means the location information of an e-scooter in use is not available.

Only one vendor provides the vehicle status even when the vehicle is in use (with a status "is reserved"). Therefore, it was possible to pinpoint trip trajectories through high-frequency scrapes. Based on the availability status of an e-scooter in real time, it is possible to define an e-scooter trip by tracing all locational points between the trip origin, where an e-scooter was initially available, and the trip destination, where the same vehicle reappeared as "available" in the API.

The authors collected 138,362 records from the period of 5 weeks between March 11 and April 14, 2019. The vendor's API ran continuously without interruption during the course of the 5 weeks. E-scooter trips amassed rapidly as temperature climbed in March, especially with the boost of visitors in town for the Cherry Blossom Festival (March 20–April 12). The raw API data for this vendor is about one-quarter of all raw API data. Nonetheless, the statistics were not weighted to reflect system-wide information because of the aforementioned issues with the APIs.

Since the raw data are GPS tracking points, they are subject to GPS tracking errors. While there is no official documentation about the accuracy of GBFS data, it is likely that it suffers from the same GPS accuracy issues as bikeshare because of urban canyons, the unavailability of satellites, and so forth (*28*). In addition, it was intended to exclude cases of a "false start," where a user canceled a trip immediately after the booking. The sample selection procedure described in Khatri et al. (*28*) was followed. The following criteria were applied to clean GPS tracking errors as well as atypical trips, such as loop trips and excessively long trips. Specifically, trips were excluded if:

- Trip distance <0.02 mi;
- Trip distance >10 mi;
- Trip average travel velocity >20 mph;
- Trip duration >90 min;
- Trip duration <2 min;
- Trip trajectory distance >3 x trip O-D (origin-destination) distance.

A small number of the excluded trips were long distance, long duration, or high speed. Most of the excluded trips were either too short in distance (<0.02 mi), too short in duration (<2 min), or a combination of both. In a sense, this process primarily excluded GPS tracking errors and false starts. The final e-scooter trip dataset consisted of 113,437 records.

The advantage of collecting e-scooter trip data in real time is illustrated in Figure 1. A trip's trajectory can be traced from the start to the end with high accuracy, overlapping it with the street network (without distinguishing sidewalks from streetways). Previous studies on bikeshare mostly worked with trip origins and destinations with trip distance approximated using the Euclidean or network distance in GIS (*17*). The caveat of proxy can be clearly observed in Figure 1: the O-D Euclidean distance is much shorter than the true travel distance. The shortest path in a GIS network is also shorter than the true travel distance. With detailed e-scooter trip trajectory data, we can understand travel behavior associated with e-scooter rides to an unparalleled extent.

With highly accurate e-scooter share trajectory data, it is possible to explore the following research questions about shared micromobility that have not been fully studied before:

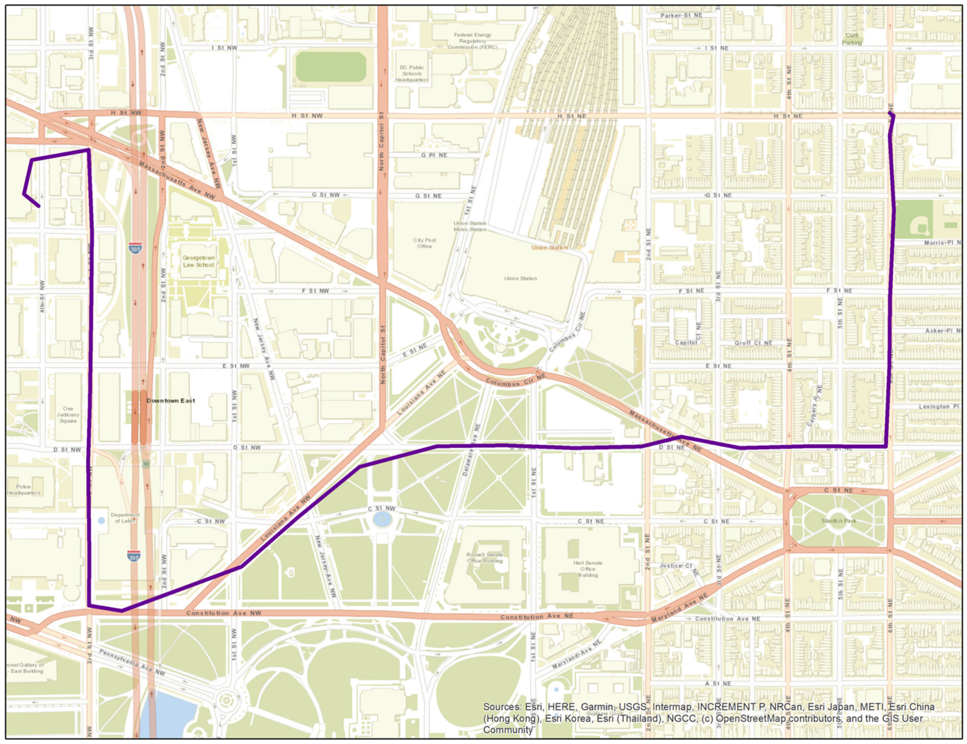

Figure 1. Example of an e-scooter trip using trajectory data.

- How do street functionality and design affect e-scooter usage?
- Which streets are risk-prone for accidents and incidents involving e-scooters?
- How many trips are taken in the street and off-street (such as parks)?
- What kind of built environment favors e-scooter share usage?

While each of these questions deserves to be studied independently, the purpose of this paper is to provide high-level understandings on these questions and point to directions for future studies on e-scooter share.

Descriptive Statistics

The first step to understand e-scooter share trips is to examine aggregated descriptive statistics. The descriptive statistics are summarized from three perspectives: trip distribution by distance, duration, and speed during the observation period; the hourly trip distribution during weekdays and weekends; and the spatial distribution of all trips at the street link level by functional classification and by traffic volume.

Trip Distribution by Distance, Duration, and Speed. The results for trip distribution by distance (O-D and trajectory), duration, and speed are presented in Table 1. Based on 113,437 trip records, the median trip distance was 0.73 mi while the median trip O-D distance was 0.56 mi. The median duration was 9.65 min and the average duration was 13.82 min, much longer than the 5.3 min average duration suggested in previous literature (*20*). The true median speed was 4.39 mph, much lower than the speed limit of 10 mph set by the D.C. government. The authors shared these preliminary statistics with DDOT staff, who receive monthly trip reports from all dockless vendors in the District, and received positive feedback on the findings.

Histograms for each benchmark trip characteristic are presented in Figure 2. The histograms suggest that e-scooter trips are mostly short in distance and duration, with a few exceptions of longer trips. Younes et al. (*16*) compared dockless trips with CaBi trips and found that the median distance of a dockless trip was about one-third shorter than a CaBi trip. The median trip duration was similar to that of a CaBi trip, and the average speed was similar to a casual CaBi trip. E-scooter trips can potentially substitute casual CaBi trips and complement membership trips, where regular commuters use the service (*16*).

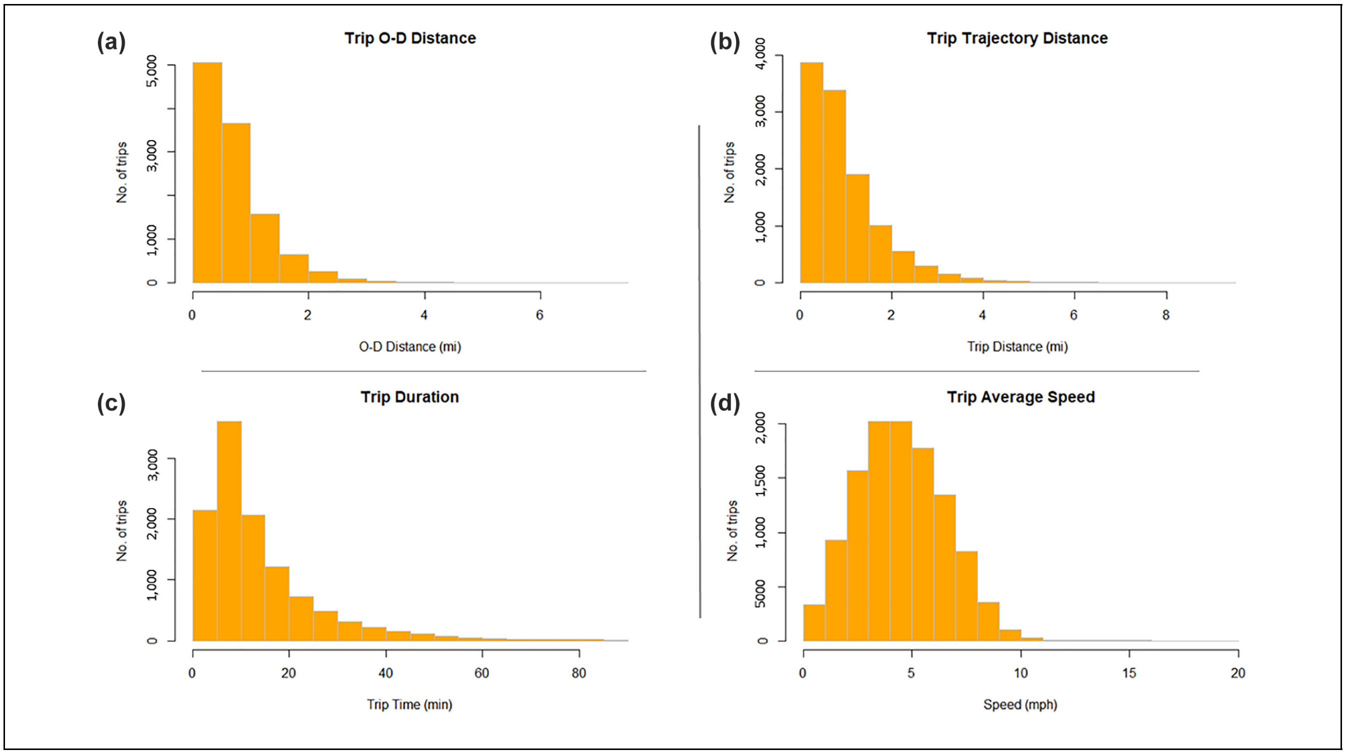

Figure 2. Trip distribution by: (*a*) origin-destination distance, (*b*) trajectory distance, (*c*) duration, and (*d*) speed.

Table 1. Trip Distribution Statistics for all E-Scooter Trips (March 11–April 14)

Measure (N = 113,437)	Min.	Max.	Mean	Median	SD
Trip O-D distance (miles)	0.01	7.35	0.71	0.56	0.57
Trip trajectory distance (miles)	0.02	9.33	0.96	0.73	0.81
Duration (minutes)	2.02	90	13.82	9.65	12.49
Trip speed (mph)	0.02	19.5	4.49	4.39	2.03

Note: O-D = origin–destination; Min. = minimum; Max. = maximum; SD = standard deviation.

Hourly Trip Distribution. It is conventional wisdom that bike-share trips are not evenly distributed across different times of a day. In addition, previous work on e-scooter share suggests that e-scooter trips are significantly concentrated during the middle of the day (*20*). The hourly distribution of one vendor's e-scooter trips is plotted in Figure 3. The average weekday's hourly distribution is shown in Figure 3*a* and the average weekend hourly distribution in Figure 3*b*. Unlike CaBi, where most trips occur during peak hours (*5*, *16*), e-scooter trips are mostly concentrated during the middle of the daytime hours (10:00 a.m.–3:00 p.m.), followed by evening peak hours (3:00–7:00 p.m.). It can be inferred that e-scooter share primarily fulfills the demand for non-commute related travel. Evening peak-hour e-scooter trips are also prominent during weekdays, suggesting that e-scooters can hopefully complement CaBi during weekday peak hours for commute purposes. During weekends, a higher concentration of e-scooter trips in the middle of the day was observed, probably because of their popularity for leisure purposes.

Overall, an almost equal number of trips per day on weekdays and weekends was observed. In previous studies (*5*, *20*), weekends are usually more popular than weekdays for e-scooter rides. However, the observation period in this study included the Cherry Blossom Festival (March 20–April 12), when it is possible that the influx of visitors to Washington, D.C. boosted e-scooter share usage during weekdays. This is an interesting observation as special events can cause fluctuations in demand for shared micromobility.

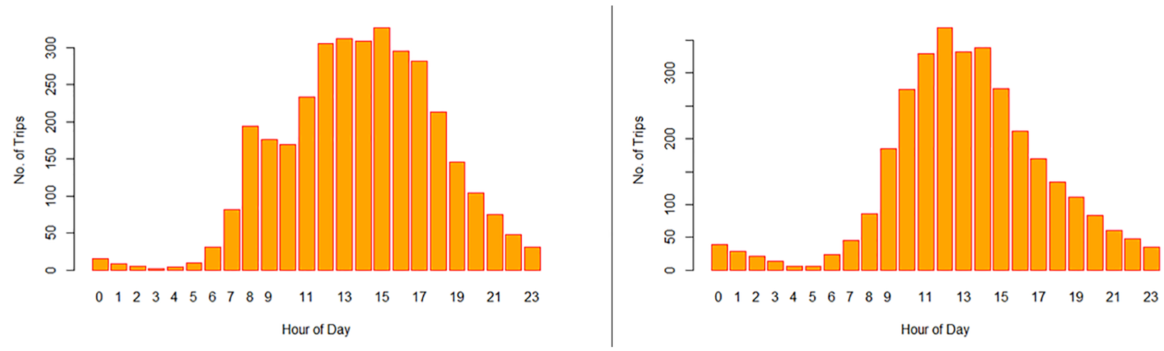

Figure 3. Average hourly trip distribution on a weekday (left) and a weekend day (right).

Table 2. Number of Trips per Hour (Normalized by Street Length in Miles) by Street Functional Class and Time of Day

	Time of day			
Street functional class	Morning peak (6:00–10:00 a.m.) per hour	Mid-day (10:00 a.m.–3:00 p.m.) per hour	Evening peak (3:00–7:00 p.m.) per hour	Night-time (7:00 p.m.–midnight) per hour
Interstate	164 (5)	502 (14)	390 (11)	94 (2)
Freeway and expressway	118 (4)	557 (16)	349 (8)	63 (2)
Principal arterial	492 (14)	1,397 (40)	1,168 (33)	316 (9)
Minor arterial	423 (12)	811 (23)	860 (25)	278 (8)
Collector	319 (9)	676 (19)	658 (19)	213 (6)
Local	91 (3)	207 (6)	223 (7)	78 (2)

Note: The average number of e-scooter trips per hour normalized by street length (in miles), that is, trip density, are provided in the parentheses.

Trip Volume by Street Functional Class and Time of Day. One of the objectives of this study is to take advantage of e-scooter trip trajectory data and investigate the operation of e-scooters in the urban transportation system, that is, where e-scooters travel in the street. Therefore, trip trajectory data was spatially conjoined with street link data sourced from the Open DC data portal (https://opendata.dc.gov) in ArcGIS. Each street link was created with a buffer of 10 ft to capture trajectories that did not fall exactly onto the street centerline and to tolerate small GPS imprecisions.

First trips falling inside a street segment were cross-tabulated by time of day and street functional class. Traffic in D.C. fluctuates significantly between peak hours and non-peak hours, as well as between arterial roads and local roads. The cross-tabulated e-scooter trip volume provided immediate insights on when and where e-scooter trips are most concentrated in the city streets. The results are shown in Table 2; in parentheses, trip volume is also normalized by street segment length. The reason for calculating the trip "density" is to offset the differences in total length among street functional classes.

Consistent with the previous findings, the middle of the day and evening peak hours are the busiest for e-scooter rides. In addition, principal arterials attract the greatest number of trips as compared with other street functional classes. Principal arterials usually serve major centers of activities with the highest traffic volume in the urban setting. In Washington, D.C., principal arterials are the major transportation corridors that connect different activity centers. These principal arterials were intentionally designed to serve the country's capital in several unique ways: (i) they are the most direct corridors

Table 3. Number of Trips per Day by Street Functional Class and AADT Volume

	AADT							
Street functional class	1–2,000	2,001–4,000	4,001–8,000	8,001–12,000	12,001–20,000	20,001–40,000	40,000 +	Total
Interstate	0	0	0	0	48	712	413	1,173 (151)
Freeway and expressway	0	0	0	40	688	107	33	868 (144)
Principal arterial	0	53	358	2,685	7,067	4,047	132	14,342 (443)
Minor arterial	44	526	3,502	4,900	5,602	917	74	15,566 (311)
Collector	162	2,181	4,120	2,961	1,835	320	0	11,579 (245)
Local	4,484	3,146	4,140	3,230	1,415	300	26	16,740 (79)
Total by AADT	4,690 (32)	5,907 (129)	12,121 (203)	13,816 (343)	16,654 (470)	6,404 (400)	677 (59)	60,268 (170)

Note: The average numbers of e-scooter trips per mile per day are provided in parentheses. AADT = annual average daily traffic.

to the National Mall, where federal government agencies and the Smithsonian Museums are located; (ii) they are close to business and cultural establishments; and (iii) they are wider streets with ample sidewalks (*29*). A surprising finding was that several e-scooter trips appeared to be made on interstate highways. On a closer look at these trips in ArcGIS, many of them were taken on the interstate highway bridges with designated pedestrian/bike lanes connecting both sides of the Potomac River: the 14th St. Bridge (I-395) and Theodore Roosevelt Island Bridge (I-66). Another possibility is that some trips were taken underneath the interstate highways. This is not a major concern for the data analysis as the majority of the interstate highways inside D.C. have no local streets underneath.

When normalized by street length in each functional class (the statistics in parentheses), the highest average trip density appears on principal arterials during middle of the day hours (40 trips/mile/hour). By absolute number, 40 is not very large compared with thousands of daily auto trips taken on principal arterials. Yet, the trip density can be expected to double or even triple with D.C.'s rapid deployment of an increasing number of e-scooters in the street.

Trip Volume by Street Functionality and Traffic Volume. In D.C. e-scooters are capped with a speed limit of 10 mph, which means they are not designed to share roadways with auto vehicles. However, it is not uncommon to observe e-scooter riders traveling on busy arterial roads. Such shared roadways may induce scooter-car crashes or near-misses, which have happened already and caused public safety concerns (*30*). To understand not only what type of street e-scooter trips are taken on, but also whether e-scooter riders tend to ride in the streets with heavy traffic, the number of trips falling inside each street link were cross-tabulated by street functional class and annual average daily traffic (AADT). AADT is a standard measure of traffic volume.

In Table 3 it can be seen that more than 70% of the trips were taken on streets with AADT volume between 4,000 and 20,000. The streets with AADT volume between 12,001 and 20,000 are mostly arterial streets that connect major activity centers in the city. The streets with AADT volume between 4,001 and 12,000 are typically minor arterials, collectors, and local streets that are located in the high-density residential and mixed-use neighborhoods, where multimodal transport is encouraged and practiced.

When factoring in the length of a street link, trip density per day was calculated by street functional class and AADT level. The trip density is highest on principal arterials and street segments with an AADT of 12,001–20,000. This raises a warning signal from the traffic safety standpoint because a significant number of e-scooter trips took place on busy arterial streets. In addition, collector and local roads with heavy auto traffic should not be ignored; these roads can also attract a non-negligible number of e-scooter rides with insufficient bike infrastructure in place.

Figure 4 shows the street segments with the greatest number of e-scooter trips accumulated in the course of 5 weeks. Local roads with few trips are excluded from the figure. The darker the color, the greater the number of e-scooter trips on a street link. It can be seen that, spatially, the streets surrounding the National Mall area

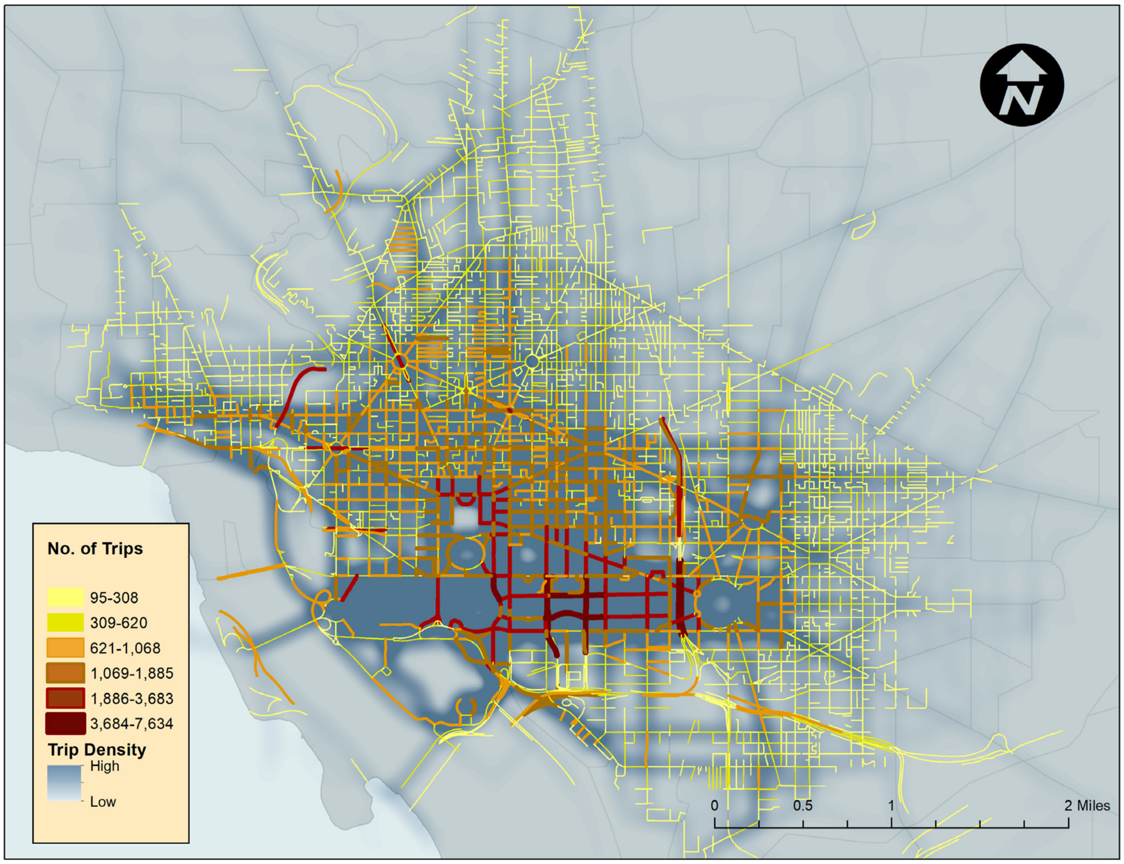

Figure 4. Heatmap of street segments with most e-scooter trips and trip kernel density.

carried the most e-scooter share trips. As a popular tourist destination, Washington, D.C. is well known for the historical landmarks and the Smithsonian Museums on the National Mall. In addition, NoMa (north of Massachusetts Avenue), Dupont Circle, the George Washington University, and the Rock Creek Potomac Parkway (connecting the Rock Creek Park to Georgetown) are all busy areas for e-scooters.

A kernel density layer is laid underneath the street layer in gray shades, as shown in Figure 4. It can be observed that a significant proportion of e-scooter trips were taken off streets—on the National Mall and within the National Park Service areas. Thus, these are likely to be leisure trips made by visitors and residents. These trips will be investigated further in the next section.

Leisure Trips in the National Park Service Areas. As an overwhelming number of the e-scooter trips were taken within or traversed National Park Service (NPS) areas, the authors were interested in the distribution of e-scooter trips among different parts of the NPS areas. Local press has reported that randomly ditched e-scooters have become a problem for the NPS (*31*), since these roads are maintained and managed by the NPS instead of DDOT. After overlaying the trip shapefile with the NPS shapefile in ArcGIS, the total mileage of e-scooter trips taken within the NPS areas was calculated. Overall, 23.44% of all trip distances fell within NPS areas (including NPS roads). This was especially prominent during the Cherry Blossom Festival.

Within the NPS areas, an overwhelming 82.40% of trip distances occurred on the National Mall, home of the Smithsonian Museums, the Washington Monument, the Lincoln Memorial, and adjoining the White House and the popular Tidal Basin—well known as the best location to observe the cherry blossoms. East Potomac Park (an island on the Potomac River) accounted for 3.79% of all trip distances within the NPS areas as it adjoins the Tidal Basin. A further 1.11% of the trip distances occurred on the other two islands (the Theodore Roosevelt Island and the Lady Bird Johnson Island), which are accessible via the Theodore Roosevelt Bridge (I-66) and the 14th Street Bridge (I-395). This explains why some e-scooter trips were observed on interstate

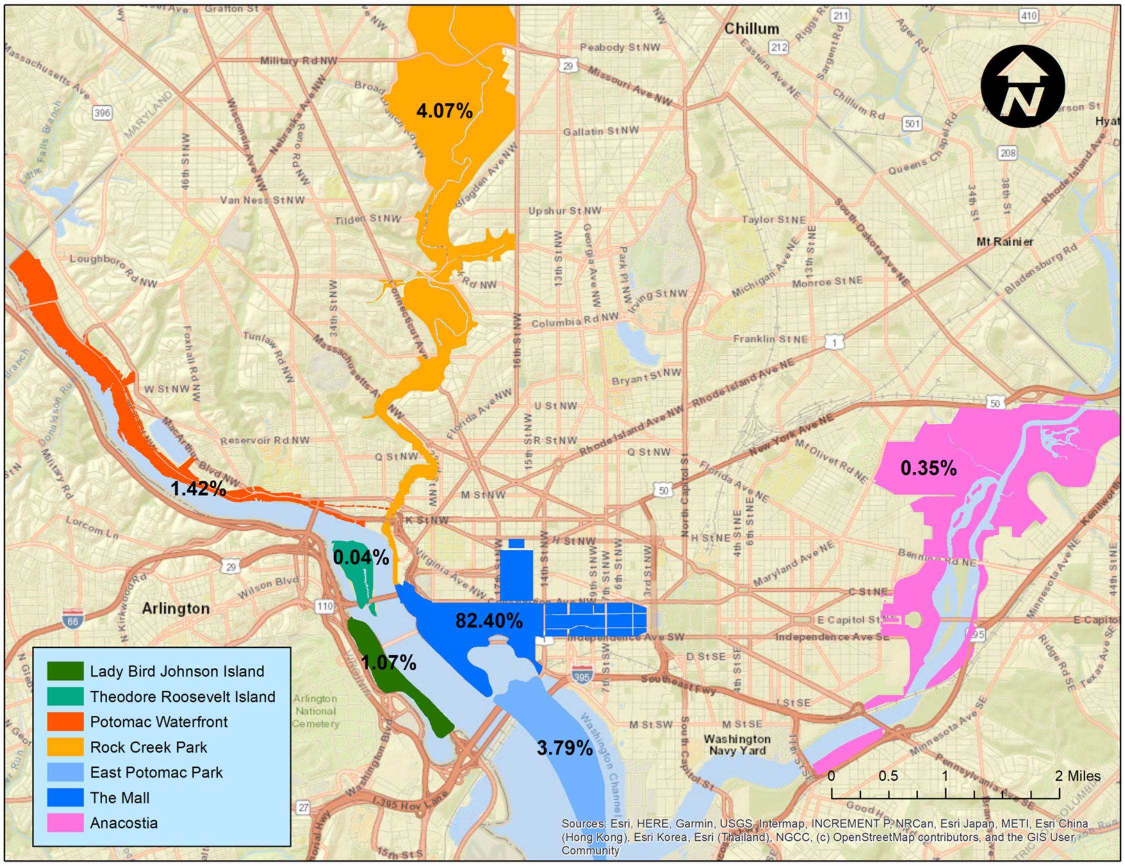

Figure 5. Main National Park Service (NPS) areas and percentages of e-scooter trips.

highways. Rock Creek Park, a popular National Park for exercise and recreational visits, accounted for 4.07% of the trip distances, and 1.42% of the trip distances were taken on the cycle-friendly Chesapeake & Ohio Canal and the Potomac Palisade Parkway at the Potomac riverfront. On the Anacostia River side, however, only 0.35% of the NPS trip distances were accumulated within the vast Anacostia River Park and the U.S. National Arboretum areas. All the major NPS administered areas are color-coded in Figure 5 with the percentage of e-scooter trips for each area.

The non-trivial number of e-scooter leisure trips in the NPS areas highlight the uniqueness of Washington, D.C. and the necessity of regulating e-scooter share operations. E-scooter share planning and management is particularly crucial on the National Mall, where pedestrians and cyclists share the public space. Since DDOT oversees the operations of the dockless program in Washington, D.C., it would be beneficial to coordinate efforts with the NPS. One strategy is to add e-scooter charging stations in NPS areas, such as the Rock Creek Park and the Potomac waterfront. These NPS areas are popular for biking and other recreational activities. The biking trails are isolated from the commercial and residential areas, however. Adding a few charging stations could potentially boost the usage of e-scooters in these locations and alleviate the issue of abandoned e-scooters.

Bikeway Design and Safety

The spatial and temporary summary statistics outline when and where e-scooter trips are distributed in the District. The spatial resolution is particularly refined with a complete trip trajectory instead of the trip origin and destination. This section takes one step further by focusing on two research topics that are relevant to e-scooter traffic management and planning: (i) the relationship between e-scooter trips and bikeway design and (ii) the relationship between e-scooter trips and potential safety risks.

Bikeway Design

E-scooter share is a form of micromobility, which means its users are likely to use existing bike facilities. In D.C. three main types of bikeway designs are put in place: bike

Table 4. Correlation between E-Scooter Trips and Bikeway Design/Historical Bike Crashes

	Bike lanes (1)	Bike trails (2)	Signed routes (3)	No. of bike crashes (4)
All e-scooter trips	0.272	0.176	0.093	0.399
Night-time e-scooter trips	0.384	0.106	0.124	0.496
Mid-day e-scooter trips	0.193	0.197	0.062	0.316
Weekday e-scooter trips	0.286	0.159	0.094	0.416
Weekend e-scooter trips	0.231	0.209	0.085	0.344

lanes, off-street bike trails, and on-street signed routes. In 2000, a mere 3 mi of bike lanes existed in the District. Today, through the efforts of DDOT, bikeways have expanded to more than 80 mi of bike lanes and 60 mi of bike trails (*5*). Previous literature suggests that bikeway design is an important built environment factor affecting bikeshare usage (*32*). In this study, the shapefiles of bikeway features were overlaid with the shapefiles of street links and e-scooter trips. The bivariate correlation was then calculated between e-scooter trips taken on a street link and whether the link has any type of bikeway design. The results are presented in Table 4, columns 1–3.

The correlation coefficients suggest that all bikeway designs are positively correlated with e-scooter trip volume. The correlation coefficient is the greatest for bike lanes. For time of day, the correlation coefficients increase significantly for bike lanes and signed bike routes and decrease significantly for off-street bike trails from all trips to night-time trips. This implies that e-scooter users increasingly rely on bike facilities during night-time on city streets, possibly out of safety concerns. Bike trails, on the other hand, primarily serve for daytime leisure trips and are less likely to be used by night-time e-scooter riders. Mid-day trips exhibited the reverse trend. When comparing the correlation coefficients between weekday and weekend trips, it was found that bike lanes and signed routes were more positively correlated with weekday trips than weekend trips, vice versa for bike trails. This, again, may indicate that bike trails primarily fulfill the recreational purpose for e-scooter trips.

The authors will conduct in-depth investigation into the positive correlations between bikeway design and e-scooter trips in future studies. The preliminary results heighten the importance of bike infrastructure to micromobility riders. To promote sustainable micromobility travel, transportation authorities should invest in construction and improvement of bike infrastructure.

E-Scooter Safety

A major concern about e-scooter share from D.C. residents and lawmakers is safety (*33*). A fatal crash involving a scooter occurred at Dupont Circle in September 2018 (*30*). To provide the transportation authority with some immediate insights into the safety issues, preliminary results from this study identified street links that are risk-prone to crash incidents involving e-scooter riders.

Without going into heavy-lifting modeling that would require significant time and research efforts, GIS overlays between e-scooter trips and historical bike crash incidents were used. The point locations of bike crash incidents from 2012 to June 2019 (data source: https://opendata.dc.gov/datasets/crashes-in-dc) were spatially joined with street links and e-scooter trips in ArcGIS. Links that are "risk-prone" for e-scooter crashes were identified by highlighting the links with both many historical bike crashes (>5 incidents) or a bike crash that involved fatality/severe injuries and e-scooter trips (>500 trips). "High crashes + High e-scooter trips" links are in dark red and "Fatal/severe injury crashes + High e-scooter trips" links are in light red in Figure 6*a*. A significant number of risk-prone links can be observed downtown and on the National Mall.

To give further priority to risk-prone street links and areas for e-scooter safety checks, two criteria were added that are deterministic to crash risks in the selection process: traffic volume (AADT >12,000) and whether the street segment has a bike lane. With these two criteria, the number of risk-prone links were trimmed from 101 to 66 and then grouped into different areas, as shown in Figure 6*b*. They are concentrated in several major employment centers and commercial strips in the city, including Georgetown, U Street corridor, Golden Triangle, downtown, Union Station, and NoMa. Several street segments around the National Mall also deserve attention from the DDOT as the National Mall is heavily populated with leisure e-scooter rides. Last but not least, the street link at Dupont Circle where the fatal e-scooter crash took place was identified. These street links can serve as a starting point for DDOT to concentrate its efforts on e-scooter traffic management and infrastructure improvements to address safety concerns.

Quantitatively, the correlation coefficients were also calculated between e-scooter trip volume and bike crash incidents at the street link level. They are significantly positive (Table 4, column 4). The correlation was

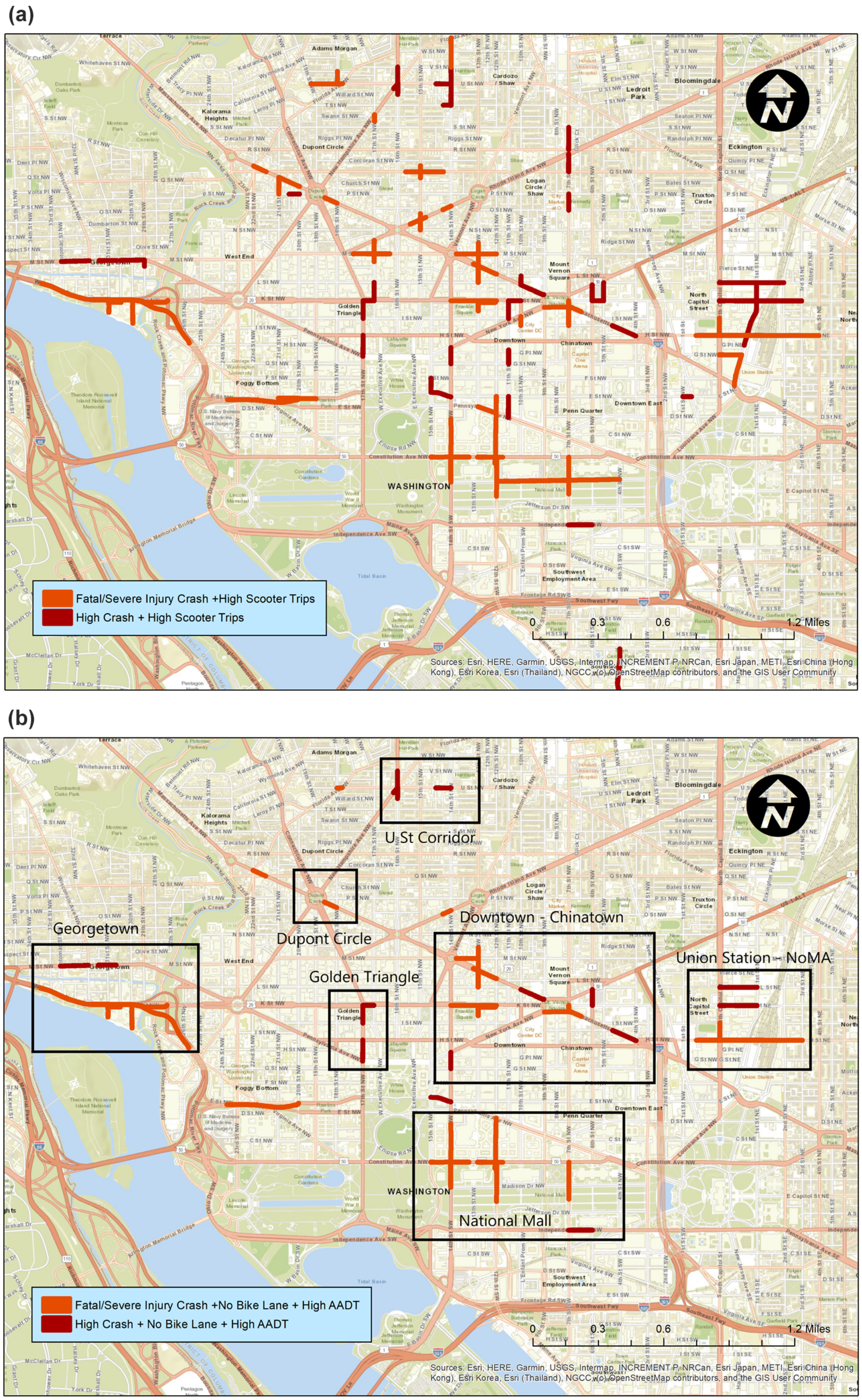

Figure 6. "Risk-prone" links for e-scooter crash incidents: (*a*) high volume of e-scooter trips and historical bike crash incidents; (*b*) high volume of e-scooter trips, historical bike crash incidents, with annual average daily traffic and links with no bike lane.

magnified during night-time. From an e-scooter safety standpoint, special attention should be given to e-scooter trips taken during night-time, especially at the “risk-prone” areas identified in Figure 6.

Planning for E-Scooters

The year 2018 witnessed a rapid influx of e-scooter share, disrupting the landscape of urban transportation system in major U.S. cities. While it shows the potential to promote micromobility as a sustainable mode of transportation, it also brings challenges, such as illegal sidewalk riding and the clutter of disorderly parked e-scooters. Joint planning efforts from the city and e-scooter share vendors are called on to maximize its benefit and minimize its nuisance. Based on preliminary analyses of e-scooter share trip trajectories, the authors propose the following strategies that can be useful for a city to manage an e-scooter share program systematically for it to thrive and to serve the public interest.

Strategy 1: Semi-Dockless

One of the major advantages of dockless micromobility over station-based bikeshare is the convenience to access and park the vehicle. However, in the high-demand areas that are busy with traffic and pedestrians, designated parking areas are necessary to prevent clutter from disorderly parked dockless e-scooters, especially on pedestrian sidewalks. An excellent example is Arlington County, VA, which added painted e-scooter parking areas, “scooter corrals”, near the Metrorail station (*34*). In addition, e-scooter share vendors like Lyft have started to install docking stations in the downtown area as well (Figure 7). It is likely that e-scooter share will enter a “semi-dockless” phase, where high-demand areas in the city will have dedicated e-scooter share parking spaces on the curbside. Geo-fencing, an idea to designate parking areas for dockless vehicles, has been the subject of a preliminary study (*35*). In February 2020, DDOT started to install off-sidewalk parking corrals across all its eight wards to regulate e-scooter parking behavior in the District (*36*). It has become clear that the end goal for the transportation authority is to minimize parking impacts while preserving the dockless feature so that e-scooters become one of the sustainable solutions to congested city streets, instead of causing congestion or chaos.

Figure 7. Lyft’s docking solution in Arlington, VA (*37*).

Strategy 2: High-Demand Corridor Management

As discussed in the section of “E-Scooter Safety”, monitoring popular pick-up and drop-off locations for e-scooters is insufficient to keep riders safe from e-scooter-vehicle crash incidents on city streets. This research highlights the importance of managing e-scooter traffic at critical street corridors, especially principal arterial roads with high volume of traffic, a high number of historical bike crash incidents, and a lack of bikeway design. The authors urge DDOT to pay close attention to high-demand corridors for e-scooters, such as 14th Street NW, the K Street corridor, and the U Sreet corridor. Multiple severe and fatal bike-vehicle crash incidents have taken place in such corridors. As e-scooter share vendors face intensifying scrutiny from the public over safety concerns, the transportation authorities should work in collaboration with e-scooter vendors, users, and other stakeholders to develop targeted corridor level solutions. In addition, as data become more available to cities, the proposed approach to creating the simple high-demand corridor map can be applicable to other cities that are also concerned about e-scooter safety issues.

Conclusion

This paper marks the first attempt to understand e-scooter share, the latest addition to the micromobility family, at the trip trajectory level. Taking advantage of the highly accurate real-time API data, it is possible to investigate how e-scooter trips interact with street design and vehicular traffic for the first time. This study took an exploratory approach initially to identify significant topics for further research rather than investigating a single problem in depth. Two research topics were identified: designing bikeways so that e-scooter trips can also be accommodated safely and addressing safety concerns. Valuable insights are provided on e-scooter share travel patterns in the District of Columbia in particular, but the authors hope that these insights will motivate other studies across the country, especially on roadway design and safety. In summary, it was found that the arterials and local streets with heavy traffic are the most popular facilities used by e-scooter share. If the streets are equipped with bike lanes, then they will likely attract more e-scooter traffic. E-scooter share is extremely popular for leisure trips in the NPS areas, especially the National Mall. Managing clutter from e-scooter vehicles and protecting pedestrian safety are priorities for the NPS in coordination with DDOT's dockless team. More importantly, this research identified street segments in Washington, D.C. that are "risk-prone" for e-scooter usage. Identifying such segments can provide local agencies with valuable information to regulate and manage e-scooter traffic and service providers as well as reinforcing protection for e-scooter share on these streets/corridors to improve safety for all roadway users.

While these exploratory results are encouraging, this study does have its own limitations. First, API data, despite being open source, require exhaustive data cleaning and wrangling before being ready for analysis. In the process of data cleaning, it was decided that only one out of the six vendors available during the data collection period can provide robust trip trajectories. Therefore, the results ideally should be weighted to gain a full picture of all e-scooter trips in D.C., provided that all six vendors offer a homogenous product. Nevertheless, this research focuses on distributional effect rather than absolute trip numbers. The insights are still valid in a general setting. Second, the API data are subject to GPS measurement errors. While it was possible to generate trip trajectories innovatively—a major step forward from analyses at the trip O-D level—it is not possible to distinguish trips taken in the streets from trips taken on the sidewalks.

To make up for the drawbacks with API data, the authors have had periodical communication with the dockless program staff at DDOT to learn about the ground truth of dockless operations in the District. In the process, not only could the data talk to stakeholders, but also stakeholders could talk about the data. The authors will continue to maintain a close partnership with the transportation authority in future studies on e-scooter operations.

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Author Contributions

The authors confirm contribution to the paper as follows: study conception and design: Zhenpeng Zou; real-time web-scraper design and data collection: Jiahui Wu, Hannah Younes, and Zhenpeng Zou; GIS processing: Zhenpeng Zou and Hannah Younes; analysis and interpretation of results: Zhenpeng Zou, Sevgi Erdoğan, and Hannah Younes; draft manuscript preparation: Zhenpeng Zou, Hannah Younes, and Sevgi Erdoğan. All authors reviewed the results and approved the final version of the manuscript.

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