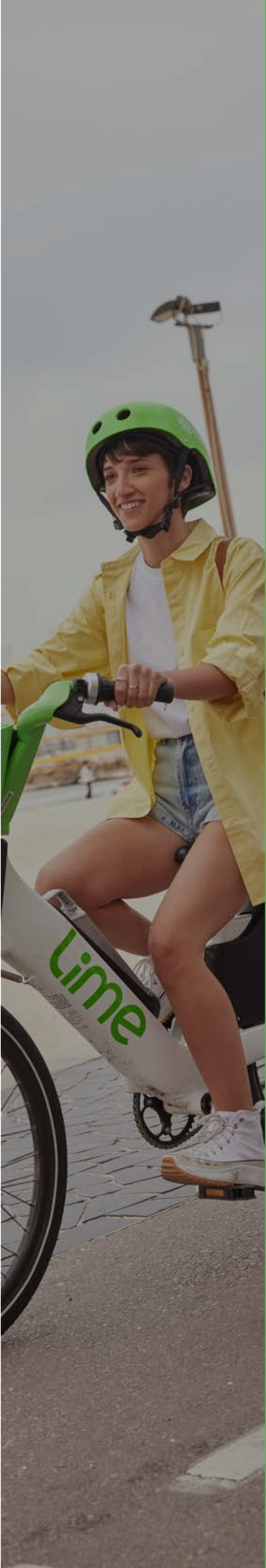
SHARED SCOOTER PARKING: THE ROLE OF PARKING DENSITY AND LAND USE IN COMPLIANCE AND DEMAND

APRIL 2024

URBANISM NEXT CENTER
UNIVERSITY OF OREGON



ACKNOWLEDGMENTS

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URBANISM NEXT CENTER

The Urbanism Next Center at the University of Oregon conducts research and convenes partners from around the world to understand the impacts of new mobility, e-commerce, urban delivery, and autonomous vehicles on the built environment. Going beyond these emerging technologies, we explore the possible implications on equity, health, safety, the economy, and the environment to inform decision-making that supports community goals. Urbanism Next brings together experts from a wide range of disciplines including planning, design, development, business, and law and works with the public, private, and academic sectors to help create positive outcomes from the impending changes and challenges confronting our cities.

LIME

Lime is the world's largest shared electric vehicle company. Lime's mission is to build a future where transportation is shared, affordable, and carbon-free. Lime provides convenient and reliable short-term rentals of electric bikes and scooters at an affordable price in more than 200 cities in nearly 30 countries on five continents.

The research team maintained clear divisions between industry and academic partners to ensure unbiased research findings. Lime provided the University of Oregon and Cornell University research team with data for the purpose of studying the role of parking density and land use in parking compliance and demand. Sian Meng, Prof. Anne Brown, and Prof. Nicholas Klein maintained academic independence during the data analysis to minimize the potential for conflict of interest. The Lime contributors, Dr. Calvin Thigpen and Brandon Haydu, provided industry experience and assisted in the interpretation and presentation of results. Lime provided no financial support for this study.

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REPORT OVERVIEW

Many shared micro-mobility systems face concerns about non-compliant parking that can obstruct sidewalks, storefronts, and pedestrian ramps. As shared e-scooter companies and communities seek to address parking challenges, a growing number of studies aim to identify which policies and strategies are most effective at regulating parking behaviors. An emerging strategy is to provide designated parking areas, often called “corrals”, where riders are either required or encouraged to park their scooter; no guidance exists, however, on how much parking to supply in order to meet demand and improve compliance.

We aim to provide clearer guidance on scooter parking planning by asking:
How do scooter parking density and land use patterns relate to shared scooter parking (1) compliance and (2) demand?

To measure parking compliance and parking demand, we collected two months’ worth of scooter trip and vehicle location data from the shared micromobility company Lime across twelve case study cities spanning the United States and Europe and encompassing a variety of parking schemes. We recorded parking availability (e.g., location of parking corrals) and incorporated built environment data to generate variables representing land use intensity and categories. Our research approach included descriptive analysis, regression, and non-linear statistical modeling, enabling us to examine the complex relationships between parking corral density, land use, parking non-compliance, and parking demand.

KEY FINDINGS

The findings translate into three primary recommendations:

[01]

Provide sufficient parking corrals - within a 1-minute walk - to meet demand and maximize parking compliance.

Parking corral density is the most influential predictor for the parking non-compliance rate: higher parking density is strongly related to higher parking compliance. Importantly, the relationship shows a clear threshold: rates of parking compliance improve dramatically from low density until about 20-30 parking corrals per square kilometer (about 50 to 80 per square mile), at which point additional parking corral density provides diminishing returns. Twenty-five corrals evenly spaced within a square kilometer results in one corral every 200 meters, so riders would never be further from a corral than about 100 meters, which is a roughly 1-minute walk.

[02]

Ensure parking corral coverage is consistent and comprehensive to avoid gaps in parking coverage and resulting parking non-compliance.

Increased parking coverage reduces parking non-compliance by minimizing the walking distance from parking corrals, highlighting the need for well-planned corral distribution. In other words, planners would benefit from focusing not just on average parking density across a wide area, but also on maintaining a consistent density across the service area, rather than clusters of parking availability surrounded by parking "deserts". To avoid large gaps in parking availability, we recommend planners focus on low-parking-density areas (less than 20 corrals per square kilometer) to ensure sufficient parking coverage.

[03]

Provide enough parking spaces within corrals to accommodate the parking demand in different land uses.

Parking non-compliance is affected more by parking density than by neighborhood land use patterns - therefore, parking density needs are relatively similar in different neighborhood types (e.g., residential versus commercial versus tourism). In other words, riders are willing to walk a similar distance to park a scooter, regardless of whether they are parking in a residential neighborhood or in a bustling commercial district. However, different neighborhood types require different parking capacities within a parking corral. Specifically, mixed-use, leisure, and tourism areas should have higher-capacity corrals that can accommodate more parked scooters. Using commercial areas as the reference, we suggest providing 80% more parking spaces in leisure areas, 65% more spaces in mixed-use, and tourism areas, 30% more spaces in transit and office areas, the same number of spaces per corral in public areas, and 25% fewer spaces in residential areas.

BACKGROUND

The Rise of Dockless Micromobility

Shared bicycle systems have existed for over half a century, beginning with the free White Bicycle Plan in Amsterdam. Fast forward to the late 2010s, the latest generation of shared micromobility is characterized by electric assist vehicles (bicycles and scooters) and by the proliferation of dockless, free-floating parking models. In contrast to a previous generation of systems that required riders to return their bike to a physical docking station, the latest shared scooter and bicycle programs often allow riders to park immediately adjacent to their destination. The flexibility and convenience of this model have contributed to their rapid uptake - the introduction of dockless scooters and bikes led to a doubling of overall shared micromobility trips in North America in just two years (Figure 1-1) (NACTO, 2022).

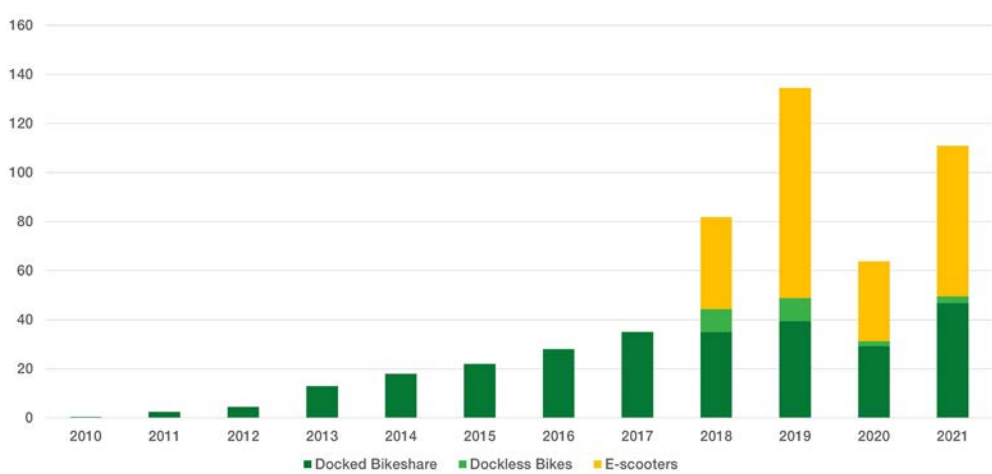

Figure 1.1. Shared Micromobility Ridership in the U.S. from 2020 to 2021 (NACTO, 2022)

New to Two-Wheeled Modes, Unfamiliar With Parking Rules

The new dockless, free-floating model has proven popular, attracting riders who had never used a bicycle or scooter or had not used a bicycle in a while (Thigpen, 2019). As such, many riders are unfamiliar with parking rules (Brown et al., 2021; James et al., 2019), and difficulties with proper parking are compounded by the presence of confusing, multi-layered, or inconsistent rules (Brown, 2021; Hemphill et al., 2022), as shown in Figure 1-2.

Figure 1-2. Variation in scooter parking regulations across different cities (borrowed from Brown 2021 with permission)

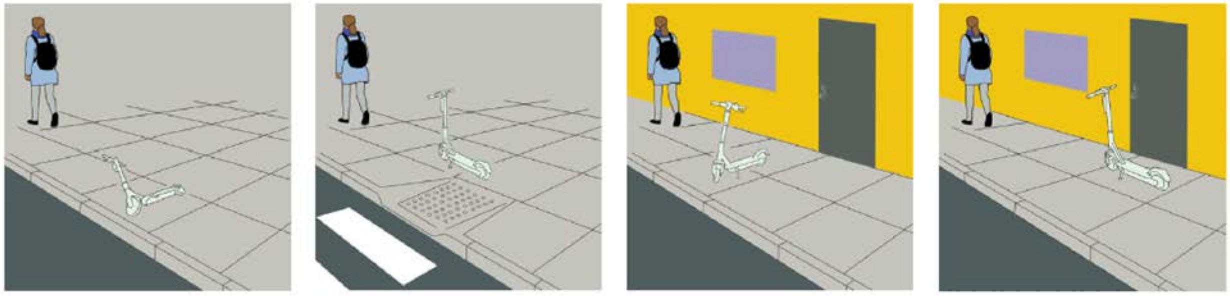

Figure 1-3. Four Non-compliant Parking Scenarios (modified from Brown et al. 2020 with permission).

Despite the confusing array of parking regulations, studies from cities around the world have confirmed that the frequency of improper parking is quite low in commercial areas (Brown et al., 2021; Fang et al., 2018; Klein et al., 2023). The majority of e-scooter riders want to park properly and can correctly identify non-compliant parking (Brown et al., 2021). Figure 1-3 depicts four common non-compliant parking scenarios, including a tipped-over scooter, a scooter blocking a curb cut ramp, a scooter parked in the middle of the sidewalk and leaving insufficient space to pass, and a scooter parked in front of a door.

Parking compliance rates inevitably vary from city to city based on the local parking regulations, as well as other factors such as local culture and familiarity with bicycling. Though improper scooter parking has received a good deal of media attention (Gössling, 2020), and was likely one of the main driving forces behind Paris' banning shared scooters in September 2023, there is evidence that car drivers are more likely to mispark their vehicles than scooter riders (Brown et al., 2020), as shown in Figure 1-4.

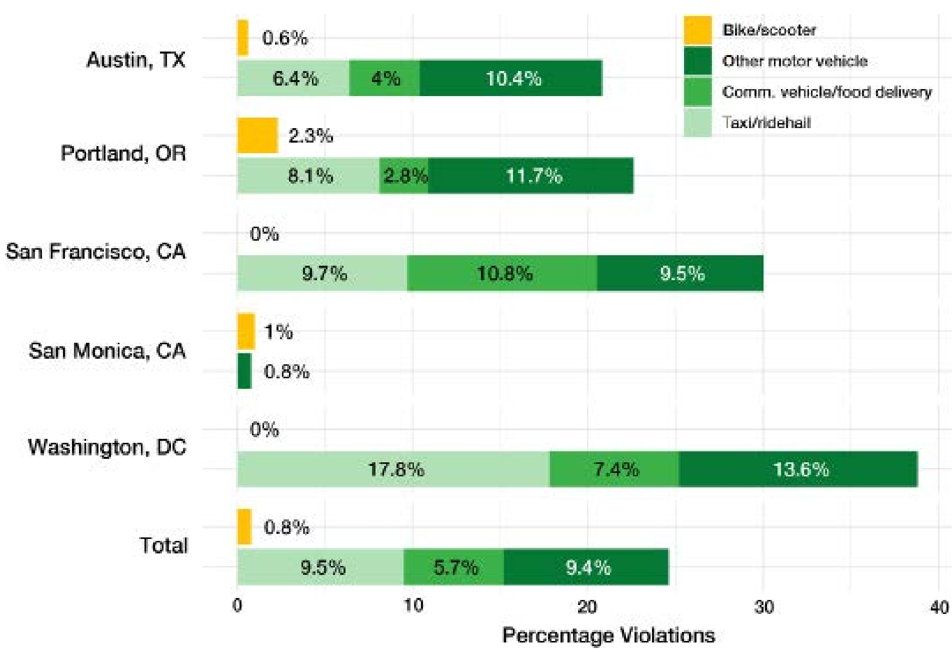

Figure 1-4. Vehicle parking compliance by mode and city (borrowed from Brown et al 2020 with permission)

Low observed rates of scooter misparking, however, are in direct contrast to public perceptions. A survey of the public and transportation professionals finds that both groups tend to overestimate rates of shared micromobility misparking and underestimate rates of improperly parked cars (Klein et al., 2023). The general public also exhibits a more negative perception of shared micromobility parking compared to people who own personal micromobility vehicles (Buehler et al., 2021). As reports suggest that both riders and non-riders are not familiar with official parking requirements (James et al., 2019), people utilize heuristics, such as pedestrian accessibility and tidiness, to evaluate parking compliance (Klein et al., 2023). Figure 1-5 (from Klein et al 2023) illustrates this conflation of clutter with compliance - noncompliant scooter parking scenarios were also perceived as cluttered, and vice versa, in a very consistent pattern. These heuristics may generate negative perceptions of shared micromobility parking due to asymmetric information and availability bias.

Public View of Scooter Parking

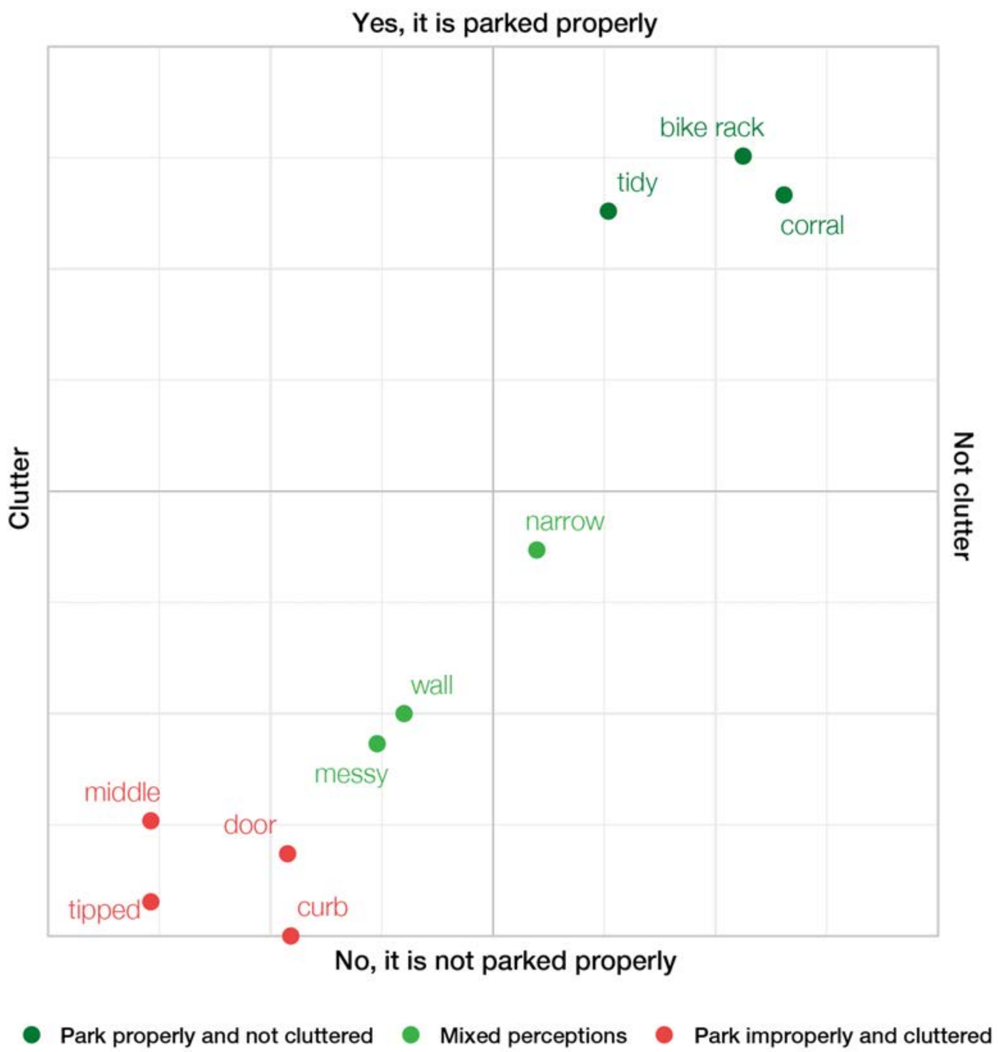

Figure 1-5. Perceptions of Non-compliant Parking and Clutter for Ten Scooter Parking Scenarios (borrowed from Klein et al., 2023 with permission)

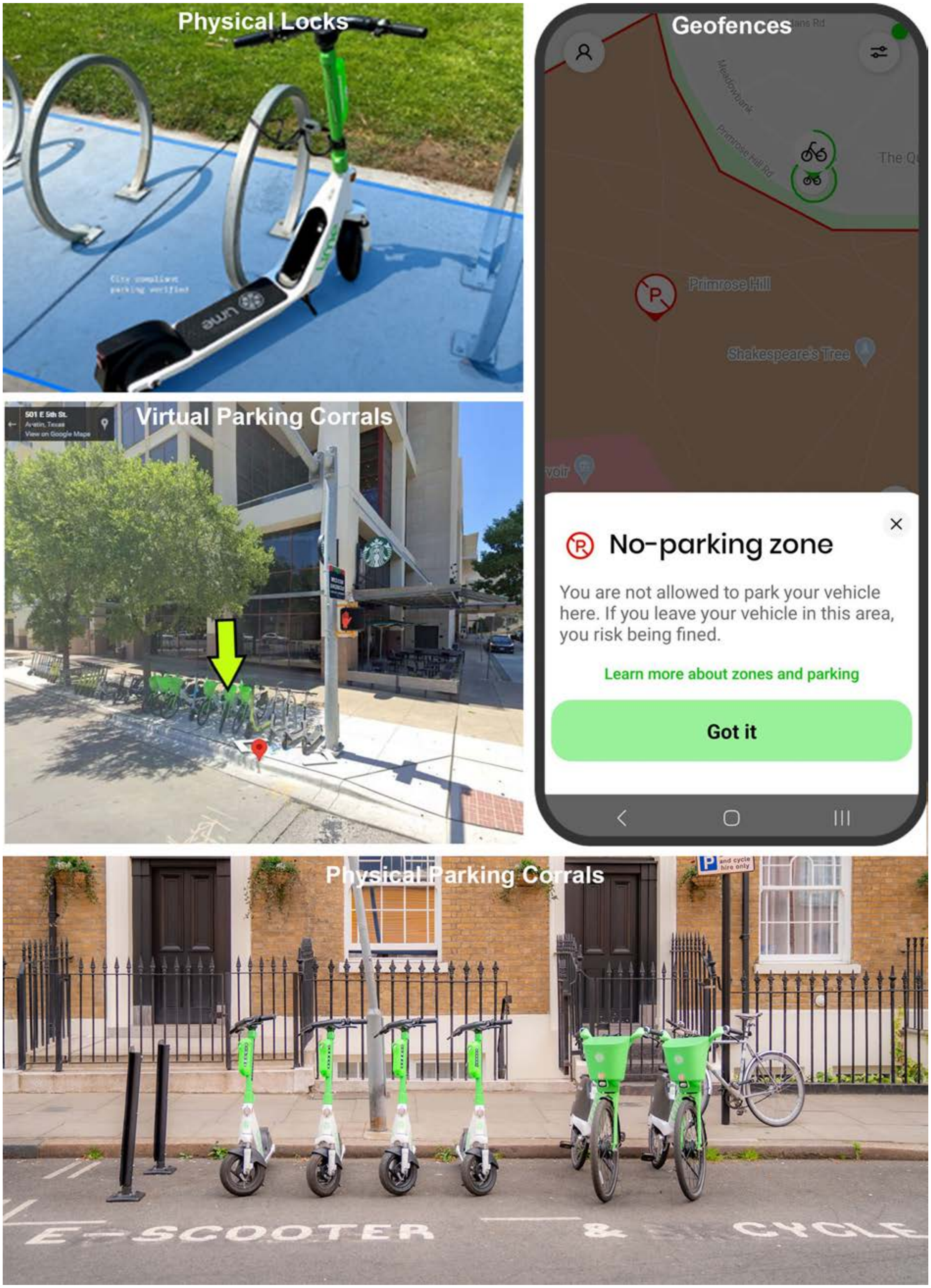

Figure 1-6. Commonly Adopted Methods for Improving Parking Compliance.

Recent Approaches To Reducing Non-Compliance

While misparking may occur relatively infrequently, shared micromobility parking is still an important research problem to investigate because of its intense scrutiny and the impacts misparked scooters can have on riders and non-riders. A comprehensive review of bicycle parking suggests that bicycle parking quality and quantity impact the use of bicycles and the number of potential users (Heinen & Buehler, 2019). Although previous research on bicycle parking has not examined the parking of shared micromobility in particular, this finding has a strong implication for planning shared micromobility. Encouragingly, it seems that improved micromobility parking is supported by the general public, which prefers high-quality micromobility parking facilities to poor or no parking facilities. People believe that sufficient and well-planned parking facilities can mitigate misparking (Jiang et al., 2019).

Many opportunities exist to further ensure that parked shared scooters and bikes do not block the right of way or pose accessibility hazards to pedestrians. Cities have tended to adopt two types of methods to improve parking compliance: area-level approaches (e.g., geofenced no-parking zones, no-operational zones, and mandatory parking zones) and street-level approaches (e.g., physical locks on the e-scooters, virtual parking corrals, and physical parking corrals) (Figure 1-6). Table 1-1 briefly introduces these approaches.

Many cities have embraced diverse strategies, incorporating both area-level and street-level approaches, to govern e-scooter parking behavior. Washington D.C., for instance, has adopted a parking strategy with different approaches in distinct locations. Notably, the National Mall, a prominent tourist destination, is designated as a mandatory parking zone where e-scooters must be parked within virtual parking corrals. Outside the National Mall, however, riders may park anywhere, adhering to local ordinances, while preferred–but not required– parking corrals are strategically positioned beyond the National Mall. Some large urban parks in suburban areas have also been designated as non-parking or non-operational zones. Starting October 1, 2021, D.C. implemented a new mandate, requiring all shared scooters to be equipped with locking mechanisms and all users to secure the scooters to bike racks or other street furniture.

Table 1-1. The Introduction of Approaches to Reduce Parking Non-compliance

Approaches	
Area-Level	
Mandatory Parking Zones	Vehicles must be parked at specific locations within the shared micromobility app.
Geofenced No-Parking Zones	Vehicles are not allowed to be parked in designated zones within the shared micromobility app.
Geofenced No-Operational Zones	Vehicles are not allowed to be parked in designated zones within the shared micromobility app.
Street-Level	
Physical Locks on E-Scooter	Parked vehicles should be locked to a bicycle rack by a physical lock, such as a cable lock.
Virtual Parking Corrals	Parking occurs at designated parking corrals shown in the app, but the parking locations are not marked with physical infrastructure.
Physical Parking Corrals	Parking occurs at a designated physical corral with signs, decals, or bicycle racks. Parking corrals will also be designated in the app.


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Need For A Dense Supply of Parking Infrastructure

All of the recent approaches to improving parking attempt to impose more control on where riders can park - through physically locking scooters to bike racks, blocking scooters from parking entirely, or parking at virtual or physical corrals. Regardless of the exact method, evidence points to the potential value of clearer parking infrastructure in improving scooter parking compliance. In a study in Washington DC, researchers found that parking compliance improved with the introduction of lock-to requirements (Klein et al., 2023), perhaps in part due to the ready availability of bike racks in the study area. In Bergen, Norway, most shared scooter operators require users to park at designated parking corrals, resulting in fewer than 4% of scooters misparked (i.e., parked more than 5 meters from the corral. Scooters from another operator in Bergen, that did not require parking at the corral, were much more likely to be parked outside the corrals (more than 50% were more than 5 meters from the corral) (Nivel, 2023).

Yet a challenge in implementing these new approaches may lie in providing sufficient infrastructure, whether it be bike racks or physical or virtual parking corrals, to improve the walking accessibility to and from a parking corral. A study in Zurich statistically modeled travelers' willingness to walk to access different modes of transportation. Compared to other transportation modes, the acceptable access/egress distance for shared e-scooters was estimated to be much lower (100 - 200 meters) than other modes like public transport (Reck et al., 2022). Additionally, a survey based on Virginia Tech's (Blacksburg, VA, USA) campus shows that two-thirds of e-scooter users desired egress times under 2 min (about 200 meters at a moderate walking pace) and one-fourth under 1 min (about 100 meters) (Buehler et al., 2023). Other studies corroborate these findings. Transit planning research suggests that 400 meters is optimal for bus stop spacing (Furth & Rahbee, 2000), and car parking research reveals that the willingness to walk from a parked car varies from around 100 meters for weekly shopping and work trips to 500 meters or more for non-weekly shopping trips (Waerden et al., 2017). Collectively, these findings suggest that if the actual walking distance from a parking corral to a rider's destination is longer than the rider's acceptable walking distance, the likelihood of non-compliant e-scooter parking will increase.

The distance between parking locations and trip destinations is directly influenced by parking corral density and coverage, so policymakers can likely enhance parking compliance rates by focusing on the accessibility of parking corrals by increasing the availability and accessibility of parking corrals. In Sweden, the staggered and varied implementation of mandatory parking requirements in the country's three largest cities allowed researchers to study how users with similar cultural backgrounds reacted to different levels of implementation (Berg Wincent et al., 2023). Riders in Stockholm, with a denser network of parking corrals compared to other Swedish cities, were more satisfied with the system and were more likely to feel they could park close to their destination compared to riders in Malmö, which implemented a more sparse network of required parking corrals. Ridership fell in each city that implemented mandatory parking corrals; by contrast, riders in Gothenburg– which delayed the implementation of mandatory parking requirements–were less likely to reduce their use of shared scooters, suggesting that without appropriate implementation, mandatory parking requirements may have adverse effects on ridership.

Planning And Design Guidance For Scooter Parking

As detailed above, previous research has examined how different types of parking regulations may affect parking compliance. However, most studies have focused on relatively small geographic areas, such as individual street segments or a single city, over short time periods. This limits the ability to draw generalizable conclusions that apply across many contexts as well as to see how parking behavior may vary across different settings, such as how parking needs vary between different land uses. Some researchers have tried using data on shared scooter trip destinations to explore the nexus of parking demand and neighborhood characteristics. However, relying only on trip destination data and omitting the impacts of scooter turnover and rebalancing activities can lead to inaccurate results.

RESEARCH QUESTIONS

Whether a city is implementing physical or virtual parking corrals or is installing bike racks for a lock-to system, a critical planning question is: how much parking should be provided, and where? To provide practical guidance for cities seeking to develop effective parking plans that cater to rider demand and enhance parking compliance, we have formulated research questions that form two sub-studies within this report.

SUB-STUDY 1:

How do parking density and land use patterns relate to shared micromobility parking compliance?

The first research question focuses on parking supply and centers around the prevalent practice of utilizing virtual parking corrals to mark preferred or required parking locations. Existing studies have primarily aimed at designing methodological frameworks to optimize the distribution of parking corrals (Liazos et al., 2022; Sandoval et al., 2021; Zhang et al., 2019). These studies mostly use single-objective or dual-objective optimization methods, and parking compliance draws little attention. In this sub-study, we aim to understand the requisite number of bike racks, virtual corrals, or physical corrals (which we collectively call “parking corrals” throughout the remainder of the report) necessary to support shared micromobility programs or privately used micromobility devices within a city. Our objective is to explore the associations between parking corral densities and different land use patterns with scooter parking compliance.

SUB-STUDY 2:

How do land use patterns and parking density relate to shared micromobility parking demand?

The second research question emphasizes parking demand. Specifically, the objective of the second sub-study is to determine whether different land uses require varied levels of parking density to meet demand. The benefit of this analysis is that it reveals riders’ parking demand without the influence of parking regulations (as in sub-study 1), and can therefore inform how to refine an existing parking network or design parking networks from scratch.

By combining the findings from both sub-studies, our aim is to offer practical recommendations that can assist cities in optimizing their parking plans to accommodate shared micromobility, improve parking compliance rates, and effectively manage the integration of these systems within their urban landscapes.


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STUDY AREAS & ANALYSIS UNITS

To effectively answer our two research questions, we selected the cities for this study that varied in both their characteristics and parking rules and regimes. To investigate parking non-compliance (sub-study 1), it was necessary to only include cities with mandatory parking zones where users are required to park their vehicles. Conversely, to explore parking demand (sub-study 2), cities with small or no mandatory parking zones were chosen to eliminate the influence of parking corrals on demand estimation. Additionally, the research team aimed to ensure the study results were applicable across different settings by incorporating multiple cities that varied in geographic location (i.e., US vs. EU), population density, and parking density, thus increasing the diversity of the dataset. In total, the study encompasses a total of twelve cities: six cities with full mandatory parking or hybrid mandatory parking zones, and six cities with either no mandatory parking requirements or small, localized mandatory parking zones. Table 2-1 presents the city-level characteristics of each study city.

We analyzed the data at an aggregated level of roughly 0.1 square kilometers using the H3 hexagon spatial framework at the resolution 9 level (Sahr et al., 2003). We chose to use the hexagon framework because this discrete grid system has been widely used to understand the trip generation and travel between grids in both industry (Brodsky, 2018) and academia (Shaji et al., 2022; Šidlovský & Ravas, 2023; Woźniak & Szymański, 2021). Given this study encompasses cities across different counties, utilizing a traffic analysis zone or census unit as the analysis unit proves challenging due to variations in their definitions. The adoption of this global discrete grid system ensures a consistent analysis unit across countries.

Figure 2-1 illustrates the dimensions of a single hexagon and showcases the distribution of hexagons in the National Mall area in Washington, D.C. After initially covering the cities' entire service areas with the H3 hexagons, we then excluded hexagons that were entirely situated within no-parking zones, where riders are prohibited from parking their vehicles. We then classified the remaining hexagons based on whether they overlapped with mandatory parking zones. If a hexagon intersected with a mandatory parking zone, it was classified as part of the study area for the parking compliance analysis (sub-study 1). Conversely, if a hexagon did not intersect with any mandatory parking zone, it was classified as part of the study area for parking demand analysis (sub-study 2). Finally, the overall study areas for both sub-study 1 and sub-study 2 were determined by aggregating these classified hexagons across all study cities.

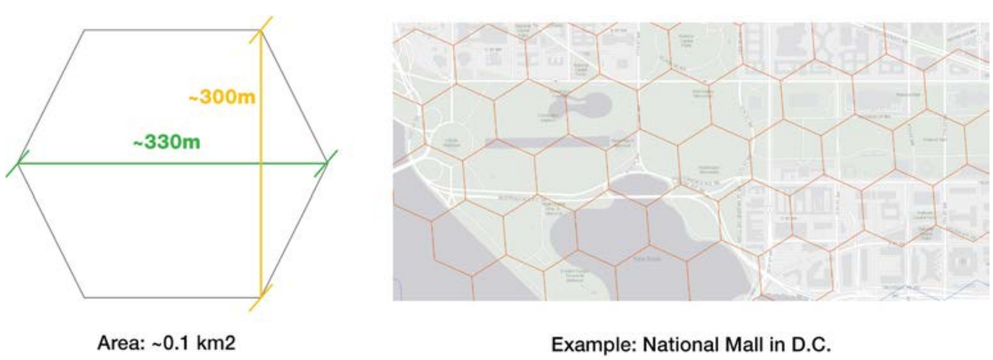


Figure 2-1. The size of an Analysis Unit (left) and distribution of Analysis Units in Washington D.C. (right) [1]

[1] The actual size of a single hexagon may vary from place to place (0.08 to 0.12 square kilometers) due to the projected coordinate systems. This variation is taken into account in the analysis.

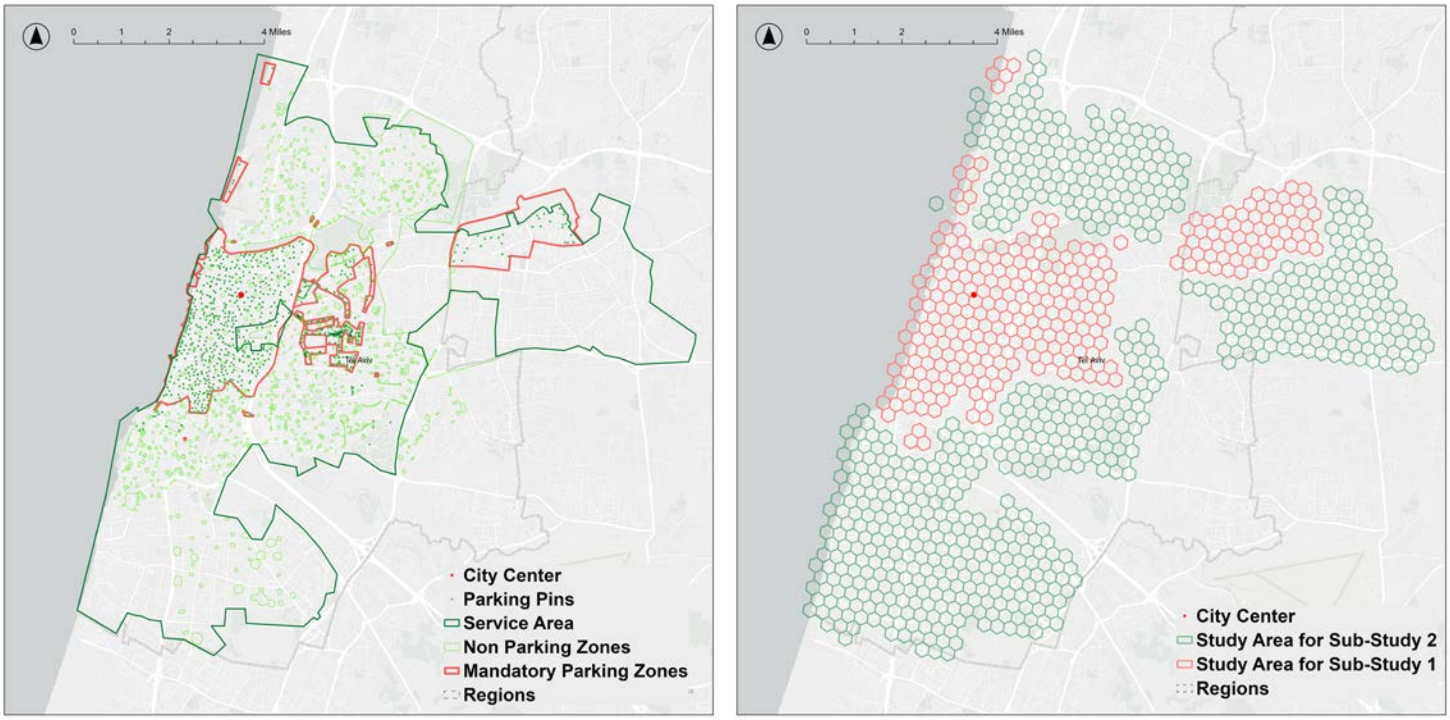


Figure 2-2. Various Designated Parking Areas (left) and Study Areas (right) in Tel Aviv

Figure 2-2 provides a visual representation using Tel Aviv as an illustrative example of the delineation of study areas as described. The left map displays the locations of the service area, parking corrals, mandatory parking zones, and no-parking zones. Notably, the majority of parking corrals are situated within mandatory parking zones, with only a few located outside these designated areas, in which case they are optional, “preferred” parking corrals where riders are not obligated to park. The right map showcases the study areas designated for the parking compliance analysis (sub-study 1) and parking demand analysis (sub-study 2). To ensure the integrity of the analyses and eliminate potential biases resulting from the presence of mandatory parking zones, blue hexagons adjacent to the red ones were removed. This precautionary measure aimed to mitigate any influence of mandatory parking zones on parking behaviors within the study areas.

Table 2-1. City-Level Characteristics of Case Study Cities (See Appendix 1 for additional city characteristics)

City	Parking Types	Operational Vehicles	Parking Corrals (Only enforced within MPZs)	Parking Corral Density (Corrals per km²)
Charlotte, NC, U.S.A.	Free Floating	618	22	13
Cincinnati, OH, U.S.A.	Full MPZ	387	331	69
Cologne, Germany	Localized MPZ	3,834	27	17
Denver, CO, U.S.A.	Free Floating	2,491	418	12
Long Beach, CA, U.S.A.	Full MPZ	947	211	12
Lubbock, TX, U.S.A.	Hybrid MPZ	768	66	27
Lubeck, Germany	Free Floating	431	0	N/A
Madrid, Spain	Full MPZ	2,791	1,390	27
Munich, Germany	Localized MPZ	5,736	69	17
Stockholm, Sweden	Full MPZ	1,260	2,622	97
Tel Aviv, Israel	Full MPZ	3,354	1,162	45
Washington D.C., U.S.A.	Small MPZ	2,545	159	14

[2] "MPZ" stands for "mandatory parking zone". "Localized MPZ" refers to cities with designated corrals for a few blocks or a street and free-floating elsewhere, "Small MPZ" refers to cities where a small portion of the city (e.g., a neighborhood or CBD) has designated corrals and free-floating elsewhere, "Hybrid MPZ" refers to cities where a large portion of the city has designated corrals and free-floating elsewhere (Hybrid MPZ), and "Full MPZ" means the entire service area requires parking at designated corrals. "Free Floating" refers to cities that have no mandatory parking requirements except no park zones (and potentially other fine-grained requirements, e.g., no parking against signs).

DATA OVERVIEW

This section begins by providing an overview of the data employed in this study, encompassing shared micromobility data and built environment data at both the city and hexagon levels. Subsequently, the analytical methods utilized to address the first two research questions are succinctly outlined.

Refer to the appendix for technical details pertaining to the generation of complex variables and the application of non-linear statistical analyses, such as land use type classification and gradient-boosting decision trees.

Shared Micromobility Data

Table 3-1 provides an overview of the variables generated from shared micromobility data, including parking corral location data, trip starting/ending location data, and vehicle location data. These data were collected during the months of March and April 2023 and then grouped into two-month intervals at the hexagon level. In the context of this study, the dependent variables are parking non-compliance rates and parking demand for sub-studies 1 and 2, respectively.

Table 3-1. Variables Generated from Shared Micromobility Data

Variable	Description	Unit	Data Source
Hexagon Level			
Parking Corrals	The number of parking corrals in a hexagon.	n	Lime
Parking Non-Compliance	The share of trips ending outside the buffers of parking corrals.	%	Lime
Parking Demand	The average count of parked vehicles in a hexagon.	n	Lime
Parking Corral Density	The number of parking corrals in a hexagon divided by the area of the hexagon (Figure 3-1 (a)).	n / km^2	Lime
Parking Coverage	The area encompassed by 200m buffers around all corrals within a single hexagon plus its six adjacent hexagons, divided by the total area of the hexagon and its adjacent hexagons (Figure 3-1 (b))	%	Lime
City Level			
City	The city in which a certain hexagon is located		Lime
Parking corral density	The number of parking corrals in a city divided by the area of mandatory parking zones	n / km^2	Lime
Operational vehicles	The total number of vehicles operating in a city	n	Lime
Parking types	Parking types include Full, Hybrid, Small, and Localized mandatory parking zones and Free Floating		Lime

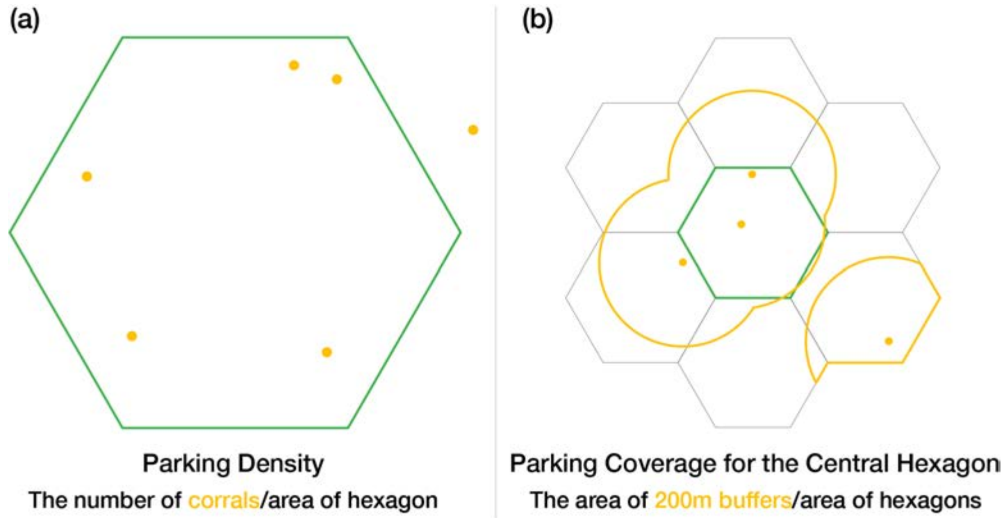


Figure 3-1. Illustrations of Parking Supply Variables

Mandatory Parking Zones typically include a small "buffer" radius around the central corral location, to account for GPS drift that is common across all GPS technology, including shared micromobility. GPS units in most modern electronic devices, including vehicles like scooters, have average accuracies of about 5 meters, or 16 feet, but can have decreased accuracy when satellite signals are blocked or interfered with by things like buildings, trees, and bridges (GPS.gov, 2022). To avoid unfairly impacting riders who are affected by GPS "drift" errors, the radius of a parking corral buffer typically ranges from 15 to 20 meters so that they can park the scooter, even with minor GPS inaccuracies (Nivel, 2023). Figure 3-2 visually depicts the process of generating the parking compliance and demand variables using simplified examples.

For the calculation of the parking non-compliance rate, we determine the ratio of non-compliant trips to the total number of trips within a hexagon (Figure 3-2 (a)). As an illustration, let's consider a scenario where two trips conclude within the buffers of parking corrals while one trip concludes outside the buffers. In this case, the parking non-compliance rate for the hexagon is 33.3% (1 divided by 3). Regarding parking demand, we calculate the average hourly counts throughout the study period (Figure 3-2 (b)). For instance, if we count the number of vehicles within a hexagon five times from 6 am to 10 am on a given day, the parking demand in this example would be determined as 2 (the sum of 3, 1, 4, 0, and 2, divided by 5).

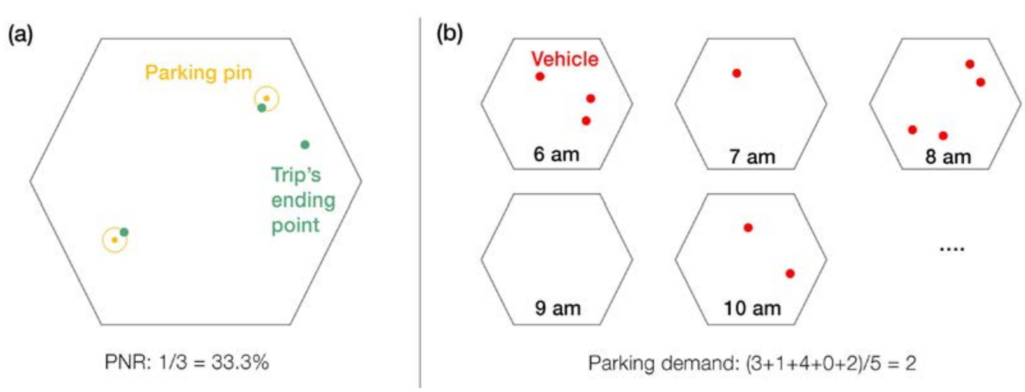


Figure 3-2. Simplified Illustrations of Generating Dependent Variables

Built Environment Data

We used built environment data from OpenStreetMap to generate land use variables (Table 3-2), which are denoted by the 5 “D” variables commonly used in travel behavior analysis (Ewing & Cervero, 2010), including density, diversity, design, distance to the city center, and destination accessibility. Land use variables are all hexagon-level independent variables for both sub-studies, as is parking corral density. The generation process of most land use variables is clear and straightforward. However, the process of generating land use type warrants further explanation, provided in Appendix 2.

Table 3-2. Variables Representing the Built Environment

Variable	Description	Unit	Data Source
Hexagon Level			
Population Density	The average of all intersected 1km by 1km grid cells	n/km2	Global Human Settlement Layer
Land Use Type	The land use types of hexagons include the following 9 categories: Commercial, Leisure, Mixed, No value, Office, Public service, Residential, Tourism, and Transit (see Appendix 2)		OpenStreetMap General Transit Feed Specification
Intersection Density	The number of intersections in an H3 R9 hexagon, which is derived from the road network	n	OpenStreetMap
Distance To City Center	The distance to the city’s old town area or downtown, which were manually identified	m	Google Maps
Destination Accessibility	The number of POIs within an H3-R9 hexagon	n	OpenStreetMap
City Level			
Population Density	Population per square kilometer	n / km^2	Brinkhoff, 2023
Continent	NA or EU		N/A

Data Analysis

The analysis in this study was carried out in several steps. Firstly, a descriptive analysis was conducted to examine the distribution of variables of interest and investigate relationships between two variables using summary statistics, histograms, scatter plots, and bin charts. This initial analysis provided an overview of the data and identified potential patterns or associations.

Subsequently, a series of regression analyses were performed to explore the relationships between independent and dependent variables. Given that the study incorporates data from multiple cities, the hexagon-level variables are nested within each city. To account for city-level variations and isolate the effects of interest, city-level fixed effects were introduced in the regression models. By doing so, we could control for the influence of city-level factors on parking non-compliance and demand. Because the parking compliance data is a continuous measure (between 0 and 100), we used a linear regression, while we used a zero-inflated negative binomial model for the parking demand model, since the trip volume data is a “count” and has a high proportion of zero-trip observations. We refer to both models as “regression analysis” in the text.

Furthermore, considering previous findings from a Lime analysis that suggest a potential non-linear relationship between parking corral density and parking non-compliance (Murphy & Haydu, 2023), we employed Gradient Boosting Decision Tree (GBDT) analysis. This allowed us to explore non-linear relationships between shared micromobility parking facilities, land use intensity, and parking non-compliance and demand. The GBDT analysis provided insights into the relative importance of features and enabled the generation of partial dependence plots, which helped examine the bivariate relationships between independent variables and the dependent variable.

For detailed information on the model specifications for the regression analysis and descriptions of the GBDT analysis, please refer to Appendices 3 and 4, which provide comprehensive model specifications and explanations of the analytical techniques employed.

SUB-STUDY 1: PARKING COMPLIANCE

Parking corral density is the most significant predictor for parking non-compliance rate.

Both linear regression analysis and non-linear GBDT analysis show that parking corral density is more closely associated with parking compliance rates than other parking or land use variables (Figure 4-1). The non-linear GBDT analysis, in particular, underscores the relative importance of parking corral density compared to other variables, with parking corral density providing 86% of the predictive power of the independent variables (Figure 4-2).

Prior studies have examined the impact of various parking regulations on parking compliance at the street level (Hemphill et al., 2022; Klein et al., 2023) or explored public perceptions related to compliance (Berg Wincent et al., 2023; Buehler et al., 2023), with findings suggesting that parking regimes such as lock-to and parking corrals are successful at improving both compliance and public perceptions. This study confirms that designating parking corrals is critical to parking behaviors, surpassing the influence of land use. This suggests that as cities strategically plan parking infrastructure for shared scooter programs, the density of their parking network is the most important step to consider to ensure high levels of compliant parking.

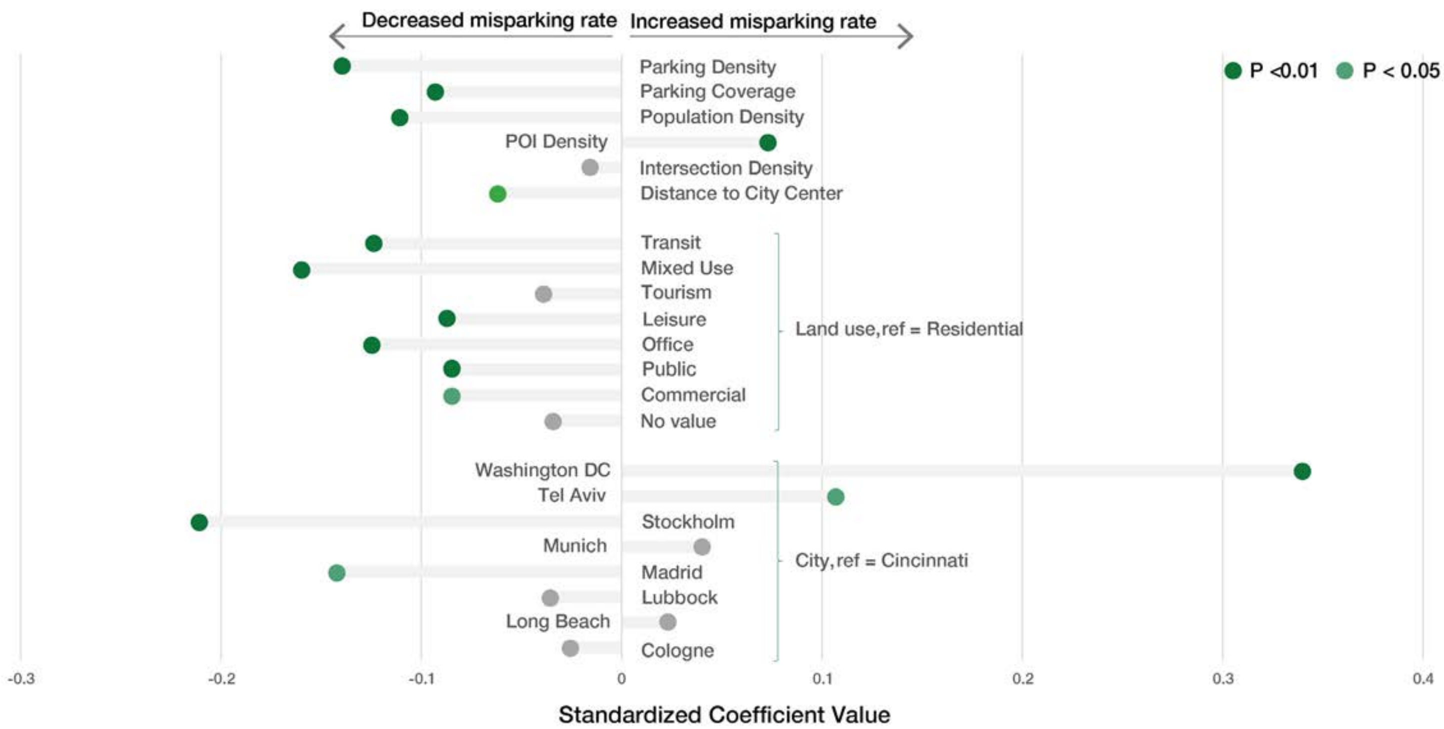


Figure 4-1. The Association between Parking Supply and Land Use with Scooter Parking Non-compliance (Linear Regression)

The magnitude or size of the coefficients indicates how strongly they are tied to parking compliance rates. Notably, the standardized coefficient of parking corral density (β = -0.139, p < 0.01) exceeds that of other hexagon-level variables of interest, signaling its outsized importance to parking compliance.

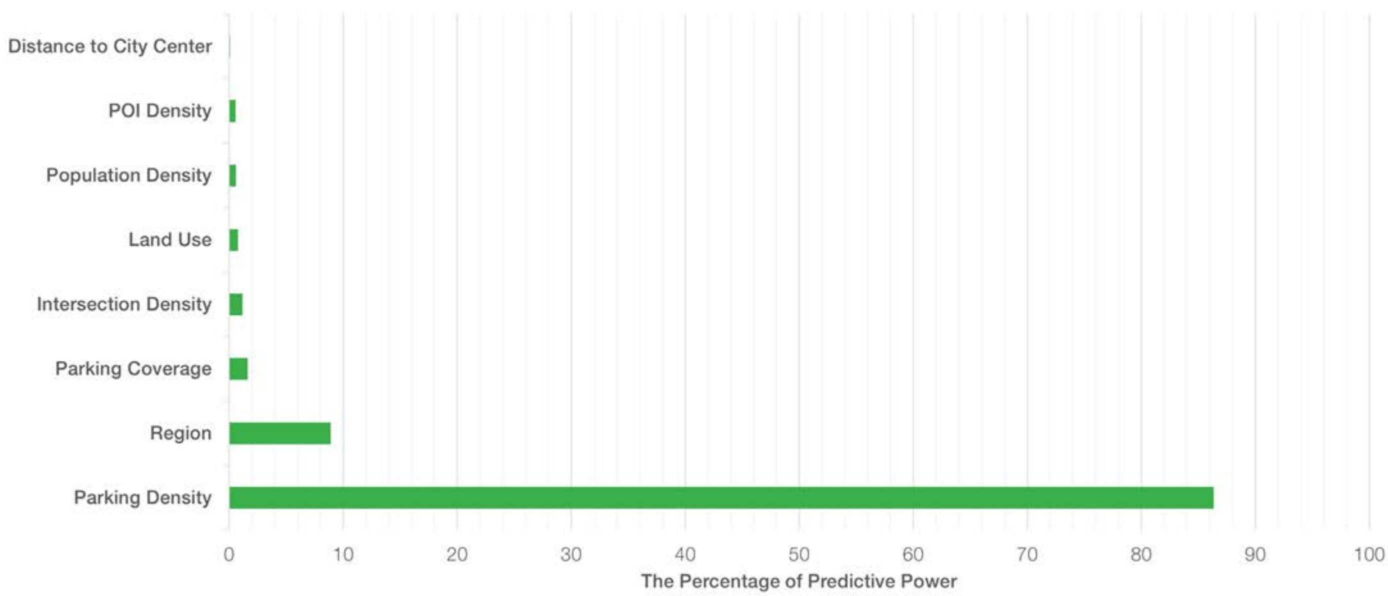


Figure 4-2. The Relative Importance of Parking Supply and Land Use on Scooter Parking Compliance (Non-Linear Analysis)

The non-linear analysis, we can estimate the relative importance of different factors, which adds up to 100%. Parking density is by far the most important variable for influencing parking compliance.

Parking corral density has a nonlinear relationship with parking compliance.

Figure 4-3 depicts a strong negative non-linear relationship between parking corral density and parking non-compliance rates. The partial dependence plot from the GBDT analysis confirms this negative non-linear relationship after averaging out the effects of other independent variables (Figure 4-3 (b)). The negative relationship is consistent with the results of linear regression analysis.

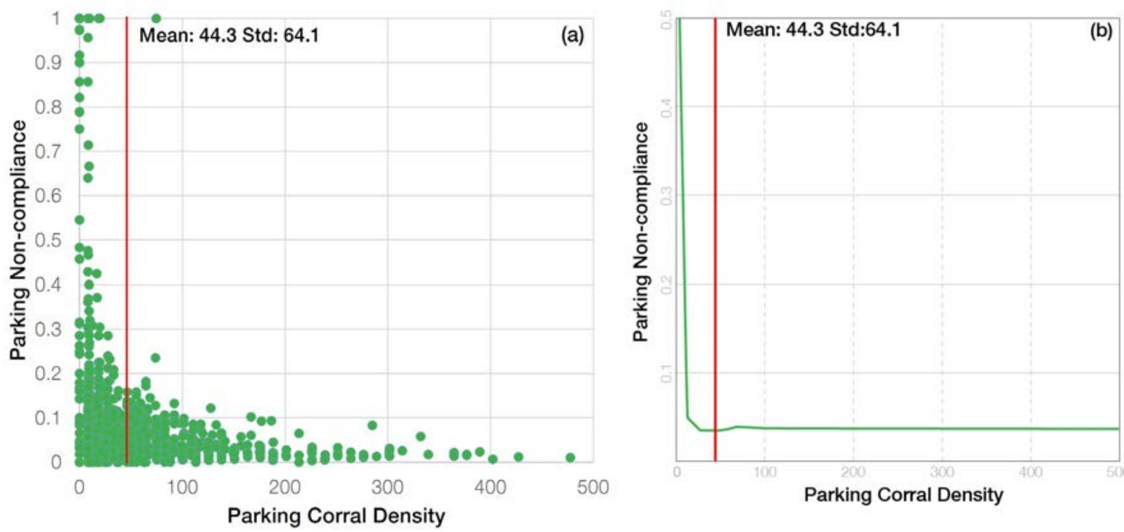


Figure 4-3. Scatter Plot and Partial Dependence Plot of Parking Non-compliance Rate at Different Levels of Parking Density

Two experimental studies provide support for the notion that parking regulations, including the establishment of virtual parking corrals, can effectively reduce misparking (Klein et al., 2023; Nivel, 2023). Additionally, a GIS-based study in Portland highlights a positive linear relationship between increased designated on-street parking with higher parking compliance rates (Hemphill et al., 2022). These results are consistent with the regression analysis in this study. However, the non-linear analysis reveals a significant threshold effect for parking corral density, wherein parking non-compliance rates decrease substantially until parking corral density reaches a certain threshold. Beyond that threshold, the marginal benefit of additional corrals diminishes considerably.

After parking a shared e-scooter, a rider must still access their final destination, which can be regarded as a new leg of their journey; previous studies find that walking is the primary active mode for this transfer travel (Buehler et al., 2023). Studies on active travel and walking to transit show that various spatial features have threshold effects on active travel behaviors (Tao, Wang, et al., 2020; Tao, Wu, et al., 2020), which implies that land use variables and parking density may also have threshold effects on egressing a shared e-scooter.

The elbow point of the negative nonlinear relationship is around 20-30 corrals per square kilometer - if corrals are evenly spaced, riders would never be farther than about a 1 minute's walk away.

Parking compliance improves at a steep rate when moving from very low parking corral densities to between 20 to 30 parking corrals per square kilometer, after which improvements to compliance rates taper off with each additional parking corral. This threshold is evident from the partial dependence plot, which shows a significant improvement in parking non-compliance when parking corrals exceed these threshold densities (Figure 4-3).

To illustrate the impact of parking corral distribution, Figure 4-4 depicts the even distribution of 25 corrals within a 1km-by-1km square (25 corrals/km2). In this arrangement, the access/egress distance to any parking corral is between 100m and 141m, and the walking time is around 1 to 1.5 minutes. Appendix 5 shows the conversion of the density to walking distance under the assumption of even distribution.

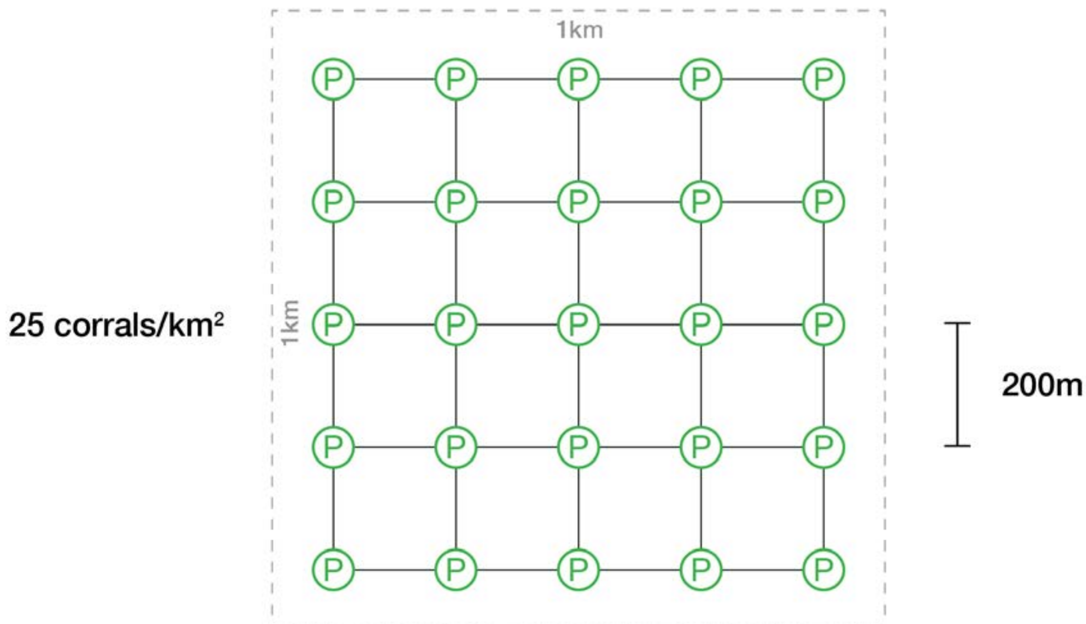
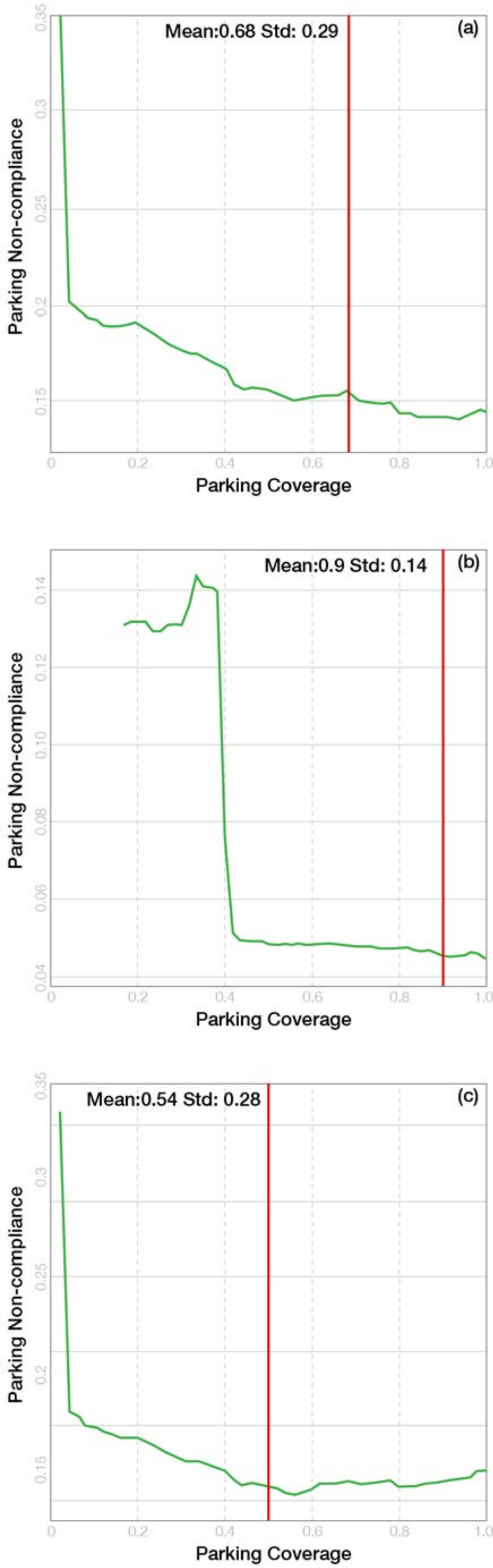


Figure 4-4. Walking Distance with a Parking Corral Density of 25 corrals/km2 with Even Corral Distribution

The shorter access/egress distance for shared e-scooters relative to e-bikes (typically <200m, see (Buehler et al., 2023; Reck et al., 2022)) can likely be explained by the shorter travel distance of e-scooter trips, averaging around 2.1 kilometers per trip (NACTO, 2022). The acceptable access/egress distance for a given travel mode is often influenced by the average trip distance of that mode. Longer trip distances are generally associated with longer access/egress walking distances. Additionally, shared e-scooters tend to be concentrated in urban cores, where walkability and access to public transit are generally more favorable compared to other areas. If the parking corral for a shared e-scooter is located far from a rider's final destination, it may lose its advantages compared to walking or using public transit, thereby influencing users' parking decisions.



Parking coverage is also important for reducing the parking non-compliance rate.

Both regression and non-linear analyses indicate that parking coverage stands as the third-most crucial variable in predicting parking non-compliance rates. As illustrated in Figure 4-5 (a), parking coverage exhibits a negative linear correlation with parking non-compliance when a corral is present. Notably, when parking coverage exceeds 90%, the marginal effect on parking non-compliance is close to zero or even negative. Parking density demonstrates a strong correlation with parking coverage (r=0.566, p=0.000), and the parking coverage almost has no association with parking non-compliance rate when examining hexagons with parking density above 30 corrals per square kilometer (Figure 3-6 (b)). By contrast, when the parking density is below 30 corrals per square kilometer, the relationship between parking non-compliance rate and parking coverage is similar to that for all hexagons. Therefore, parking coverage plays a significant role in reducing the parking non-compliance rate when shared e-scooter parking density is low.

Figure 4-5, (left). The Relationships between Parking Coverage and Parking Non-compliance:
(a) All Hexagons
(b) Hexagons with Parking Density above 30 corrals per Square Kilometer
(c) Hexagons with Parking Density below 30 corrals per Square Kilometer

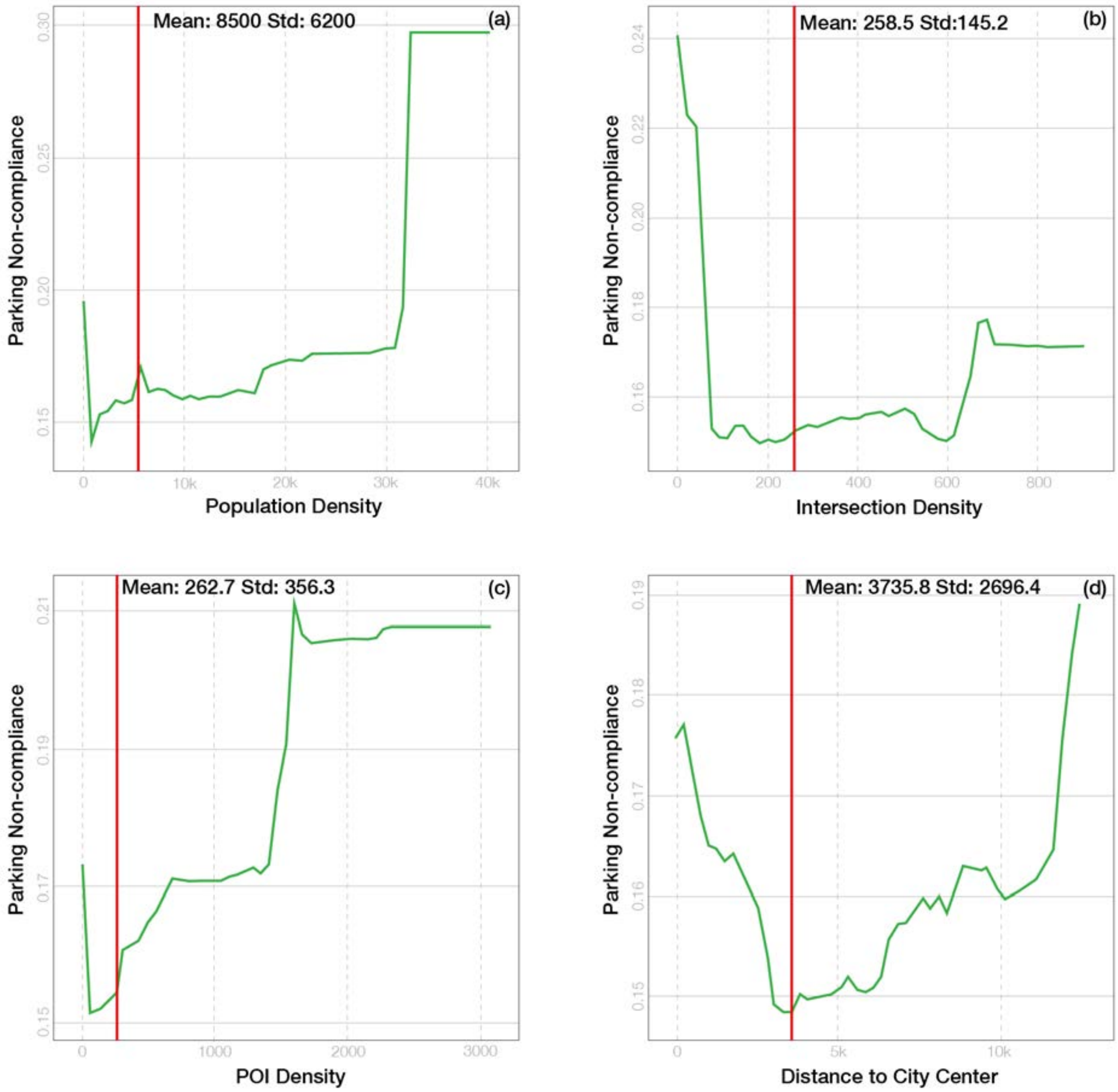


Figure 4-6. The Relationships between Land Use Intensity Indicators and Parking Non-compliance

Land use and parking compliance have a “U” shape relationship.

The partial dependence plots presented in Figure 4-6 clearly demonstrate the trend of the parking non-compliance rate decreasing and then increasing as urban activity becomes more intensive; the parking non-compliance rate tends to be higher in both high-density and low-density environments compared to medium-density environments. The existence of these quadratic relationships between land use variables and parking non-compliance rate is further supported by the insignificance of most land use intensity variables in the linear regression model.

One interpretation of this finding is that people are more willing to walk and park at designated corrals in moderately dense environments than in high- or low-density environments. We would expect to observe higher rates of non-compliant parking in low-density and single-use environments due to limited parking facilities and generally low walkability levels (Owen et al., 2007; Saelens & Handy, 2008).

However, it is surprising to find low parking compliance in high-density environments, where parking coverage and walkability are typically high. We consider two potential explanations for this phenomenon. First, the analysis of parking coverage (i.e., the area of 200-meter buffers of parking corrals divided by the area of a hexagon) suggests that the coverage ratio is slightly higher in high-density environments than in medium-density environments. Therefore, if a cluster of destinations is not covered by parking facilities in high-density areas, the parking non-compliance rate may be dispositionally high. On the other hand, GPS drift is a serious issue in high-density environments due to the blocks of high-rise buildings (GPS.gov, 2022). Therefore, the high non-compliance rate may simply result from inaccurate geo-locating.

Noncompliant parking is higher in residential and tourism areas.

The bar charts in Figure 4-7 show that the average parking non-compliance rate at the hexagon level is higher in tourism and residential land use areas than in other land uses. In contrast, commercial and mixed-use areas consistently have the lowest levels of parking non-compliance.

In tourism areas, it is likely that a significant proportion of shared scooter riders are tourists who may be unfamiliar with the city or neighborhood, let alone the specific parking requirements of the city's shared micromobility system, which vary widely across cities (Brown, 2021). Riders' lack of familiarity may contribute to a higher parking non-compliance rate among these users. Furthermore, residential and tourism hexagons tend to have fewer parking corrals and lower parking density compared to other types of hexagons, which could further contribute to the observed higher non-compliance rates in these areas by the indirect effects through parking corral density. This study did not differentiate between different types of residential land use, such as low-density residential areas versus high-density residential areas. The low-density residential areas tend to be more car-oriented and less walkable and bikeable, which discourages accessing and walking from designated parking corrals. Therefore, the inclusion of the broader category of low-density residential land use may shift parking compliance rates.

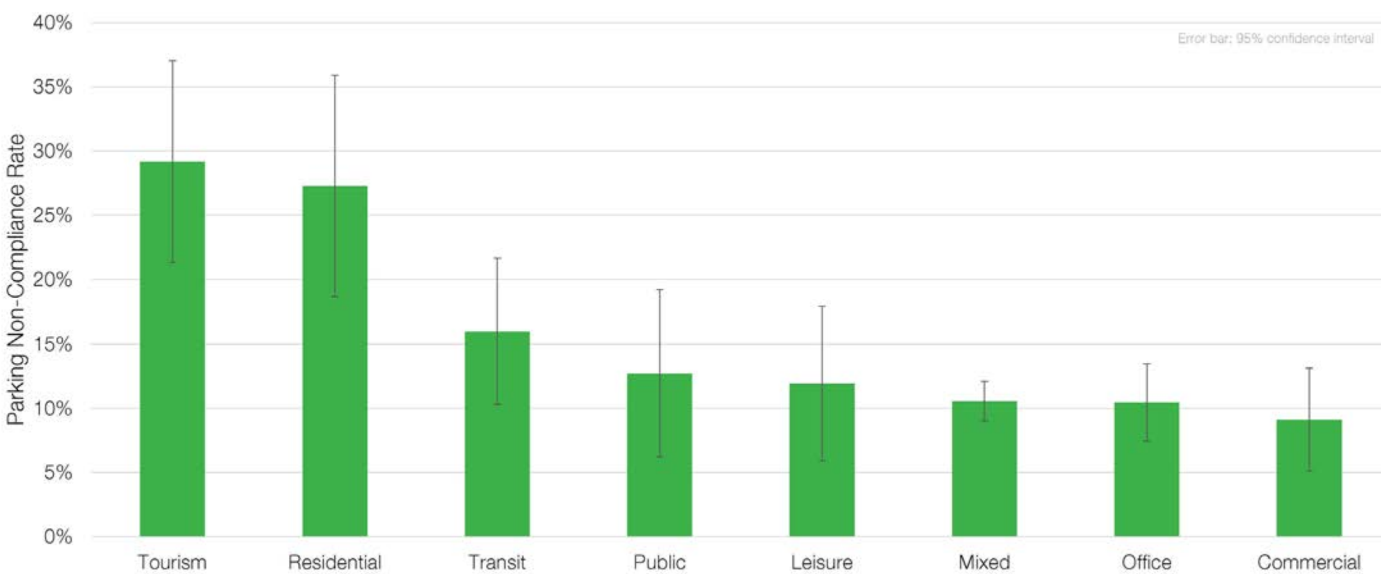


Figure 4-7. Parking Non-compliance Rate by Land Use at the Hexagon Level

Noncompliant parking is higher in residential and tourism areas.

The results from the regression model, including city-level fixed effects, indicate that the parking non-compliance rates vary across the case study cities. Specifically, the parking non-compliance rate is relatively low in Stockholm and Madrid, while it is relatively high in Washington, D.C. and Tel Aviv (Figure 4-8).

To explore the potential impact of city-level characteristics on parking non-compliance, we conducted additional regression models, replacing the city-level fixed effects with city-level variables. However, due to the limited number of case study cities, the examination of city-level variables is not robust. Therefore, we compare the cities of Washington, D.C. and Stockholm to gain insights into the potential influence of city-level characteristics on parking non-compliance.

Figure 4-8 clearly illustrates that the overall parking corral density in Stockholm is considerably higher than that in Washington, D.C. Yet, in hexagons with no parking corrals, the parking non-compliance rate is substantially lower in Stockholm compared to Washington, D.C. This suggests a possible relationship between increased city-level parking corral density and decreased parking non-compliance rate, as higher parking density enhances accessibility. Also, this may suggest that ensuring consistent parking coverage is significant in addressing non-compliant parking issues, as parking deserts (i.e., a hexagon and its adjacent hexagons having no parking corrals) generate much higher parking non-compliance rates than a single hexagon with no parking corrals, surrounded by hexagons with parking corrals.

It is important to note, however, that parking non-compliance may be influenced by other compounding city-level factors, such as the higher proportion of tourism hexagons within the mandatory parking zones of Washington, D.C. Studying more cities is vital to understanding how city factors affect shared micromobility parking. While comparing Washington, D.C. and Tel Aviv is a good start, including diverse cities is crucial for a thorough analysis.

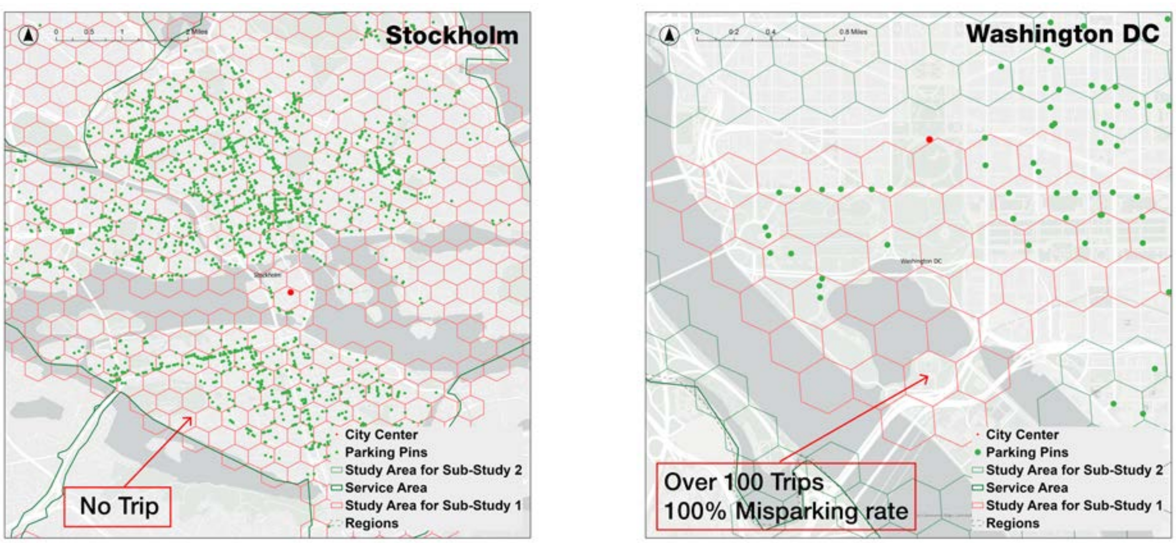


Figure 4-8. The Distribution of Parking Corrals in Mandatory Parking Zones in Stockholm and Washington, D.C.

SUB-STUDY 02: PARKING DEMAND

Greater land use intensity has higher parking demand.

The regression analysis demonstrates that hexagons with better destination accessibility and greater intersection density have higher demand for scooter parking, while hexagons at a greater distance to the city center have lower parking demand (Figure 4-9). Also, the partial dependence plots from the GBDT analysis confirm that these land use intensity variables are linearly related to parking demand.

Our measure of parking demand consists of parked scooter vehicles, vehicles out of service, and vehicles deployed by the operator. Parked vehicles (measured as trip ends) are the predominant component of parking demand. Many classic studies on active travel and built environment reveal that high density is related to high active travel levels (Eren & Uz, 2020; Guo et al., 2022; Saelens & Handy, 2008), so the finding that land use intensity is positively related shared e-scooter parking demand is consistent with previous research.

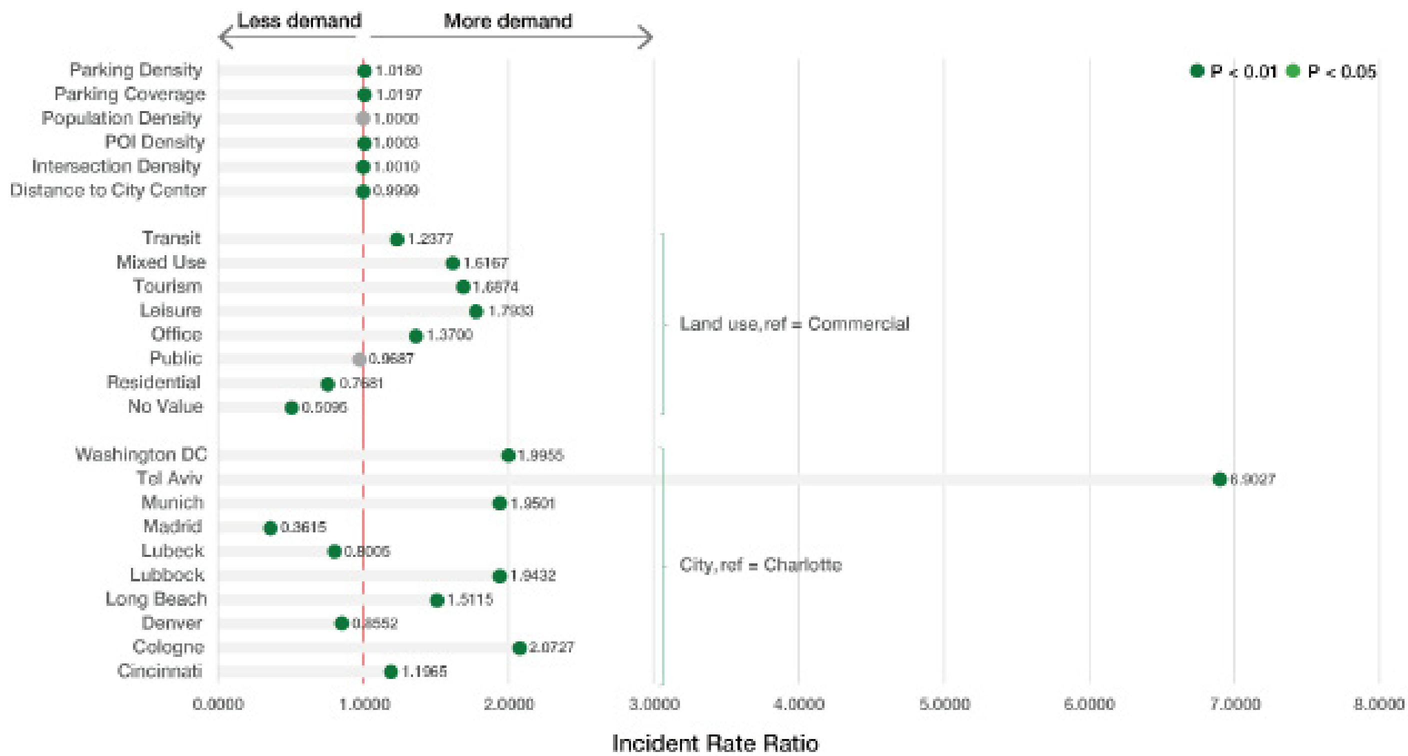


Figure 4-9. The Association between Parking Supply and Land Use with Scooter Parking Demand (Zero-Inflated Negative Binomial Regression)

The magnitude, or size, of the coefficients indicates how strongly they are tied to parking demand - below one indicates they reduce demand and above one indicates they are tied to higher demand for scooter parking. Notably, land use categories showed the strongest variability in demand.

The parking demand is relatively high in leisure, mixed, and tourism hexagons and relatively low in residential hexagons.

Both descriptive analysis and regression analysis show variations in parking demand across land use types. Previous studies have shown that mixed and leisure land use are related to high active travel levels (Owen et al., 2007; Saelens et al., 2003), as these land uses often provide a diversity of destinations within short distances. By comparison, the concentration of low-density residential land is more likely to hinder walking and biking. The physical features of different land use types, such as intersection density, the connectivity of sidewalks and bike lanes, and the proportion of first-floor commercial areas, may determine parking demand to a great extent.

For cities with similar characteristics to the case study cities, all else equal, leisure areas should expect to provide 80% more shared e-scooter parking space than commercial areas; mixed-use and tourism areas should offer 65% more; transit and office areas should provide 30% more; residential areas should provide 25% less; public and commercial areas should provide same number of scooter parking spaces as in commercial areas.

It is challenging to provide concrete recommendations on the absolute number of parking spaces in any given city, without taking into account the city's characteristics - the parking spaces needed in Washington, D.C. are unlikely to be the same as the spaces needed in Charlotte, since the cities have very different built environments. But for the sake of illustration, we examine the parking capacity needs of the Penn Quarter neighborhood of Washington, D.C., the setting of the Transportation Research Board annual conference.

In the Penn Quarter, the results of the model suggest that the D.C. Department of Transportation would meet parking demand by providing 220 scooter parking spaces per square kilometer in public and commercial areas (roughly 9 spaces per corral if 25 corrals are provided); 400 parking spaces per square kilometer in leisure areas (16 spaces per corral); 360 parking spaces per square kilometer in mixed and tourism areas (14 spaces per corral); 285 parking spaces per square kilometer in transit and office areas (11 spaces per corral); and 165 parking spaces per square kilometer in residential areas (7 spaces per corral).

Parking corral density is positively related to parking demand.

The regression of parking demand on parking density, land uses, and other characteristics demonstrates that holding all other variables constant, parking corral density is positively associated with parking demand (Figure 3-9), even though riders are not required to park at these parking corrals.

Since this study utilizes cross-sectional data, we cannot infer a causal relationship, largely due to the reverse causality issue. On the one hand, the designation of recommended parking space may be based on existing travel patterns: planners may provide more parking corrals in areas with high parking demand. On the other hand, the presence of parking corrals in free-floating markets may impact riders' parking behaviors, despite not being required to park there, leading to the concentration of parked scooters within parking corrals. Furthermore, the existence of parking corrals may facilitate social contagion - the first scooter parked in an area is likely to influence subsequently parked scooters (Nivel, 2023).

Considerations and Limitations

We recommend that planners and policymakers use these findings and recommendations as general guidance for their jurisdiction, rather than applying the reported numbers directly. We offer this caution due to a number of important considerations that could cause the results to vary from city to city. First, the land use designations used in this study may be different from those used by planners and policymakers. Second, the recommendations from this study are only expected to apply to cities with similar contexts from the case study cities in this research and may not apply in other settings. Finally, the density of any individual land use type can vary greatly (e.g., single-family versus multifamily residential), and we estimated the variations in different land uses' parking demand and compliance while controlling for density.

POLICY RECOMMENDATIONS

This study provides valuable insights into the relationship between scooter parking compliance and demand, parking corral density, and land use patterns. The implications derived from these findings can inform policy decisions related to parking management and capacity planning in shared micromobility systems to ensure orderly parking. We offer three primary ways planners and policymakers can effectively intervene to meet parking demand and improve parking compliance.

[01]

Provide sufficient parking corrals - within a 1-minute walk - to meet parking demand and maximize compliance

The findings from the first sub-study on parking non-compliance underscore the importance of providing at least 25 parking corrals per square kilometer, which translates to around a 150-meter walk to the final destination, which takes roughly 2 minutes. This finding is very robust and consistent across regions, cities, and built environments, which suggests that riders have a consistent "acceptable" distance they are willing to walk from their parking location to their destination. At lower corral densities – and therefore longer walk distances – people may be more willing to abandon scooters outside of designated parking areas, increasing parking non-compliance. More attention needs to be paid to the distribution of parking corrals in high-density areas, where parking demand is high, which can lead to large non-compliance rates. Parking corral density above a threshold of about 25 corrals per square kilometer, however, has limited returns; above this threshold, adding more parking corrals has a very minimal effect on improving parking compliance.

[02]

Ensure parking corral coverage is consistent and comprehensive to avoid gaps in parking coverage and resulting parking non-compliance.

When parking density is lower than 25 corrals per square kilometer, the parking coverage is positively related to parking compliance. By contrast, parking coverage is not significantly related to parking compliance in areas with high parking corral density. Also, inter-city comparisons show that parking deserts (i.e., a hexagon without a parking corral, surrounded by adjacent hexagons without parking corrals) generate much higher parking non-compliance rates than a single hexagon with no parking corrals, surrounded by hexagons with corrals. Therefore, planners should maximize the parking coverage in the low-parking-density environment.

[03]

Provide enough parking spaces within corrals to accommodate the parking demand in different land uses.

Planners and policymakers should provide different numbers of parking spaces within parking corrals across different land use types. The second sub-study reveals that parking demand increases at greater land use intensity and varies across land use types. The strong nonlinear relationship between parking corral density and parking compliance indicates that the necessary parking corral density is relatively fixed across different land use types, and corrals in mixed-use, leisure, and tourist areas should have higher capacity. Using commercial areas as the reference, we suggest providing 80% more parking spaces in leisure areas, 65% more spaces in mixed-use and tourism areas, 30% more spaces in transit and office areas, the same number of spaces in public areas, and 25% fewer spaces in residential areas.

SUGGESTIONS FOR FUTURE RESEARCH

The conclusions from these sub-studies offer insights into parking planning for shared micromobility systems, but several considerations warrant further exploration in future research. First, a cross-sectional study with parking capacity data or an experimental study could examine the relationship between the capacity of a parking corral and parking non-compliance. Second, further research should focus on the impacts of parking capacity and its distribution on parking demand. Even though the thresholds of parking corrals and capacity have been examined, future studies can explore how the increase in parking facilities or the different combinations of these two metrics may impact parking demand, travel behaviors, equity, and operations. Lastly, there are important questions remaining about how the design of parking corrals affects parking compliance, as well as how the findings of this study may apply to lock-to systems. While we hypothesize that the findings about the importance of parking density, coverage, and capacity would apply to the need for prevalent bike rack availability for cities with lock-to requirements, further research is needed to evaluate this relationship.

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APPENDIX 01 : CASE-STUDY CITY CHARACTERISTICS

City	City Population	Urban Area (km²)	Population Density (n/km²)
Charlotte, NC, U.S.A.	879,709	801	1,099
Cincinnati, OH, U.S.A.	308,935	202	1,531
Cologne, Germany	1,086,000	410	2,650
Denver, CO, U.S.A.	711,463	396	1,795
Long Beach, CA, U.S.A.	466,742	131	3,557
Lubbock, TX, U.S.A.	260,993	349	748
Lubeck, Germany	216,227	214	1,010
Madrid, Spain	3,223,000	586	5,505
Munich, Germany	1,472,000	307	4,788
Stockholm, Sweden	975,551	186	5,260
Tel Aviv, Israel	1,452,400	172	8,444
Washington D.C., U.S.A.	712,816	168	4,232

APPENDIX 02 : METHOD FOR GENERATING LAND USE TYPES

We selected 7 major POI types based on the OpenStreetMap's official classification (Geofabrik, 2023), including commercial, leisure, office, public service, residential, tourism, and transit POIs. Each type of POI point data was aggregated at the hexagon level. Then, we generate the land use type for each hexagon based on the following equations:

$$F_{ij} = \frac{n_{ij}}{N_{ij}} \quad \text{and} \quad S_{ij} = \frac{F_{ij}}{\sum_{i=1}^{7} F_{ij}}$$

... where *i* represents the POI type; *j* is the individual hexagon; *n* denotes the number of POI type *i* within hexagon *j*; *N* is the sum of POI *i* in a city; *F* represents the frequency density of POI *i* in the city; *S* signifies the share of frequency density of POI *i* in hexagon *j*. If every $S\_ij = 0$, land use for hexagon *j* is "no value"; if every $0 < S\_ij < 50\%$, land use for hexagon *j* is "mixed-use"; if any $S\_ij > 50\%$, land use for hexagon *j* is the single-use *i*.

This method gives the share of POI type *i* in a hexagon a weight of 1/N_i, which represents the relative importance of POI type *i*. For instance, there are typically many more restaurants in a city than there are tourist attractions. Therefore, for a hexagon with a single tourist attraction and several restaurants, it may be reasonable to define this hexagon as a tourism hexagon rather than a commercial hexagon, unless the number of restaurants is extremely high. If the total number of POI type *i* in a city is included as the weight, this hexagon is more likely to be defined as a tourism hexagon.

Figure 6-1 shows the identified land uses for hexagons in Washington, D.C. Our classification method effectively mirrors the city's designated land use map. For instance, residential zones are predominantly situated in the outskirts, with the core city being predominantly mixed-use, commercial, or office spaces.

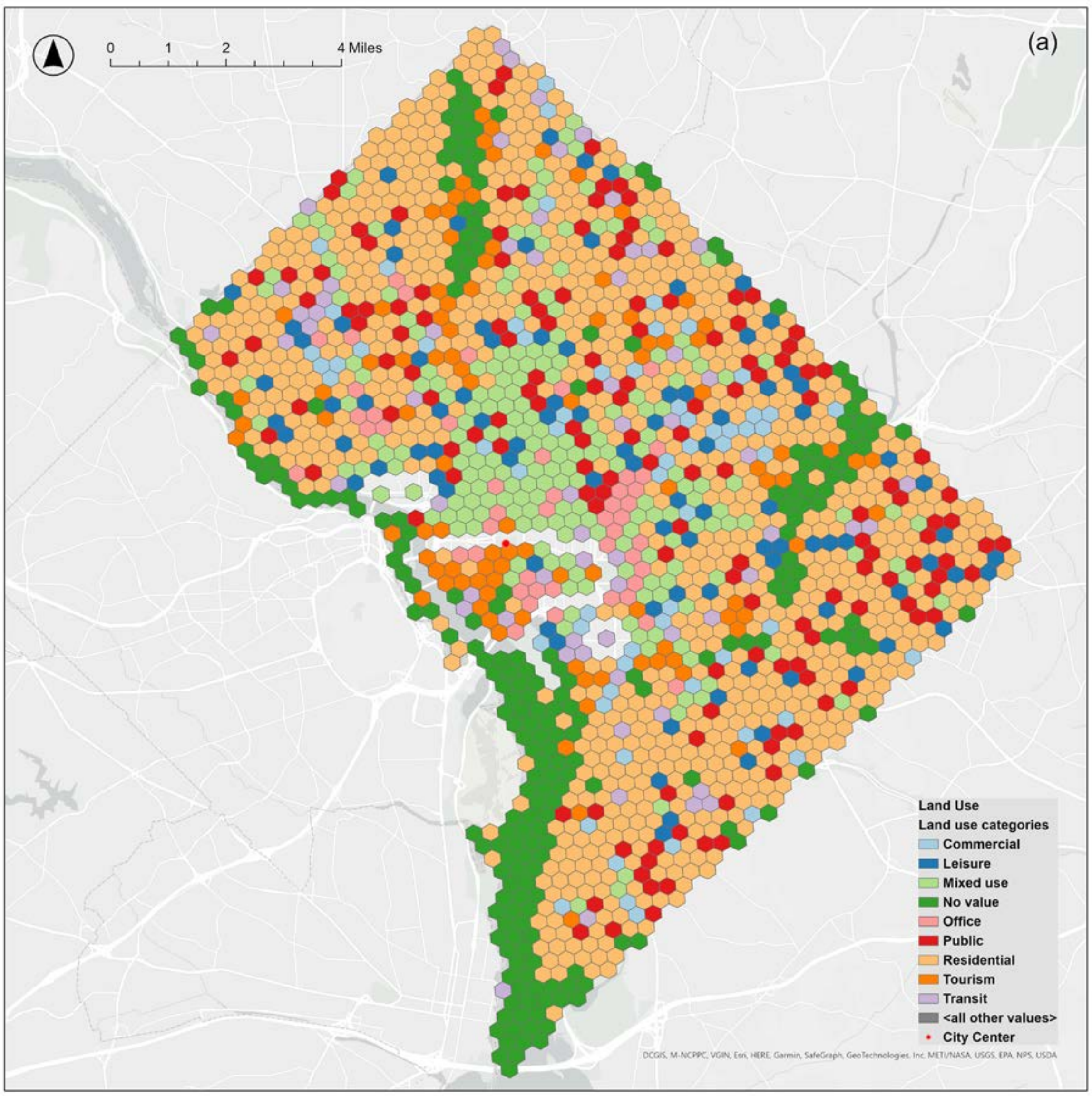


Figure A 1-1. Identified Land Uses for Hexagons in Tel Aviv, Israel

APPENDIX 03 : NON-LINEAR STATISTICAL ANALYSIS

We utilize gradient-boosting decision trees (GBDT) to examine the potential non-linear relationships between parking facilities, land use intensity, and parking non-compliance. GBDT combines two machine-learning approaches: decision trees and gradient boosting (Friedman, 2001, 2002). A decision tree is an algorithm that uses a tree-like structure to make decisions or predictions. It recursively partitions the data based on features to create a flowchart-like structure. Each internal node represents a decision based on a feature, and each branch represents a possible outcome or decision rule.

Gradient boosting improves the decision trees by creating a decision tree sequence. The algorithm starts by building a single decision tree, which serves as the initial weak learner. It then iteratively builds additional decision trees, each one focusing on the errors or residuals of the previous trees. The subsequent trees are constructed to minimize the residual errors by fitting them to the negative gradient of the loss function.

One drawback of GBDT is that the P values for features cannot be generated. Instead, GBDT can produce the relative importance of each feature in the predicting process, which can be regarded as practical significance. The relative importance of features in a GBDT model can be calculated based on the accumulated feature contributions across all the trees in the ensemble, which is reported as a percentage. One common method to measure feature importance in GBDT models is known as "feature importance by mean impurity reduction." The formula for calculating the relative importance of a feature can be summarized as follows:

$$I_j^2 = \frac{1}{M} \sum_{m=1}^{M} I_j^2 \left(T_m \right)$$

Where Ij2 (Tm) refers to the relative importance of a feature. Here's a step-by-step explanation of how to calculate the relative importance of a feature:

[1] For each tree in the GBDT ensemble, identify the feature's contribution or importance to that particular tree. This contribution is typically calculated by measuring the reduction in impurity (such as Gini impurity or entropy) achieved by splitting on that feature in that tree.

[2] Sum up the feature contributions across all trees in the ensemble for the specific feature. This sum represents the total contribution of the feature in the GBDT model.

[3] Calculate the total sum of feature contributions for all features in the model. This sum represents the overall importance of all features in the GBDT model.

[4] Divide the sum of feature contributions for the specific feature by the total sum of feature contributions. This ratio gives the relative importance of the feature.

Overall, the GBDT analysis provided insights into the relative importance of features and enabled the generation of partial dependence plots, which helped examine the bivariate relationships between independent variables and the dependent variable. This allowed us to explore non-linear relationships between shared micromobility parking facilities, land use intensity, and parking non-compliance and demand.

APPENDIX 04 : ZERO-INFLATED NEGATIVE BINOMIAL REGRESSION

Zero-Inflated Negative Binomial (ZINB) regression is a statistical modeling technique used for counting data, where the outcome variable has an excess of zeros compared to what would be expected in a standard count model. It combines two components to address excessive zeros: a binary model (logistic regression) for predicting the excess zeros, and a count model (negative binomial regression) for predicting the count values.

A Zero-Inflated Negative Binomial model consists of two components:

[1] Binary Model (Zero-Inflation Component): This part of the model addresses the excess zeros in the dependent variable. It is a logistic regression model that predicts whether an observation is a zero or whether it is subject to the count model.

[2] Count Model (Negative Binomial Component): The count model is used for modeling the count values, assuming a negative binomial distribution. This distribution is suitable for count data when there is over-dispersion, meaning the variance is greater than the mean. The negative binomial distribution allows for flexibility in handling variability in the data.

By combining these two components, the ZINB regression allows for a more nuanced analysis of count data with excess zeros. It is particularly useful when the excess zeros cannot be explained solely by a standard count distribution and when there is a need to account for zeros arising from separate processes.

In summary, the Zero-Inflated Negative Binomial regression is a powerful tool for modeling count data with excess zeros, providing a more accurate representation of the underlying processes generating the observed counts.

APPENDIX 05 : WALKING DISTANCES AT DIFFERENT PARKING DENSITY LEVELS

We provide several illustrative examples of how different parking corral densities translate into maximum walking distances to a parking corral, with the corrals arranged in 3x3, 5x5, and 9x9 grids. We chose square grids in order to roughly approximate placing parking corrals on corners of city blocks.

Note that a general rule of thumb for walking time is 1 minute per 100 meters.

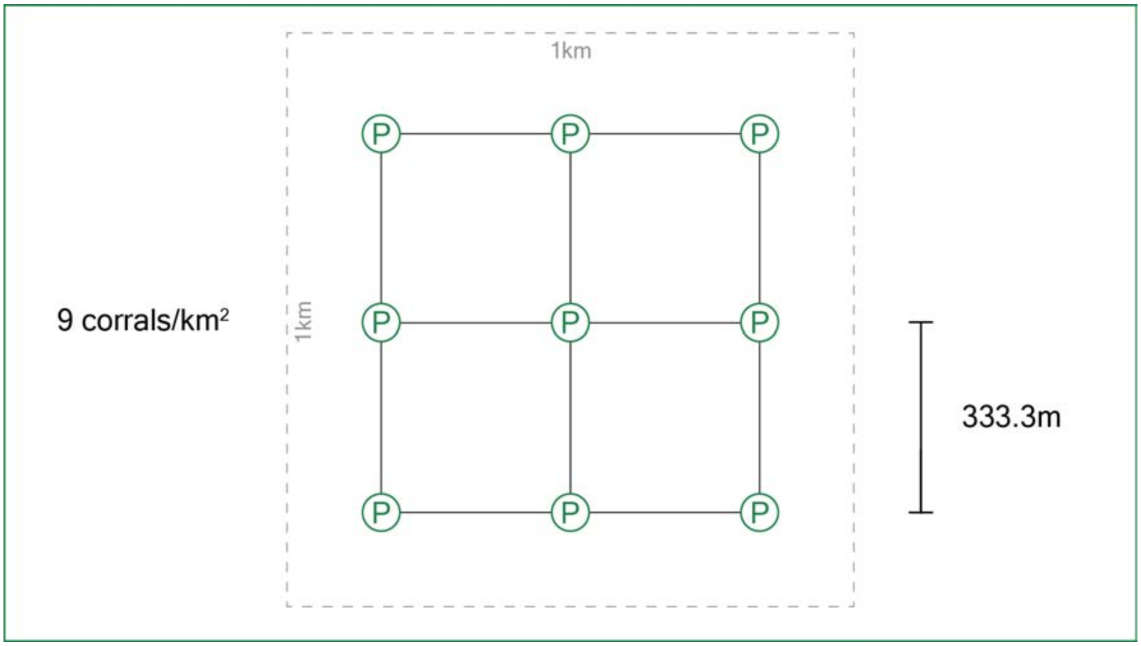
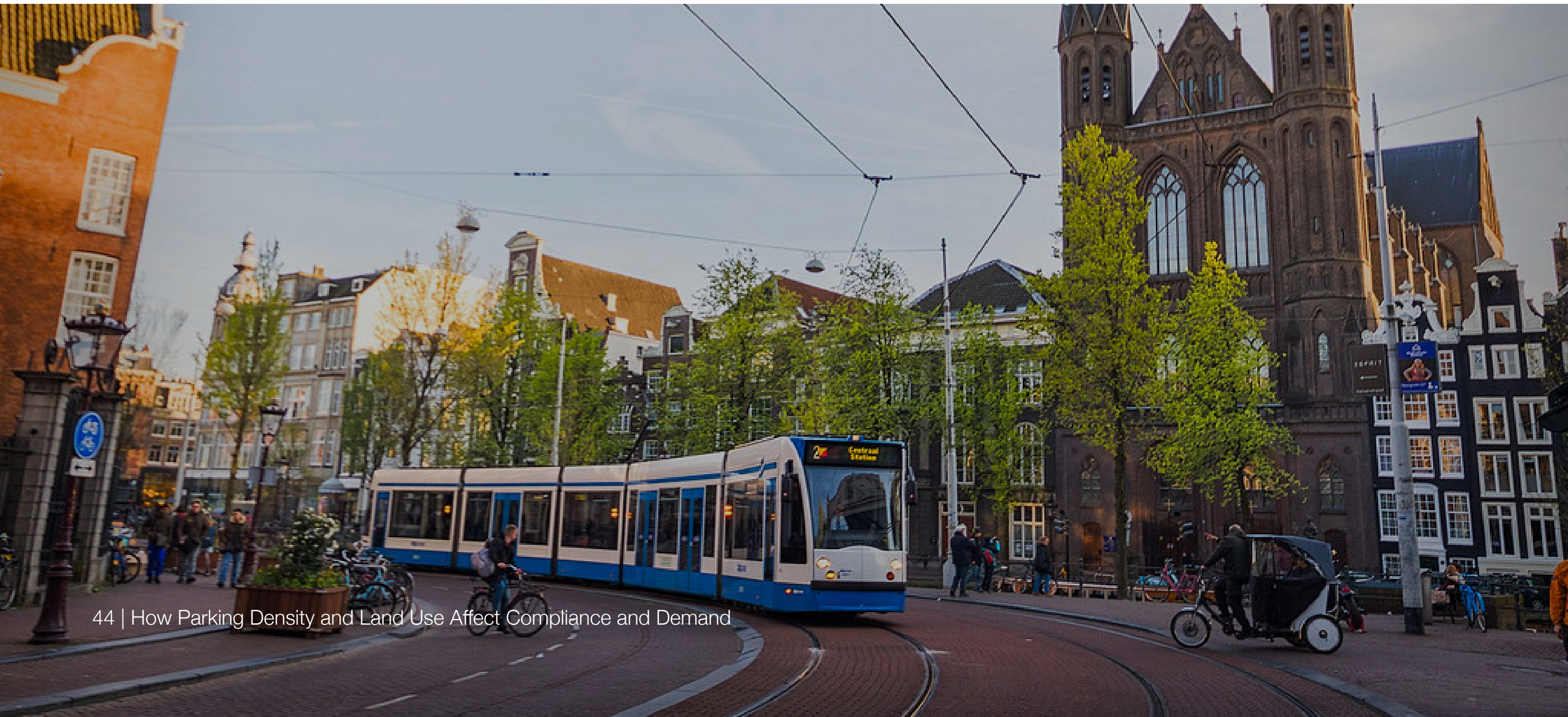


Figure A-4-1. Walking Distance with a Parking Corral Density of 9 corrals/km2, with Even Corral Distribution in a 3 x 3 Grid.



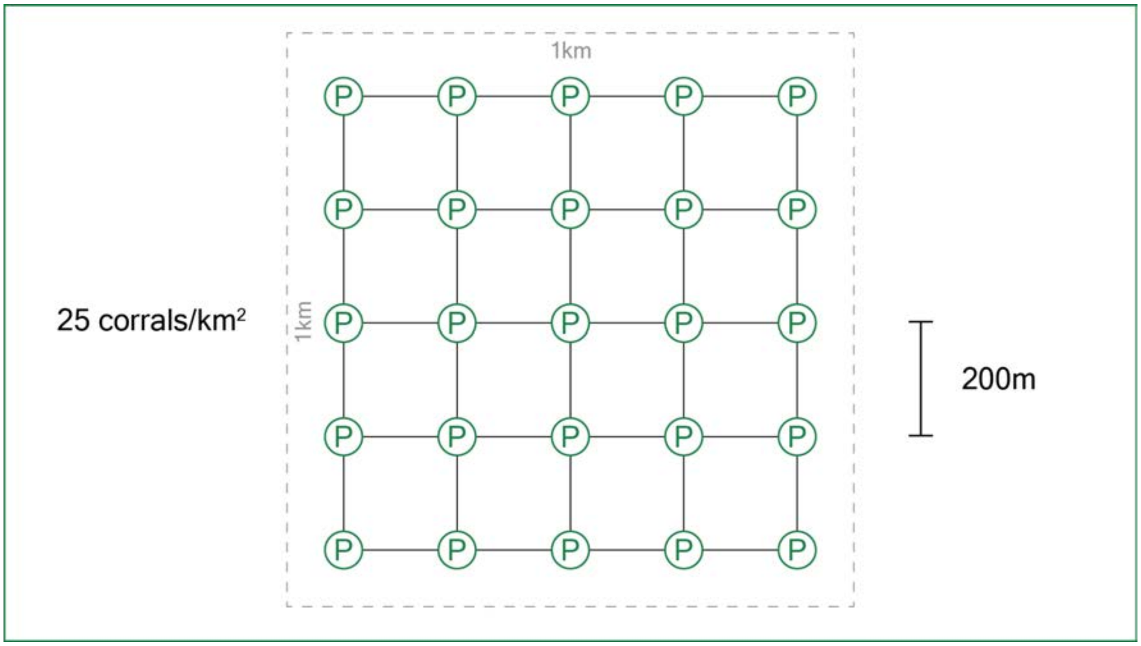


Figure A-4-2. Walking Distance with a Parking Corral Density of 25 corrals/km2, with Even Corral Distribution in a 5 x 5 Grid

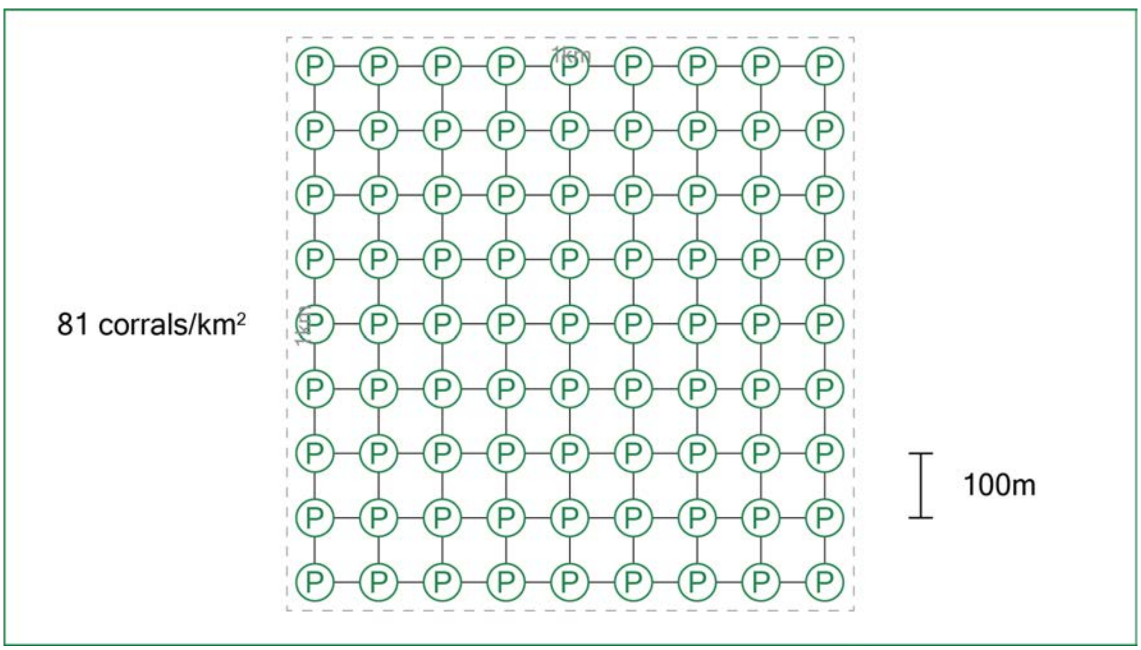


Figure A-4-3. Walking Distance with a Parking Corral Density of 81 corrals/km2, with Even Corral Distribution in a 9 x 9 Grid.

Calculation Method:

If a set number (N) of parking corrals are distributed in a grid fashion within a 1 km by 1 km square, the density is N per square km. With parking corrals arranged in a √N x √N grid, the distance between two corrals is 1000/√N meter, and the walking distance to/from a corral is between 1000/√N/2 (halfway along the edge of the square formed by the grid of corrals) and 1000*√2/√N/2 (halfway along the diagonal of the square formed by the grid of corrals).

APPENDIX 06 : ANNOTATED BIBLIOGRAPHY

Berg Wincent, B., Jenelius, E., & Burghout, W. (2023). Parkering av elsparkcyklar: Enkätundersökning av effekter och åsikter kring parkeringsförbudet i Stockholm, Göteborg och Malmö. https://kth.diva-portal.org/smash/record.jsf?pid=diva2%3A1753529&dswid=-8313

This study conducted in Sweden investigates the effects and perspectives regarding the implementation of a parking ban targeting users of shared electric scooters across the cities of Stockholm, Gothenburg, and Malmö. The primary objective of the survey is to comprehensively comprehend the desires and attitudes of users concerning the parking of e-scooters. As of 1 September 2022, a nationwide parking ban was enforced in Sweden, mandating that shared electric scooters be exclusively parked in designated areas allocated for electric scooters or bicycle parking lots. Notably, the cities of Stockholm and Malmö adopted divergent designs for their respective electric scooter parking systems. Stockholm built 700 scooter parking spaces in addition to the existing 75 spaces in the central city, while Malmo created 100 scooter parking spaces in central areas, otherwise expected to park at bike racks. However, the city of Gothenburg chose to postpone the introduction through localized traffic regulations.

After implementing the parking ban, Gothenburg riders were less likely to reduce their use, and e-scooter trips became longer in Stockholm and Malmö. Also, riders in these two cities reported walking further for access and egress. Riders in Stockholm were most positive about the parking ban, while riders in Malmö were most negative. The difference in perceptions can be explained by the higher density, more extensive location, larger size of the mandatory parking zone, and easier to close to a destination in Stockholm compared to Malmö. The median access distance to e-scooters is 200 meters, so half of the riders walk up to 200 meters to use an e-scooter. Lastly, the perceived orderliness of micromobility parking increased substantially, even though perceived availability declined substantially in both cities.

Brown, A., Klein, N. J., Thigpen, C., & Williams, N. (2020). Impeding access: The frequency and characteristics of improper scooter, bike, and car parking. Transportation Research Interdisciplinary Perspectives, 4, 100099. https://doi.org/10.1016/j.trip.2020.100099

This study aims to better understand how often micromobility and motor vehicles impede travelers' right-of-way. The authors hired research assistants to observe the parking behaviors of motor-vehicle drivers, bicyclists, and scooter users in five cities: Austin, TX; Portland, OR; San Francisco, CA; Santa Monica, CA; and Washington, D.C. Research assistants were trained to record parking behavior for 8h on both sides of a commercial street in high-density areas for three days a week. Results reveal that motor vehicles impede right-of-way more frequently than bicycles and scooters, which implies that cities should take a comprehensive approach to regulate the parking behaviors of all transportation modes.

Brown, A., Klein, N. J., & Thigpen, C. (2021). Can you Park your Scooter There? Why Scooter Riders Mispark and What to Do About It. Findings. https://doi.org/10.32866/001c.19537

The authors administered a survey on Lime scooter users to understand the reasons for misparking and potential measures for incentivizing proper parking behaviors. The online survey was conducted in five cities across three continents: Auckland, New Zealand; Cologne, Germany; Milton Keynes, England; Nashville, U.S.; and Rome, Italy. Results show that only 9% of users reported non-compliant parking and 19% were ambivalent. For those who had misparked, the primary reason was unfamiliarity with the parking rules, and users relied on the intuition of whether scooters impede access to assess parking compliance. The suggested incentives include providing an in-app reminder (37%), fining riders for misparking (18%), building physical signage (18%), and adding additional designated scooter parking spaces (16%).

Buehler, R., Broaddus, A., White, E., Sweeney, T., & Evans, C. (2023). An Exploration of the Decline in E-Scooter Ridership after the Introduction of Mandatory E-Scooter Parking Corrals on Virginia Tech's Campus in Blacksburg, VA. Sustainability, 15(1), Article 1. https://doi.org/10.3390/su15010226

This survey study investigates the impact of mandatory parking corrals on e-scooter ridership, egress time, and riders' perceptions of parking corrals. The authors aim to examine how e-scooter ridership and rider perceptions change in Virginia Tech's Blacksburg campus after the introduction of mandatory e-scooter parking corral in January 2022. The study utilizes a panel of 131 e-scooter riders surveyed in Fall 2021 and Spring 2022.

Findings suggest that perceptions of parking corrals became negative after the implementation, even though respondents perceived it favorably before. Ridership decreased by 72% overall and also declined for all socio-economic groups. The perceived problems include the parking corrals were not well-distributed, hard to find, fully occupied, and taking too much time to use. Additionally, some users reported that apps did not allow them to end trips sometimes. Regarding the desired and actual egress time, more than half of users desired egress times under 2 min, while roughly 70% of users desired less than 2 min after parking corral implementation. By comparison, more than 80% of users walked less than 2 min, but the actual egress time increased after parking corrals were available.

Buehler, R., Broaddus, A., Sweeney, T., Zhang, W., White, E., & Mollenhauer, M. (2021). Changes in Travel Behavior, Attitudes, and Preferences among E-Scooter Riders and Nonriders: First Look at Results from Pre and Post E-Scooter System Launch Surveys at Virginia Tech. Transportation Research Record: Journal of the Transportation Research Board, 2675(9), 335–345. https://doi.org/10.1177/03611981211002213

The authors utilize the e-scooter system at Virginia Tech as a case study to examine changes in travel behavior, attitudes, and preferences among e-scooter riders and nonriders. This study presents findings derived from two cross-sectional surveys administered prior to (n = 462) and subsequent to (n = 428) the introduction of a fleet of shared e-scooters on Virginia Tech's campus in Blacksburg, VA. This study investigates the perceptions about e-scooter parking, finding the perception of proper parking increased after launching the e-scooter system and perceptions shifted more significantly for riders. Additionally, non-riders were much more likely to notice improper parking than riders. The authors suggest that design incentives and infrastructure, such as bicycle racks, marked parking areas, and docked stations, can decrease the misparking rate to promote the positive perception of a shared micromobility system.

Fang, K., Agrawal, A., Steele, J., Hunter, J., & Hooper, A. (2018). Where Do Riders Park Dockless, Shared Electric Scooters? Findings from San Jose, California. Mineta Transportation Institute Publications. https://scholarworks.sjsu.edu/mti_publications/251

This early report examines where and how e-scooters were parked in San Jose, California. Results show: 1) Most shared e-scooters were parked on sidewalks; 2) The non-compliant parking is very low (less than 10%); And 3) almost 15% of e-scooters were parked on private properties.

Gössling, S. (2020). Integrating e-scooters in urban transportation: Problems, policies, and the prospect of system change. Transportation Research Part D: Transport and Environment, 79, 102230. https://doi.org/10.1016/j.trd.2020.102230

This study aims to investigate the challenges related to introducing shared e-scooter systems in ten cities. The author collected news items from print media, TV, and radio websites and conducted content analysis to analyze concerns before and after the implementation of e-scooters. Results indicate that parking is one of the most frequently discussed conflicts of implementing the shared e-scooter system, and the designation of parking (rental/return) areas may address this issue.

Heinen, E., & Buehler, R. (2019). Bicycle parking: A systematic review of scientific literature on parking behaviour, parking preferences, and their influence on cycling and travel behaviour. Transport Reviews, 39(5), 630–656. https://doi.org/10.1080/01441647.2019.1590477

This literature study systematically reviewed studies on bicycle parking. The number of studies on bicycle parking done in the past two decades is increasing significantly, but several empirical and methodological gaps have been identified and most studies did not exclusively focus on bicycle parking. The authors summarized three common findings across reviewed studies: 1) bicycle parking supply is positively related to bicycle parking; 2) The quantity and quality of bicycle parking determine the use of bicycles and the number of potential bicyclists; And 3) bicycle rides and non-riders prefer high-quality parking facilities over low-quality facilities or no facilities.

Hemphill, R., MacArthur, J., Longenecker, P., Desai, G., Nie, L., Ibarra, A., & Dill, J. (2022). Congested sidewalks: The effects of the built environment on e-scooter parking compliance. Journal of Transport and Land Use, 15(1), Article 1. https://doi.org/10.5198/jtlu.2022.2110

This study uses Portland's e-scooter pilot program as a case study to explore the effects of the built environment on parking compliance. The authors conducted a field survey to record non-compliance parking based on Portland's parking regulations and utilized GIS to generate parkable areas at the street level. The research specifically aims to examine the spatial pattern of parking non-compliance and the associations between dedicated parking areas and parking compliance.

Results show that 76% of e-scooters parked violated at least one of the officially designated parking requirements and 59% violated at least two requirements. The parking non-compliance rate reported in this study is much higher than those in other studies, but this may result from the complex and obscure parking requirements designated by Portland. Parking compliance is higher in streets with dedicated parking areas than in streets without dedicated parking spaces. Additionally, the amount of designated parking space is positively correlated to parking compliance.

James, O., Swiderski, J., Hicks, J., Teoman, D., & Buehler, R. (2019). Pedestrians and E-Scooters: An Initial Look at E-Scooter Parking and Perceptions by Riders and Non-Riders. Sustainability, 11(20), 5591. https://doi.org/10.3390/su11205591

This study examines shared e-scooter parking through surveys and field observations in Rosslyn, Virginia. The aim of the survey of riders and non-riders is to explore perceived safety and sidewalk-blocking issues, and the field observation investigates the association between micromobility parking and the built environment.

A dichotomy in perceptions of safety and improper parking has been observed between riders and non-riders, and non-riders perceive shared e-scooters more negatively than riders. A high proportion of non-riders (64%) and riders (46%) are not familiar with the e-scooter laws. The common misparking behaviors include not being upright (28%), blocking the pedestrian right-of-way (23%), or on private property (22%). Regarding land use, users are more likely to park e-scooters improperly near offices (25%), followed by off-street car parking (19), retail (16%), restaurants (16%), and residences (13%). Additionally, the overall misparking rate is not high (16%), and only 6% of e-scooters blocked the sidewalk.

Jiang, Q., Ou, S.-J., & Wei, W. (2019). Why Shared Bikes of Free-Floating Systems Were Parked Out of Order? A Preliminary Study based on Factor Analysis. Sustainability, 11(12), 3287. https://doi.org/10.3390/su11123287

This early research aims to investigate the reasons for the misparking of the shared bicycle. The authors developed a two-phase survey, with the first phase focusing on collecting reasons for the misparking and the second phase constructing structure and factors of disorderly parking. Factor analysis identifies 6 factors that may account for mispkaring: 1) supervision and management of enterprises; 2) supervision and management of users; 3) parking space; 4) guidance of parking shared bikes; 5) user self-discipline; and 6) operation and maintenance.

Klein, N., Brown, A., & Thigpen, C. (2023). Clutter and Compliance: Scooter Parking Interventions and Perceptions. Active Travel Studies, 3(1), Article 1. https://doi.org/10.16997/ats.1196

This study examines the effects of different interventions to address non-compliant parking and investigate public perceptions of misparking. The authors conducted field experiments, observations, and surveys in Washington, D.C., and Auckland, New Zealand. The field experiments explored the efficacy of three interventions: In-app messaging, sidewalk decals, and lock-to requirement, and the intercept surveys examined the public's perception of the quantity and definition of improper parking.

In-app messaging and sidewalk decals slightly decreased parking non-compliance, while lock-to requirements significantly improve compliance in D.C. The public tends to overcount the misparking of scooters and undercount the improper parking of bicycles and cars. Pedestrian accessibility and tidiness were the criteria for those unfamiliar with parking requirements to determine non-compliant parking.

Liazos, A., Iliopoulou, C., Kepaptsoglou, K., & Bakogiannis, E. (2022). Geofence planning for electric scooters. Transportation Research Part D: Transport and Environment, 102, 103149. https://doi.org/10.1016/j.trd.2021.103149

This study develops a methodological framework for planning geofence for e-scooters. Compared to Sandoval et al. 2021 and Zhang et al. 2019, this framework aims to enhance safety for e-scooter operation and considers the travel time impacts for users. Speed reduction and access restrictions are identified for geofences at the street level and A non-dominated sorting Genetic Algorithm (NSGA) is adopted to address the conflicts between users and operators.

Nivel. (2023). Test report—Scooter parking compliance Bergen. Google Docs. Retrieved June 14, 2023, from https://drive.google.com/file/d/1zrL7S9zU97Cu9L2uO-33HpxAkXZ7Qe-N/view?usp=embed_facebook

This report aims to compare the parking non-compliance between operators with and without designating virtual parking corrals in Bergen, Norway. In all, 6 operators inserted parking corrals into their apps, and Ryde did not implement this requirement, even though vehicles are required by the local ordinance to park within the marked parking area. Field observation was conducted to record misparking of all operators' scooters.

For regulated scooters, only 3.8% were parked 5 meters or longer away from the marked parking areas (counted as misparking), while 50.3% of Ryde scooters were misparked. The report acknowledges the effects of social contagion - the first scooter parked in an area is likely to influence subsequently parked scooters. Additionally, this observation study seems to indicate that compliance was achieved without the need to add further technological solutions (e.g., Bluetooth triangulation concepts). Nevertheless, all the parking spots were clearly marked in Bergen, which can decrease parking non-compliance.

Reck, D. J., Martin, H., & Axhausen, K. W. (2022). Mode choice, substitution patterns and environmental impacts of shared and personal micro-mobility. Transportation Research Part D: Transport and Environment, 102, 103134. https://doi.org/10.1016/j.trd.2021.103134

This study utilizes multi-source data to explore the factors influencing the selection of transportation modes, specifically shared and personal micromobility options. The study aims to establish a foundation for understanding the substitution patterns and environmental implications associated with these modes. Notably, the results reveal a notable distinction in the penalization of access distance for shared e-scooters (-5.89) compared to public transport (-2.29) and shared e-bikes (2.43), signifying a substantial disparity in the perceived impact on access distance among these modes.
wShared scooter riders are not willing to walk long distances to a vehicle: "Users of shared e-scooters are willing to walk an average of 60m and a maximum of 210 m to access a vehicle, while users of shared e-bikes are willing to walk an average of 200 m and up to 490 m to access a vehicle. Public transport users are willing to walk even longer (average: 400m) to reach their preferred stop." The authors provide three potential explanations for the disparity in the penalty of the access distance across public transport, shared e-bikes, and e-scooters: the concentration of shared micromobility services in the urban center, shorter travel distance of e-scooters, and the inability for users to pre-reserve vehicles so that they will be available when they arrive at the vehicle.

Sandoval, R., Van Geffen, C., Wilbur, M., Hall, B., Dubey, A., Barbour, W., & Work, D. B.

(2021). Data driven methods for effective micromobility parking. Transportation Research Interdisciplinary Perspectives, 10, 100368. https://doi.org/10.1016/j.trip.2021.100368

The authors develop a methodological framework to determine the location of parking corrals. Different from Zhang et al 2019's work, they take the width of the sidewalk into account to address problematic trips parked on the narrow sidewalks, even though the overall trips served would decrease by 13%. Nevertheless, this OD data-based approach still bears the disadvantages of Zhang et al's work.

Su, D., Wang, Y., Yang, N., & Wang, X. (2020). Promoting considerate parking behavior in dockless bike-sharing: An experimental study. Transportation Research Part A: Policy and Practice, 140, 153–165. https://doi.org/10.1016/j.tra.2020.08.006

This study examines the efficacy of three behavior interventions to improve orderly parking. A randomized field experiment was conducted on the campus of Beijing Jiaotong University. The trial randomly assigned participants to receive one of three interventions, including being informed about the social norm, receiving a warning message, or being offered a monetary incentive. Results show that warning messages and monetary incentives are more effective in promoting parking compliance than social norm interventions.

Tucson Department of Transportation and Mobility (TDOT). (2020). Tucson E-Scooter Pilot Program Evaluation. https://www.tucsonaz.gov/files/bicycle/documents/E-Scooter_Pilot_Evaluation.pdf

This report comprehensively reviews the e-scooter pilot program by analyzing trip, survey, and field observation data. Four evaluation metrics were developed, including ridership & utilization, safety & rider behavior, public input & stakeholder feedback, and equity. Regarding e-scooter parking, the research team observed: "76% of all e-scooters were well parked; 17% were improperly parked; and approximately 7% were questionably parked." Additionally, for survey respondents, the top response for changes the public would like to see is to increase designated e-scooter parking.

Zhang, Y., Lin, D., & Mi, Z. (2019). Electric fence planning for dockless bike-sharing services. Journal of Cleaner Production, 206, 383–393. https://doi.org/10.1016/j.jclepro.2018.09.215

This paper develops a methodological framework to plan electric fences (parking corrals) for dockless bikeshare services. The authors utilized trip data to identify high parking demand areas and employed maximum coverage methods to select locations for parking corrals. The final accurate location will be adjusted by the road network.

This demand-based parking corral designation is efficient but problematic. First, trip generation and attraction cannot directly translate to parking demand, since turnover, rebalanced vehicles, existing vehicles, vehicles out of service, and the existence of other micromobility vehicles are neglected. Second, this approach overlooked the parking compliance that the general public is concerned about to a great extent. Lastly, shared micromobility systems evolve quickly, so this planning method for parking corrals may not meet the latent demand of many potential users and discourage them from using the service.

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