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Inventory of private parking spaces: Approaches to estimating the supply of off-street parking spaces in residential areas

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Abstract: Data on private, off-street parking infrastructure are scarce, as the data are generally not systematically collected by public institutions and difficult to survey due to often inaccessible locations. As data are needed for targeted parking policies and for research related to parking, good estimates are required. Although such estimations are used in several studies, no study has yet compared different estimation approaches or evaluated their accuracy. Based on a literature review, we develop four approaches to estimating residential private parking supply and apply them to the city of Aachen, Germany. By comparing the estimates to a manually conducted survey in diverse neighborhoods, we evaluate and discuss the accuracy of the approaches. Our results highlight the difficulty of obtaining reliable data on private parking spaces, as the estimates vary considerably. Among the tested approaches, the application of a binary logit model based on real estate data provides the closest match to the surveyed parking supply. As this approach is capable of accounting for the large spatial variety in parking space availability within a city, it is not only suitable for city-wide estimations, but also for estimating the residential private parking supply in smaller spatial units like city blocks.

Keywords: Private parking spaces, residential off-street parking, parking policies, real estate data, logit model, synthetic residential building stock

1 Introduction

Parking spaces play a significant role in shaping the urban landscape, as they occupy large areas, both on and off the street. As space is scarce in most cities, parking competes with other uses. While on-street parking competes with bicycle infrastructure, outdoor catering areas, and street greening, off-street parking spaces take up space that could often otherwise be used for climate adaptation measures or urban consolidation, which is of great importance given the shortage of housing in many European cities. Efficient parking policies and other mobility measures could help reduce the amount of land used for parking in many districts.

For efficient and space-saving parking policies, all parking spaces within a neighborhood should be considered. However, in practice, private parking spaces are often neglected due to a lack of data and a focus on high competition for on-street space. These non-public parking spaces are located off the street and probably account for a large proportion of all parking spaces, as in most cities, their construction is obligatory when constructing new or converting existing buildings (Merten & Kuhnimhof, 2024). While city administrations can influence the private parking supply by setting such minimum parking requirements, they cannot directly manage how these spaces are subsequently used, as they are located on private property.

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The consideration of private parking spaces in parking policies or studies often fails due to incomplete data, as even city administrations usually do not have compiled and up-to-date data on this. While the number of parking spaces on-street and in public parking garages is often known or can quite easily be surveyed, e.g., with aerial image recognition or measuring vehicles, surveying private parking spaces is more difficult, as they are often located in inaccessible and hidden areas. As the exact number of private parking spaces is usually unclear and surveying them is very complex, adequate estimates of the private parking supply are required (Li et al., 2022).

Knowing the total number of private parking spaces in a city is essential for targeted parking policies, which should aim to provide the right number of parking spaces to meet the objectives of transport and urban planning (Davis, Pijanowski, Robinson, & Kidwell, 2010; Hoehne et al., 2019; Kimpton et al., 2021; Weinberger, 2012). Data on the private parking supply are needed in research and practice. For the latter, it can be used to improve the cities' parking policies, for example, when evaluating the necessity of establishing residential parking permit zones, analyzing parking demand in residential neighborhoods, assessing possibilities to reduce on-street parking spaces, or planning district garages for residents. On the other hand, data on the private parking supply allow for assessing several research questions and methods, for example, considering the residents' parking behavior in transport models, evaluating the overall land consumption of parking spaces, or analyzing the impact of parking supply on mode choice or car ownership.

As studies on parking are often in need of data on the overall parking supply, different approaches to estimate the private parking supply can be found in the literature (e.g., Davis, Pijanowski, Robinson, & Engel, 2010; Volker & Thigpen, 2022; Li et al., 2022, Weinberger, 2012; Ou et al., 2018). However, there is no study comparing different approaches and evaluating their accuracy yet. With our study, we contribute to closing this research gap and to answering the following research questions: Is it possible to accurately survey private off-street parking spaces? Which approaches can be used to estimate the private parking supply, and how accurate are these approaches?

After a brief literature review, we present our research methodology, study area, the conducted survey, and the estimation approaches used. We then apply the approaches to the city of Aachen, Germany. By comparing their results to the survey data, we evaluate the approaches' overall accuracies as well as their precision in neighborhoods with different characteristics. Finally, we discuss the applicability of the approaches depending on the research objective and existing challenges in estimating or surveying residential private parking spaces.

2 Literature

Several studies have shown that minimum parking requirements are often set too high and therefore lead to an oversupply of off-street parking (De Gruyter et al., 2023; De Gruyter et al., 2020; Merten & Kuhnimhof, 2024; Taylor, 2020; Willson & Roberts, 2011). This can impact travel behavior, as studies have revealed that car ownership, car use frequency and driving distances increase if residents have access to private off-street parking spaces (Christiansen et al., 2017; Currans et al., 2022; Guo, 2013; Weinberger, 2012; Weinberger et al., 2009).

Despite this proven impact on travel behavior, good data on the private parking supply is scarce. Even though the number of off-street parking spaces is often stated in building applications or in building tax data, the data are generally not publicly accessible. Depending on the respective data privacy regulations, it might be possible to query this information for separate buildings, as done by Gabbe et al. (2020). However, this is only practicable for small study areas. The same restriction accounts for manual surveys, like those done by Rogers et al. (2016), as surveying private parking spaces is very complex due to their often inaccessible and hidden locations.

Many studies on parking need data on the private parking supply and therefore apply various estimation approaches. However, there is no study comparing different approaches or evaluating their accuracy. In the following, we categorize and describe different approaches used to analyze the private parking supply found in the literature. While some of the studies mentioned determine a specific parking capacity in a study area, others apply the approaches to analyze interactions between the private off-street parking supply and other factors without extrapolating a specific number of parking spaces.

Some authors use **aerial images** to detect parking spaces (Davis, Pijanowski, Robinson, & Engel, 2010; Davis, Pijanowski, Robinson, & Kidwell, 2010; Guo, 2013; Hellekes et al., 2023; Li et al., 2022; McCahill & Garrick, 2012; Scharnhorst, 2018; Weinberger et al., 2009; Weinberger, 2012). While some studies manually scan the images, others use AI image recognition models. Apart from inaccuracies in image recognition, both methods can only detect uncovered above-ground parking spaces. Furthermore, it is not possible to allocate the parking space to different user groups, e.g., residents, employees, or customers, or to distinguish between private and public off-street parking. Davis, Pijanowski, Robinson, and Kidwell (2010) and Hellekes et al. (2023) use the results of aerial image detections to generate models that relate parking capacities to structural characteristics of the surroundings, which allows for transferring the detection results to other areas.

In some studies, the residential private parking supply is estimated with **household survey** data, both with national travel survey data and own surveys (Bates, 2014; Chester et al., 2010; Christiansen et al., 2017; Leibling, 2014; Scheiner et al., 2020; Volker & Thigpen, 2022). If national travel surveys are conducted in a country, they often include questions regarding private parking spaces (Porschen & Kuhnimhof, 2025). However, usually they do not survey the absolute number of private parking spaces per household but ask for the car's ordinary type of parking space at home or only question whether a private parking space is available to a household or not.

Another approach found in the literature is based on minimum **parking requirements** (Chester et al., 2015; Currans et al., 2022; Hoehne et al., 2019; Li et al., 2022; McCahill & Garrick, 2012; Merten & Kuhnimhof, 2024). Parking requirements usually define the minimum number of private parking spaces that must be built when constructing new or converting existing buildings. Merging these minimum requirements with building data allows for estimating the private parking supply. While some authors apply current parking requirements to all existing buildings, others use current and historic parking requirements and apply them to all buildings built in the respective period. However, this approach only provides an estimate of the number of parking spaces required, which is likely to differ from the supply that was actually built.

The analysis of existing **spatial data**sets, like census, cadastral or tax data, represents a further approach in the literature that is used to estimate the number of private parking spaces (Kimpton et al., 2021; Simons, 2020; Weinberger et al., 2009; Weinberger, 2012). These datasets usually contain spatial information on buildings, including their use. However, they often only cover data on parking buildings, like garages or carports, while data on uncovered parking spaces and sometimes also on parking spaces integrated in or under buildings for other purposes are not included.

Other studies evaluate **real estate data** regarding the availability of residential private parking spaces (Currans et al., 2022; Cutter & Franco, 2012; Leibling, 2014; Ou et al., 2018; Simons, 2020). Such datasets can, for example, be provided from different real estate trading platforms and allow for estimating the share of buildings or dwelling units with private parking spaces with regard to specific characteristics, like living space, building type, or year of construction.

Even though many examples for the estimation of the private parking supply could be found in the literature, none of the stated studies compare several approaches or evaluate the approaches' accuracy. Furthermore, most studies focus on cities in the United States, while there are very few studies on European cities. Table 1 summarizes the aforementioned studies that analyze the private parking supply.

Table 1. Literature overview on approaches to estimate off-street parking supply

Author	Study area	Approach	Purpose
Bates, 2014	UK	Household survey	Analysis of variations in parking demand
Chester et al., 2015	Los Angeles County	Parking requirements	Impact of parking requirements on urban form and car travel
Chester et al., 2010	USA	Household survey	Environmental impact of parking spaces
Christiansen et al., 2017	Norway	Household survey	Impact of parking supply on car ownership and use
Currans et al., 2022	Los Angeles	Parking requirements, real estate data	Impact of residential off-street parking on travel behavior
Cutter & Franco, 2012	Los Angeles County	Real estate data	Impact of parking requirements on parking supply
Davis, Pijanowski, Robinson, & Engel, 2010	Tippecanoe County	Aerial images	Land consumption of parking
Davis, Pijanowski, Robinson, & Kidwell, 2010	5 states in the USA	Aerial images	Land consumption of parking
Guo, 2013	New York City	Aerial images	Impact of parking supply on car ownership
Hellekes et al., 2023	Brunswick, Germany	Aerial images	Parking space inventory
Hoehne et al., 2019	Phoenix	Parking requirements	Development of land consumption for parking
Kimpton et al., 2021	Brisbane, Sydney, Melbourne	Spatial data	Impact of parking supply on mode choice
Leibling, 2014	London	Household survey, Real estate data	Comparison of demand and supply, evaluation of parking policies
Li et al., 2022	San Francisco Bay Area	Parking requirements, Aerial images	Parking space inventory
McCahill & Garrick, 2012	12 cities in the USA	Aerial images	Impact of car use on land consumption
Merten & Kuhnimhof, 2024	Aachen, Germany	Parking requirements	Evaluating the adequacy of parking requirements
Ou et al. 2018	China	Real estate data	Impact of parking at home on electric vehicle ownership
Simons, 2020	15 metropolitan areas in the USA	Real estate data, spatial data	Impact of driverless cars on urban parking and land use
Scharnhorst, 2018	5 cities in the USA	Aerial images	Parking space inventory
Scheiner et al., 2020	Dortmund, Germany	Household survey	Use of private parking spaces at home
Volker & Thigpen, 2022	Sacramento	Household survey	Realizability of accessory dwelling units
Weinberger et al., 2009; Weinberger, 2012	Neighborhoods in New York City	Spatial data, aerial images	Impact of residential off-street parking on car ownership and use

3 Methods

3.1 Research methodology

Based on the results of the literature review, we develop four approaches to estimate the number of residential off-street parking spaces. Figure 1 provides an overview of the input data, the necessary preparation steps, the application of the estimation approaches and the evaluation of their accuracy.

For the application of most of the estimation approaches, structural data like the living space, construction year, building type, or number of residents and cars are needed. As the data are not available on building or apartment level in Germany, we generated a synthetic residential building stock by combining spatially detailed datasets, like cadastral and three-dimensional building information, with spatially more aggregated data, like census and car registration data. This synthetic residential building stock is then used to apply the different estimation approaches to our study area, the city of Aachen, Germany.

In order to assess the accuracy of the approaches, ground truth data on the actual residential off-street parking supply are needed. For this purpose, we conducted extensive manual surveys in selected neighborhoods. By comparing the estimation results to this survey data, we evaluate and compare the approaches' accuracy. For detailed evaluations, we not only compare the total number of parking spaces, but also perform spatially more detailed comparisons on the level of city blocks, considering characteristics such as the population density and the share of single-family houses in all residential buildings.

The following sections introduce the study area and the survey data, followed by descriptions of the synthetic residential building stock and the estimation approaches.

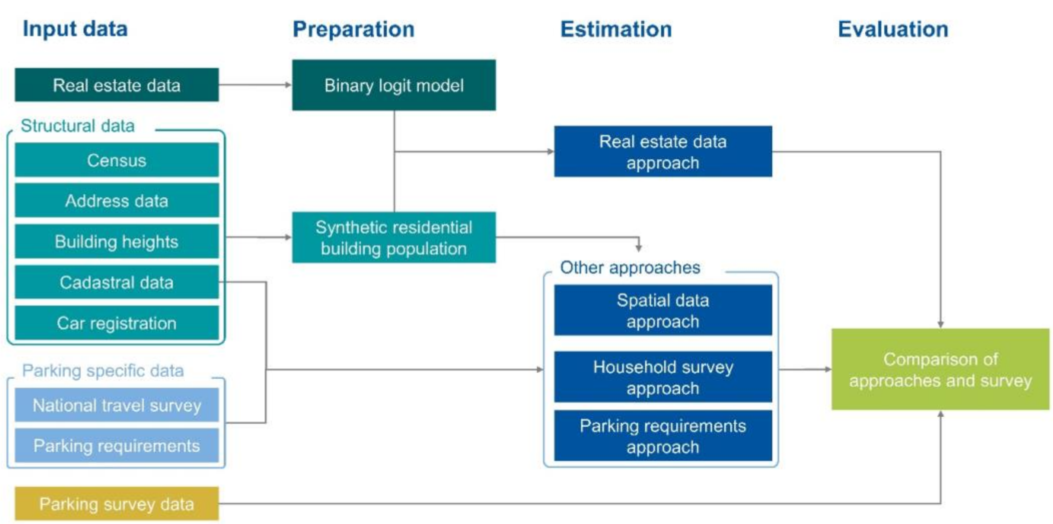


Figure 1. Procedure overview

3.2 Area of study

The city of Aachen, which is located on the western border of Germany, directly neighboring the Netherlands and Belgium, represents our study area. Approximately 260,000 inhabitants live in the city, of which around 58,000 are students (City of Aachen, 2025b). Aachen is a historic city, and its heart is defined by the cathedral and its historic surroundings. As the city has a compact size, many destinations can be reached on foot or by bicycle. While residents make 30% of all trips on foot, only 11% are travelled by bicycle (Gruschwitz et al., 2019), which is probably due to the hilly topography and the partly inadequate bicycle infrastructure. Furthermore, Aachen has a rather high car ownership rate of 444 cars per 1000 residents (City of Aachen, 2025b), and 47% of all trips made by residents are car trips (Gruschwitz et al., 2019). As there is no tram system, the public transport strongly relies on buses and is supplemented by a station-based round-trip car-sharing service and several free-floating e-scooter providers.

Except for pedestrian zones in the city center, on-street parking is present in almost all streets in Aachen. Parking permit zones have been established in many, mostly centrally located districts (see Figure 2). In these zones, residents can purchase an annual parking permit that allows them to park a car on-street within the zone for an unlimited period of time, while all other users are charged an hourly parking fee during the day. The price for such an annual residential parking permit was recently increased from 30 € per car to 30 € per square meter of vehicle space, so that the fee now depends on the size of the car (City of Aachen, 2025a).

While the city has an inventory of public parking spaces, which was generated in 2023 using aerial images and site visits, private parking spaces were only partially recorded (Frehn et al., 2023). However, private parking spaces, which are usually located off-street, probably account for a large proportion of the total parking supply in the city of Aachen, as relatively high minimum parking requirements have been in place for decades, requiring the construction of parking spaces when constructing new or converting existing buildings (Merten & Kuhnimhof, 2024).

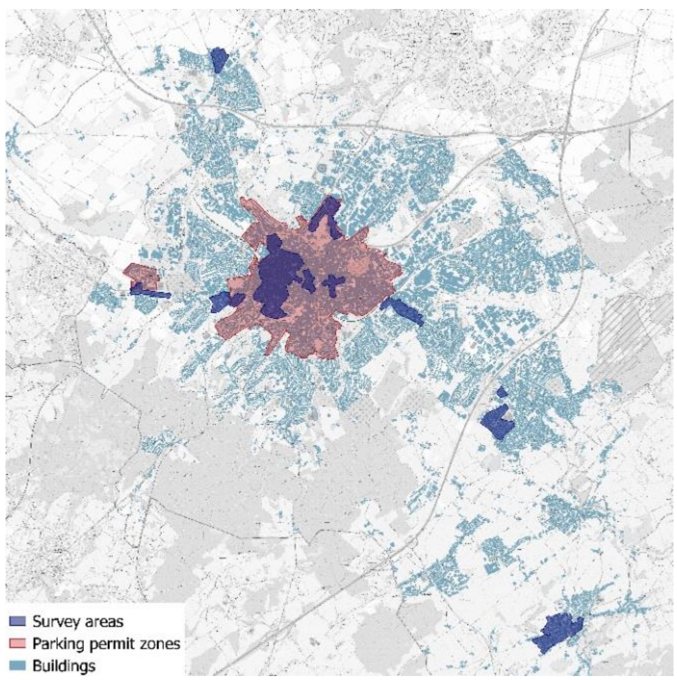


Figure 2. Map of survey areas
Source of background map: Federal Agency for Cartography and Geodesy, 2025

3.3 Survey of residential private parking spaces

Using site visits, aerial images, Google Street View, Apple Look Around, and cadastral building data, we created a private parking inventory covering multiple neighborhoods within the city of Aachen. As this requires time-consuming manual surveys, we did not survey the whole city but selected survey areas that cover diverse neighborhoods, regarding location (central vs. more peripheral), building types (mostly multi-family houses vs. a high share of single-family homes), uses (mixed vs. purely residential areas), and history (historic vs. rather recently constructed neighborhoods). Figure 2 shows the location of the chosen survey areas within the city.

The generated private parking inventory consists of geo-coded objects, which represent the surveyed parking areas and contain information on the location, size, and parking capacity. As such manual surveys represent the most accurate approach to obtaining a complete picture of private parking spaces in our study area, we use the data as "ground truth."

However, some challenges and possible inaccuracies of these surveys should be noted. The data was collected by several surveyors. To assess the quality of data collected by different surveyors, their results were compared for some neighborhoods in the city center where the survey areas of several surveyors overlapped. The comparison showed that different surveyors have different degrees of precision and assess the same situation in other ways, e.g., by assigning different parking capacities to the same parking area. Especially underground garages are very difficult to recognize, as usually only their access gate is visible. While the surveyors defined the capacity of visible parking areas by counting the marked parking spaces or estimating how many cars could fit in these areas, the capacity of underground garages could only be approximated based on the building's footprint. Even easily visible parking areas, like driveways, can lead to inaccuracies. Long driveways or driveways in front of garages or carports might offer enough space to park several cars in a row, but they are possibly only rarely used by multiple cars due to inconvenient maneuvering processes. Therefore, we assume that driveways, regardless of their length, have a maximum capacity of one parking space if they are located in front of garages or carports and a maximum capacity of two parking spaces otherwise. Another challenge was filtering for residential private parking spaces, as all off-street parking spaces were included in the surveys, but the estimation approaches can only consider residential parking. For mixed-use neighborhoods, the surveyors recorded if parking spaces were obviously not used by residents, e.g., if signs indicate that a parking space is reserved for employees, customers or patients. Furthermore, for parking spaces linked to buildings, like attached garages or driveways, we only kept those parking spaces linked to buildings with residential use. To reduce inaccuracies, some areas were revisited to check and supplement the survey data.

3.4 Synthetic residential building stock

Information on buildings and apartments, like living space, building type, and year of construction, is often published in different datasets and aggregated for data protection reasons, e.g., to the grid cell level. In order to apply the private parking estimation approaches to our study area and to evaluate the results in detail, we need housing information on a small spatial level, preferably at the level of individual buildings or dwelling units. Therefore, we developed a procedure that combines housing information from different publicly available datasets and disaggregates data from the grid level to the level of single dwelling units. In this way, a synthetic residential building stock is generated. This procedure depends on the type of input data available. As our approach is developed for the data available in Germany, it would need to be adjusted when transferring it to other countries. Figure 3 summarizes the input data and the applied preparation steps to generate the synthetic residential building stock.

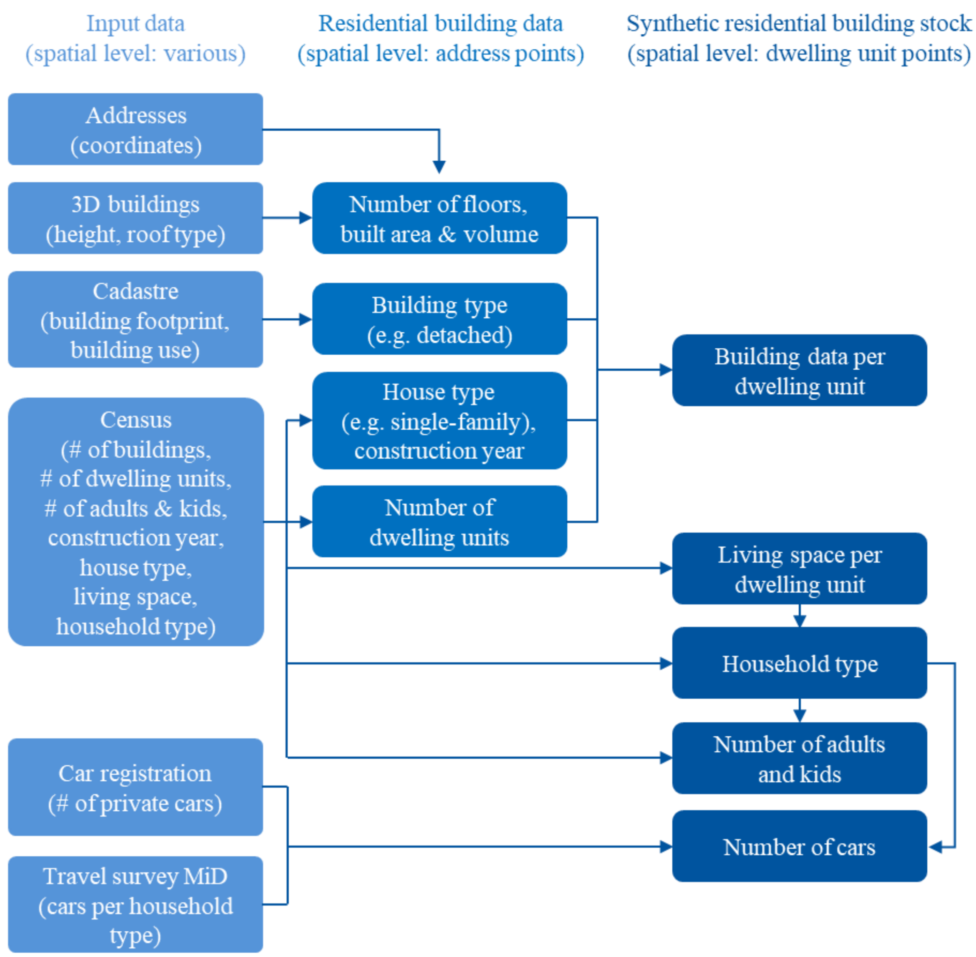


Figure 3. Flowchart of synthetic residential building stock generation

In Germany, housing and population data are collected as part of the census, of which the most recent data date back to 2022 (Federal Statistical Office of Germany, 2025). The census data are published in spatially aggregated form at several grid levels, of which a 100-by- 100-meter grid is the smallest. Despite this spatial aggregation, many published variables are grouped. For example, for the construction year, only the number of buildings constructed within a period of time (e.g., from 1919 to 1948) is published. Furthermore, a disclosure control method is applied, so that the published data deviate slightly from the original data. For the generation of the synthetic residential building stock, we use data of the 100-by-100 meter grids on the number of buildings in total, per construction year class, and per house type, the number of dwelling units in total and per living area class, as well as the number of residents.

In addition to the census data, the synthetic residential building stock is built on three-dimensional building data, address point data, car registration statistics, and cadastral data (City of Aachen, 2024; District government of Cologne, 2025a, 2025b, 2025c). The latter data source contains geocoded building polygons, which enable to calculate building types depending on the availability of neighboring buildings (detached, semi-detached, terraced). By merging cadastral, address and three-dimensional building data, we get information on the area, volume, height, number of floors, and building type of each residential address point in our study area.

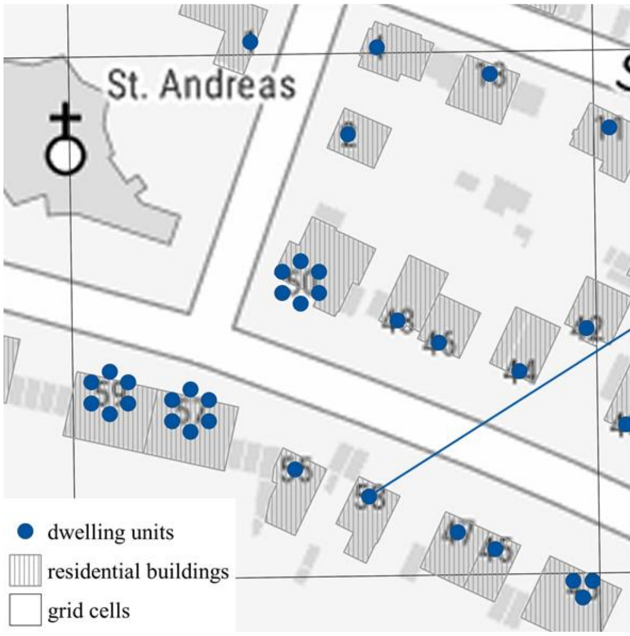
In the next step, we further enrich this data by distributing the census data to the address points. For this purpose, we randomly assign the information available on the grid level to the address points while considering several conditions to make the assignment more realistic. For example, the assignment of house types considers building volume and building type, e.g., detached single-family houses are assigned to buildings with rather small volume that are classified as detached. These house types, together with the buildings' floor area, are then used to allocate the number of dwelling units and the living space per dwelling unit to each building. Finally, we reformat our data from the building to the dwelling unit level by duplicating the address points by the number of dwelling units per building and assigning the respective data per dwelling unit.

Apart from building and dwelling data, we add a simple people and car population to this synthetic residential building stock. The number of adults and children in a grid cell is obtained from the census and assigned to the dwelling units based on their size. For this purpose, we first assign household types (e.g., 2 adults with children) to the dwelling units with a random assignment with weights and then add the number of adults and children accordingly, always complying with the number of people in the grid. For the weights, we use a statistic based on census data, which indicates the probability that certain household types live in a specific dwelling unit size class. The car population is based on car statistics per statistical district published by the city of Aachen, as no nationwide data on a small spatial level is available in Germany. Based on the average car ownership per household type in large cities, which is published by the German national travel survey "Mobilität in Deutschland," we first assign the average number of cars to each dwelling unit according to the dwelling unit's household type. In the following, we calculate adjustment factors for each statistical unit to comply with the overall number of registered cars in this unit and multiply the assigned number of cars per dwelling unit by the respective factor.

As a result of these extensive data preparation steps, a synthetic residential building stock is achieved, which contains information for each dwelling unit on its location, living area, the building's year of construction and house type, the number of adults and children living in the dwelling unit and the number of registered cars. Figure 4 illustrates the results for an exemplary 100-by-100 meter grid cell.

Even though this building stock certainly does not perfectly match reality, comparisons to other data sources, like housing and population statistics of the city of Aachen and census data at the municipal level, show that it seems to reflect the real conditions quite well. To this end, we compared indicators such as the number of dwelling units and residents, as well as the share of apartments per living space class, with these datasets at the city and statistical district level.

In the following, the synthetic residential building stock is used in all approaches, except the spatial data approach, to estimate the number of private parking spaces within our study area.



Feature	Value
id	105155
use	residential
footprint	107,80
height	10,54
volume	1136
floors	2
building_type	detached
house_type	single_family
living_space	f160t169m2
construction_year	f1949t1978
adults	2
kids	0
cars	1

Figure 4. Example of the synthetic residential building stock
Source of background map: Federal Agency for Cartography and Geodesy, 2025

3.5 Approaches to estimate residential private parking supply

3.5.1 Real estate data approach

Real estate data, for example, published by real estate trading platforms, can represent a suitable data source for estimating residential private parking spaces. In Germany and many other countries, private parking spaces are often marketed together with the dwelling unit (Deschermeier et al., 2023). However, some private parking spaces used by residents are certainly rented or sold separately from a house or apartment. This approach neglects these parking spaces.

We use data on residential property listings in Aachen from Immobilienscout24, a large property portal in Germany. For research purposes, this data can be used free of charge and is provided by the Research Data Centre Ruhr at the RWI Leibniz-Institute for Economic Research (RWI - Leibniz-Institut für Wirtschaftsforschung & ImmobilienScout24, 2024a, 2024b, 2024c, 2024d).

The datasets contain all listings on Immobilienscout24 of residential houses and apartments for sale and rent in Germany between 2007 and June 2024. Duplicate listings, for example, due to changes in the advertisement or re-letting of the dwelling unit, are labelled as such by the RWI and excluded from further analyses. Apart from building and dwelling characteristics, the data contain information on whether a private parking space is available or not. Based on this data, we built a binary logit model that explains the availability of private parking with different characteristics of the dwelling, building, and its surroundings. The model's binary dependent variable equals 0 if the listing does not have a private parking space, while a value of 1 implies that there is at least one private parking space available. We tested different independent variables with the constraint that the variables must also be present in our synthetic residential building stock in order to be able to apply the model to our study area. The best model regarding the variables' significance and the model's explanatory power, measured by the pseudo-R^2 value, includes variables for the construction year, living area, house types, and location. The model's coefficients and p-values are presented in section 4.2.2. This model is then applied to our synthetic residential building stock to estimate the number of residential private parking spaces within our study area.

3.5.2 Spatial data approach

For this approach, we use cadastral geodata on buildings and parcels from the ALKIS database of the state of North Rhine-Westphalia (District government of Cologne, 2025c). Apart from geocoded building and parcel polygons, the database contains information on their use. To filter for residential private parking areas, we extract all buildings with parking use located on parcels with residential uses. The number of parking spaces within the extracted buildings is then estimated by assuming a mean space consumption of 14.5 m^2 per parking space, which represents a typical size for a single parking space in Germany, without taking into account space for access and exit (Forschungsgesellschaft für Straßen- und Verkehrswesen, 2023). We decided to disregard these access spaces, as the cadastral data contain many single and double garages, as well as garage blocks, which do not include any access spaces, but only a few larger car parks. To compare the results of the approach to the survey data and the estimates from other approaches, the detected parking spaces are then aggregated at the city block level (see section 3.5.5).

3.5.3 Household survey approach

The German national travel survey "Mobilität in Deutschland" monitors mobility aspects in Germany. In the most recent yet published survey period in 2017, 316.000 persons in 156.000 households were surveyed (Nobis & Kuhnimhof, 2018). Among many other questions, the participants were asked about the usual type of parking space at home for each car. For large cities like our study area, on average 60% of all cars are parked on private parcels at home. As a simple approach, we assume that this proportion represents the average in our study area and is constant over the whole city. We then estimate the number of residential off-street parking spaces by multiplying this share with the number of private cars in the synthetic residential building stock.

3.5.4 Parking requirements approach

This approach is based on current and historic minimum parking requirements for residential buildings. Parking requirements have a long history in Germany, as the first parking requirements were already defined in 1939. First, we research all parking requirements relevant to our study area and indicate the period in which they applied, the distinguished building or dwelling unit categories, and the minimum number of parking spaces required (see Table 2). While buildings constructed before 1939 are assumed to have no off-street parking spaces, the number of private parking spaces for all other buildings in the synthetic residential building stock is estimated by the required number of parking spaces for a building with these characteristics in the parking requirements applicable at the building's time of construction. Therefore, this approach assumes that for each building, the minimum parking requirements valid at the time of construction were exactly observed.

Table 2. Historic and current minimum parking requirements valid for the city of Aachen

Period of validity **Name of regulation**		**bef. 1939** **none**	**1939-1949** **Reichs-garagen-ordnung**	**1950-1959** **Runderlass NRW 1950**	**1960-1983** **Runderlass NRW 1960**	**1984-1996** **NRW VV BauO 1984**	**1997-2017** **NRW VV BauO 1997/ 2000**	**since 2018** **Stellplatz-satzung Aachen**
Required parking spaces for a …	single-family house	-	1	-	1	1.5	1	1
	two-family house	-	2	-	0.5	1.25	1	1
	multi-family house	-	2	-	0.5	1.25	1	0.6-2.1 (dep. on size and location)
	detached house	-	-	0.67	-	-	-	-
	semi-detached house	-	-	0.29	-	-	-	-
	terraced house	-	-	0.1	-	-	-	-
Reference unit		-	building	dwelling unit	dwelling unit	dwelling unit	dwelling unit	dwelling unit

3.5.5 Assessment of the accuracy of the estimation approaches

The accuracy of the estimation approaches is evaluated by comparing the estimated numbers of private parking spaces to the surveyed numbers. This comparison is made at the level of city blocks and is evaluated regarding structural characteristics like population density and the proportion of single-family houses in all residential buildings. The city blocks are generated based on cadastral parcel data by eliminating parcels with traffic use, like streets, footpaths, or railway tracks, and by merging the remaining neighboring parcels. In this way, city blocks account for spatial barriers and merge contiguous areas. In contrast, a comparison at the grid level would result in parking spaces being allocated rather randomly to cells, depending on whether the approach estimates the number of parking spaces for each parking area or each dwelling unit. Figure 5 illustrates the difference between city blocks and 100-by-100 meter grid cells.

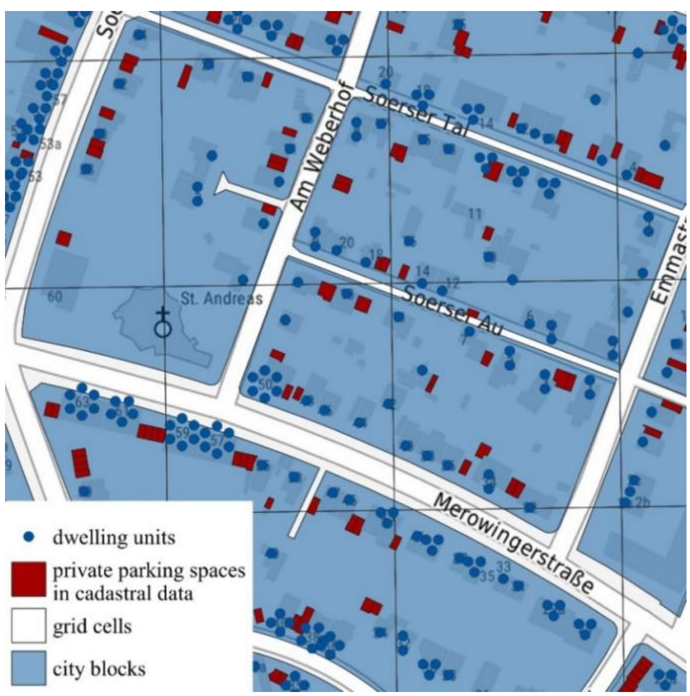


Figure 5. Difference between city blocks and grid cells

Source of background map: Federal Agency for Cartography and Geodesy, 2025

A comparison for small spatial units, like city blocks, allows us not only to consider the overall accuracy of the approaches across all surveyed areas, but also to analyze whether the accuracies vary between city blocks with different characteristics. For this purpose, the relative error is calculated for each city block using the following equation:

$$err_{rel,i} = \frac{n_{est,i} - n_{sur,i}}{n_{sur,i}} \tag{1}$$

with $n_{est,i}$ = estimated number of parking spaces in block i
$n_{sur,i}$ = surveyed number of parking spaces in block i

A negative relative error indicates an underestimation of the recorded parking capacity, while a positive value signals an overestimation. As the relative error divides the absolute difference between the estimated and the surveyed number of parking spaces in a block by the surveyed number, only blocks with at least one surveyed parking space can be considered. To evaluate the models' accuracy in relation to the characteristics of the city blocks, the surveyed blocks are grouped according to the population density, the share of single-family houses and further structural variables. Based on these groups, boxplots of the relative error are created.

In addition to the relative errors, we consider mean squared errors, which can be calculated by the following equation:

$$MSE = \frac{1}{n}\sum_{i=1}^{n}(n_{est,i} - n_{sur,i})^2 \tag{2}$$

with $n_{est,i}$ = estimated number of parking spaces in block i
$n_{sur,i}$ = surveyed number of parking spaces in block i

A smaller mean squared error signifies a better fit of the estimation to the survey. However, this measure does not allow for differentiating over- and underestimations.

4 Results

The approaches to estimate the residential off-street parking supply, which are described in section 3.5, are applied to the city of Aachen. In the following, we present the results of the conducted survey of private parking spaces and compare the results for each approach to this survey data.

4.1 Parking survey results

Our survey of private parking spaces within the selected survey areas in Aachen identified about 7,870 parking spaces, of which 6,490 are probably accessible to residents. This results in an average of 0.2 residential private parking spaces per resident, 0.4 parking spaces per dwelling unit, and 0.7 parking spaces per private car. However, these values vary strongly within the study areas, as illustrated in Figure 6. The figure displays boxplots of the number of private parking spaces per dwelling unit depending on the city blocks' population density and share of single-family houses. The boxes in this and all following boxplot figures range from the 25th to the 75th percentile of all city blocks with the respective characteristics, the horizontal middle line indicates the median, and the whiskers cover all values except for outliers. The boxplots in Figure 6 show that while the number of private parking spaces per dwelling unit is rather low in highly populated city blocks with few single-family houses, more than one private parking space per dwelling unit is available in most city blocks with low population densities and a high proportion of single-family houses among all residential buildings.

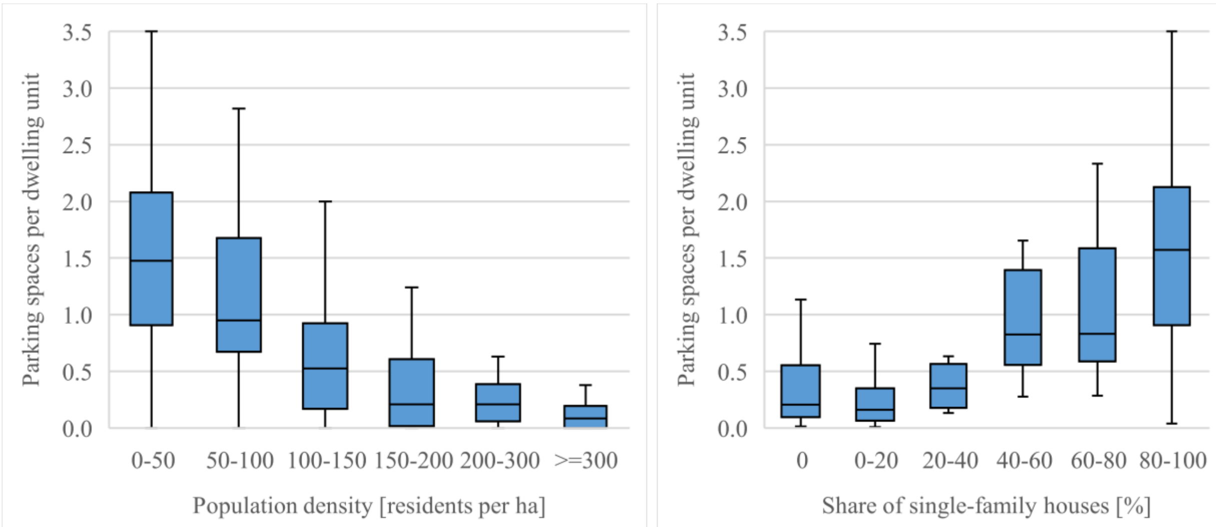


Figure 6. Private parking spaces per dwelling unit depending on population density and share of single-family houses

4.2 Results of the real estate data approach

4.2.1 Data preparation

The real estate data contain about 180,000 listings in the city of Aachen, of which about 52,000 are detected as duplicate entries. Of those duplications, only the most recent listing of each unit is considered in the further analysis. Another factor limiting the scope of the data concerns the information on the availability of a private parking space. As this information has only been indicated since 2017, we can only include the listings published between 2017 and 2024. However, also for the approximately 59,000 listings published in this period, this parking information was specified for only about 20,500 listings, of which around 20,000 have access to a parking space. Consequently, it is rarely indicated if there is no private parking space available.

To account for this incomplete information, we tried different assumptions for listings without information on the availability of a private parking space. As a private parking space is probably not taken for granted for apartments in multi-family houses and represents a selling argument, we assume that no private parking space is available for such apartments with missing information on parking. The situation is different for single- or two-family houses on the outskirts of the city. As in these areas almost all the houses have at least one private parking space, it is probably not considered necessary to state this explicitly. Therefore, we suppose that the availability of private parking spaces for single- and two-family houses for which parking information is missing depends on the location of the house. If such a house is located in an area with tense parking situations for residents, we assume that it does not have access to a private parking space. As residential parking permit zones are usually established in such areas and locations in the data are aggregated to 1 km² grid cells, we define such areas as grid cells that are at least 25% covered by parking permit zones. For single- and two-family houses in all other grids, it is assumed that a private parking space is available, even if this is not specified in the house's advert.

For house listings, the data specify eleven different house types, which we summarize to five house types to get categories comparable to our synthetic residential building stock – detached, semi-detached, terraced, multi-family and other. As the vast majority of the apartment listings are probably located within multi-family houses, and because we want to estimate the availability of private parking spaces per dwelling unit, we drop listings of multi-family houses from further analysis and only consider the apartment listings within these buildings. Furthermore, we also drop houses of "other" house types, as only a few houses belong in this category and as it is not possible to define a comparable category within the synthetic residential building stock. Apart from that, some listings have to be dropped due to missing information on the year of construction or the living area.

The location of the listed houses and apartments in the real estate data is not specified by exact coordinates but aggregated to 1 km^2 grid cells. To be able to consider location characteristics in our analyses, we calculated different location variables for these cells, like the distance to the city center, which we defined by the center of Aachen's old town, the share of the cell's area occupied by buildings, and the mean height of all residential buildings within the cell.

4.2.2 Binary logit model based on real estate data

After this excessive data preparation, a binary logit model is built based on the remaining about 36,300 listings. The availability of a private parking space represents the model's binary dependent variable (0: no private parking space, 1: at least one private parking space). We tested different independent variables to find a model with high significance and high explanatory power. Table 3 summarizes the results of the best model achieved.

Table 3. Results of the binary logit model. Dependent variable: Availability of a private parking space (1: yes, 0: no)

Cat.	Variable	coef	p	Sig.
Intercept	-	-1.918	<0.001	***
Year of construction (reference: before 1949)	1949-1978 [0; 1]	0.664	<0.001	***
	1979-1990 [0; 1]	2.231	<0.001	***
	1991-2000 [0; 1]	2.157	<0.001	***
	2001-2010 [0; 1]	1.914	<0.001	***
	2011-2019 [0; 1]	3.005	<0.001	***
	since 2020 [0; 1]	2.443	<0.001	***
Living area (reference: up to 30 m2)	30-50 m2 [0; 1]	0.677	<0.001	***
	50-70 m2 [0; 1]	1.081	<0.001	***
	70-90 m2 [0; 1]	1.305	<0.001	***
	90-110 m2 [0; 1]	1.898	<0.001	***
	≥ 110 m2 [0; 1]	2.489	<0.001	***
House type (reference: apartment)	Detached house [0; 1]	3.572	<0.001	***
	Semi-detached house [0; 1]	4.112	<0.001	***
	Terraced house [0; 1]	2.808	<0.001	***
Location	Distance to city center [km]	0.064	<0.001	***
	Share of built-up area [-]	-1.509	<0.001	***
	Mean height of surrounding buildings [m]	-0.084	<0.001	***

Number of observations: 36,282; pseudo-R^2: 0.3343
Sig.: p-value <0.001: ***, 0.001-0.01: **, 0.01-0.05: *

The model includes dummy variables for the construction year classes, living area classes and house types, as well as three metric location variables. The original metric variables for the year of construction and the living area were categorized in order to match the classes in the German census data and in the synthetic residential building stock.

All variables have a significant correlation to the dependent variable, and the model achieves a pseudo-R^2 of 0.334. The results show that dwelling units in recently constructed houses are more likely to have a private parking space than units in older houses and that large dwelling units are more likely to have a private parking space than small dwelling units. The results further demonstrate that single- and two-family houses are more likely to have a private parking space than apartments in multi-family houses, with detached and semi-detached houses having a higher probability of having access to private parking than terraced houses. The location variables indicate that dwelling units located in less densely built-up areas, further away from the city center, are more likely to have a private parking space than dwelling units in centrally located areas with high building density. The results correspond to the correlations we expected.

4.2.3 Application of the model to the study area

For each dwelling unit in the synthetic residential building stock, the probability of having access to a private parking space is calculated based on the model parameters presented in Table 3. We assume that the number of private parking spaces per dwelling unit is equal to this probability. These values are then aggregated to the city block level by summing up the calculated numbers of private parking spaces of all dwelling units located within the block, and only then rounded to equal numbers.

The approach estimates a total supply of about 60,150 private parking spaces for the whole city of Aachen. About 4,810 of these private parking spaces are located within the survey areas, compared to 6,490 private parking spaces surveyed. To provide a more detailed analysis at the level of city blocks, Figure 7 illustrates boxplots of relative errors depending on population density and the share of single-family houses among all residential buildings.

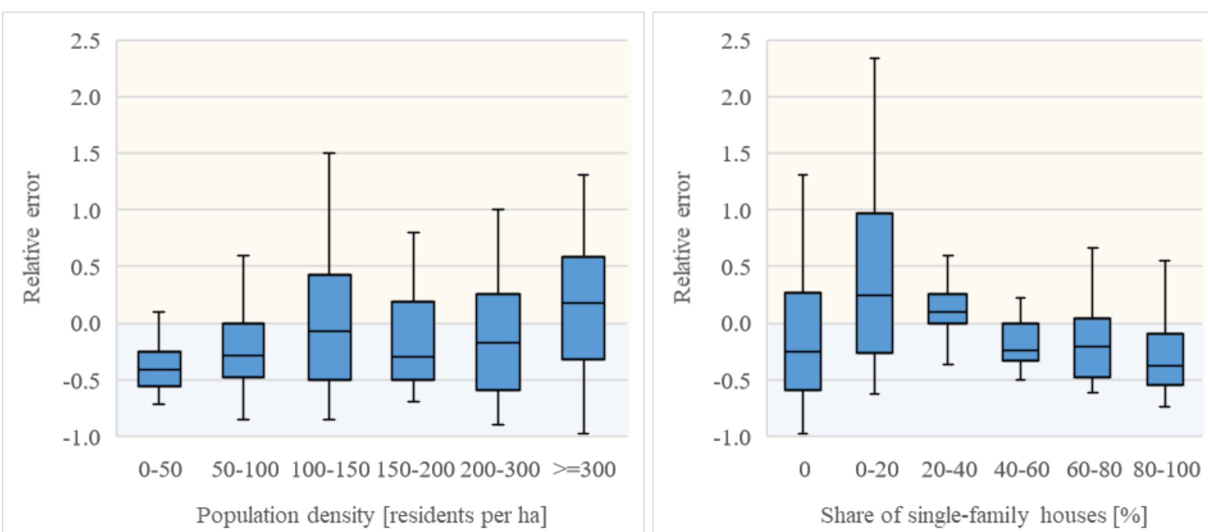


Figure 7. Relative error of the real estate data approach depending on population density and share of single-family houses

The figure shows that the estimated numbers of private parking spaces of the real estate data approach correspond quite well to the surveyed numbers in most city blocks with a rather high population density. However, the approach underestimates the number of private parking spaces in most of the city blocks with low population densities and many single-family houses, which are usually located on the outskirts of the city.

This deviation might arise as the model only considers the probability that a dwelling unit has access to at least one private parking space, while, especially for single-family houses on the outskirts of the city, probably more than one parking space is available in most cases. To account for this, we tried different simple adjustments. The best results were achieved by doubling the estimated number of private parking spaces belonging to detached and semi-detached single-family houses. This adjustment assumes that houses of this category that have access to a private parking space have two parking spaces, e.g., one parking space in a garage and one in front of the garage.

This adjusted real estate data approach results in an estimated supply of about 75,800 private parking spaces for the whole city of Aachen, of which 5,910 parking spaces are located within the survey areas. The adjustment reduces the overall divergence between estimation and survey to 580 parking spaces or 9% of the surveyed capacity and improves the results per city block (see Figure 8). While the results for densely populated blocks without single-family houses remain unchanged, the adjustment improves the consistency of the results with the survey in most city blocks with low population density and many single-family houses.

Possible shortcomings of this approach can arise as not all residential private parking spaces are marketed together with the dwelling unit. Another possible reason for inaccuracies is that the data might represent a biased sample of the real building structure, e.g., as socially subsidized housing might be underrepresented.

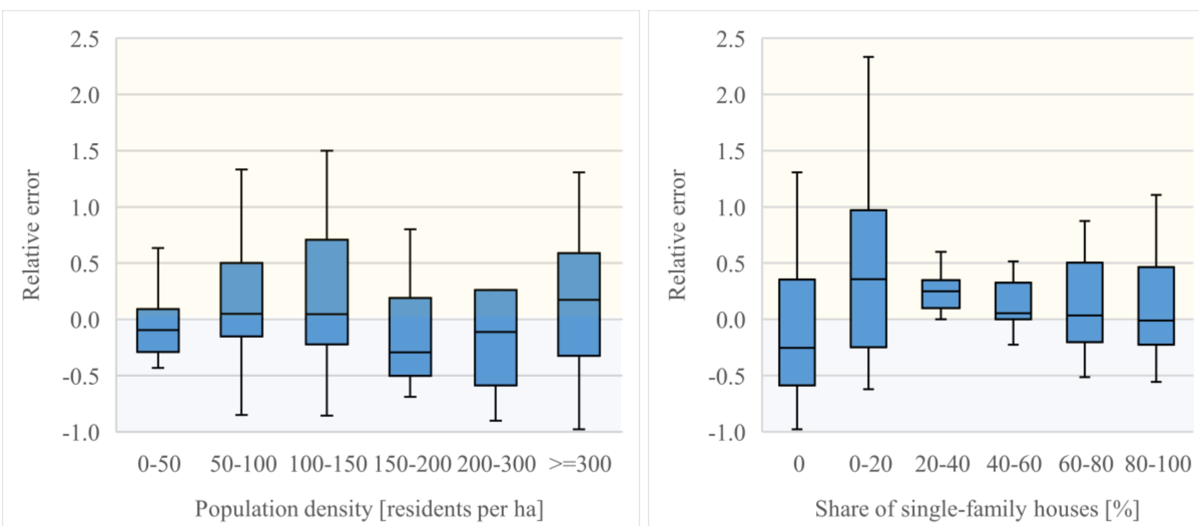


Figure 8. Relative error of the adapted real estate data approach depending on population density and share of single-family houses

4.3 Results of the spatial data approach

The approach based on cadastral data estimates a total number of about 51,200 residential private parking spaces for the whole city of Aachen, of which about 4,480 are located within the survey areas.

The results on the level of city blocks (see Figure 9) indicate that this approach tends to underestimate the residential private parking supply in most city blocks. This underestimation is most pronounced in blocks with low population densities and a high proportion of single-family houses, as well as in blocks with very high population densities and no single-family houses.

This result can be explained by the fact that the cadastral data only contain information on parking buildings, like garages and carports, while it does not include information on uncovered parking spaces, e.g., in backyards or driveways. Furthermore, most parking spaces located in underground garages or on the ground floor are neglected, as each building is assigned exactly one use category, and other uses generally dominate parking use. In contrast to that, there are also a few blocks with an overestimated parking supply. This overestimation is probably the result of inaccuracies in converting the area of the parking building into the number of parking spaces, as space for access and exit is neglected.

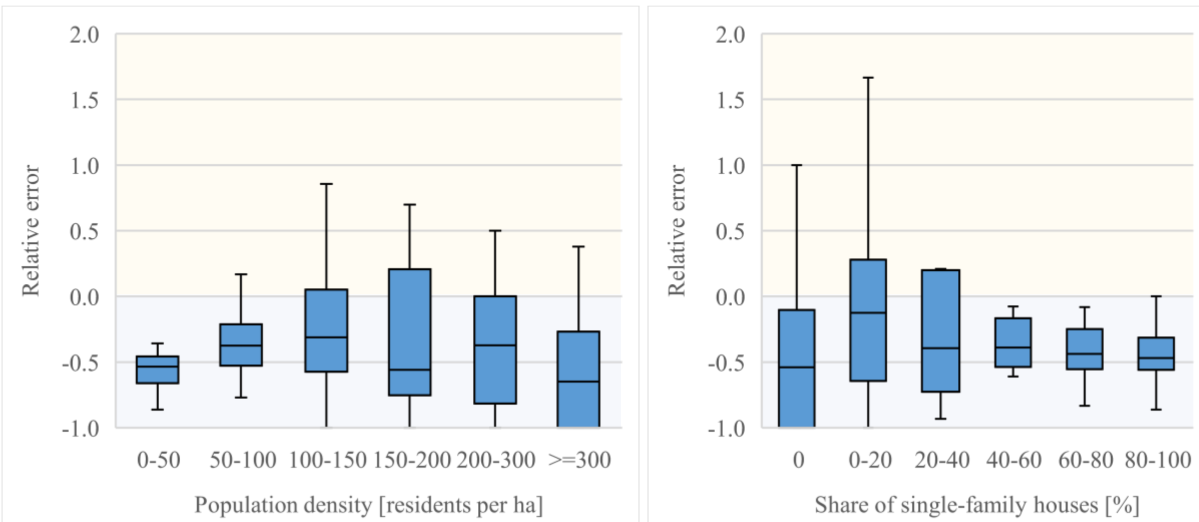


Figure 9. Relative error of the spatial data approach depending on population density and share of single-family houses

4.4 Results of the household survey approach

For the whole city of Aachen, the approach based on the national travel survey data estimates about 57,200 residential private parking spaces. Within the survey areas, the approach results in about 5,360 parking spaces, so about 1,130 parking spaces fewer than were surveyed. Figure 10 illustrates the results on the level of city blocks.

The results of the household survey approach show both over- and underestimations of the private parking supply depending on the location and characteristics of the city blocks. While the approach rather underestimates the parking supply in blocks with low population density and many single-family houses, it overestimates supply quite strongly in many densely populated blocks with few or no single-family houses.

The results indicate that although the assumption that 60% of all cars are parked off-street at home may be accurate for the city as a whole, this proportion varies strongly within the city. While fewer cars are parked off-street in densely populated, usually centrally located, areas, more private parking is available in neighborhoods with low population densities and many single-family houses, which are usually located on the outskirts of the city. Therefore, the results are not reliable for small spatial units. Further inaccuracies of this approach arise due to the question design. In the household survey, only regularly used private parking spaces are considered, and the number of parking spaces per household is limited by the household's number of cars, as it was not possible to state more parking spaces than cars.

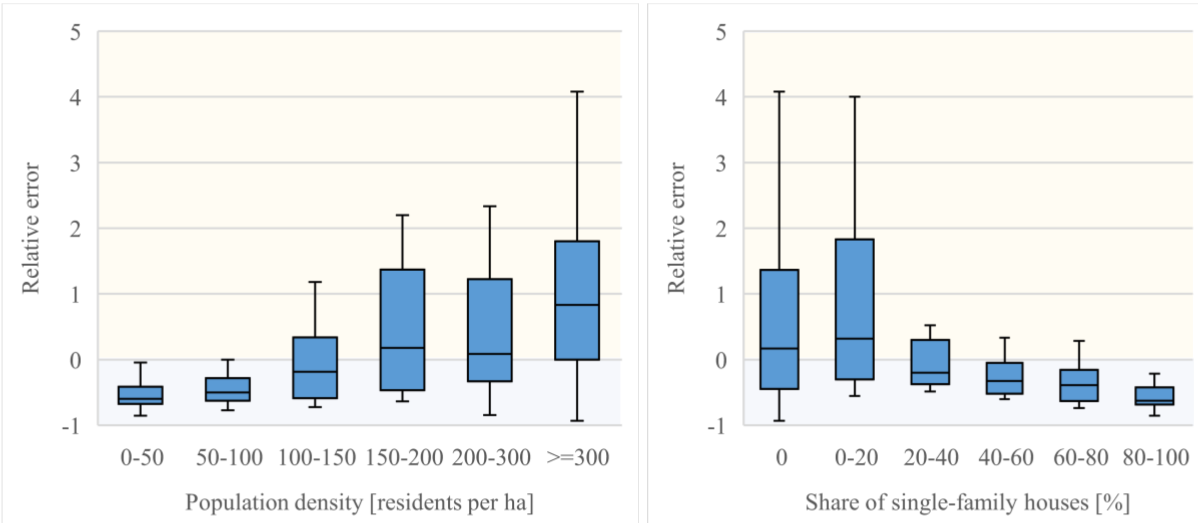


Figure 10. Relative error of the household survey approach depending on population density and share of single-family houses

4.5 Results of the parking requirements approach

The approach based on current and historic minimum parking requirements estimates a total number of about 75,500 parking spaces for the whole city of Aachen. As about 7,670 of these parking spaces are located within the survey areas, it overestimates the surveyed parking supply by about 18%. These divergences can also be observed when looking at the results per city block, which are illustrated in Figure 11.

The parking requirements approach shows both over- and underestimations of the surveyed parking supply depending on the city block's characteristics. The deviations are similar to the household survey approach, but even more profound: While the approach rather underestimates the residential private parking supply in blocks with low population density and many single-family houses, it vastly overestimates the parking supply of most high-density city blocks with few or no single-family houses.

These results indicate that the minimum parking requirements were not always exactly observed. While in low-density areas, more parking spaces than required were built, the required number of parking spaces was often not realized in high-density neighborhoods, usually located in central areas of the city, e.g., due to reduction factors specified in the parking requirements, which are not considered by the estimation approach. Furthermore, the buildings in centrally located blocks are rather older. While approximately 12% of all residential buildings in the city were built before 1919 and 11% between 1919 and 1948, this applies respectively to 26% and 17% of buildings in the parking permit zones. Therefore, the overestimation of the surveyed parking capacities in central areas may also be due to parking requirements not being strictly observed in earlier years, particularly during the reconstruction period after the Second World War. Further inaccuracies might arise due to conversions of buildings that changed the number of parking spaces.

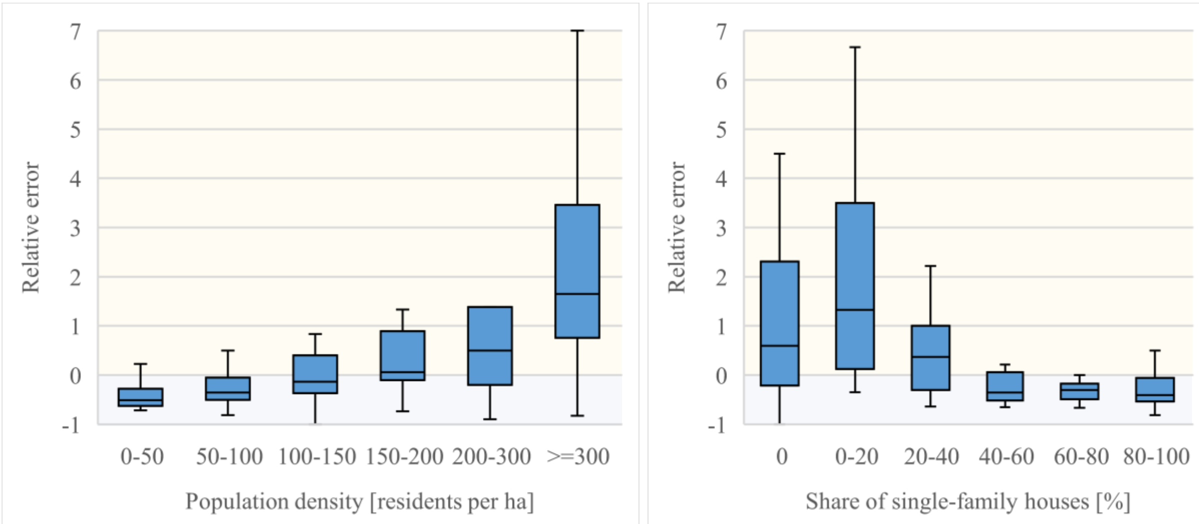


Figure 11. Relative error of the parking requirements approach depending on population density and share of single-family houses

4.6 Comparison of all estimation approaches

The calculated number of private parking spaces of the different approaches differs quite strongly, both over the whole city and only within the parking permit zones, which cover the central areas of the city (see Figure 12). The estimated private parking supply of the adapted real estate data approach and the parking requirements approach are very similar over the whole city, but much higher than the results of the other approaches. However, for the areas located within the permit zones, the parking requirements approach estimates a much higher number of private parking spaces than the adapted real estate data approach.

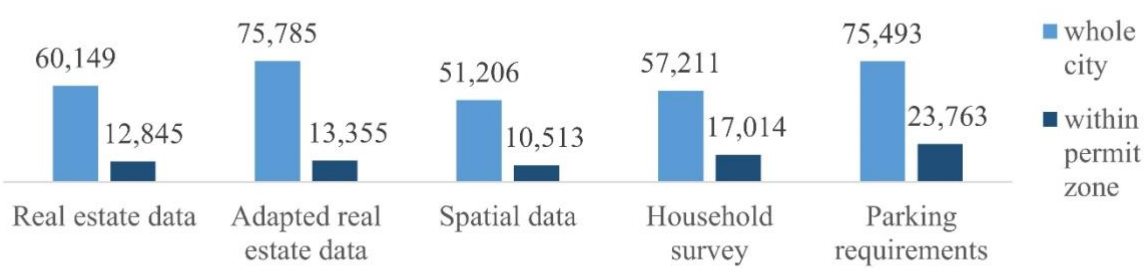


Figure 12. Comparison of the number of private parking spaces estimated with the different approaches

While the actual number of residential private parking spaces in the whole city and within the parking permit zones is unknown, the comparison of the estimation to the results of the survey in selected neighborhoods allows for assessing the accuracy of the approaches. While this has been discussed separately for each approach in sections 4.2 to 4.5, it is also interesting to compare the accuracy of the different approaches directly. The boxplots in Figure 13 show the relative errors between the estimated and the surveyed number of private parking spaces over all surveyed city blocks for each approach, while Figure 14 depicts the mean squared errors.

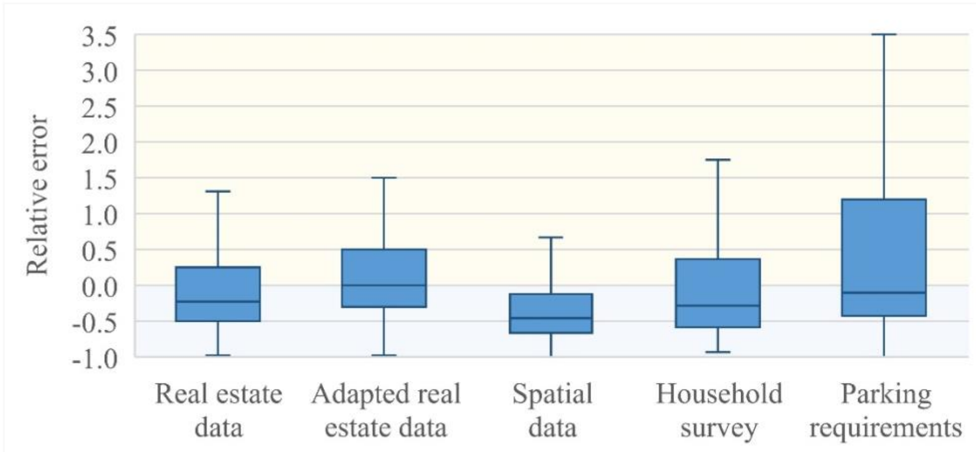


Figure 13. Comparison of the relative error of the approaches over all surveyed city blocks

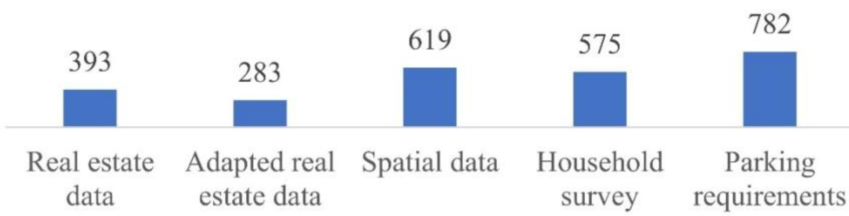


Figure 14. Mean squared error of the approaches over all surveyed city blocks

The figures indicate that the spatial data approach underestimates the surveyed number of private parking spaces for the vast majority of city blocks and has a rather high mean squared error. For the other approaches, over- and underestimations are more balanced. The parking requirements approach shows the worst match to the survey data, as the relative errors scatter the most widely, and the mean squared error is the highest. This indicates that its estimates deviate strongly from the surveyed parking supply in many city blocks, even though the estimated city-wide number of parking spaces is very similar to that of the adapted real estate data approach.

In contrast to that, the adapted real estate data approach shows a rather small variance of the relative error, with the median error being equal to 0, and achieves the smallest mean squared error. Therefore, the adapted real estate data approach appears to provide the most accurate estimate of the number of residential private parking spaces.

5 Discussion

The comparisons of the estimation approaches to the survey data revealed that the approaches' results and accuracies vary quite strongly. Our analysis showed that the adapted real estate data approach produces the best results, both city-wide and on small spatial units such as city blocks. This approach can be transferred to other cities with data on real estate characteristics or listings that contain information on the availability of private parking spaces. However, the accuracy of the approach in other cities may differ from our study, so the transferability of the results needs to be examined. Furthermore, the approach requires extensive data preparation, which, though, might be less complex for cities in other countries, if more detailed data on apartments and buildings are publicly accessible and if fewer datasets need to be merged.

Depending on the research aim, simpler approaches which require less data preparation may be sufficient. If one is only interested in estimating the actually used number of residential private parking spaces in an entire city, the household survey approach could be adequate. However, depending on the question design in the household survey, this approach underestimates the total number of private parking spaces. When using the German national travel survey, the approach neglects those spaces that are not usually used to park a car at home, e.g., if they are used for storage or if a household has more private parking spaces than cars. Therefore, the difference between the estimates of the household survey approach and the adapted real estate data approach can indicate the proportion of private parking spaces that are regularly used to park a car at home. As the adapted real estate data approach, which seems to correspond best to reality, estimates around 18,600 more parking spaces for the whole city of Aachen than the household survey approach, this indicates that about 25% of all private parking spaces associated with residential properties are not regularly used to park a car. This deviation can be caused by parking spaces used for other purposes, but also by households having more private parking spaces than cars. This finding is in line with studies focusing on the use of off-street parking spaces, which find that many of these spaces are not regularly used for parking (Scheiner et al., 2020; Taylor, 2020; Volker & Thigpen, 2022).

Apart from such a city-wide assessment, the household survey approach does not allow good estimations at smaller spatial levels, like neighborhoods. To improve the estimates for smaller areas, the proportion of cars that are usually parked in private parking spaces at home would need to vary depending on the characteristics of the surrounding area, such as population density and the share of single-family houses. Such variation is possible if the national travel survey contains information on these characteristics or the precise locations of the households' homes.

For studies that are only interested in the area footprint of pure parking buildings or in finding potential areas for urban consolidation, the spatial data approach could enable a simple and sufficient estimation. However, this approach underestimates the total number of residential private parking spaces, as it neglects parking spaces that are not included in the cadastral data. In the data used in this study, this includes uncovered parking spaces, most of the underground garages, and garages integrated in buildings. The comparison to the results of the adapted real estate data approach indicates that only around 68% of all private residential parking spaces are recorded in the cadastral data used.

While the parking requirements approach is not suitable to estimate the private parking supply for smaller areas, its city-wide estimate is quite close to the results of the best approach. This indicates that for the city of Aachen, over- and underruns of the number of parking spaces required in the parking requirements are roughly balanced. However, as this might differ from city to city, the parking requirements approach is not universally suitable to estimate private parking capacities. Nevertheless, the approach can be of interest when analyzing the impact of private parking requirements, as it allows for estimating the number of private residential parking spaces that should have been built according to the parking requirements and, if such data are available, to compare this estimate to the built parking supply. The comparison to the adapted real estate data approach indicates that the required number of parking spaces was not observed for centrally located buildings. Within the permit zone, the estimates indicate that only about 44% of the required parking spaces were built. However, this could be at least partly explained by reduction factors in the parking requirements, which we did not consider in our estimation. On the contrary, the results point out that more parking spaces than required are built on the outskirts of the city, e.g., around 21% more parking spaces than required were built in areas outside the parking permit zones.

Some limitations of our study should be noted. As already discussed, we had no access to real ground truth data on private parking spaces and therefore assumed our survey results as ground truth, even though we identified challenges that could lead to inaccuracies (see section 3.3). As we had no detailed building or apartment data, we had to perform extensive data preparation and make several assumptions to generate the synthetic residential building stock. Apart from these inaccuracies in the input data, each approach has its limitations, which were described in section 4. In our study, we only considered private parking spaces associated with residential properties. Other private parking spaces, such as those at workplaces, were neglected, as only the spatial data approach can take these into account. Furthermore, we do not have data on the actual usage or usability of the parking spaces. As other studies show, private parking spaces are often used for other uses, like storage, and older garages might be too small for new cars.

Despite these limitations, our analysis allowed us to evaluate and discuss the accuracy of several approaches to estimate the number of private parking spaces. To our knowledge, this is the first study to systematically apply different estimation approaches to a study area and evaluate their accuracy. Although the available input data and results may differ in other cities, our study can support researchers and practitioners in defining appropriate estimates for private parking supply in their study areas.

6 Conclusions

There is a lack of data on private parking spaces, as related information is usually not systematically collected by city administrations or other public institutions. As such data are needed for targeted parking policies and for analyzing various research questions related to parking, reliable estimates are required. The literature review showed that simple estimates of the private parking supply are used in several papers, but no study has compared estimation approaches and evaluated their accuracy yet.

Due to the lack of proper ground truth data, we surveyed private parking spaces in several neighborhoods. Even though the survey revealed limitations that are likely to lead to deviations from reality, it represents the most reliable data source of private parking spaces available to us. The exemplary application of the estimation approaches for the city of Aachen and the evaluation of their accuracy on the basis of this survey data revealed great differences in the approaches' results and highlighted the difficulties of obtaining reliable estimates of the private parking supply. Even though each of the applied approaches has its limitations, we could show that the adapted real estate data approach yields the best results, both city-wide and for smaller spatial units like city blocks. This approach is based on data on real estate listings taken from a large property portal in Germany. The data are used to generate a binary logit model estimating the availability of a private parking space per dwelling unit with regard to property and location characteristics. Such a model could also be generated based on other housing datasets if they include information on housing characteristics, location and parking space availability. As detailed information on the residential properties located within the intended study area is needed for applying the binary logit model, we generated a synthetic residential building stock by merging different datasets on housing, population and registered cars. We further slightly adapted the results of the model application in order to account for the fact that single-family houses often have access to more than one parking space and to further increase the model's accuracy.

Although this adapted real estate data approach showed the best result, depending on the research aim, other simpler estimation approaches might be suitable, e.g., if one is only interested in the ground area of parking buildings or the actually used number of residential private parking spaces in an entire city. However, it is important to keep in mind that all of the discussed approaches, except for the spatial data approach, can only take private parking spaces into account that are associated with residential properties and neglect other private parking spaces, e.g., at workplaces.

Further research could involve transferring the presented approaches to cities in other countries with sufficient ground truth data on private parking spaces, but with input data and city characteristics different from those in our study. A more detailed analysis of the national travel survey data should be conducted to improve the household survey approach, enabling the proportion of cars parked off-street at home to vary depending on the characteristics of the surrounding area. Furthermore, estimates of the number and location of private parking spaces based on real estate data could be used when analyzing various research questions regarding parking, e.g., modelling residents' parking behavior, evaluating the overall land consumption of parking spaces, or analyzing the impact of parking supply on mode choice or car ownership.

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Author contribution

The authors confirm their contribution to the paper as follows: Conceptualization: L. Merten, T. Kuhnimhof; Methodology: L. Merten; Formal analysis: L. Merten; Investigation: L. Merten; Writing - Original Draft: L. Merten; Writing - Review & Editing: L. Merten, T. Kuhnimhof; Visualization: L. Merten; Supervision: T. Kuhnimhof.

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