

## Cities with dense networks of shared scooter parking have higher parking compliance

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**Abstract:** Many cities seek solutions to address public concerns about non-compliant shared electric scooter (e-scooter) parking. One strategy is to provide designated parking areas, called “corrals.” However, it remains unclear how much parking infrastructure is needed to improve compliance, or how this varies by land use. To address this gap, our study investigates: How dense does a network of dedicated shared micromobility parking need to be to increase compliance? How large should parking corrals be to meet demand? And how do these relationships vary by land use? We used e-scooter and built environment data in 12 cities worldwide and conducted descriptive, regression, and non-linear analyses. Results reveal that providing at least 20-30 parking corrals per square kilometer (about 50-80 per square mile or a one-minute walk in gridded areas) dramatically improves parking compliance. The spatial distribution of corrals is particularly important in areas with low corral density, where providing uniform coverage can significantly reduce parking non-compliance rates. Land-use intensity variables are non-linearly associated with parking non-compliance but suggest that parking corrals should have greater capacity in areas with more leisure, mixed-use, office, transit, and tourism destinations compared to places with more commercial or residential destinations. These findings offer direct policy recommendations to improve parking compliance and better match demand.

**Keywords:** shared e-scooter, parking density, parking compliance, land use, parking demand

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## 1 Introduction

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 free-floating dockless parking. In contrast to previous systems that required riders to return vehicles to a physical docking station, the latest shared scooter and bicycle programs often allow riders to travel point-to-point and park adjacent to their destinations. The flexibility and convenience of this model have contributed to rapid adoption: overall shared micromobility trips in North America doubled from 2017 to 2018 following the introduction of dockless scooters and bikes (NACTO, 2022).

However, many shared micromobility systems face concerns that non-compliant parking can obstruct sidewalks, storefronts, and pedestrian ramps (Chen et al., 2020; Fang et al., 2018; Hemphill et al., 2022). Some cities have subsequently moved to designate parking spaces for shared micromobility vehicles and either require or encourage riders to park vehicles in identified locations. We refer to designated parking for shared micromobility vehicles—which includes varying implementation models such as bike racks, geofenced virtual corrals, and physical corrals—collectively as “parking corrals” throughout the remainder of the paper. However, it remains unclear how much parking infrastructure is needed to improve compliance, and how infrastructure needs vary by land use. In other words, how much shared micromobility parking should be provided, and where?

In this paper, we consider two dimensions of parking need. First, how dense does a network of dedicated shared micromobility parking need to be to reach high levels of parking compliance? Second, how large should parking corrals be to meet demand? And finally, how do these relationships vary by land use? We used e-scooter trip data from 12 international cities to answer these questions, with findings offering practical implications for cities seeking to refine an existing parking network or implement new parking networks across a range of built environments.

## 2 Literature review

### 2.1 Shared micromobility parking challenges

The new dockless, free-floating model of shared micromobility 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). People report misparking when they do not know parking regulations, parking rules are unclear, suitable parking is unavailable, they are in a hurry, or they observe others misparking nearby (Brown et al., 2021). Despite the confusing array of parking regulations, studies from cities around the world confirm that the rate of improper parking is less than 10% in urban commercial areas (Brown et al., 2021; Fang et al., 2018; Klein et al., 2023). Research also finds that the majority of e-scooter riders want to park properly and can correctly identify non-compliant parking (Brown et al., 2021).

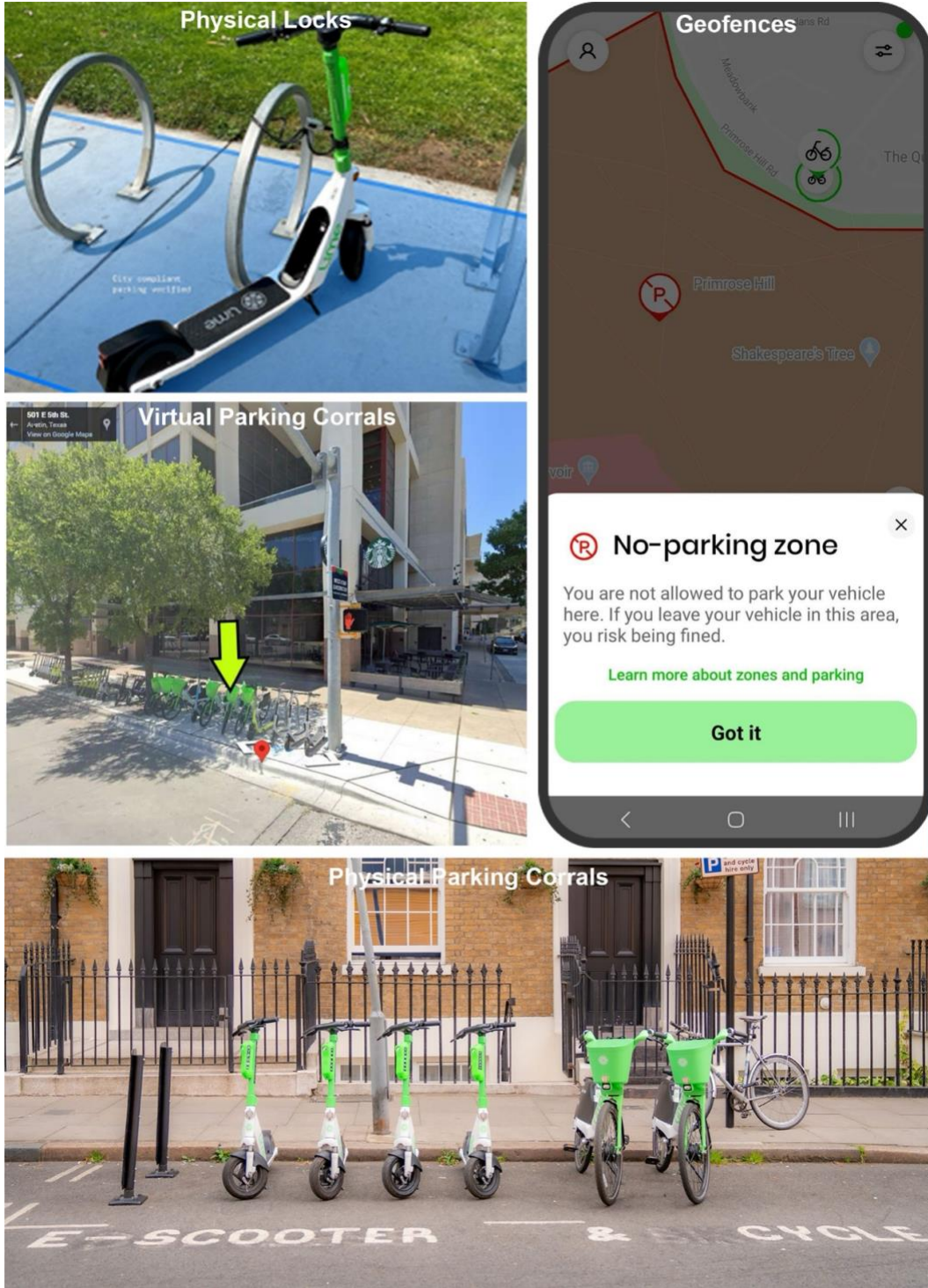
Parking non-compliance rates inevitably vary from city to city based on the local parking regulations, as well as other factors such as familiarity with bicycling, norms, and local culture. Though improper e-scooter parking has received a good deal of media attention (Gössling, 2020), and was likely one of the main driving forces behind Paris’ ban on shared e-scooters in September 2023 (Keane, 2023), there is evidence that car drivers are more likely to mispark their vehicles than e-scooter riders (Brown et al., 2020). The low observed rates of e-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 public also exhibits a more negative perception of shared micromobility parking compared to people who own personal micromobility vehicles (Buehler et al., 2021); similarly, riders observe fewer parking issues compared to non-riders (Brown et al., 2025). As neither riders nor non-riders are familiar with official parking requirements (James et al., 2019), people often utilize heuristics, such as pedestrian accessibility and tidiness, to evaluate parking compliance (Klein et al., 2023).

## 2.2 Efforts to manage shared micromobility parking

While studies report relatively infrequent rates of misparking in commercial districts, shared micromobility parking remains critical due to its potential impact on non-rider access and the outsized effect it plays in both public dialogue and reception of shared micromobility services. Shared e-scooter parking management relies heavily on the actions of three key stakeholders: the government, shared e-scooter riders, and service providers. This “iron triangle” of roles can play a significant part in mitigating improper parking behaviors (Jiang et al., 2019). Cities have implemented a range of schemes to manage shared micromobility parking, including a mix of spatial planning interventions and aspatial policy incentives, such as rewards, penalties, and guidelines (Si et al., 2024). Spatial planning interventions can apply area-level approaches (e.g., service areas, no-parking zones, no-operational zones (Moran et al., 2020), and mandatory parking zones (MPZs)), hybrid parking approaches (including a mix of mandatory and free-floating areas), and street-level approaches (e.g., physical locks on the e-scooters, virtual parking corrals or geo-fence (Mangold et al., 2022), and physical parking corrals) (Figure 1). Table 1 briefly introduces these approaches. Washington, DC, USA, offers one example of how cities may combine approaches in a hybrid parking scheme within a single context. The city implements variable spatial requirements, including MPZs at the National Mall (a prominent tourist destination) alongside free-floating parking elsewhere in the city with preferred (but not required) corrals located at strategic locations. Aspatially, the city implemented a lock-to requirement in 2021, requiring all shared e-scooters to be locked to bike racks or other street furniture (Nabizad, 2021). The city has also tested wayfinding, corral design, and in-app messaging as both spatial and aspatial approaches to managing shared micromobility parking. Previous research identifies positive, albeit limited, effects of app-based messaging and corral design on shared micromobility parking behaviors (Brown et al., 2024; Klein et al., 2023). Relatedly, improved micromobility parking is supported by the 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).

Previous research suggests that individual parking behaviors are shaped by both extrinsic factors such as city efforts to provide parking, enforce compliance, or levy fees, but also intrinsic factors. A study based on the theory of planned behavior and prosocial behavior motivations suggests that social norms, reciprocity, fairness, and a sense of responsibility are key factors related to compliant parking (Wang et al., 2021). Therefore, policies that foster social responsibility, such as community engagement campaigns, could improve compliance, although the effects of such efforts on parking behaviors have not been studied. This paper similarly sets aside these potential intrinsic motivators to focus on spatial interventions, particularly how providing dedicated parking for shared micromobility vehicles can affect misparking.



**Figure 1.** Commonly adopted methods for improving parking compliance  
*Sources: Lime*

**Table 1.** Approaches to reduce parking non-compliance

Approaches	Descriptions
<i>Spatial: Area-level planning interventions</i>	
Mandatory parking zones	Vehicles must park at specific locations designated in the shared micromobility app.
No parking zones	Vehicles are not allowed to park in designated zones within the shared micromobility app.
No operational zones	Vehicles are not allowed to be ridden or parked in designated zones within the shared micromobility app.
<i>Spatial: Street-level planning interventions</i>	
Physical locks on e-scooters	Parked vehicles must be locked to a stationary object (e.g., bicycle rack) using a physical lock, such as a cable lock.
Geofenced virtual parking corrals	Designated parking corrals shown virtually in the app but not marked with physical infrastructure.
Physical parking corrals	Designated physical corral marked with signs, bollards, striping, decals, and/or bicycle racks. Parking corrals may also be designated in the app.
<i>Aspatial policy incentives</i>	
Fines and penalties	Imposing fines on users who park e-scooters improperly. These penalties are often enforced by the e-scooter company or local authorities.
Reward programs	E-scooter operators encourage proper parking by offering discounts, ride credits, or loyalty points for users who follow parking rules or move improperly parked vehicles to designated parking spots.
In-app education	Apps include information to instruct users where and how to park their scooters responsibly before starting the ride, during the ride, or before ending the ride.
In-app photo verification	Apps require users to upload a photo of the parked scooter at the end of their ride to encourage proper placement in designated zones.
Public education	Cities and companies run awareness campaigns to educate riders on the importance of parking compliance to minimize disruption to public spaces.

**2.3 Spatial interventions to manage parking: Opportunities and challenges**

Current literature on dedicated micromobility parking suggests its promise to mitigate misparking, but also substantial challenges when insufficient parking is provided. In Bergen, Norway, most shared e-scooter operators require users to park at designated parking corrals, resulting in fewer than 4% of e-scooters being misparked (i.e., parked more than 5 meters from the corral). Scooters from another operator in Bergen, which 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). In neighboring Sweden, however, a staggered and varied implementation of mandatory parking requirements suggests nuance in how mandatory parking and infrastructure are implemented (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 sparser 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 e-scooters, suggesting that without appropriate implementation, mandatory parking requirements may have adverse effects on ridership.

Providing sufficient infrastructure, whether it be bike racks or physical or virtual parking corrals, relates to 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 that for 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 minute (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 studies on the relationship between trip distance and acceptable access/egress walking distance suggest that e-scooter riders are likely to tolerate a walking distance of 100 to 200 meters, given the generally short nature of e-scooter trips. However, in the absence of dense parking infrastructure, the actual walking distance from designated parking corrals to riders' final destinations often exceeds the acceptable range. This discrepancy increases the likelihood of non-compliant parking behavior, as users may opt for convenience over regulatory compliance. Such findings motivate this study: how much parking is needed to increase compliance? Specifically, how dense does a parking network need to be? How large should parking corrals be to meet demand? And how do these relationships vary by land use?

### 3 Methods

#### 3.1 Study areas and analysis unit

We selected 12 cities worldwide representing a range of built environments, parking approaches, and geographic contexts (see Table 2).<sup>1</sup> Importantly, sampled cities present varied parking approaches. One city operated a full mandatory parking zone, meaning that e-scooters must park in designated corrals throughout the entire service area. Three cities had no parking requirements and instead allowed free-floating parking anywhere within the service area (except for select no-parking zones or other fine-grained parking requirements like no parking adjacent to bus stops, etc.). The remaining eight cities used a hybrid approach in which portions of the city had designated MPZs (typically in a central business district, park, and/or residential neighborhood), but other areas offered free-floating parking.

Our first question sought to answer: how dense does a parking network need to be to increase compliance? To investigate this, we examined one city with full MPZs and portions of cities with hybrid approaches. In the one city with full MPZs (Stockholm, Sweden), we included the full operating area in the analysis. In cities with hybrid approaches—although corrals may be located both in and outside of MPZs—we included only the MPZ portion of the service area (see Figure 2; described in further detail in subsequent paragraphs). We excluded free-floating portions of hybrid-approach cities as we anticipated that parking behaviors varied across spaces due to (lack of) enforcement. We used a different subset of cities or service areas to answer our second question: how large should parking corrals be, and how does this vary across space? For this analysis, we sought to measure organic e-scooter travel demand rather than demand shaped by MPZ policy, which by definition constrains parking locations. To measure rider-driven

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<sup>1</sup> Geographical boundaries varied across the sample cities. Many micromobility systems, for example, operated within a single incorporated city (e.g., US and European cities); Tel Aviv, however, incorporated the broader Tel Aviv District, which includes both Tel Aviv and neighboring cities. Boundaries were selected to match e-scooter service areas. When service areas spanned multiple cities (e.g., Tel Aviv), we reported district-level characteristics for the metropolitan area.

demand for parking, we therefore included only cities with either an entirely free-floating parking approach or only the portion of hybrid-approach cities that operated outside of the MPZ (i.e., free-floating) to estimate organic demand for parking rather than one affected by parking policy.

**Table 2.** Characteristics of case study cities.<sup>2</sup>

City	Parking Approach	Region	City Population	Urban Area (km <sup>2</sup> )	Population Density (n/km <sup>2</sup> )	Operational Vehicles	Number of Parking Corrals	Parking Corral Density (corrals per km <sup>2</sup> )
Madrid, Spain	Hybrid MPZ	EU	3,223,000	585.5	5,505	2,791	1,390	27.11
Tel Aviv District, Israel	Hybrid MPZ	MENA	1,452,400	172	8,444	3,354	1,162	45.36
Stockholm, Sweden	Full MPZ	EU	975,551	185.5	5,260	1,260	2,622	96.61
Lubeck, Germany	Free Floating	EU	216,227	214.2	1,010	431	0	N/A
Cologne, Germany	Hybrid MPZ	EU	1,086,000	409.8	2,650	3,834	27	17.06
Munich, Germany	Hybrid MPZ	EU	1,472,000	307.4	4,788	5,736	69	17.36
Charlotte, NC, USA	Free Floating	US	879,709	800.5	1,099	618.16	22	13.02
Denver, CO, USA	Free Floating	US	711,463	396.4	1,795	2,491	418	12.2
Long Beach, CA, USA	Hybrid MPZ	US	466,742	131.2	3,557	947	211	11.98
Cincinnati, OH, USA	Hybrid MPZ	US	308,935	201.79	1,531	387	331	69.19
Lubbock, TX, USA	Hybrid MPZ	US	260,993	348.9	748	768	66	27.37
Washington, DC, USA	Hybrid MPZ	US	712,816	168.4	4,232	2,545	159	13.62

While it may seem counterintuitive to select portions of the same hybrid service areas in each of the two analyses rather than selecting two entirely different sets of cities, we argue that this approach offers two critical strengths. First, it creates a uniform backdrop of cultural and environmental factors across the analyses to foster a more cohesive understanding of parking compliance and demand. And second, because MPZ designation is not random and correlates strongly to land-use factors and the number of corrals installed (i.e., more parking corrals deployed in MPZs compared to non-MPZs), we mitigate potential multicollinearity issues by focusing on either the MPZ or the free-floating portion of a service area.

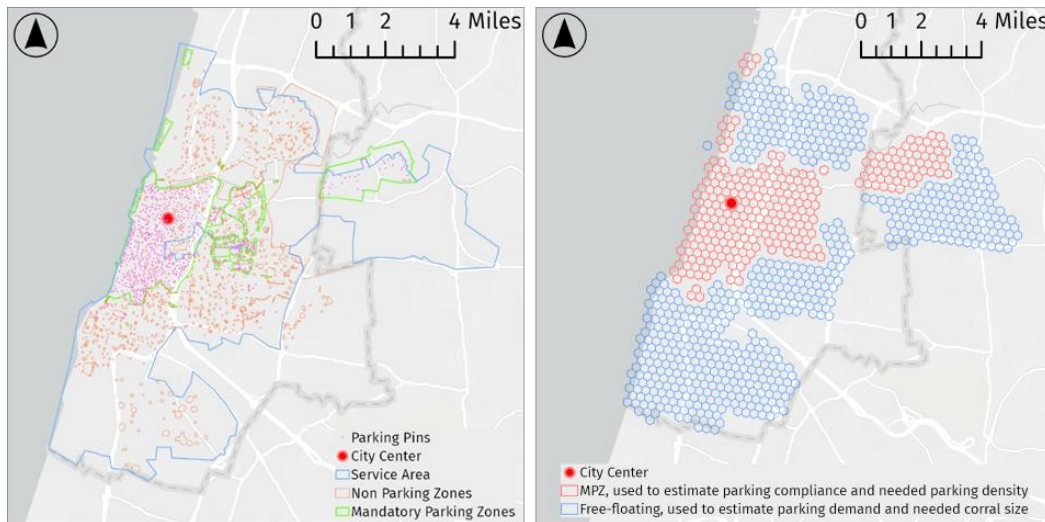
The analysis unit in this study is spatial: a fine-grained hexagonal area representing approximately 0.1 square kilometers (H3 hexagon spatial framework at the resolution 9 level (Sahr et al., 2003)). The uniform grid ensures trip anonymity for travelers, while also providing a consistent analysis unit across cities and countries with variable census

<sup>2</sup> The data source of these city-level characteristics regarding e-scooters is shown in the next section. The US represents the United States, the EU signifies the European Union, and MENA is an acronym for the Middle East and North Africa region.

units and traffic analysis zones. The discrete hexagonal grid system has been widely used to understand trip generation and travel in both the transportation industry (Brodsky, 2018) and academia (Shaji et al., 2022; Šidlovský & Ravas, 2023; Woźniak & Szymański, 2021).

Figure 2 illustrates the hexagonal unit of analysis in Tel Aviv (hybrid MPZ). The left-hand map displays the service area, parking corrals, mandatory parking zones, and no-parking zone boundaries. Notably, most parking corrals are situated within MPZs, with only a few located outside these MPZs, where riders are not obligated to park at the corrals. The right-hand map highlights the hexagonal units of analysis, including how different portions of the operating area are alternately used to measure parking compliance in red (how dense does a parking corral network need to be in order to improve compliance?) or organic parking demand in blue (how large should corrals be to meet rider demand?). Hexagons that intersected with or were contained by the MPZ were classified as part of the study area to examine parking compliance. Conversely, if a hexagon did not intersect with any MPZ, it was classified as part of the study area for parking demand analysis.

Not all portions of the service area were included in the analysis. We excluded hexagons entirely situated within no-parking zones, where riders are prohibited from parking their vehicles. To ensure the integrity of the analyses and eliminate potential bias on organic travel behavior resulting from being near the MPZs, we removed any blue hexagons immediately adjacent to the red ones (Figure 2). This precautionary measure aimed to mitigate any influence of MPZs on parking behaviors within the free-floating (blue) study areas.



**Figure 2.** Example of designated parking areas (left) and study areas (right) in Tel Aviv, Israel

### 3.2 Data and variables

To ensure consistent data collection across multiple cities in different regions and minimize bias in subsequent statistical analyses, we adopted a dual approach. First, shared micromobility data were acquired using the Mobility Data Specification (MDS), a standardized framework designed to facilitate uniform communication and data-sharing between micromobility providers and cities. Second, we mainly used OpenStreetMap (OSM), a globally recognized, community-driven database of geographic features, and

the Global Human Settlement Layer (GHSL), a database developed by the European Commission for assessing human presence, to construct built environment variables. This combined approach ensured data consistency and replicability of this study. All data and variables were aggregated into the hexagonal unit of analysis.

3.2.1 Variables generated by shared e-scooter data

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

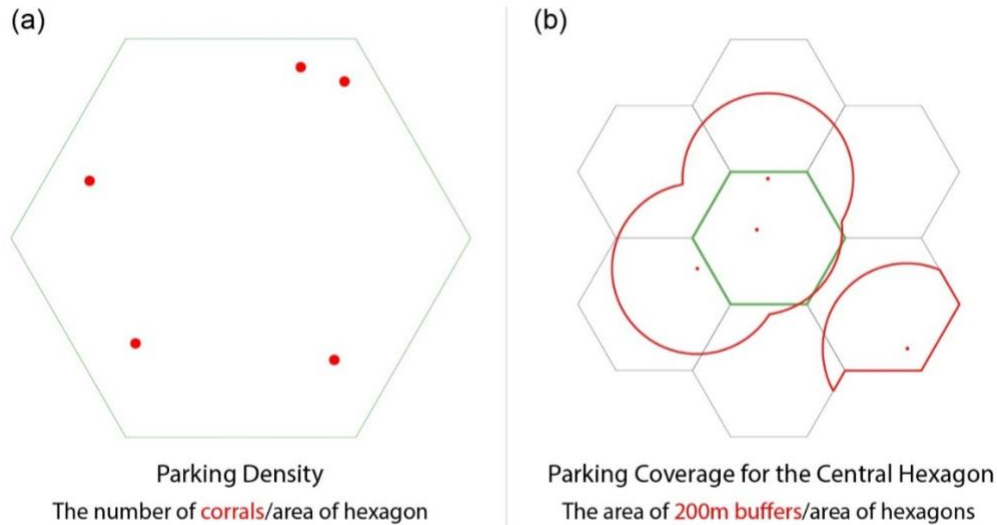
**Table 3.** Variables generated from shared e-scooter data

Variable	Description	Unit	Data source
<i>Hexagon level</i>			
Parking corrals	The number of parking corrals in a hexagon	n	Lime
Parking non-compliance	The share of trips ending outside the parking corral buffers	%	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 (a))	n/km <sup>2</sup>	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 (b))	%	Lime
<i>City level</i>			
City	The city in which a certain hexagon is located	n/a	Lime
Parking corral density	The number of parking corrals in a city divided by the area of mandatory parking zones	n/km <sup>2</sup>	Lime
Operational vehicles	The total number of vehicles operating in a city	n	Lime
Parking types	Parking types include full and hybrid mandatory parking zones and free-floating systems	n/a	Lime

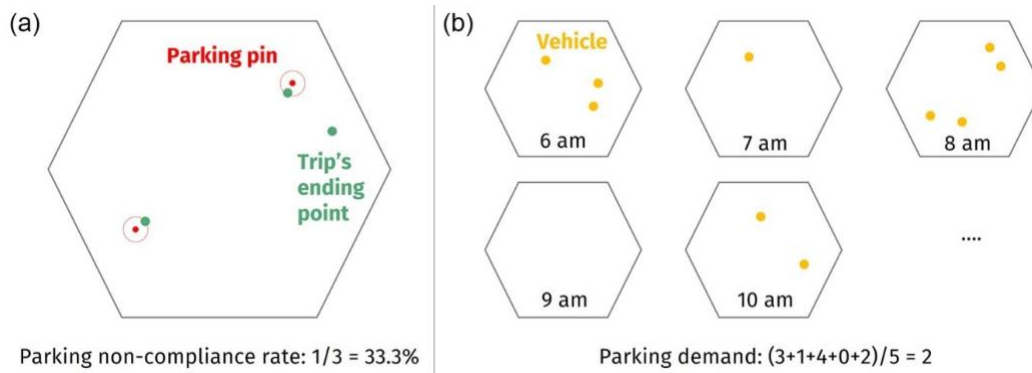
MPZs typically include a small “buffer” radius around the central corral location to account for GPS drift that is common across all GPS technologies, including shared e-scooters. GPS units in most modern electronic devices, including vehicles like e-scooters, have average accuracies of about 5 meters, 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 parking corral buffers typically ranges from 15 to 20 meters so that riders can park the e-scooter even with minor GPS inaccuracies (Nivel, 2023). Figure 3 visually depicts the process of generating parking density and coverage variables using simplified examples.

For the parking non-compliance rate, we determined the ratio of non-compliant trips to the total number of trips within a hexagon (Figure 4 (a)). As an illustration, let us 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). For parking demand, we calculated the average e-scooter occupancy throughout the study period, which was similar to the method of

calculating vehicle parking demand developed by ITE (2023). For instance, if we count the number of e-scooters within a hexagon five times from 6 am to 10 am on a given day, the individual counts might be 3, 1, 4, 0, and 2 (Figure 4 (b)). The parking demand would then be calculated as the average of these counts, which is 2 (i.e.,  $(3 + 1 + 4 + 0 + 2) / 5$ ). The measure of parking demand consists of parked e-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. Also, it represented the current demand for e-scooter parking with respect to the existing fleet size, which did not include the latent parking demand.



**Figure 3.** Illustrations of parking density and coverage variables



**Figure 4.** Illustrations of generating dependent variables: parking non-compliance rate and parking demand

3.2.2 Variables generated by built environment data

We used built environment data from various sources to generate land-use intensity variables at the hexagon level (Table 4), which are denoted by the 5 “D” variables commonly used in travel behavior analysis: density, diversity, design, distance to the city center, and destination accessibility (Cervero et al., 2009; Ewing & Cervero, 2010). We also created a specific land-use type for each hexagon, corresponding to seven major point-of-interest (POI) types based on OpenStreetMap’s official classification (Ramm, 2022), including commercial, leisure, office, public service, residential, tourism, and transit POIs. The technical details of generating the land-use type variable are attached in Appendix A.

**Table 4.** Variables generated from built environmental data

Variable	Description	Unit	Data source
<i>Hexagon-level</i>			
Population density	The average of all intersected 1km by 1km grid cells	n/km <sup>2</sup>	Global Human Settlement Layer - Population 1km Grid in 2020 (Schiavina et al., 2023)
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 A)	n/a	OpenStreetMap General Transit Feed Specification (GTFS)
Intersection	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
<i>City-level</i>			
Population density	Population per square kilometer	n/km <sup>2</sup>	(Brinkhoff, 2023)
Population	The population of the city	n	(Brinkhoff, 2023)
Urban area	The area of the city	km <sup>2</sup>	(Brinkhoff, 2023)
Continent	NA, EU, or MENA	n/a	N/A

*Note: Table B1 details the means of variables for each city used in the analysis.*

3.3 Data analysis

We analyzed data in this study in several steps. First, we conducted descriptive analyses to examine the distribution of variables of interest (see Appendix B). Second, we used linear and zero-inflated negative binomial regression models, with e-scooter parking non-compliance rate and parking demand as dependent variables, respectively. The model choice for each regression analysis depends on the type of the dependent variable. Because parking demand is a count variable and has an over-dispersed and zero-inflated distribution, the zero-inflated negative binomial regression model is more suitable than the linear regression model. We reported the Incidence Rate Ratio (IRR) instead of regression coefficients to enhance interpretability. An IRR greater than 1 indicates an increase in the incidence rate, while an IRR less than 1 signifies a decrease. For example, an IRR of 1.1 for parking corral density suggests that adding one additional

corral per square kilometer is associated with a 10% increase in parking demand, assuming the effects of all other variables are held constant statistically. Additionally, 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 included in the regression models. By doing so, we could control the influence of city-level factors on parking non-compliance and demand.

Previous findings from a Lime analysis suggest a potential non-linear relationship between parking corral density and parking non-compliance (Murphy & Haydu, 2023); we, therefore, employed Gradient Boosting Decision Tree (GBDT) analysis (Friedman, 2001, 2002). GBDT combines two machine-learning approaches: decision trees and gradient boosting. 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 the feature's 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 (Breiman, 2017):

$$I_k^2(T) = \sum_{t=1}^{J-1} \hat{\tau}_t^2 I(v(t) = k) \quad (1)$$

Where  $\hat{\tau}_t^2$  refers to the reduction in squared error,  $v(t)$  denotes when variable  $x_k$  is utilized in splitting variables;  $J$  represents the number of partitioned regions by the tree  $T$ . Equation 3 calculates the importance of a variable in a single tree, and the overall importance can be generated by averaging all trees in the sequence. 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 relations between independent variables and the dependent variable. This allowed us to explore non-linear relationships between shared e-scooter parking facilities, land-use intensity, and parking non-compliance and demand. Additionally, we conducted several analyses to determine the robustness of both linear and non-linear analyses, with the dataset split based on cities and land-use types. The results of robustness tests are shown in Appendix C.

### 3.4 Limitations

This study utilized e-scooter trip, vehicle, and parking facility data and open-sourced built environment data to examine how parking density and land-use patterns relate to parking compliance and demand. However, we acknowledge several limitations regarding the methods. First, although this study collected data in multiple cities worldwide, the cross-sectional study design was subject to heterogeneities due to the omitted variables and reverse causality. Thus, it is hard to claim that parking facilities and land-use patterns have causal effects on parking compliance and demand. Second, the parking demand was measured according to the current fleet size and use pattern, so the latent demand for e-scooter parking was not included in this study. For instance, the study does not account for unmet demand in areas where e-scooter availability or usage is low or nonexistent, including many disadvantaged neighborhoods (Dill & McNeil, 2021). Underestimating the need for parking infrastructure in these underserved locations may

further discourage using e-scooters and create a vicious circle. Third, the spatial resolution of the parking corral was limited by using a radius to define parking areas due to the GPS drifting issue. This radius (around 20 meters) is larger than typically painted corral spaces in the street and may not accurately capture whether e-scooters blocked sidewalks or caused other localized issues. Therefore, non-compliant parking behaviors examined in this study were beyond the street level. Future studies should incorporate finer-grained spatial data to better assess micro-level misparking behaviors. Last, this study does not account for temporal variations in the results. Factors such as peak hours, days of the week, and seasonality may influence riders' parking behaviors. Future research could address this limitation by utilizing datasets with a longer time span to explore temporal heterogeneity and better understand how parking behaviors fluctuate over time.

## 4 Results

### 4.1 How dense does parking need to be to increase compliance?

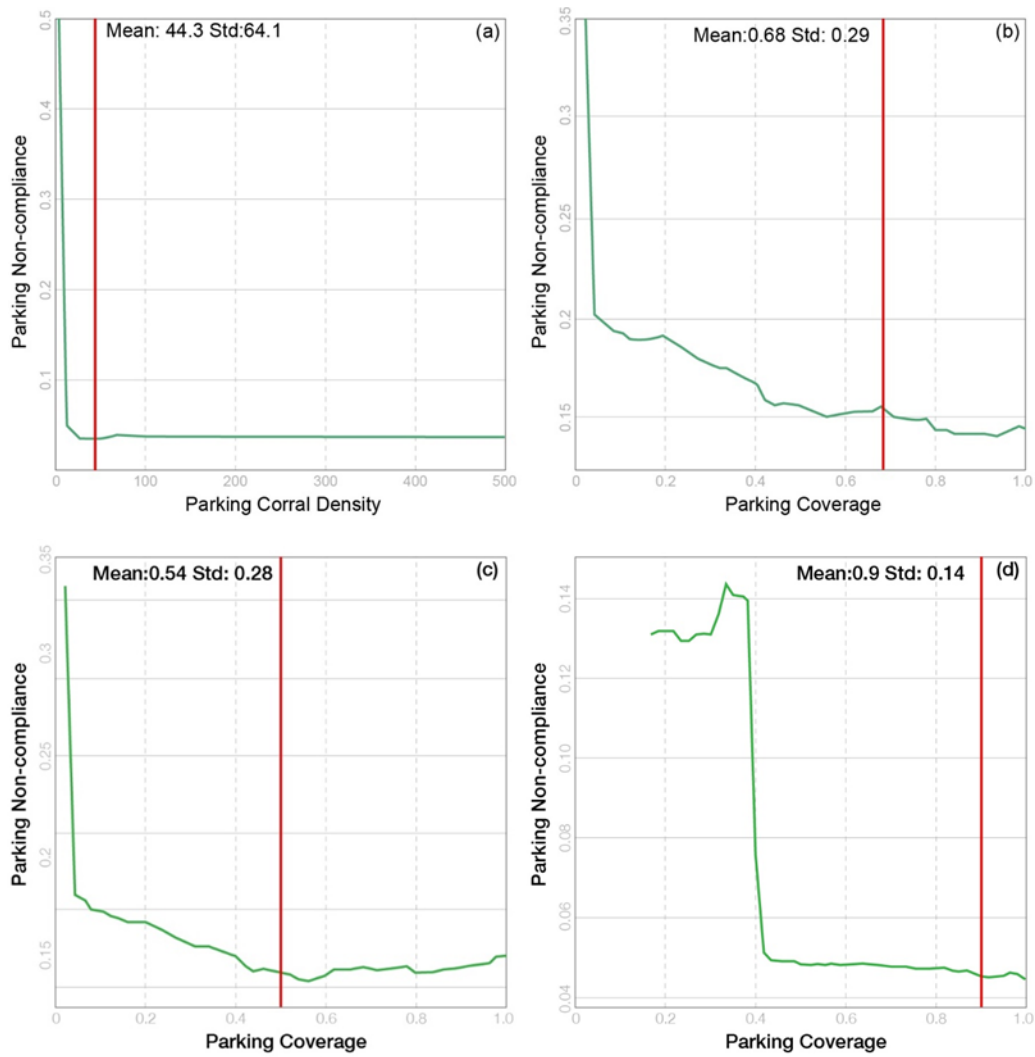
Overall, higher non-compliance rates were observed in cities with the lowest corral density. In both linear regression and non-linear GBDT analyses, parking corral density is the most significant predictor of parking non-compliance and is more strongly associated with parking compliance rates than other parking or land-use variables (Table 5). The non-linear GBDT analysis underscores the relative importance of parking corral density, which alone provides 86% of the predictive model power.

Parking corral density has a nonlinear relationship with parking compliance after averaging out the effects of other independent variables (Figure 5 (a)). The elbow point of the negative nonlinear relationship is around 20-30 corrals per square kilometer. At this density, if corrals are evenly spaced, riders would never be farther than about a 1-minute walk away. Parking compliance improves at a steep rate when moving from extremely low parking densities to between 20 to 30 parking corrals per square kilometer, after which improvements to compliance rates taper off with each additional parking corral. To further illustrate the threshold-level parking corral distribution, Figure 6 depicts the even distribution of 25 corrals within a 1km-by-1km square (25 corrals/km<sup>2</sup>) within a gridded street network. In this arrangement, the access/egress Manhattan distance to any parking corral is between 0m and 100m, and the maximum walking time is around 1 minute.

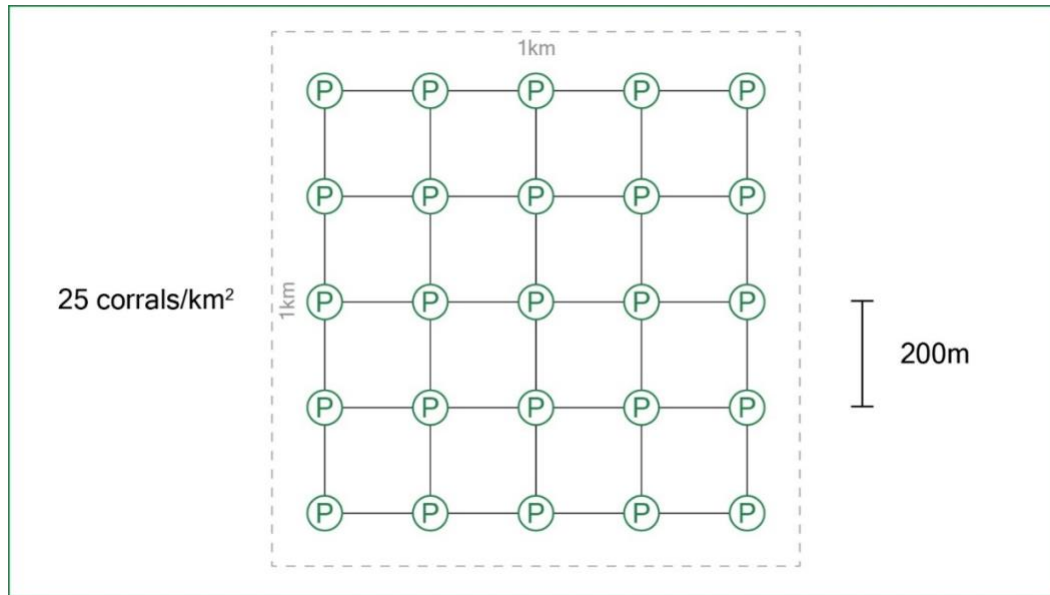
**Table 5.** Linear regression and non-linear analysis for parking non-compliance rate

Variables	Linear regression		Non-linear analysis
	Beta	T-value	Relative importance
Parking metrics			
Parking density	-0.139***	-2.79	86.3%
Parking coverage	-0.092***	-3.76	1.67%
Land-use intensity			
Population density	-0.112***	-2.92	0.6%
POI density	-0.072**	2.28	0.5%
Intersection density	-0.015	-0.61	1.1%
Distance to city center	-0.062*	-1.91	0.1%
Land-use type (ref = residential)			
Commercial	-0.087**	-2.41	
Leisure	-0.086***	-2.99	
Mixed Use	-0.16***	-2.9	
No Value	-0.035	-1.44	
Office	-0.125***	-2.99	
Public	-0.086***	-2.92	
Transit	-0.124***	-3.71	
Tourism	-0.038	-1.09	
City (ref = Cincinnati)			
Cologne	-0.025	-0.89	
Long Beach	0.022	0.59	
Lubbock	-0.035	-1.29	
Madrid	-0.144*	-1.94	
Munich	0.039	1.33	
Stockholm	-0.21***	-3.68	
Tel Aviv	0.107*	1.94	
Washington, DC	0.34***	10.11	8.8%
	Number of obs	1404	
	Prob > F	0.000	
	R-squared	0.321	
	F-test	29.680	

Note: Asterisks mean significant level: \*\*\*  $p < 0.01$ , \*\*  $p < 0.05$ , \*  $p < 0.1$ . In 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.



**Figure 5.** Non-linear relationships: (a) parking corral density vs. non-compliance, (b) parking coverage vs. non-compliance, (c) parking coverage vs. non-compliance: hexagons with parking density below 30 corrals per square kilometer, and (d) parking coverage vs. non-compliance: hexagons with parking density above 30 corrals per square kilometer. Figures represent partial dependence plots from the GBDT analysis.



**Figure 6.** Walking distance with a parking corral density of 25 corrals/km<sup>2</sup> with even corral distribution and a gridded street network

#### 4.1.1 Evenly spacing corrals is important to achieving compliance at low densities

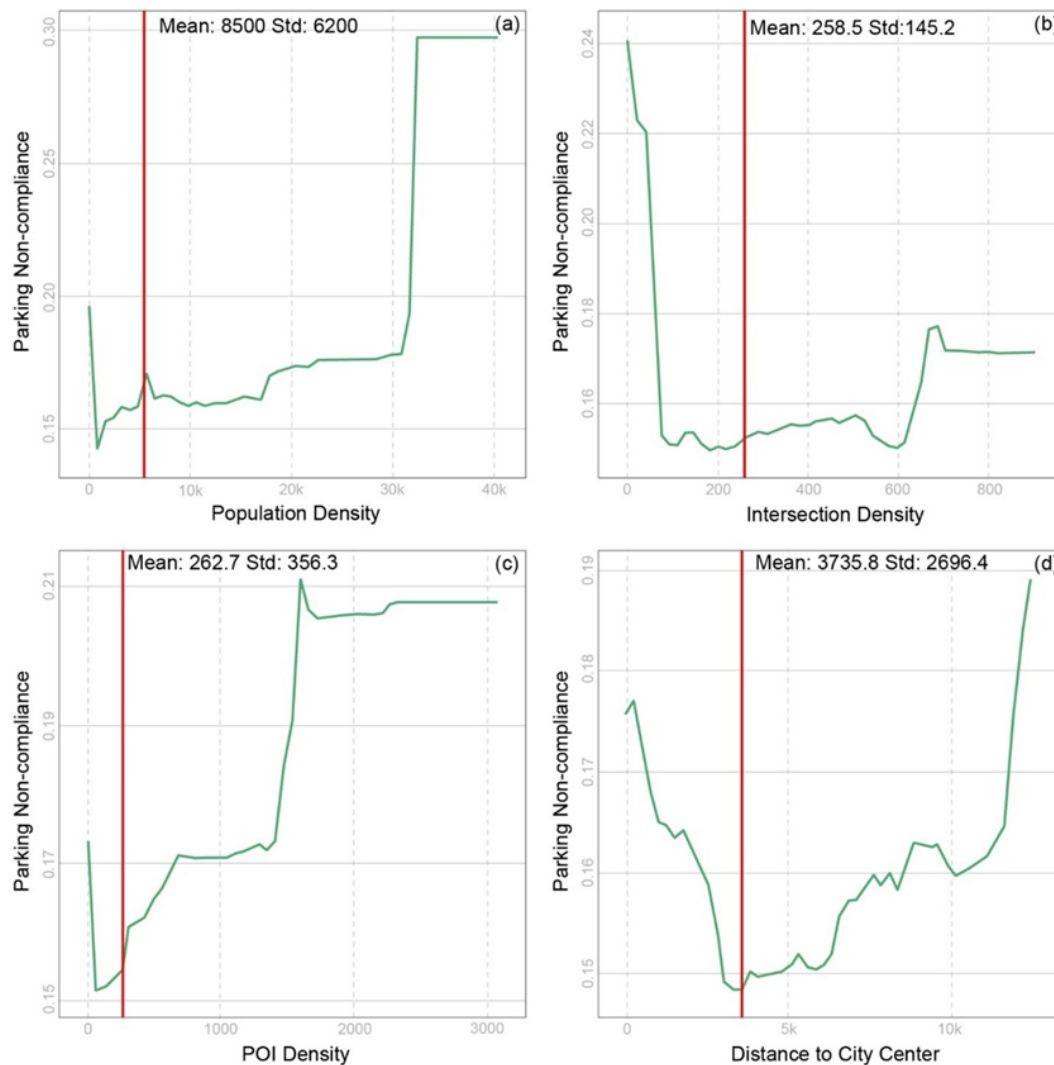
Parking coverage—the share of a hexagon within 200m of at least one parking corral—is also important for reducing the parking non-compliance rate. Both regression and non-linear analyses indicate that parking coverage is the third-most crucial variable in predicting parking non-compliance rates after parking density and city. Parking density demonstrates a strong correlation with parking coverage ( $r = 0.566$ ,  $p = 0.000$ ) and Figure 5(b) illustrates that 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 of additional corrals on parking non-compliance is close to zero or even negative. In other words, once coverage is achieved, additional corrals—beyond the minimum 20 to 30 per square kilometer needed to achieve high rates of parking compliance—do not meaningfully improve parking compliance. Parking coverage has almost no association with parking non-compliance rates when examining hexagons with parking densities above 30 corrals per square kilometer when essentially full coverage has been reached (Figure 5 (c)). 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 of all hexagons (Figure 5 (d)). Therefore, parking coverage plays a significant role in reducing the parking non-compliance rate when shared e-scooter parking density is low. In such settings, parking non-compliance can be minimized by ensuring a relatively uniform distribution of corrals across space.

#### 4.1.2 Parking compliance varies by land use and presents challenges at density extremes

Figure 7 illustrates the associations between various land-use intensity variables and parking non-compliance, revealing distinct patterns across different urban environments. Population density (Figure 7 (a)) and intersection density (Figure 7 (b)) exhibit U-shaped relationships, where parking non-compliance is higher in both low- and high-density

areas but lower in medium-density areas. A similar U-shaped trend is observed for distance to the city center (Figure 7 (d)), with non-compliance peaking in peripheral areas while remaining lower in mid-range urban zones. In contrast, POI density (Figure 7 (c)) shows a generally increasing trend, indicating that areas with a higher concentration of points of interest tend to experience greater parking non-compliance. These findings suggest that medium-density urban environments generally maintain better parking compliance, whereas both very low- and very high-density settings face more challenges.

Regarding the relationship between land-use types and non-compliance, the regression results reveal that commercial and mixed-use areas exhibit the lowest levels of parking non-compliance compared to residential areas. Leisure, office, public, and transit areas also show lower non-compliance. In contrast, tourism areas do not show a statistically significant difference in non-compliance, implying that tourism areas may not have a markedly higher or lower rate of non-compliance than residential areas. Therefore, both land-use intensity variables and land-use types are significantly related to e-scooter parking compliance.



**Figure 7.** The relationship between land-use intensity indicators and parking non-compliance

#### 4.2 How large should parking corrals be to meet demand?

Greater land-use intensities are associated with higher parking demand, suggesting cities should consider installing larger corrals to accommodate the higher demand to end trips in these areas. The zero-inflated binomial regression analysis demonstrates that hexagons with better destination accessibility and greater intersection density have higher demand for e-scooter parking (the dependent variable), while hexagons located farther from the city center have lower parking demand (Table 6). Also, the partial dependence plots from the GBDT analysis confirm that these land-use intensity variables are linearly related to parking demand.

Regression analysis also indicates significant variations in parking demand across different land-use types. Compared to commercial areas (the reference category), leisure (IRR = 1.793,  $p < 0.01$ ), mixed-use (IRR = 1.617,  $p < 0.01$ ), and tourism areas (IRR = 1.687,  $p < 0.01$ ) exhibit significantly higher parking demand, suggesting that these areas experience greater parked shared e-scooters during the study period. Office areas (IRR = 1.37,  $p < 0.01$ ) and transit-related areas (IRR = 1.238,  $p < 0.01$ ) also see elevated parking demand. Conversely, residential areas (IRR = 0.768,  $p < 0.01$ ) demonstrate notably lower parking demand, and public land-use areas ( $p = 0.614$ ) do not exhibit a statistically significant difference in parking demand relative to commercial areas, indicating comparable levels of usage. Taken together, analysis results show that larger parking corrals are needed in commercial, mixed-use, leisure, tourism, transit-oriented, and office areas relative to commercial areas. Residential or public land-use areas need to provide smaller-capacity corrals relative to commercial areas.

**Table 6.** Zero-inflated binomial regression analysis for parking demand

Variables	IRR	z-value	p-value
Parking supply			
Parking Density	1.018***	4.64	0.000
Parking Coverage	1.02***	15.69	0.000
Land-use intensity			
Population Density	0.999	-0.96	0.336
POI Density	1.000***	3.69	0.000
Intersection Density	1.001***	13.64	0.000
Distance to City Center	0.999***	-13.57	0.000
Land-use categories (ref = commercial)			
Leisure	1.793***	9.66	0.000
Mixed Use	1.617***	9.45	0.000
No Value	0.51***	-7.51	0.000
Office	1.37***	4.96	0.000
Public	0.969	-0.50	0.614
Residential	0.768***	-5.08	0.000
Transit	1.238***	3.72	0.000
Tourism	1.687***	7.82	0.000
Cities (ref = Charlotte)			
Cincinnati	1.197***	2.64	0.008
Cologne	2.073***	12.86	0.000
Denver	0.855***	-2.91	0.004
Long Beach	1.512***	5.14	0.000
Lubbock	1.943***	11.13	0.000
Lubeck	0.801***	-3.15	0.002
Madrid	0.362***	-5.99	0.000
Munich	1.95***	12.44	0.000
Tel Aviv	6.903***	32.47	0.000
Washington, DC	1.996***	13.02	0.000
Model summary			
Mean dependent var	1.900	SD dependent var	29.186
Number of obs	17561	Chi-square	5643.314
Prob > chi2	0.000	Akaike crit. (AIC)	41728.092

\*\*\* p<0.01, \*\* p<0.05, \* p<0.1

## 5 Discussion

### 5.1 At least 20 corrals per square kilometer: threshold effects of corral density on parking non-compliance

This study reveals that designating a dense network of at least 20 parking corrals per square kilometer (50 per square mile) may help reduce parking non-compliance. This finding aligns with previous research on the impact of parking regulations on street-level

compliance (Hemphill et al., 2022; Klein et al., 2023; Nivel, 2023) and public perceptions of compliance (Berg Wincent et al., 2023; Buehler et al., 2023). Our results further confirm that designating sufficient parking corrals is the most critical element in shaping parking behaviors, surpassing the influence of land use.

A GIS-based study in Portland, Oregon, USA highlights a positive linear relationship between designated on-street parking and parking compliance rates (Hemphill et al., 2022). The non-linear analysis in this study reveals a significant threshold effect for parking corral density. The threshold effect suggests that additional parking corrals substantially improve parking compliance rates until corral density reaches more than 30 corrals per square kilometer. Beyond that threshold, the marginal benefit of additional corrals diminishes considerably. Previous studies find that most riders walk between a parked e-scooter and their final destination (Buehler et al., 2023). Studies on active travel and walking to transit likewise exhibit various spatial features that 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 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 relative to e-bikes, averaging around 2.1 kilometers per trip (NACTO, 2022). The acceptable access/egress distance for a given travel mode is often influenced by the trip characteristics of that mode, and riders tend to be tolerant of longer walking distances for longer trips in general (El-Geneidy et al., 2014). Additionally, shared e-scooters tend to be concentrated in urban cores, where walkability and access to public transit are more favorable compared to other areas. If a parking corral is located far from a rider's destination, it may lose its advantages compared to walking or using public transit, thereby influencing users' parking decisions.

## 5.2 Non-compliance varied by density and land uses

Land-use intensity and parking compliance largely have a “U” shape relationship. 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 low walkability levels (Owen et al., 2007; Saelens & Handy, 2008). However, it is surprising to identify low parking compliance in high-density environments, where parking coverage and walkability are typically high. We consider three 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 only 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 disproportionately high. Second, even if parking corrals cover most destinations, insufficient parking spaces at some corrals may result in non-compliant parking. Lastly, GPS drift is a significant 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.

The regression shows 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 considerable proportion of shared e-

scooter riders are tourists who may be unfamiliar with the city or neighborhood, let alone the specific parking requirements of the city's shared e-scooter 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 indirectly contribute to the observed higher non-compliance rates in these areas 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 observed non-compliance rates.

### 5.3 Different land uses need different sized parking corrals

Many recent studies on the effects of the built environment on e-scooter trips reveal that higher density is related to more frequent e-scooter trips (Huo et al., 2021; Jiao & Bai, 2020; Yang et al., 2022), making our finding that land-use intensity is positively related shared e-scooter parking demand consistent with previous research. Relatedly, previous studies have shown that mixed and leisure land use are related to high active travel levels (Owen et al., 2007; Saelens & Handy, 2008), 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.

Parking demand is relatively high in leisure, mixed, and tourism hexagons and relatively low in residential hexagons, with commercial hexagons as the reference. Since land-use types are categorical variables, the incidence rate ratio (IRR) compares the rate of the parking demand for each category relative to the reference category (i.e., commercial land use). 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 spaces within a parking corral 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 offer the same amount of scooter parking spaces as commercial areas. Notably, these recommendations on the distribution of parking spaces across land-use types are only meaningful for neighborhoods with similar parking corral distribution and land-use intensity characteristics.

## 6 Conclusions

This study provides valuable insights into the relationship between shared e-scooter parking compliance and demand, parking corral density, and land-use patterns. The results show that parking compliance increases significantly when at least 20-30 parking corrals per square kilometer are installed, with only marginal improvements beyond that point. The spatial distribution of corrals is crucial at low densities, as providing uniform coverage in these areas can help reduce parking non-compliance. Land-use intensity variables have a non-linear relationship with parking non-compliance but are linearly and positively associated with parking demand. Additionally, land-use categories, developed

based on points of interest, are significant predictors of both e-scooter parking compliance and demand. The implications derived from these findings can inform policy decisions related to parking management and capacity planning in shared e-scooter systems to ensure orderly parking. We offer three primary ways planners and policymakers can effectively intervene to meet parking demand and improve parking compliance.

First, provide sufficient parking corrals—within a 1-minute walk in gridded areas—to meet parking demand and maximize compliance. The findings regarding parking non-compliance underscore the importance of providing at least 20 to 30 parking corrals per square kilometer, which translates to around a maximum 100-meter walk to the destination using gridded streets, which takes roughly 1 minute. When parking density is lower than 20 corrals per square kilometer, additional corrals are associated with greater parking compliance. Parking corral density above a threshold of 30 corrals per square kilometer, however, has limited returns; above this threshold, adding more parking corrals has a very minimal effect on improving parking compliance. These findings are 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 e-scooters outside of designated parking areas, increasing parking non-compliance. More attention needs to be paid to the distribution of parking corrals in areas with high land-use intensity, where parking demand is high. One high-density hexagon with sparse parking corrals can lead to more non-compliant parking incidents compared to multiple low-density hexagons.

Second, ensure parking corral coverage is consistent and comprehensive to avoid gaps in parking coverage and resulting parking non-compliance. Inter-city comparisons show that parking deserts (i.e., hexagons without a parking corral, surrounded by adjacent hexagons without parking corrals) generate much more frequent non-compliant parking than a single hexagon with no parking corrals, surrounded by hexagons with corrals. Therefore, planners should aim to create even parking coverage, particularly in low-parking-density environments.

Third, provide enough parking spaces within corrals to accommodate the parking demand across different land uses. This paper 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 fixed across different land-use types, and corrals in mixed-use, leisure, and tourist areas should have higher capacity than corrals in strictly commercial or residential areas.

The conclusions offer insights into planning parking for shared e-scooter 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 impact 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. Third, important questions remain about how the design of parking corrals affects parking compliance and how this study’s findings 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. Last, future research should examine how e-scooter parking policies

intersect with broader societal challenges, such as accessibility, potential gentrification effects, and other transportation equity issues. While this study primarily focuses on parking compliance and demand, understanding how parking policies shape mobility access for different socioeconomic groups, influence behavioral change, and integrate with wider urban planning goals will be crucial for developing more inclusive and sustainable shared micromobility systems.

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### **Author contribution**

The authors confirm contribution to the paper as follows: Study conception and design: Sian Meng, Calvin Thigpen, Brandon Haydu, and Anne Brown; data collection: Sian Meng and Brandon Haydu; data analysis: Sian Meng; interpretation of results: Sian Meng, Calvin Thigpen, Brandon Haydu, Nicholas J. Klein, and Anne Brown; draft manuscript preparation: Sian Meng, Calvin Thigpen, Brandon Haydu, Nicholas J. Klein, and Anne Brown. All authors reviewed the results and approved the final version of the manuscript.

### **Appendices**

Appendices available as supplemental files at <https://doi.org/10.5198/jtlu.2025.2469>.

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