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Large-Scale Mapping of Urban Parking from Aerial Images: A Case Study in Berlin, Germany

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Abstract

Existing nationwide spatial datasets for Germany's traffic infrastructure, particularly parking areas, are fragmented and incomplete, hindering effective traffic management and urban planning amidst growing demands for mobility transition and livable cities. This paper presents a novel approach to create a comprehensive parking area inventory for Berlin using aerial imagery. The methodology integrates AI-based traffic area segmentation and DINO-based vehicle detection with cadastral data. A key innovation is a workflow that classifies parking areas by their orientation and accessibility for refined capacity calculation. The resulting Berlin-wide inventory comprises 1,333,953 parking spots. Our method significantly contributes by mapping private (19 %) and semi-private (21 %) parking areas, which are largely missing from existing inventories, alongside publicly accessible (60 %) spaces. Vehicle detection identified 1,039,155 vehicles (1,019,690 LDV, 19,465 HDV). Initial classification shows 36 % parallel, 27 % diagonal, 20 % vertical, and 17 % unclassified parking spots, with notable variability across districts. This comprehensive inventory addresses a critical data gap, providing a more accurate understanding of urban parking resources. The highly automated and repeatable nature of this aerial imagery-based approach offers significant potential for large-scale applications and temporal change analysis. Future work will focus on developing correction factors for capacities in partially occluded areas and integrating information on underground parking facilities to further enhance completeness.

1. Introduction

The existing nationwide spatial datasets in Germany do not adequately represent the country's traffic infrastructure. They are often fragmented, exhibit varying quality, and lack sufficient documentation regarding their acquisition methods and spatial coverage. This is particularly evident for spatial data on parking areas, despite the growing demand for such information in both traffic management and urban planning. While some large German cities, for example Berlin and Hamburg , maintain their own spatial parking inventories, most smaller cities do not. Germany's federal administrative structure further contributes to this challenge, by distributing datasets through various portals with differing data access for different states. As early as 1991, Bonsall (1991) concludes that the absence of parking data was primarily due to administrative and bureaucratic reasons, rather than technical one—a finding that remains relevant today.

This data gap must be understood within the context of the growing importance of spatial data on traffic infrastructure. This is especially true given global challenges such as climate change, the mobility transition, and a growing focus on creating livable cities, all of which necessitate fundamental changes to traffic infrastructure. Thigpen and Volker (2017) highlight the growing importance of data on parking areas in discussions concerning the repurposing of on- and off-street parking in urban environments, while Shoup (2021) proposes on demand priced curb parking to minimize cruising for parking. The impact of such policy measures and structural changes to infrastructure can be analyzed through traffic modeling, which itself relies on consistent and accurate spatial data on parking (Kehlbacher et al., 2025).

To address the deficit in parking data, a variety of sensors and approaches have been explored in the literature. Coric and Gruteser (2013) tackle the problem of on-street parking by generating crowd-sourced maps from car-mounted sensors; however, their study was specifically focused on on-street parking and limited to roads traversed by equipped vehicles. The existing and publicly available spatial parking area inventory for the city of Berlin is based on georeferenced 360° panoramic optical images collected via vehicle-mounted camera systems (Senatsverwaltung für Mobilität, Verkehr, Klimaschutz und Umwelt, 2023). All covered areas where parking or temporary stopping is permitted are mapped, with restrictions (e.g., temporal) added as attributes to the parking polygons. This approach is limited to public areas, thereby excluding private and semi-private parking. Our study indicates that approximately 40 % of the total parking areas are not captured using such an approach (see chapter 4). Furthermore, it is both expensive and time-intensive, as all roads need to be driven, limiting it's potential for regular updates. Aryandoust et al. (2019) use travel time data provided by Uber to create parking density maps. An approach with citywide applicability as proved with a case study on the city of Melbourne. Yamada et al. (2022) utilize fixed LiDAR sensor systems in public parking facilities for monitoring parking space utilization. Di Mauro et al. (2019) develop a classification approach for images captured by fixed cameras near parking spaces to estimate occupancy status, though this method is not applicable to larger areas. Drouyer (2020) uses satellite imagery to estimate the occupancy ratio of parking lots from above. Peng et al. (2018) also focuse on the occupancy of parking slots, detecting vacant spaces using drone-based imagery. Mahaarachchi et al. (2023) present initial results from small case studies on the detection of vacant parking lots from aerial imagery. Ashqer and Bikdash (2019) employ aerial images for the detection of parking areas, with a focus on individual parking spots. While this study differentiates between various parking types, its limited to line-marked parking and its applicability to areas beyond single parking facilities is yet to be fully proven. Hellekes et al. (2023) combine a neural network-based approach for segmenting parking areas and other traffic areas from aerial images with statistical methods to estimate parking areas in structurally similar regions.

Large-scale mapping using aerial imagery can help bridge this persistent gap in current knowledge regarding parking, enabling efficient coverage from city to national scales due to broad availability of aerial images from regular flight campaigns. The view from above allows to map, areas that are inaccessible to ground surveys. High levels of efficiency and automation make image segmentation less costly than on-the-ground mapping and measuring campaigns. This study presents a novel method for the creation of parking area inventories derived from aerial imagery through a combination of AI-based image analysis methods. Further we roll out our method to the city of Berlin for a case study to prove its applicability. In a first step, a deep neural network, trained with a novel dataset, is applied to aerial images to detect roads, accessways, and parking areas. In a second step, these detected parking areas are intersected with cadastral data to obtain information on accessibility. The combination of the parking areas with results of an AI-based vehicle detection algorithm enables the derivation of information on the orientation of parking areas, which is then used for refined capacity calculation. A simplified representation of the workflow is depicted in Figure 1. Our results include parking areas, enriched with information on their accessibility and capacity.

2. Methodology

For the detection of parking areas high resolution aerial imagery is required. These are captured at periodic intervals on behalf of public authorities using aircraft mounted sensor systems and often provided free of charge (in Germany depending on the federal state). The provided Digital Orthophotos do have ground sampling distances (GSD) of 5 cm (DOP5), 10 cm (DOP10) or 20 cm (DOP20).

2.1 Segmentation of traffic areas in aerial images

The presented method is based on aerial imagery with a GSD of 10 cm, such as the DOP10 provided by the German state surveying offices. Traffic areas are segmented using a widely-successful and robust segmentation model based on the U-Net and DenseNet architectures (Henry et al., 2021). Following the original architecture recipe from U-Net (Ronneberger et al., 2015), it uses a Dense-Net-121 backbone (Huang et al., 2017) for both its encoder and its decoder interconnected via skip connections, with the inference direction of the latter being reversed and interweaved with bilinear up-sampling layers to recover the spatial information from the network bottleneck. It leverages the ability from the former to extract fine-grained information from every feature level of input images, while benefitting from the latter's efficient information flow and optimization in both the encoder and decoder. Moreover, and compared to the custom encoder of U-Net, pre-trained weights on datasets like ImageNet readily available for its standard encoder, which reduces the number of training iterations necessary to reach a convergence on a new dataset. It was also shown to have excellent generalization capability to unseen imagery from other regions worldwide outside of the training set domain (Schneibel et al., 2022; Wieland et al., 2023; Schneibel et al., 2024).

The segmentation model was trained and validated on the novel TIAS (Traffic Infrastructure and Surroundings) dataset (Merkle et al., 2024). The TIAS dataset comprises 51 manually annotated aerial images. Of these, 45 images, sized 5616 x 3744 pixels with a GSD varying between 7 and 14 cm, were acquired using DLR's own 3K and 4K camera systems (Kurz et al., 2012, 2014). The remaining 6 images, sized 5000 x 5000 pixels with a GSD of 10 cm, are DOP10 aerial images provided by German authorities. These images were selected from various regions, including the cities of Berlin, Hamburg, Munich, Braunschweig, Oldenburg, Landsberg, and Kaufbeuren. They primarily depict urban and suburban traffic scenes, ranging from simple to complex traffic situations. The dataset features a fine-grained classification system with nine distinct classes: road, accessway, bikeway, footway, keep-out area, parking area, railroad bed, road shoulder, and water. To capture areas used by multiple transportation modes, a "shared" attribute was introduced. For instance, if cars are parked on the side of a road without a specifically marked parking area, that space is annotated as "road" (primary class) shared with "parking" (secondary class). This approach helps reflect the actual use of traffic areas, which often serve more than just one intended or unintended purpose. For this study, we focused on segmenting only roads, accessways, and parking areas as those are relevant for the parking inventory. Roads and accessways are different classes in the sense that roads, in the TIAS dataset, are defined to have a connecting function within the network whereas in contrast access ways only serve to link the road network to specific destinations, for example, parking lots. Areas with the "shared with parking" attribute were considered as parking areas to improve the completeness of our segmented parking data. The inference step was run on a sliding window with a 10 % overlap between patches, where the logits values output by the model were merged via a extrema selection (i.e. the positive or negative values farthest from 0), so as to take the predictions with the highest confidence into account and reduce inconsistencies on borders between windows.

The resulting segmented raster maps were converted into vector format, and their polygon edges were smoothed using a Douglas-Peucker algorithm (Douglas and Peucker, 1973). This process helps eliminate pixelated edge structures and reduces the number of vertices, which speeds up subsequent data processing. These vector maps were then imported into a PostGIS spatial database for easy access, visualization, and efficient data handling. Within the database, the tile-like boundaries of neighboring polygons (which arise from segmenting and uploading data tile by tile) were dissolved. This creates a continuous network of roads, accessways, and parking areas that extends seamlessly across the original tile borders.

2.2 Accessibility classification of parking areas

To assign an access class to each parking polygon, these polygons are intersected with cadastral data on land parcel usage. Each usage type in the cadastral dataset was classified into one of three access categories: public, semi-public, or private. Public areas are herein defined as areas that are publicly available in the sense that they belong to the public or are dedicated to public use. Examples include roads and other public traffic areas, public administration, or public recreational areas. Semi-public areas are areas that are mostly accessible to the public but might be subjected to restrictions like opening hours. Examples are supermarkets, or other areas dedicated to shopping and leisure. Private areas are areas that are not dedicated towards the public and might have access restrictions like residential property, offices or factories. This access class was then

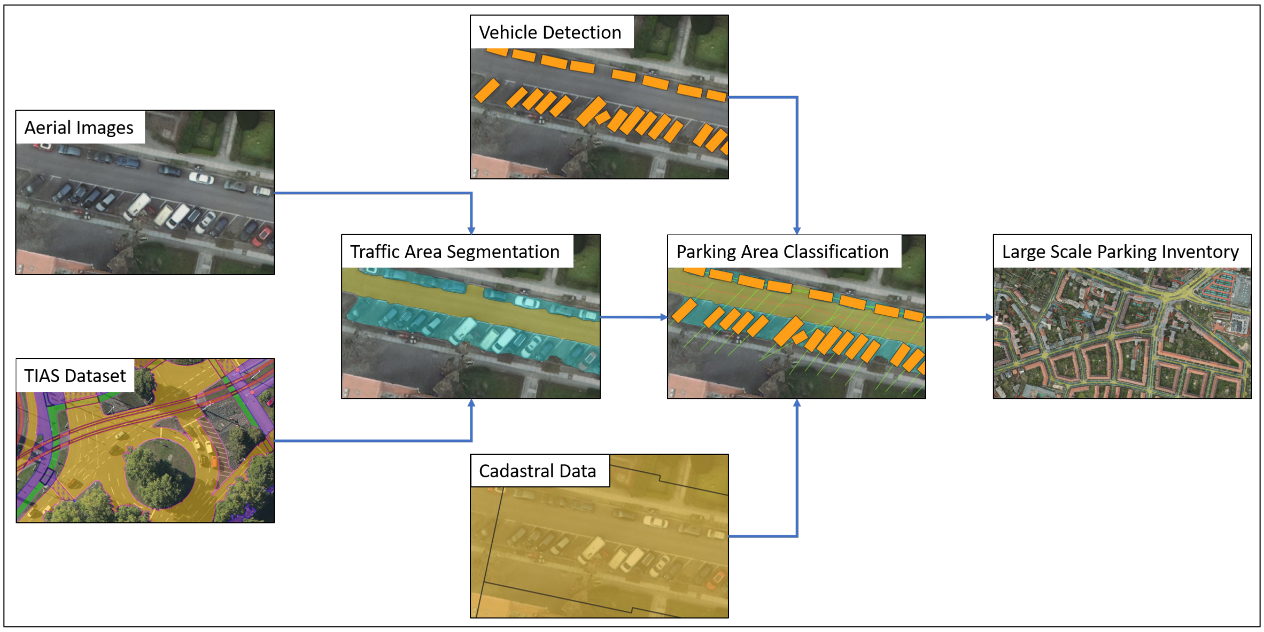

Figure 1. The simplified workflow for the creation of a large-scale parking area inventory for Berlin from aerial images. From left to right the cascade of processing steps and inputs is shown.

added to the cadastral polygons. It's important to note that the assignment of accessibility classes to cadastral usage types isn't always straightforward and often requires case-by-case consideration. If a parking area intersects two or more cadastral plots, it was assigned the access category of the cadastral plot that covers more than 50 % of the parking area's total space.

2.3 Parking area capacity calculation

To accurately estimate the number and orientation of parking spots within each vectorized parking area, the parking type—whether parallel, diagonal, or vertical—must first be determined. This is crucial as each type requires different dimensions as for example defined in German parking layout standards (Forschungsgesellschaft für Straßen- und Verkehrswesen (FGSV), 2023). The process involves three main steps: (1) centerline extraction from road and accessway polygons, (2) detection of vehicles from aerial images and calculation of their orientation relative to the road, and (3) determination of parking type based on the average orientation of vehicles intersecting the parking area.

The centerlines of road and accessway polygons are extracted using PostGIS's ST_VoronoiLines function (PostGIS Project Steering Committee, 2025). This function initially creates a two-dimensional Voronoi diagram from the vertices of each input polygon. To ensure consistent spacing of vertices around the polygon's edge, the polygon geometry is first segmentized with a 2-meter threshold prior to the construction of the Voronoi diagram. This pre-processing step also helps maintain consistent segment lengths in the resulting centerlines. Unwanted support lines of the Voronoi diagram, pointing towards the polygon edges, are then removed through a three-stage filtering process. This process evaluates the length and orientation of lines within the polygon to distinguish relevant centerlines from these edge-directed support lines. The resulting cleaned centerlines are then smoothed using the Douglas-Peucker algorithm.

Light-duty (LDV) and heavy-duty vehicles (HDV) are detected using a transformer-based object detection framework called DINO, which was adapted by (Mühlhaus et al., 2023) for oriented bounding box detection in aerial imagery, replacing the standard horizontal bounding box representation. The model was trained for 12 epochs on the Eagle dataset, an aerial dataset for vehicle detection (Azimi et al., 2020), achieving an mAP50 (mean Average Precision with 50 % overlap) of 78.5. Large aerial images are processed using a sliding window of 1024 × 1024 pixels with a 20 % overlap, which also multiscales the image patches to 0.5, 1, 1.5. To avoid multiple detections for each object, intraclass and interclass Non-Maximum Suppression (NMS) was applied with Intersection over Union (IoU) thresholds of 0.1 and 0.3, respectively.

The resulting vehicle bounding boxes of LDVs and HDVs are also stored in a PostGIS database. To minimize false positives only vehicles with a confidence score of 0.3 or higher are considered for further processing. For a precise calculation of a vehicle's orientation relative to the road, an intersection between the vehicle's longitudinal axis and the road's or accessway's centerline is desired. This is achieved by elongating the vehicle's longitudinal axis by five meters in both directions beyond its bounding box and then intersecting it with the road and accessway centerlines. The resulting intersection angle between the two lines represents the vehicle's orientation relative to the road. For vehicles whose extended longitudinal axis does not intersect a centerline, an alternative approach is used. A 10-meter buffer is created around the vehicle. Within this buffer, the road segment's mean deviation angle from the north-south axis is compared with the north-south axis deviation of the vehicle's longitudinal axis. The difference between these orientations, relative to the north-south axis, is considered the vehicle's orientation relative to the road. This method is particularly relevant for on-street parking where vehicles are often parallel to the road and no intersection occurs. The mean orientation of all vehicles intersecting a parking polygon is then added to the parking polygon's attributes and used for refined capacity calculations.

Figure 2. Different types of parking: (A) shows vehicles parked diagonally with non vertical intersection angles between vehicle axis and road centerlines. (B) shows vertical parking with intersection angles close to 90°. Both images also show parallel parking with no intersections along the opposite side of the road.

Based on the mean orientation relative to the road of all vehicles intersecting a parking polygon the parking polygons are classified into three parking types: parallel (0° to 30°), diagonal (31° to 75°), and vertical (76° to 90°). Figure 2 shows the three different types of parking along with vehicles from the vehicle detection and the roads centerline. Using this parking classification, the parking capacity of each parking polygon can be calculated by dividing the parking polygon's area by the recommended slot sizes for each parking type as specified in FGSV (2023): parallel (5.5 m x 2.15 m), diagonal (5.42 m x 2.7 m) and vertical (5.14 m x 2.7 m). For polygons without identified parking type (e.g., due to no vehicle intersecting the parking polygon), a default slot size of 5.2 m × 2.4 m is used.

2.4 Berlin case study

Our case study for Berlin is based on DOP10 aerial imagery from 2024 with 10 cm GSD and a coverage of the whole city of Berlin in its administrative federal border. The cadastral dataset on land parcel usage used for the classification of accessibility of parking areas is publicly available for the city of Berlin (Senatsverwaltung für Stadtentwicklung, Bauen und Wohnen Berlin, 2025). The parking areas capacities are calculated following the recommendations for parking slot size specified in Forschungsgesellschaft für Straßen- und Verkehrswesen (FGSV) (2023) FGSV.

3. Results

The newly generated Berlin-wide parking area inventory, comprises a total of 1,333,953 parking spots. Concurrently, the vehicle detection process identified 1,039,155 vehicles across the aerial imagery, consisting of 1,019,690 LDVs and 19,465 HDVs. The intersection of parking areas with cadastral data reveals the accessibility profile of these parking spots: 60 % are classified as publicly accessible, 21 % as semi-private, and 19 % as private. Table 1 provides a comprehensive overview of the distribution of parking types and their accessibility. Of the total parking spots, 36 % are classified as parallel, 27 % as diagonal, and 20 % as vertical. The remaining 17 % remain unclassified due to the absence of detected vehicles. Notably, publicly accessible parallel parking spots constitute about 90 % of all parallel spots, roughly double the share observed for other parking types. Diagonal, vertical, and unclassified parking spots all show a rather similar distribution of accessibility, with unclassified parking areas having the lowest share of public parking at 41 % but a higher share of semi-private parking at 34 %. Analyzing the parking area inventory at the district level shows variability in parking accessibility. Central districts, such as Mitte and Kreuzberg, exhibit the highest share of publicly accessible parking, accounting for 73 % (67,760 parking slots) and 76 % (43,010 parking slots) of their total parking spots, respectively. In contrast, larger districts extending into the city's outskirts, like Spandau and Reinickendorf, have a notably lower share of publicly available parking, at 53 % (50,638 parking slots) and 49 % (49,080 parking slots) of their total parking, respectively. These peripheral districts, in turn, show higher proportions of private (Spandau 20 % (20,906 parking slots), Reinickendorf 24 % (21,949 parking slots) and semi-private parking (Spandau 31 % (32,043 parking slots), Reinickendorf 24 % (22,014 parking slots)).

4. Discussion

This paper presents a novel approach for estimating parking capacities from aerial imagery. The methodology combines traffic area segmentation, vehicle detection, the combination with cadastral data, and a new workflow for classifying parking areas based on their orientation relative to the centerline of the road. Our case study for Berlin highlights a significant finding: inventories limited to publicly accessible parking areas notably underestimate the total parking availability; in Berlin this share is at approximately 40 %. The results also demonstrate a considerable variability in the distribution of parking types across different districts. While our findings suggest a higher share of publicly accessible parking in central districts, it's crucial to consider the settlement structure of these areas before drawing definitive conclusions.

A major advantage of using aerial imagery for creating parking area inventories is the broad availability of data across large geographical areas. This enables the highly automated and efficient processing of entire cities, states, and even whole countries. This characteristic also makes such studies highly repeatable, allowing for change analysis over multiple time steps as new aerial imagery becomes available. Furthermore, the georeferencing of aerial images generally offers higher precision compared to imagery acquired from moving ground vehicles (Hellekes et al., 2023). However, aerial imagery comes with inherent limitations. Occlusion from elements like vegetation, buildings, and shadows poses a significant challenge. While

	Vertical	Diagonal	Parallel	Unclassified
Share of Total	20 %	27 %	36 %	17 %
Accessibility				
Public	46 %	46 %	90 %	41 %
Semi-private	27 %	30 %	6 %	34 %
Private	27 %	24 %	4 %	25 %

Table 1. The share of each parking type (vertical, diagonal, parallel, unclassified) from all parking areas and the accessibility (public, semi-private, private) of parking areas for the different parking types.

fully occluded traffic areas cannot be mapped, partially occluded parking areas can lead to an underestimation of actual parking capacity within parking polygons. Developing a correction factor for capacities of partially occluded parking areas will be a focus of future research.

Another source of potential underestimation in mapped parking areas relates to how ”shared with parking” areas are annotated in the TIAS dataset. Since parking on a road is only annotated as ”road shared with parking” if vehicles are actually present in the image, the segmentation algorithm will only map such areas if vehicles are detected (Merkle et al., 2024). This makes the parking area inventory a snapshot of the parking situation at the time the image was captured. This limitation primarily affects parallel parking along roads and does not apply to dedicated parking areas that are physically separated from roads and accessways by curbs, markings, or changes in pavement. An approach to maximize the mapped ”shared with parking” areas involves fusing segmentation results from different timestamps, as applied by Hellekes et al. (2023). However, this significantly increases processing time and effort, and the typical time difference of at least one year between updated DOP10 imagery can compromise the timeliness of the results by mixing data from multiple years.

Applying the developed workflow from this study to areas outside of Berlin will be a topic of further research. A potential limiting factor could be the size of the TIAS dataset. The initial batch of annotations currently features only 51 images , primarily due to the considerable effort involved in manual semantic annotation. The inclusion of imagery from various cities and regions across Germany within the dataset is intended to ensure that methods trained on it generalize well to different environments. However, the current focus on German and mostly urban and suburban scenes may limit the applicability to areas with significantly different traffic infrastructure or to predominantly rural areas. A planned expansion of the TIAS dataset will place a greater emphasis on rural areas and additional regions.

The classification of parking areas by access category (public, semi-private, or private) relies on the intersection with cadastral land parcel usage data. Each usage type within the cadastral dataset was assigned one of these three tags. It’s important to acknowledge that this assignment was based on an educated guess by the authors. The complexity of real-world land use means that not all cases are unequivocally clear, leading to instances where the classification involved a degree of personal judgment. Furthermore, the generalizability of these specific access category assignments may require reconsideration when extending this approach to other German federal states or to a nationwide scale. This is due to the varying availability and structure of cadastral data across different federal states, which could necessitate adjustments to how cadastral units are categorized for access. This potential variability should be a consideration for future applications of the methodology beyond the Berlin case study.

The capacity calculation is based on the guideline for parking slot sizes provided by Forschungsgesellschaft für Straßen- und Verkehrswesen (FGSV) (2023). It is important to consider that these are recommendations, and actual parking areas can be laid out differently. For example, parking slots for disabled people are generally larger than standard slots, a detail not yet accounted for in the current workflow . Further existing parking slots are not updated with the release of new guidelines and local conditions can lead to the need of constructing parking slots in a way that deviates from the recommendations in the guideline. The use of default slot sizes for parking polygons where no vehicles were detected, or where no intersections occurred between vehicle axes and centerlines, contributes to uncertainties in the results. The fact that 17 % of the total mapped parking spots could not be classified underscores the need for further development and refinement of the classification method where no detected vehicles or centerlines are present.

5. Conclusion and Outlook

This paper presented a case study demonstrating the creation of a comprehensive parking area inventory for the city of Berlin, leveraging aerial imagery. The developed workflow combines traffic area segmentation from aerial images, vehicle detection, and cadastral data with a novel approach for classifying parking areas by their orientation and accessibility. This integrated methodology enables a refined calculation of parking capacities. The resulting inventory provides a detailed overview of Berlin’s parking situation, together with a brief analysis of parking area distribution across different districts. A key contribution of our method lies in its ability to significantly enhance existing parking inventories by including previously unmapped private and semi-private parking areas. This comprehensive inclusion addresses a critical data gap, as traditional inventories have often been limited to publicly accessible spaces, leading to a substantial underestimation of total parking availability. Despite these advancements, certain aspects of the method present opportunities for future refinement. A recognized shortcoming is the underestimation of parking capacities due to partial occlusion of parking areas by vegetation, buildings, or shadows in the aerial imagery. Future research will address this by developing a robust correction factor to account for such occlusions, thereby improving the accuracy of capacity estimations. Further efforts will explore the integration of publicly available data from sources such as public authorities or OpenStreetMap to generate comprehensive information on underground parking facilities, which are inherently undetectable from aerial imagery. This fusion of data sources promises a more complete picture of urban parking infrastructure.

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