



ELECTRIC VEHICLES IN THE CITY

THE RELATIONSHIP OF
EV INFRASTRUCTURE
AND SPATIAL
DEVELOPMENT IN BEIJING

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for Energy Policy

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INTRODUCTION

The increasing environmental crises including air pollution and carbon emissions have caused great social concern. The World Health Organization (WHO) reported in 2012 that over a million people died from outdoor air pollution in China within one year. Pressed by severe environmental consequences as well as resulting social discontent, the Chinese government has carried out aggressive measures to promote the electrification of the transportation sector, in addition to other policies such as relocating heavy industries and increasing energy efficiency.

Stimulated by generous consumer incentives, enormous investments in infrastructure, and tough regulations by local governments to discourage gasoline vehicles, the production and sale of electric vehicles have surged in China. In 2019, EVs registered in China have reached 3.44 million, accounting for 60 percent of the world's total electric fleet.

The EV has also been promoted enthusiastically worldwide. Many developed countries have defined goals in terms of the number of EVs on the road within a certain timeframe. For example, EVs in the United States will predictably increase to 3.6 million by the end of 2025. In Europe, EVs and hybrid-energy cars accounted for over 50 percent of new car sales in 2017, and keep growing; Germany has set up a goal to reach a million EVs by 2020.

Correspondingly, many questions have arisen in terms of charging demands and infrastructure planning to accommodate such growth, as well as the impact on urban

layout and urban lifestyle. Deployment of infrastructure and supply–demand management will need to develop in coordination with proper urban form designed around the principles of smart growth, urban livability, and social inclusion. Otherwise, it might backfire: with a system that underperforms, aggravates socio–environmental inequality, and acts against urban sustainability.

This study focuses on infrastructure planning through studying actual EV owners' charging demands, using Location-Based Service (LBS) data embedded in individual smartphones. Although Public Charging Stations (PCS) account for less charging activities than households and workplaces, and have a smaller portion in supporting routine commuters, it is crucial to estimate the dynamic charging demands currently provided by public charging stations.

Like other public amenities, these stations are a shared amenity without a set of dedicated users. However, the availability and location of PCS can significantly influence EV driver behavior. These features can also influence the choice of purchasing an EV or a gasoline vehicle. Travel range due to limitation of battery power can cause driver anxiety.

With an increase in EVs on the road, the demands for public charging infrastructure must also grow rapidly, especially from EV owners without access to dedicated charging and those who travel long distances. This is particularly important for EV users in China, because most of them live in high-density neighborhoods without or with a shortage of charge stations.

A lack of public charging stations also puts pressure on the urban electric grid by increasing the frequency of home or workplace charging. For these reasons, the density and layout of charging infrastructure are important issues for both the adoption and efficiency of the EV system and the sustainable development of cities.

We use Beijing, China as the main case study in this project. China's capital has been leading in this decisive move toward electric transportation with enormous support from the government to improve the city's environmental quality. Spatially, Beijing's historic centripetal structure, characterized by a series of ring roads, dominates the urban layout and land use of the city, resulting in perennial traffic congestion and environmental degradation as the city grows to an unsustainable scale.

Research indicates that transportation accounts for 25 percent of air pollution in Beijing. The city has implemented aggressive measures in transportation to encourage EV over gasoline vehicles. This includes separating the quota of license plates for EVs and that for conventional cars, with the former increasing year by year and latter being reduced incrementally, making

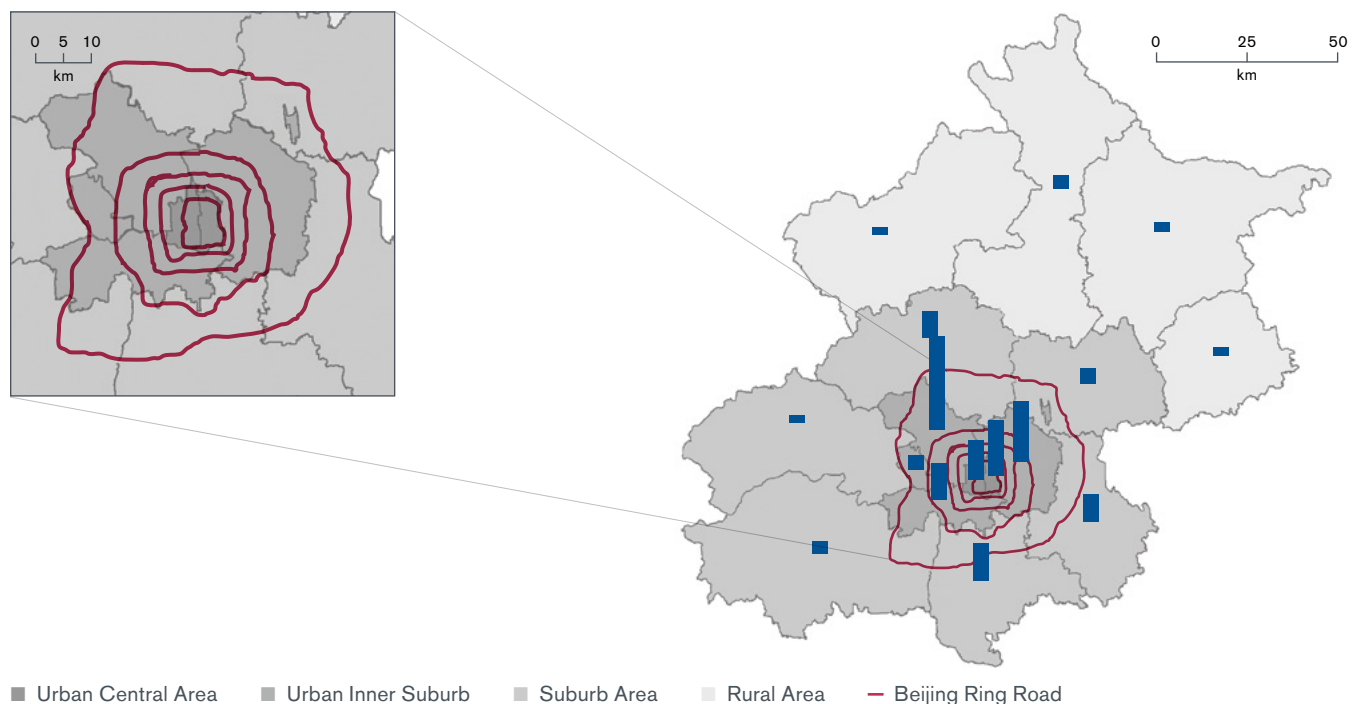
it more difficult for drivers to get a license for gasoline cars through already competitive lottery cycles. As the result, the number of EVs has recorded a growth of 2,630 percent in five years to reach 224,000 in 2018.

In the meantime, 3,075 public charging stations have been installed for public usage; each station normally includes more than four charging piles. Several questions draw our particular interest with such rapid increase:

- How well does new infrastructure match the growing charging demands?
- Is there any correlation between the most used facilities and the spatial characteristics of the neighborhood and urban environment?
- How does the rapid growth of PCS influence the changing urban form in Beijing?

Probing these questions will allow us to understand which policies, investment, plans, and guidelines of developing new infrastructure serve the growing EV fleet in Beijing and other cities. Furthermore, exploring the options of infrastructural development for EVs in large cities like Beijing can also inform our discussions of

FIGURE 1: DISTRIBUTION OF REGISTERED EVS IN BEIJING



The blue histogram represents the number of electric vehicles registered in each district, referenced in Table 2.

climate change, energy policy, and urban sustainability with the foreseeable growth of transport electrification in the cities throughout the world.

RESEARCH DESIGN AND DATA ANALYSIS

Location-based service (LBS) embedded in individual smartphones provides datasets for navigation, route planning, and location inquiry. It generates an enormous amount of real data and facilitates a deeper understanding of human mobility, including EV. In this study, we use the data generated by Baidu Map, the leading map service provider and big data operator in China. EV drivers use LBS for different purposes including:

1. **Searching for nearby charging stations.** The most common charging demands occur when the EV drivers on the road realize that the car is in low battery, then search for nearby PCS.
2. **Navigation to charging destination.** When EV drivers travel somewhere distant, they often consider battery power and plan the trip with an end-of-route charging location.
3. **Route optimization.** EV drivers tend to route plan in order to avoid congestion and maximize energy efficiency, particularly when commuting in a large city like Beijing, even though they know how to get to the destination.

With these three behaviors in mind, this study involves collecting and sorting EV user data to map the locations of charging demands and charging activities. 13,621 EV drivers' records of public charging activities are extracted from LBS during a 5-day period. All location data is processed and downsampled to a 100m resolution grid, which balances privacy protection and data accuracy.

We use Kernel Density Function and spatial statistics to investigate the distribution of charging activities, and to analyze to what extent the charging demands match the current distribution of EV infrastructure. The combination of macro-scale and micro-scale analyses reveals a spatial-temporal heterogeneity of charging activities.

We also compare the mapping of charging activities with the spatial characteristics of urban districts and neighborhoods, and explore the reciprocal relationship between the frequency of usage of charging stations and the land use and transportation conditions of the location. This methodology is described in more details in the appendix.

MAPPING THE CHARGING SUPPLY AND DEMAND

The research generates findings in several aspects of EV drivers' travel and charging behaviors, as well as their relation to the geo-spatial pattern of the city. In line with the findings of previous studies in other countries and cities, Beijing's urban center witnesses a higher level of concentration of deployment of PCS. According to the 2017 Beijing Traffic Statistics Annual Report, 68 percent EVs are registered in the six central districts—Dongcheng, Xicheng, Haidian, Chaoyang, Fengtai, and Shijingshan. These center city districts have a total area of 1381 km².

Consequently, 51 percent of the 3,075 PCS are deployed in these six districts, compared to 35 percent in the suburb districts, and the remaining 14 percent in the rural areas in the greater Beijing Metropolitan Region (figure 2a, table 1). However, the locations where EVs are registered do not accurately reflect the dynamic spatiality of actual usage of vehicles or their travel patterns, because it is common for an owner to register the car at one location but live in another due to such factors as registration quota availability, financial incentive, and ownership of multiple properties.

Therefore, what the previous studies and initial statistics cannot tell us is the substantial spatial heterogeneity in charging demands, and the characteristics in land use or density associated with different charging demands. Some issues arising from the rapid development without sufficient study or suitable precedent include mismatch of supply and demand, non-interoperability and sharing

of charging piles, low overall utilization for layout, and time constraints for parking.

Our initial study focuses on the issue of mismatch between the deployment of charging stations and the actual charging demand. We classify the conditions into four categories: high demand–high availability (HH), high demand–low availability (HL), low demand–low availability (LL), and low demand–high availability (LH), as described in table 1. The demand is characterized by the frequency of LBS associated with the identified locations (Figure 2 & 3). HL and LH are what we consider mismatched conditions and deserve attention or intervention (Figure 3).

TABLE 1: CLASSIFICATION OF CHARGING DEMAND AND SUPPLY

Four Categories	Description
High–High (HH)	High Charging Demand and High Density of Charging Stations
High–Low (HL)	High Charging Demand and Low Density of Charging Stations
Low–High (LH)	Low Charging Demand and High Density of Charging Stations
Low–Low (LL)	Low Charging Demand and Low Density of Charging Stations

The HL areas are places where new infrastructural investment is needed. Based on the geo–spatial data, H4, H5, H9, H11, and H12 belong to this category (Figure 3). Different from the city center where a high-density charging facility network has been established, HL areas are mainly located between the Fifth and Sixth Ring Roads in Beijing connecting the urban center and suburban areas (Table 2, Figure 3).

They can be further divided into two groups by location, land use, and density, namely large-scale residential community areas (such as H4, H5) and transportation hubs (H9, H11, and H12). The latter refers to the places located at the intersection of metro lines and highways, especially highways leading to airports or high-speed rail stations, or connecting Beijing and rural county seats.

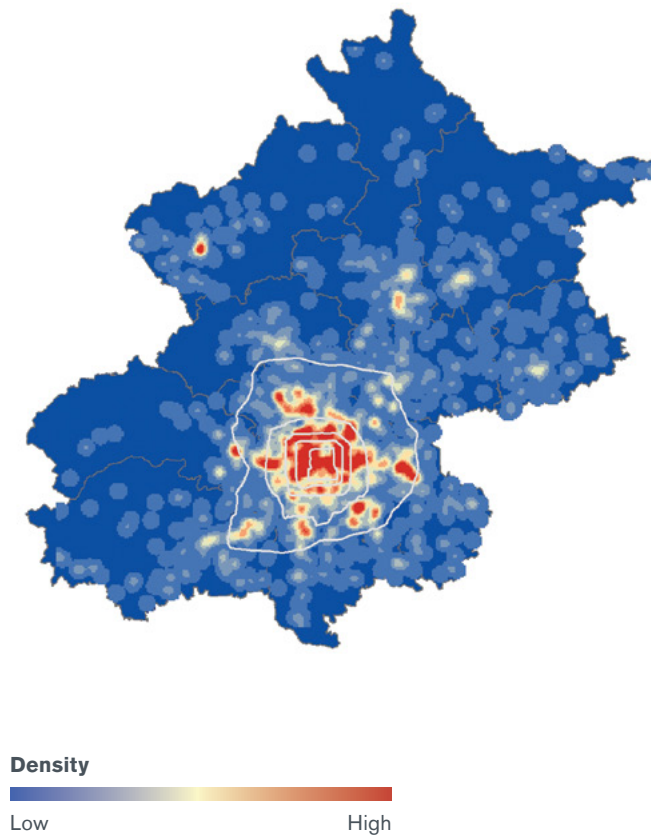
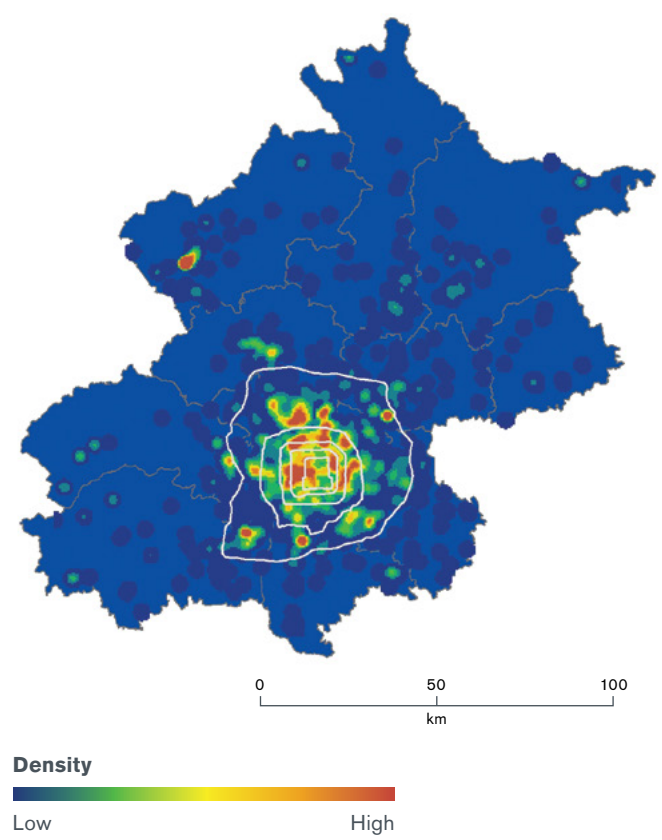
We recommend that new installation be restricted in the LH areas, until the supply–demand dynamics become more balanced. Our mapping indicates that both Tongzhou New Town (which has been designated as the new administrative district of Beijing as part of the effort to consolidate the old city as the National Capital) and Dongcheng District (east side of Beijing’s city center) are equipped with a high density of charging stations that are underutilized. New infrastructural investment should be cautiously considered in these areas.

We use the Search Origin-Destination (SOD) survey to estimate EV owners’ charging demands. It confirms that EV users are more dependent on path optimization than drivers of conventional cars. They tend to choose a route with charging stations and consistent with the direction from the origin to the destination (Figure 3). The SOD survey indicates different patterns based on the distance between the original location and destination location of route search. When the SOD distance is less than 5km, the charging demands are more likely occur near the original point, or the target PCS. When SOD is father than 5km, the charging demands tend to occur near the destination point.

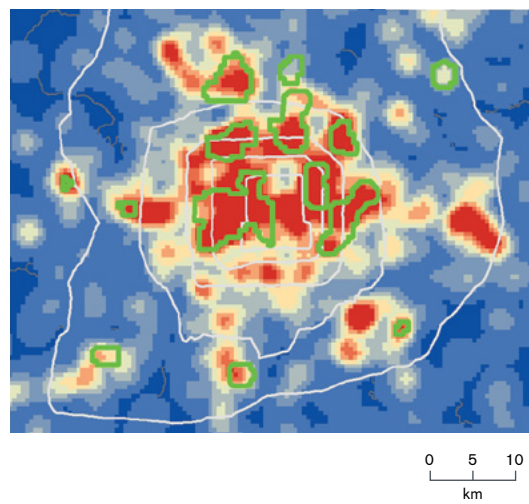
The patterns of charging activities associated with PCS also show significant differences on weekdays and on weekends. The charging activities on weekdays are distributed in various functional areas across the whole city, and are often tied to commuting and business activities (Figure 5).

In contrast, charging activities on weekends are notably concentrated at certain city areas, including two specific types of functional areas. The first features the cultural and entertainment centers and the historic attractions within the city center, as well as the CBD of Chaoyang District where large shopping malls and entertainment facilities are located.

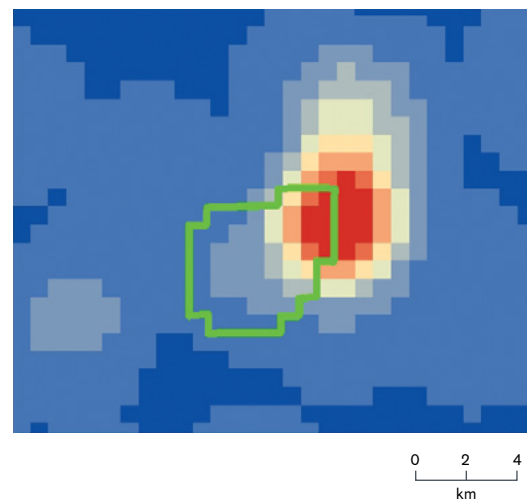
The second type includes large residential neighborhoods mostly located in the northern part of the city center. These residential areas are characterized by middle-class residents and migrant populations, yet underserved by commercial facilities, i.e. Huilongguan and Tiantongyuan neighborhoods.

FIGURE 2: KERNEL DENSITY ANALYSIS MAP, BEIJING, CHINA**(a) Distribution of Public Charging Stations****(b) Actual Charging Activity Density**

a) density map of public charging stations; b) actual EV owners' charging demands derived from LBS data.

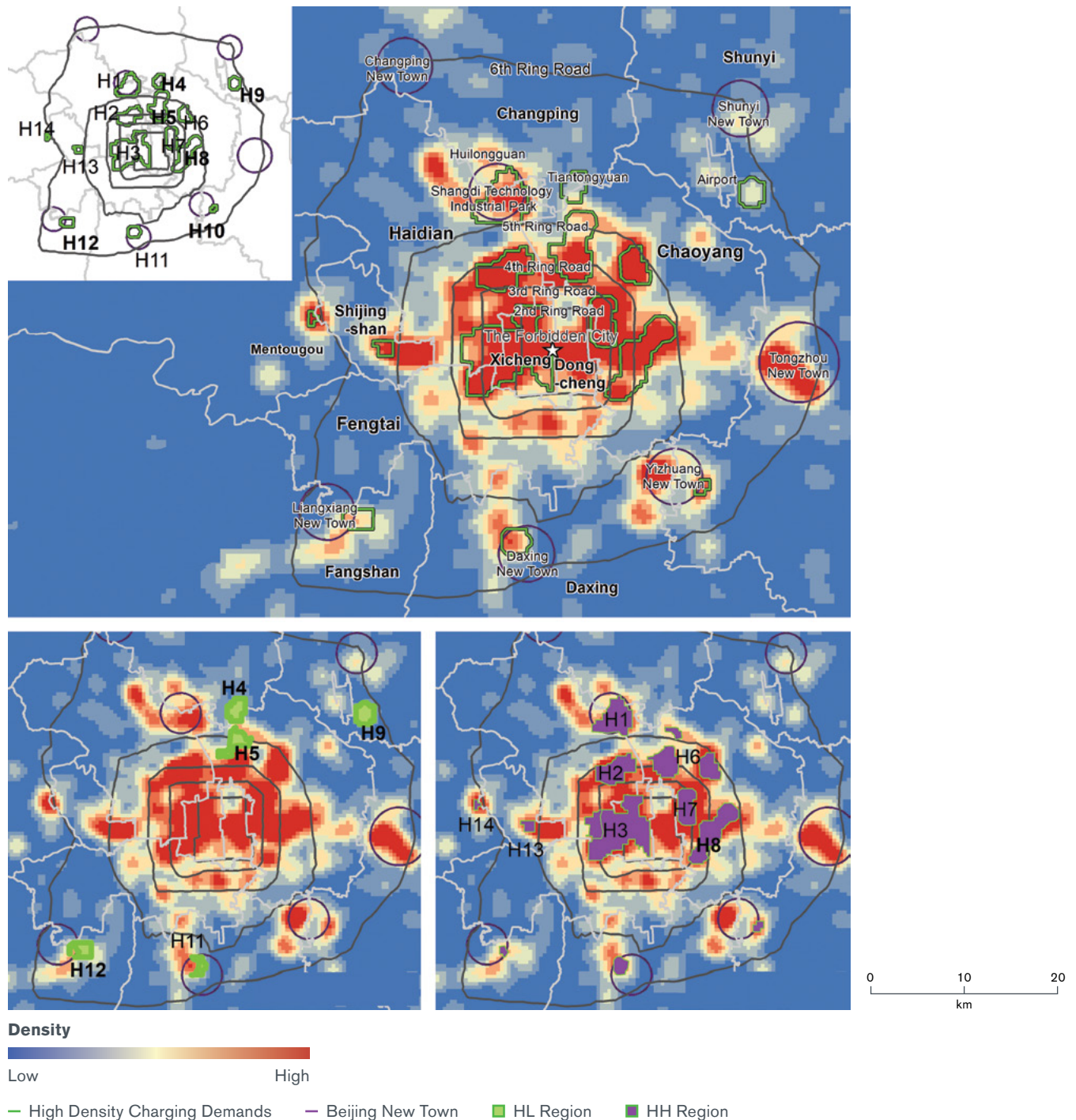
(c) Mismatch in Urban Area

— Beijing Ring Road — The Extent of High Charging Activities

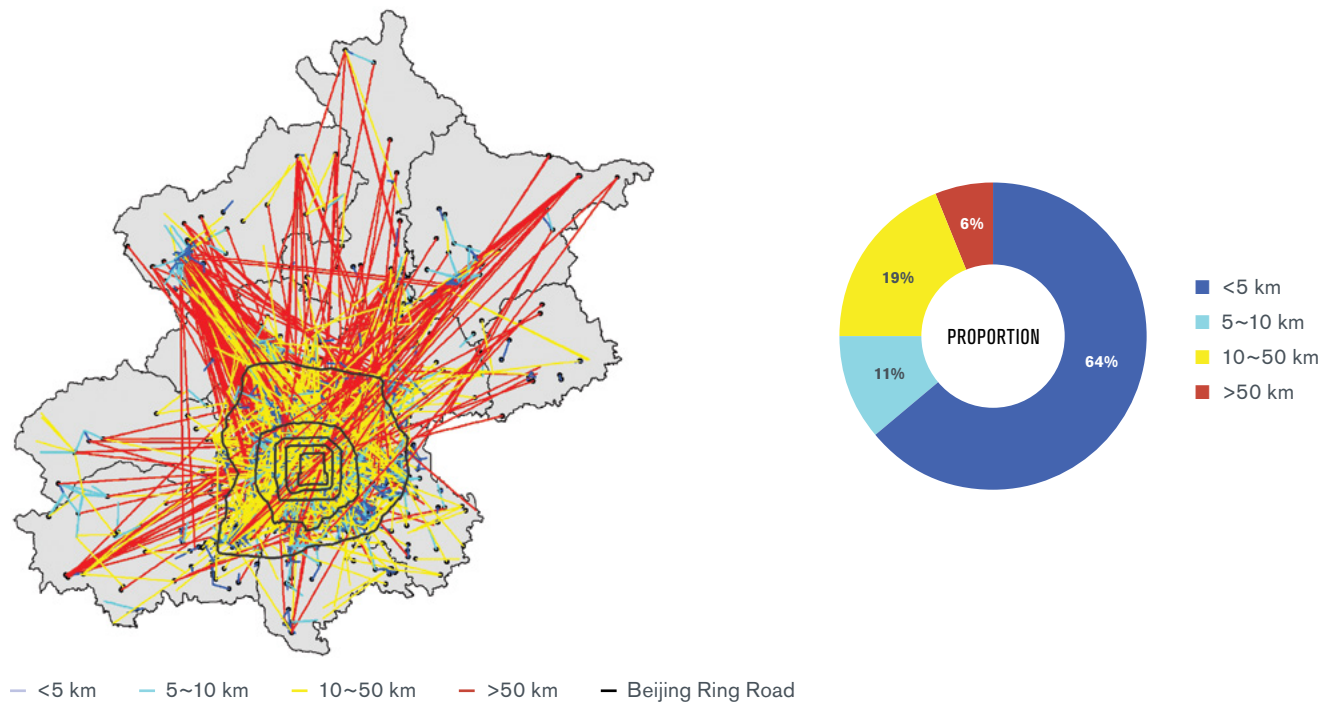
(d) Mismatch in Rural Area

— Beijing Ring Road — The Extent of High Charging Activities

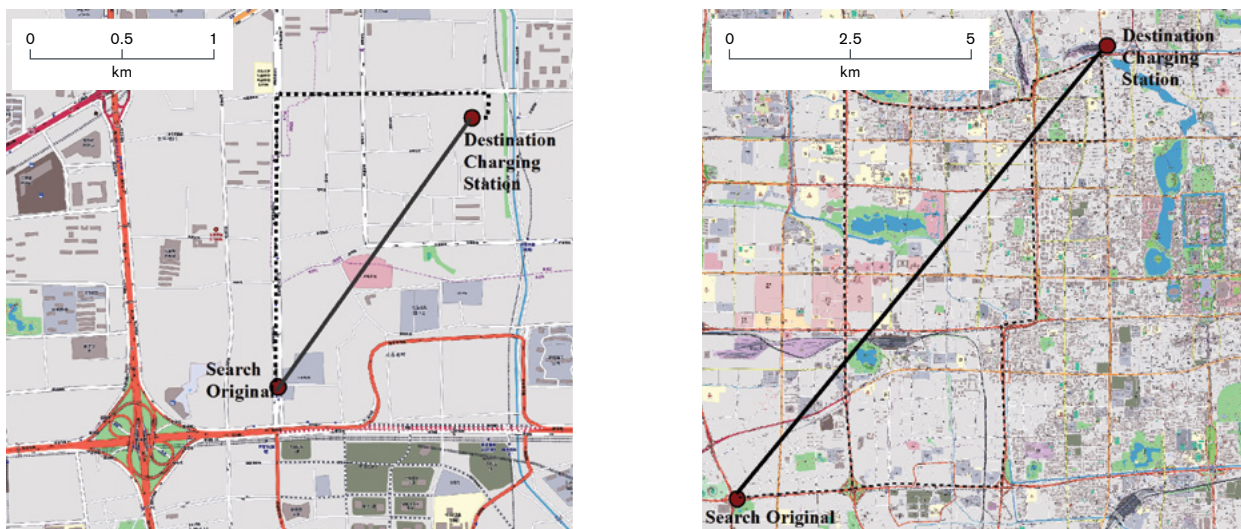
FIGURE 3: SPATIAL CONSISTENCY MAP BETWEEN HIGH-DENSITY CHARGING DEMANDS AND THE PUBLIC CHARGING STATIONS, SHOWING BOTH LOCATIONS OF MATCH AND MISMATCH



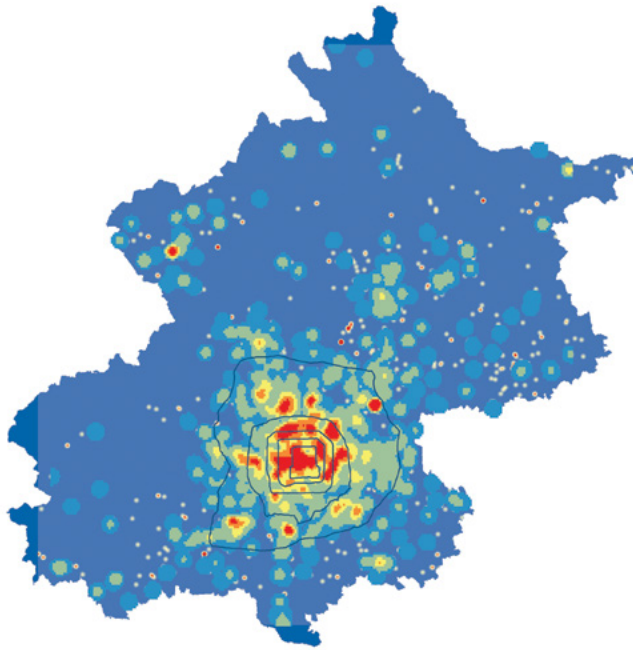
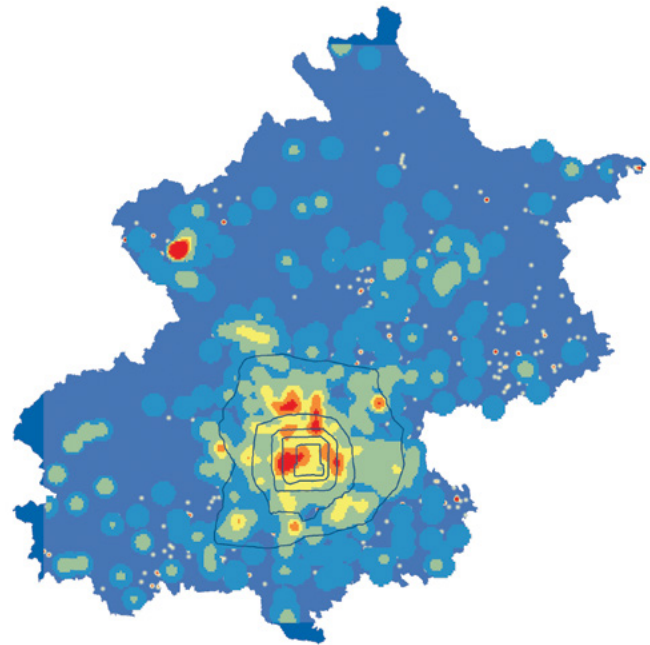
The star represents the Forbidden City, the heart of the city. Areas enclosed by green lines indicate areas with high density charging requests, almost all of which are located within the Sixth Ring Road, marked with H1~H14 for further micro-scale analysis. Further, these high demands areas are divided into 4 categories of HH, HL, LH, LL regarding each match pattern with distributions of PCS. Here, we focus on HL and HH patterns, representing them on the map. HL areas are referred to as the suggested areas for new deployment of PCS. HH shows the concentration in urban center areas. While we can also see many places with overestimate assignment.

FIGURE 4: SEARCH ORIGIN-DESTINATION (SOD) SURVEY**(a) SOD Survey**

a) Mapping indicates that 64 percent of SOD charging trips are within 5km (short-distance), and 75 percent of SOD charging trips are within 10 km distance.

(b) Examples of Short- and Long-Distance Charging Demands

b) Examples of short-distance charging demands (more likely close to the original point) and long-distance charging demands (more likely close to the destination-recharging)

FIGURE 5: KERNEL DENSITY OF WEEKDAY AND WEEKENDS BASED ON SEARCH ENGINE QUERIES OF “CHARGING STATION”**(a) Weekdays****(b) Weekends**

0 50 100
km

Request Density

Low High

— Beijing Ring Road

Map of temporal pattern of charging activities on a) weekdays, and b) weekends, representing significant differences of charging patterns.

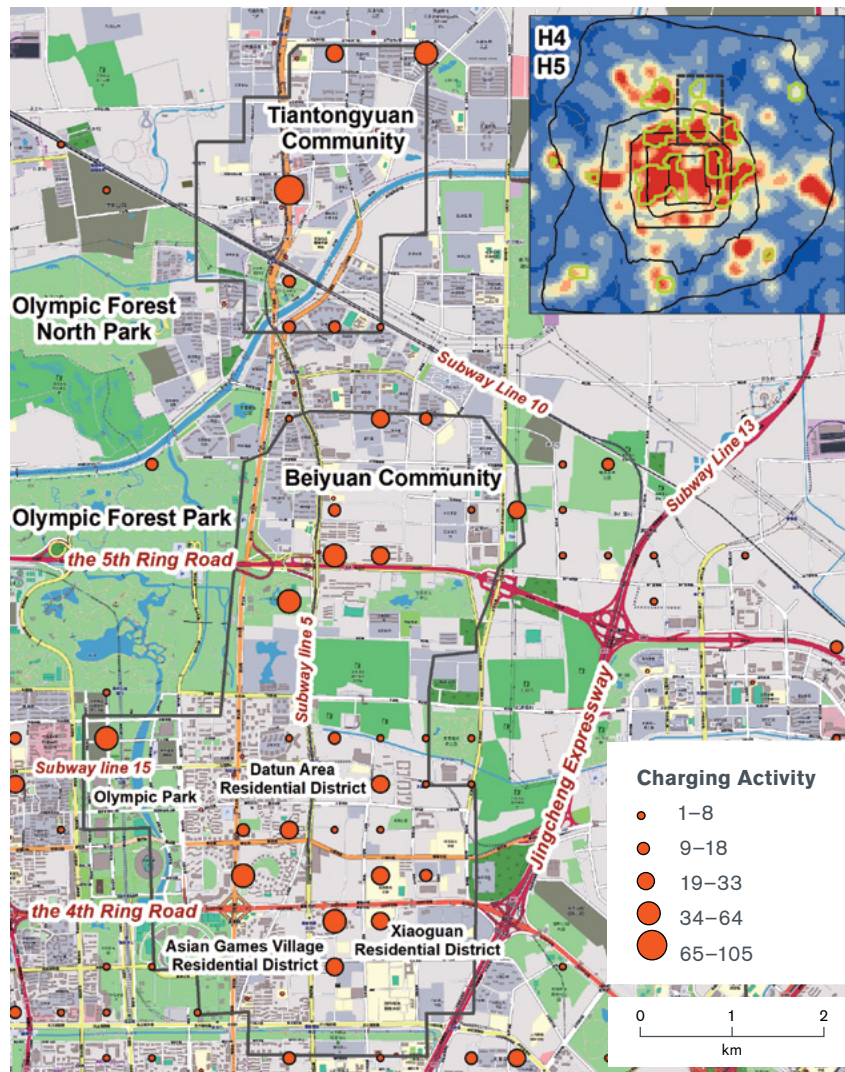
SPATIAL HETEROGENEITY AND SOCIAL INEQUITY

HH represent the areas where the supply and demand of charging facilities match and are both at a high level. We zoom in scale to analyze these areas and investigate their differences with the HL areas in order to learn more about the characteristics of high charging demands. Why do these types of areas draw higher charging activities? Most of large-scale HH areas are located within the Fifth Ring Road, and are characterized by high level of mixed use, business zones and education zones, as well as high-tech new towns.

The connection between land use/density and charging demand is further verified by the underutilized charging

stations just outside these zones. It is also worth noting that, although in general the HH areas have sufficient supplies of charging stations, the “matching” pattern has to be attributed to a certain degree of over-deployment of infrastructure in these areas. The level of redundancy is necessary due to the prospect of continuing growth of these economic zones and new towns in the near future.

In sharp contrast to the HH areas, the mismatch HL areas often expose the problem of social inequity in association with their spatial heterogeneity in the micro-scale analysis. For example, Tiantongyuan (H4) is a residential neighborhood developed during Beijing’s rapid urbanization in the 2000s. Often regarded as the largest high-density community in Asia, it houses more than 700,000 residents over an area of 8 km², most of whom are migrant workers attracted by the relatively low housing price and rent.

FIGURE 6: MAPPING OF Tiantongyuan COMMUNITY IN BEIJING AS AN EXAMPLE OF SOCIAL INEQUITY IN THE SUPPLY OF PCS**(a) Charging Activities in Northern Beijing Neighborhoods****(b) Charging Activities in Tiantongyuan Community****(c) Public Charging Stations**

Tiantongyuan high resolution remote sensing image from Google Earth, 2019

There is, however, an insufficient supply of amenities including commercial facilities, education resources, open spaces, and parking. This area suffers from overcrowding as well as poor urban sanitation. The investment of EV infrastructure also lags behind other high-density neighborhoods in Beijing and is unable to meet the large and growing demand of such a population.

POLICY IMPLICATIONS

The findings from this research generate a deeper knowledge of the EV system, which can potentially inform the planning of cities in the age of electric mobility. They can be broken down to several aspects:

Heavy Use Areas

- **Compact, mixed-use, and socially inclusive urban areas** including commercial centers and mixed-use neighborhoods tend to produce higher charging demands.
- **Higher-education and high-tech industrial parks** also perform better with high-level charging activities if these urban job centers are surrounded by residential communities. Some new towns in the outskirts of Beijing also testify this rule.

Lower Use Areas

- **New towns located away from the city center** tend to rely on public transportation systems like metro, airport, and railway. These areas may not justify new charging infrastructural investment.

Variable Use Areas

- **Shopping districts, parks, and attractions** have charging activities that fluctuate more significantly between weekdays and weekends or holidays. This requires consideration of flexibility in the deployment of charging stations.

Building infrastructural systems that support electric transportation is a significant public investment, especially considering the rate of growth in a city like Beijing. Therefore, decisions must be made based on concrete investigations of the need and the trend of urban growth. The current PCS network in Beijing basically follows the city's centripetal pattern, with more resources concentrated in the urban center.

Spatial study at a finer-grain, however, suggests an asymmetric and less centralized pattern of demand. Greater attention must be paid to the high-density condominium neighborhoods. As a prevalent housing typology in Chinese cities, this kind of neighborhood often sees high numbers of EV users who rely on public charging facilities as few residents can afford private parking spaces.

Locations linked to public services, particularly transit stations, shopping centers, parks, and institutions around the communities provide opportunities for destination-charging and parking, and represent optimal locations for charging facilities in the city.

FUTURE CONSIDERATIONS

Two fundamental changes are influencing the spatial pattern of Beijing as well as many other large cities, and thus require adjustment in the way in which we plan and develop the EV infrastructure.

On the one hand, as the directive from the central government to decentralize Beijing is carried out in phases, the current spatial structure of a centralized pattern will be gradually dissolved as more and more residents and industries will be relocated to the urban periphery, forming clusters of urban zones with specific focuses on demography and industry. The spatial heterogeneity discovered in this study will become stronger and thus requires more in-depth analysis of the actual demand–supply dynamics affecting the wider territory.

On the other hand, the rapid development of ride-sharing continues to reduce the demand for car ownership. And the world of electric mobility is moving toward a higher level of automation as the technology of driverless vehicles is advancing.

These trends imply not only a more decentralized distribution of EV infrastructure but also a greater role that PCS has to play in the industry. The importance of coordination with other sectors of transportation including mass transit, regional rail, and aviation will significantly increase, a trend this research indicates.

TABLE 2: OVERVIEW OF STATISTICAL REPORTS AND PRELIMINARY SPATIAL ANALYSIS

	Functional Definition	District	Registered EVs	Proportion %	Total	Public Charging Station	Proportion %	Total	Charging Activities from Navigation	Proportion %	Total
Urban	Central Area	Dongcheng	21118	13%	68%	94	3%	51%	327	2%	57%
		Xicheng	14378	9%		142	5%		755	6%	
	Inner Suburb	Chaoyang	23356	14%		588	19%		2915	21%	
		Fengtai	13435	8%		242	8%		1127	8%	
		Haidian	36497	22%		416	14%		2284	17%	
		Shijingshan	4204	3%		90	3%		408	3%	
Suburb		Changping	9475	6%	26%	175	6%	35%	1088	8%	33%
		Daxing	13821	8%		249	8%		1050	8%	
		Fangshan	3745	2%		182	6%		682	5%	
		Mentougou	1452	1%		69	2%		391	3%	
		Shunyi	4913	3%		157	5%		613	5%	
		Tongzhou	9838	6%		251	8%		685	5%	
Rural		Huairou	3992	2%	6%	151	5%	14%	268	2%	10%
		Miyun	2193	1%		96	3%		239	2%	
		Pinggu	1983	1%		80	3%		54	0.30%	
		Yanqing	1406	1%		90	3%		732	5%	

Sources: Beijing Traffic Statistics Annual Report 2017; Beijing Urban Master Plan (2016–2035)

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APPENDIX

RESEARCH METHODOLOGY

We use data derived from individual smartphones. This raw data is highly sensitive, containing private information. In order to protect data security and personal privacy, we include a three-step process for data cleaning to ensure data validity. First, we use keywords associated with “charging station” as the “index” to identify the EV users from the search engine records—with the reasonable assumption that non-EV users would not search for charging. These records come from the above three scenarios and represent the actual EV users. Second, we downscale all the location records to a 100-meter resolution and merged the nearby single records into these units. Thus, EV users’ records located in one geographical unit of 100m×100m are counted as one attribute of the unit, namely, the number of users. Third, we use ESRI ArcGIS software to generate and visualize the records as point shapefile.

In addition, if the original location of a dataset is located outside of Beijing, it is categorized as a non-local user and removed. Ultimately, 13,621 EV drivers’ records are retained within a 5-day period (including 3 weekdays from September 24th through 26th, and the weekends of October 26th–27th, to avoid the effects of the nine-day holiday period around Chinese National Day,

2019). The data for 3075 PCS locations is stored as the point data, with the attributes of longitude, latitude and number of PCS in each 100m×100m unit.

Kernel Density Function, a spatial analysis method, is employed to create a continuous surface based on the input charging-activity-point data from a smartphone, to represent the spatial distribution pattern of charging activity and infrastructure, and to investigate to what extent the charging demands match the current distribution of EV infrastructure. The search radius is significant and should be robust to spatial outliers, that is, input points should be far away from the rest of the points.

In our study, the empirical and actual experiments determine that the best threshold of search radius distance is 2,500m with an output grid size of 500m. We use the 1/2 standard deviation interval size to classify and map the results. We use the same parameter setting and operation for current public charging station. Figure 2 shows the results of mapping the spatial density pattern of distributions of infrastructure and charging activates. Considering that the time factor may affect the spatial pattern, we use the same method to map the density on weekdays and weekends separately (Figure 5). The process is completed on ESRI’s ArcMap software using Spatial Analyst Tools.

TABLE 3: DESCRIPTION OF DATA STRUCTURE

ID	The Unique ID of Each Data
PCS_X	The longitude of the destination searched by smartphone app
PCS_Y	The latitude of the destination searched by smartphone app
SO_X	The longitude of the location where the EV drivers use the app to search for charging
SO_Y	The latitude of the location where the EV drivers use the app to search for charging
Number	The number of users records of this unit

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