Demographics and Mobility

Correlating the spatial accessibility of Dutch bus stops with local factors using Voronoi polygons

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Abstract

The challenges and processes of the mobility transition lead to an increasing interest in the role that public transit could play in engineering this transition. As of now, the problem of optimising the accessibility of public transit is done in a non-standardised way, reliant on planners' individual knowledge and expertise. Nonetheless, this paper presents evidence that the accessibility of bus stops is correlated with local demographic, spatial and economic factors: specifically, the analysis measures bus stop accessibility through the use of Voronoi diagrams and relates this measurement to local factors around the bus stop, such as population density; average home value; average household size; the percentage of the population with a Dutch background; percentage of rental units; the percentage of apartments; and the percentage of the population in age groups 15-25 and over 65. The findings of this study have implications for transit planning practices and public transit research.

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1. Introduction

Background

In a changing world, keeping up current standards of personal mobility will present a number of challenges over the coming decades, both in the Netherlands and globally. (Geerlings et al. 2012) Among others, such challenges may be related to climate change, the ongoing energy crisis, population growth and increasing population densities, and protecting biodiversity. This bundle of challenges and processes is collectively referred to as the "mobility transition" (Geerlings et al. 2012). Within this (Dutch) context, it seems prudent that both researchers and policymakers give attention to the role public transit could play in engineering this mobility transition.

Bus transit plays an important role within the Dutch public transport network. While bus, tram and metro transit only make up 2.9% of all distance travelled against 11.3% for train transit (CBS 2019), a notable aspect of bus transit is that its usage levels do not diminish with lower levels of urbanisation as rail transit does. (CBS 2019).

Figure 1. Bus stops around central Eindhoven (A) and Steenbergen (B), at the same scale.

In this light, it is important that access points for bus transit are not equally distributed within the Netherlands. Figure 1 serves to illustrate this: the figure shows the distribution of bus stops between central Eindhoven (Figure 1A), a municipality with a population of 238,326 as of 2022, versus Steenbergen (Figure 1B), with a population of 24,333 (CBS 2022a). The disparity in density between the two is easily visible: even within the built-up area of Steenbergen, distance between bus stops is far greater than in the built-up area of Eindhoven.

Literature has often focused on the relationship between population density and public transit viability (Cooke & Behrens 2017) or the built environment and travel (Ewing & Cervero 2010). While such work may cover the situation in urban areas, it is not concerned with ease of access: lower densities of bus stops mean that the average distance to the nearest bus stop for inhabitants might be larger regardless of population density.

Additionally, bus public transit can be a contentious topic: for example, the removal of an existing bus line may stir political controversy and lead to the creation of petitions from local residents and users of these bus lines (Petities.nl 2016, Petities.nl 2021). Residents' investment in these bus lines goes beyond mere practicality: one example is a petition with 1223 signatures, pertaining to the modification of a bus line between Edam and Amsterdam. The author of this petition cites the fact that a direct connection between the cities of Hoorn and Amsterdam, through Edam, has existed since the 16th century (Petities.nl 2016).

If the mobility transition is to be an inclusive process, it is of importance that the spatial patterns and dimensions of ease of access of bus transit be investigated, as to solidify the role public transit can play in this transition. This has relevance both for those in low-density areas, as well as the segment of the population that does not have access to a private vehicle (Mavoa et al. 2012).

While some research on the relation between local factors and public transit flows has already been done (Cooke & Behrens 2017, Ewing & Cervero 2010), it appears that none have focused yet on a specifically Dutch context, and most focus mainly on specific urban areas. Additionally, this research focuses mainly on identifying areas for future expansion of public transit, rather than doing a "backwards-looking" analysis concerned with the effects of public transit planning practices.

Research Aim

The central aim of the proposed research is to gain insight into the following central question: *How does the spatial accessibility of Dutch bus stops correlate with local demographic, spatial and economic factors?*

Answering this main question requires first investigating a number of secondary issues:

- What are the methods used to determine bus stop placement by planners? That is, to what degree are measurable factors considered?
- What factors might be considered by planners in the placement of bus stops?
- What measures of bus stop accessibility exist?
    - More specifically, how can a bus stop's accessibility be quantified?

Reading Guide

Beyond this introduction, this paper is divided into four main sections: a *theoretical framework*, which introduces the concepts of transit accessibility and density as it pertains to this research problem and formulates expectations; a *methodology and data* section which explains the nature and process of the research; a *results* section which describes the findings of this research; and lastly, a *conclusions and discussion* section, which interprets these findings, discusses research limitations and gives research and policy recommendations.

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2. Theoretical Framework

Accessibility

The term "accessibility" is tied up with several meanings. In popular usage (and in many disciplines), "accessibility" explicitly refers to design and planning that includes disabled people, or, more broadly, allows more people to make use of technologies (Annable et al. 2007).

Within transport planning, however, the term "accessibility" refers to *spatial* accessibility, that is, the ease of reaching and interacting with destinations (Farber & Fu 2017). Modelling accessibility by public transmit modes presents a challenge because of the complexity of public transit journeys: these journeys often include multiple transit modes and "legs" in one journey, such as walking to an access point and the actual travel on a public transit vehicle (Mavoa et al. 2012).

Mavoa et al. (2012) describe two measures of public transit accessibility: one based on a combined index of walking and public transit, and one based on transit frequency, in order to measure the level of transit service in an area. Other factors to transit accessibility have been considered as well, such as the number and type of change-overs a traveller has to make between different transit lines (Hadas & Ceder 2010).

This research only pertains to the first measure of public transit accessibility: it is assumed that the accessibility of a bus stop is analogous to the walking distance to this bus stop. Doing network analysis on transit services and lines is beyond the scope of this research, and therefore transit frequency will not be considered as a factor in public transit accessibility for the purposes of this research.

The Transit Planning Process

The problem of designing transit networks (and the accompanying decisions about which stops ought to be served by which transit lines, and how often) to optimise accessibility while minimising cost and negative externalities is referred to as the Transit Network Design and Frequency Setting Problem (TNDFSP) (Durán-Micco & Vansteenwegen 2022). However, in practice, this problem is usually solved by transit planners' own knowledge and experience. This implies that the spatial patterns of transit networks are not immediately apparent, as no kind of systematic or standardised method is used.

However, some possible determinants can still be considered. It is reasonable to assume that, if transit planners base network design on personal knowledge and experience, their solutions would tend towards those considered the most viable in the available literature.

Factors in Public Transit Viability

One important aspect to consider is population density: in the past decades, the literature on the relationship between land use and the viability of public transit has focused on urban population density (Cooke & Behrens 2017). Based on this, a minimum threshold for population density is often used to determine whether a line or network is viable.

However, Cooke & Behrens (2017) question population density as being the sole significant determinant of public transit viability. Their research demonstrates a number of other aspects which are relevant as well, such as land use mix, the length of transit corridors and the *distribution* of density within a city. These may broadly be considered ***spatial*** factors.

Economic factors play a role as well. Both Polat (2012) and Albalate & Bel (2010) focus on economic factors in determining public transit demand, such as the *cost* of public transit and levels of income inequality.

Demographic factors also influence public transit demand. Demographic factors that are particularly of note are age and cohort effects, as described by Metz (2012). This is of particular relevance to the Netherlands as, similarly to the UK, demographic shifts and an ageing population will continue to have an increasing effect on public transit demand.

Lastly, ***institutional*** factors play a role. For example, Albalate & Bel (2010) found that a city being a political capital has a positive effect on both public transit demand and supply.

Conceptual Model

This study's theoretical framework is encapsulated schematically in the conceptual model in Figure 3.

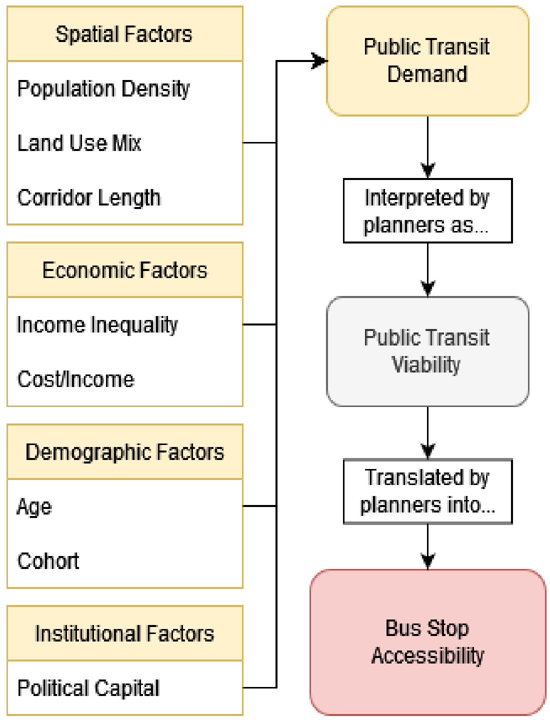

Figure 3. Conceptual model for bus stop density.

For the purposes of this research, bus stop accessibility and bus stop service area are assumed to be analogous: a high accessibility of bus stops in an area of a given size implies that the portions of this area "served" by individual bus stops are smaller, which means that service areas are smaller.

Expectations

Based on the available information outlined earlier, is it hypothesised that the demographic factors named in the conceptual model are correlated with bus stop accessibility, but that this relationship is rather weak. While planners may be influenced by demographic factors in their placement of bus stops, the lack of standardised procedures makes this relationship somewhat tenuous.

3. Methodology and Data

Overview

To solve the research problem, a combination of spatial and statistical analysis is used. The *Spatial analysis* portion of this research involves the preparation of the data as well as operationalising bus stop accessibility through Voronoi polygons, which represent a bus stop's service area. Each bus stop is then joined with local data. The resulting table will then be used in the *statistical analysis* portion of the research. Multiple regression analysis will be performed on the data in order to examine the relationship between the dependent variable, service area, and local demographic data. Both of these processes will be expanded upon in the corresponding *Spatial Analysis* and *Statistical Analysis* sections of the Methodology chapter.

Data Collection

Because high-quality data from reputable sources is readily available and collecting primary data on a large number of bus stops would be impractical, all data used in this research is secondary data. Data was collected from two main sources:

The first is the Public Transit in the Netherlands (*Openbaar Vervoer in Nederland*) dataset provided by the Geodienst at the University of Groningen (University of Groningen Geodienst 2022). This dataset contains data on public transit stops and lines in the Netherlands. It is based on open GTFS (General Transit Feed Specification, a format for public transit schedules) data provided by OpenOV, dated to October 2021.

The second is the 500 by 500 metre statistics (*Kaart van 500 bij 500 meter met statistieken)* dataset provided by CBS, the Dutch government's statistical organisation (CBS 2022b). This dataset divides the Netherlands into square planes of 500 by 500 metres and contains demographic data about these squares, such as population, age statistics, migrants, household size, average home value and the total number of residences, including a separate statistic for the number of apartments (*meergezinswoningen*). The dataset used was compiled in April 2022 and refers to the year 2021, to match the public transit data.

Voronoi Diagrams

For the purposes of this study, accessibility is operationalised based on Voronoi polygons. A Voronoi diagram is a partition of a plane into regions, known as *cells.* For each cell there exists a *seed*, which is a point on the plane. The cell corresponding to a seed is defined as the region that is closer to that seed than to any other seed on the plane (Voronoï 1908a, 1908b). A visual example of this can be seen in Figure 4 (Ertl 2015).

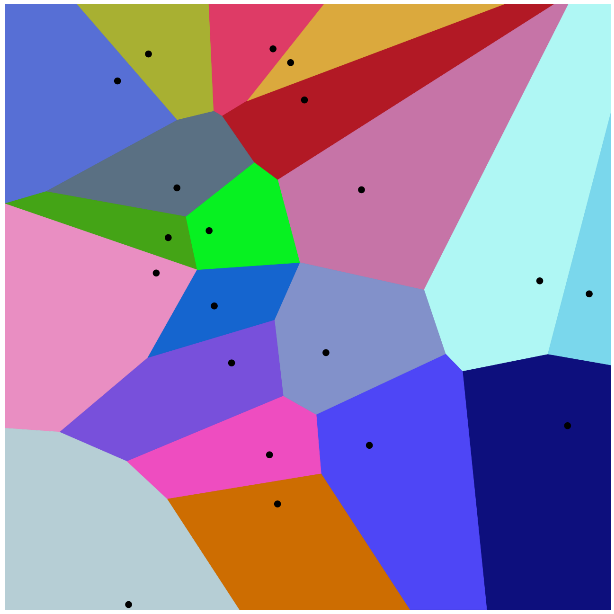

Figure 4. Example of a Voronoi diagram. (Ertl 2015)

Voronoi diagrams are relevant to this research because they can be used to represent a bus stop's theoretical service area. If each seed is understood to be a bus stop, then each cell represents the area that is closer to that bus stop than it is to any other, and therefore a theoretical person residing in that area would choose that bus stop over any other, as it is the shortest walk away. This is, of course, a simplification of reality, as it disregards the geography surrounding the bus stop (physical barriers or street patterns may affect walking distance) and the transit frequency and line connectivity at the bus stop, but those factors are considered to be outside the scope of this research.

Despite these limitations, Voronoi diagrams have previously been applied in research regarding public transit, and specifically those regarding bus stops, such as the method for optimised placement of bus stops proposed by Stadler, Hofmeister & Dünnweber (2022). This shows that there is a precedent for the application of Voronoi diagrams in researching bus stop placement. It is therefore considered appropriate to apply this technique in this research – we may use Voronoi diagrams to quantify a bus stop's spatial accessibility.

Preparation and Data Quality

As the data from the Public Transit in the Netherlands dataset is from a reputable source, it can be expected that the data is of high quality. However, due to the way the data is presented, some significant preparation was required before it could be used in this research.

Firstly, the trivial step was taken of removing all stops from the dataset that were not *bus stops* (as metro, ferry & tram stops, as well as train stations, were also included). The first complexity that presented itself was that stops were organised in terms of *quays*, individual platforms for buses to stop at, so that an ordinary bus stop actually has two quays (one of each side of the road), and a bus station may have many more. This problem is illustrated in Figure 5.

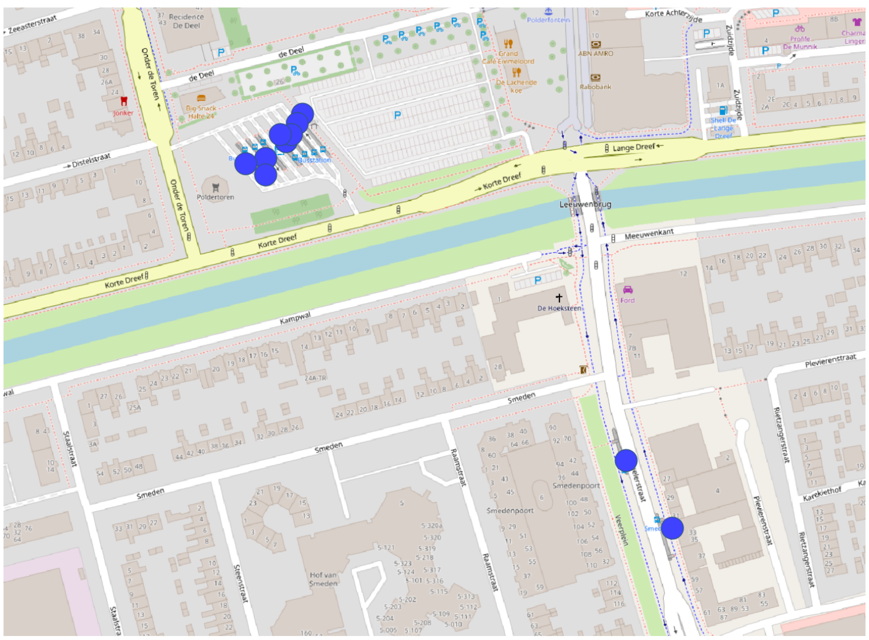

Figure 5. Example of individual “quays” in the dataset, showing the Emmeloord bus station and bus stop *Smeden.*

This is a deceptively simple issue to solve, as any solution requires a decision on what exactly counts as “one” bus stop. Possible solutions fall into one of two categories: either quays are joined based on their shared name, or they are joined based on spatial proximity. The conflict between these two options is illustrated in Figure 6. In this figure, four quays at an intersection are shown, with a buffer of 50 metres around each quay. These quays are close enough to be considered one stop, but are presented to the public as two separate stops. Depending on the method chosen, these count as either one or two bus stops.

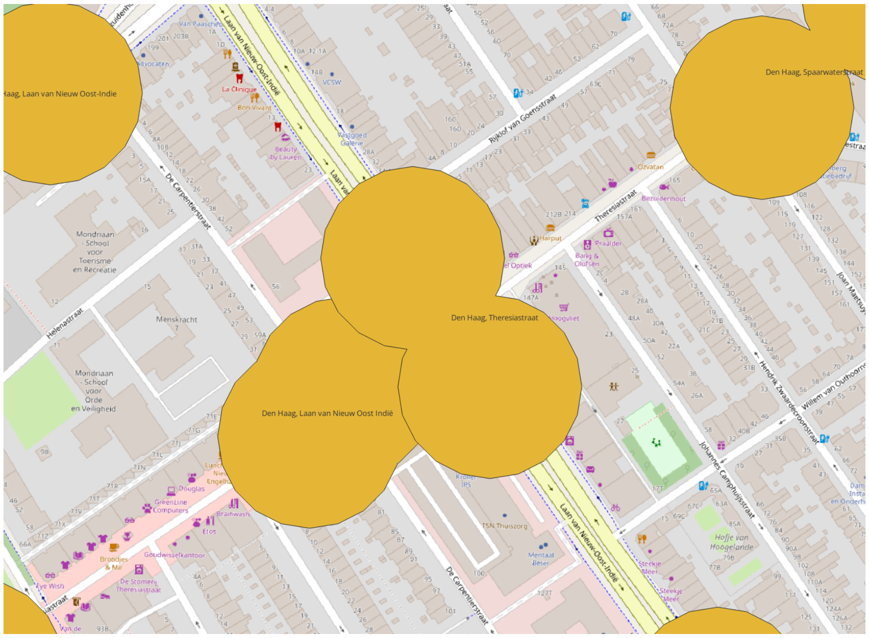

Figure 6. Example of quays in conflict: *Theresiastraat* and *Laan van Nieuw Oost Indië* in The Hague.

Ultimately, it was decided to join bus stops by their name, or, in the case of bus stations, by their shared *parent station.* This method was chosen because it produces less ambiguity than its alternative: it is impossible to determine a satisfactory distance at which quays should be joined based on physical proximity, as some quays are located over 200 metres from one another, while some separate "stops" are separated by less distance. The "location" of each new bus stop was set to the geographical centre of each quay that makes up the bus stop.

The last part of preparing the bus stop data consisted of removing stops not considered relevant to this research: this includes removing bus stops located outside of the Netherlands (as some stops on lines in Belgium and Germany served by Dutch bus companies are included) and removing stops that are not served by ordinary scheduled bus services, such as those used by train-replacement buses.

Following this data preparation, the total number of stops in the dataset (and therefore the total number of bus stops in the Netherlands, for the purposes of this research) was determined to be *20,569.* A map of these bus stops is provided in Figure 7.

Preparation for the CBS 500 by 500 metre dataset was simpler. For privacy reasons, CBS does not supply any data for squares with a population under five. However, all squares are included in the dataset, including those without data, so at this stage, preparation consisted of removing any squares that did not have any population data. This is relevant for the research, as some bus stops are located in areas for which CBS supplies no data – these stops are not included in the research.

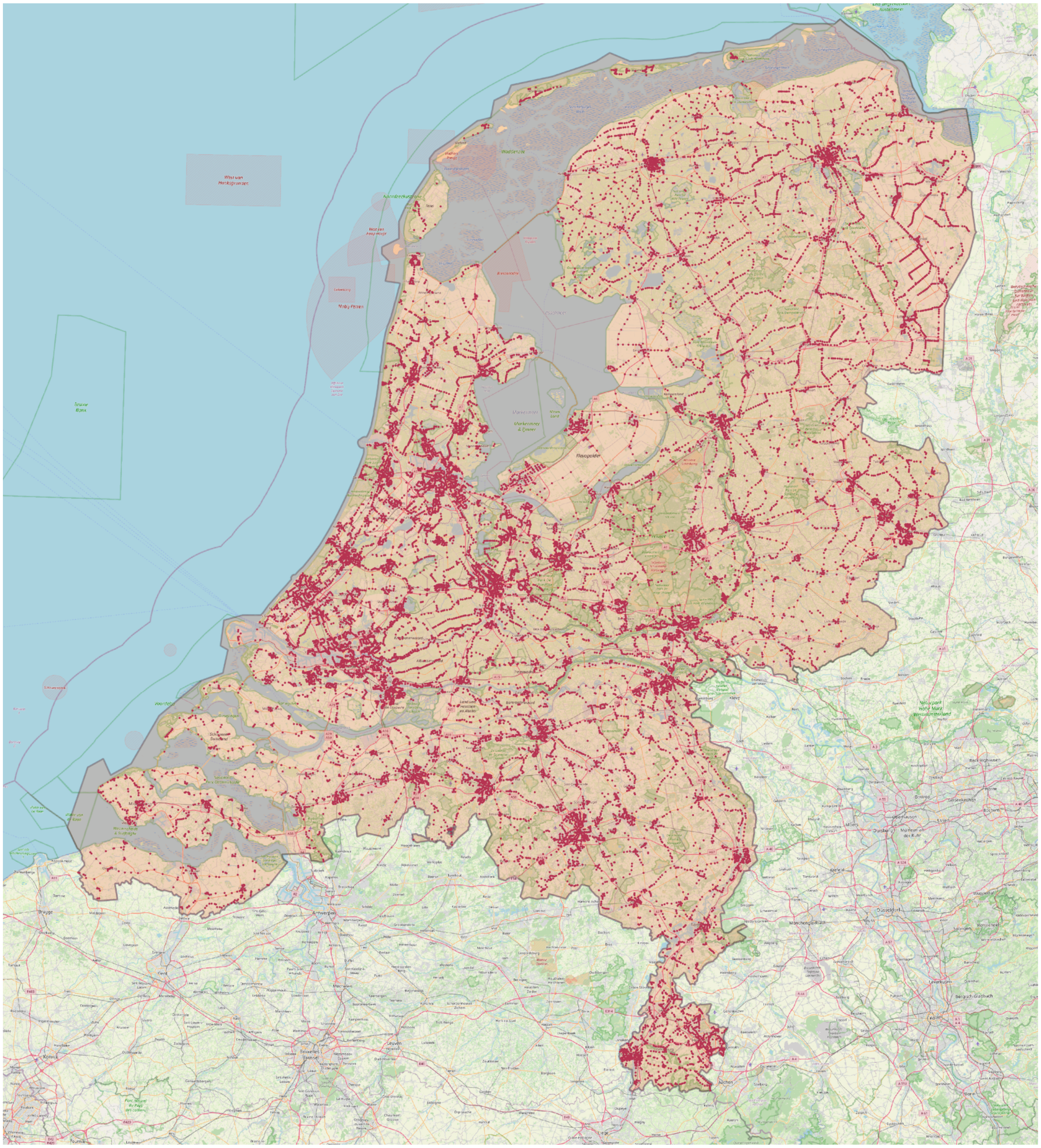

Figure 7. A map of every bus stop in the Netherlands.

Spatial Analysis

After data preparation, the spatial analysis portion of the project consisted of generating a Voronoi diagram with cells for every bus stop in the Netherlands. This Voronoi diagram was then clipped to only include areas within the Netherlands, and had all major bodies of water clipped off. For this, data from the TOP100NL dataset provided by PDOK was used (PDOK 2022). TOP100NL is a topographic dataset based on the BRT (*Basis Registratie Topografie)*. A simplified version of the data on water coverage was used in order to cut on processing time: the operation with simplified geometry took roughly three hours to process.

The final result of this process is shown in Figures 8 and 9. Of note in Figure 8 are the rough and serrated edges of the water coverage layer caused by simplifying the water coverage layer.

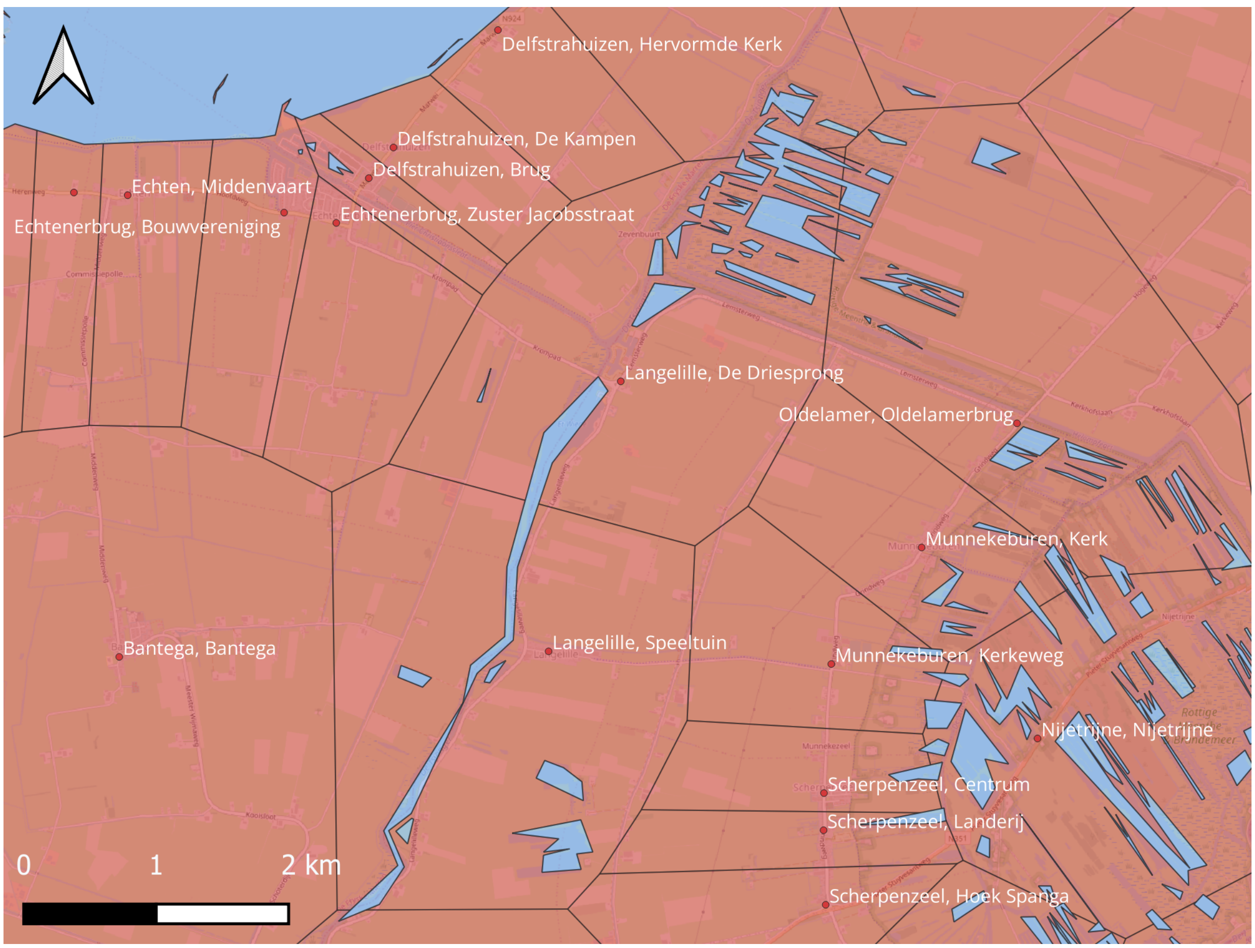

Figure 8. Voronoi Diagram for bus stops around the town of Echtenerbrug, with bodies of water overlaid.

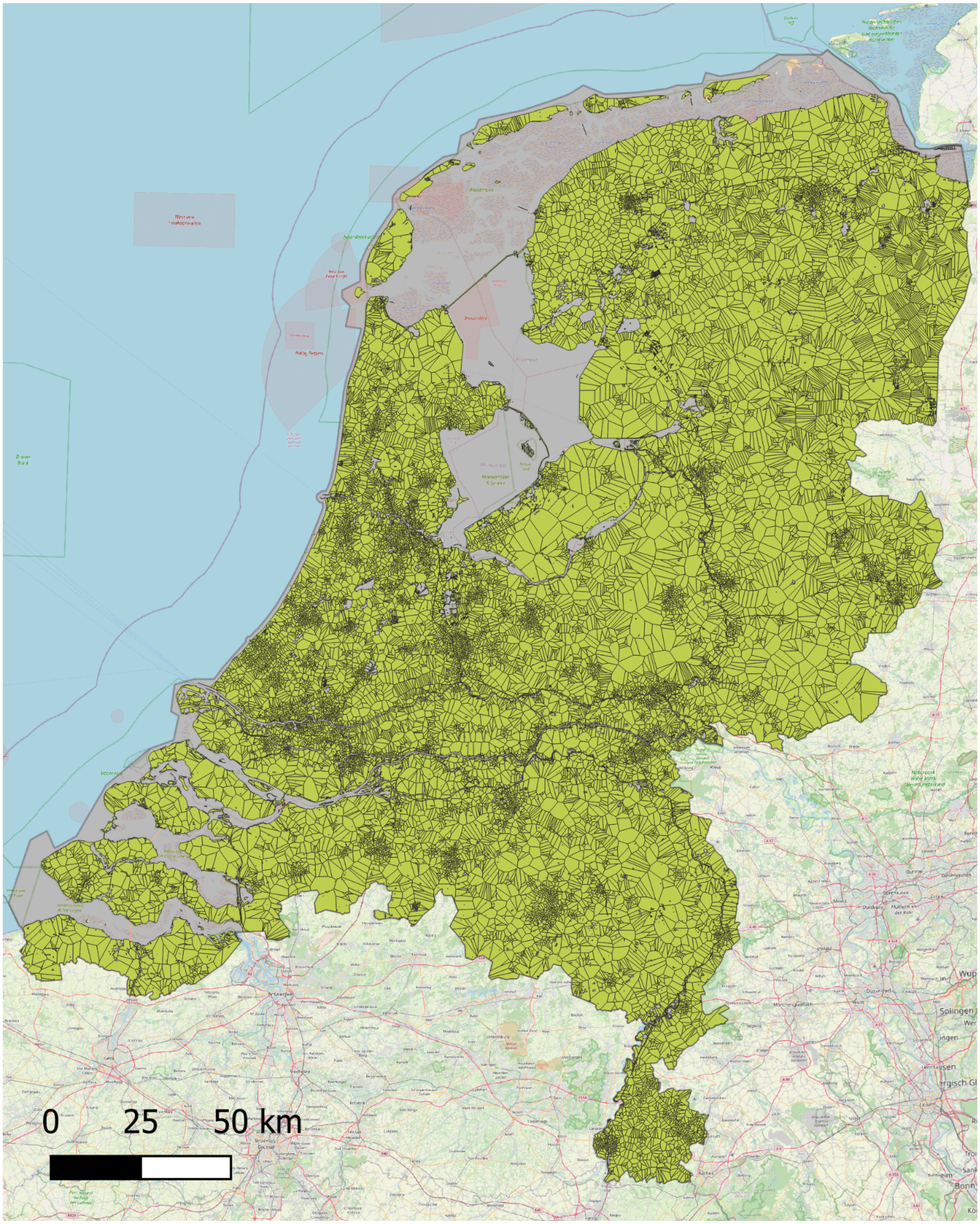

Figure 9. Voronoi Diagram for all bus stops in the Netherlands.

The surface areas of these Voronoi cells were then calculated, and this area was added into the attribute table of each corresponding bus stop as the bus stop's *service area*. These tables were then spatially joined with demographic data from the square in the CBS dataset that the bus stop is located within. The resulting table is used for statistical analysis.

Data

Table 1 shows descriptive statistics for the variables used in this analysis. Service area, Average home value and the percentage of the population that is 15-25 years old exhibit very strong skewness and kurtosis, which implies that they are not normally distributed.

	N	Minimum	Maximum	Mean	Std. Deviation	Variance	Skewness	Kurtosis
Service Area (m^2)	15649	20,397	30,282,379	1,230,834	2,037,786	4.153E+12	4.889	38.192
Population	15649	30	7295	964.11	790.85	625,449.94	1.611	4.947
Avg. Home Value (Euro, x1000)	15649	59	2540	293.76	132.45	17544.44	3.457	26.632
Avg. Household Size	15649	1.1	4.7	2.19	0.37	0.14	0.342	0.890
Pop. with Dutch background (%)	15649	10	100	79.27	15.96	254.70	-1.359	2.051
Rental homes (%)	15649	0	100	37.73	23.22	539.29	0.363	-0.666
Apartments (%)	15649	0.00	100.00	28.47	28.34	803.10	0.865	-0.325
Pop. 15 to 25 years old (%)	15649	0.88	70.59	11.85	4.53	20.48	3.374	24.575
Pop. over 65 years old (%)	15649	0.68	84.21	22.15	9.76	95.17	1.040	2.321

Table 1. Descriptive statistics table for all variables used.

Statistical Analysis

The statistical analysis portion of this research consists of computing the correlation between bus stop service area and each of eight variables which correspond to its "square": a list of these variables with descriptive statistics can be seen in Table 1.

For privacy reasons, CBS reports the percentage of rental homes and the percentage of persons with a Dutch background only in multiples of 10; therefore, these are considered ordinal variables for the purposes of this research. CBS reports average household size in multiples of 0.1, but this is considered accurate enough to be considered a ratio variable. All other variables are ratio variables.

A Spearman Rank-Order Correlation Coefficient is used. The reason for this is that the data, specifically bus stop service area, does not follow a normal distribution. This complicates a possible regression analysis (although it is not ruled out entirely). Spearman Rank-Order is a non-parametric test that is less sensitive to the highly skewed data in the dataset than its parametric alternative, the Pearson Correlation Coefficient.

Some of these variables were computed manually from the given data – absolute data on the number of rentals and population over 65 was transformed to percentages. All cases (bus stops) that did not have data for all these variables were removed, and some low-end outliers on service area were removed (perhaps resulting from issues in merging quays), which left a total of 15,649 cases for the statistical analysis out of the total of 20,569 bus stops in the Netherlands.

Research Ethics

Care must be taken to appropriately interpret both the data and results of this research, as existing societal attitudes may be embedded in the data. For example, the CBS data used in this research uses the concept of *personen met een niet-westerse migratieachtergrond* ("persons with a non-western migration background") (CBS 2021), which, according to CBS, refers to people born in Africa, Latin America, Asia (excepting Indonesia and Japan) or Turkey (CBS 2022c). Persons from Indonesia and Japan are included as western based on their "social-economic and social-cultural position", which suggests a conception of "western-ness" that is somewhat arbitrary and tied up in more than just cultural background.

CBS itself seems to be aware of the flaws of this classification: the 2021 data used in this research is the last year that the classification is used, with a new classification being developed for 2022 (CBS 2022c). Because of the flaws in this distinction, as well as a lack of data specifically regarding this distinction (data seems to be more readily available for migrants *in general*), it was elected to only look at the proportion of persons with a migration background of any kind (by making use of its inverse – the proportion of of persons with a "Dutch background")

4. Results

Exploratory Analysis

The skewness and kurtosis of bus stop service area are further illustrated in Figure 10. Service area is strongly skewed towards the left end of the distribution, implying a large number of bus stops with very small service areas and a relatively small number with comparatively very large service areas.

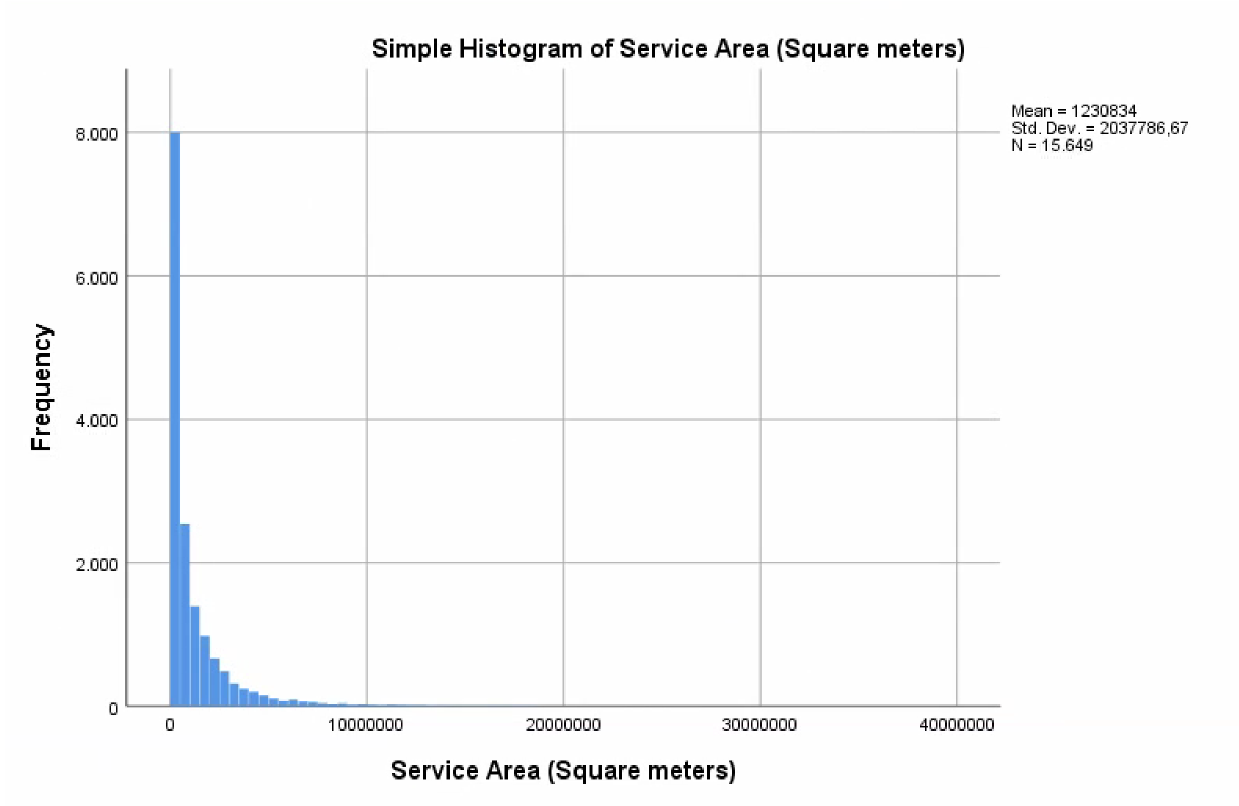

Figure 10. Frequency histogram of bus stop service area

An example of how a strongly skewed distribution can create difficulties in interpreting the data at a glance can be seen in Figure 11. Figure 11 shows the scatter plot for bus stop service area measured against population. The "shape" of the scatter plot is sloped, which indicates the possibility of a negative correlation between bus stop service area and local population. As population in this data is analogous to population density, this would mean that service area decreases (and accessibility increases) with increasing population density.

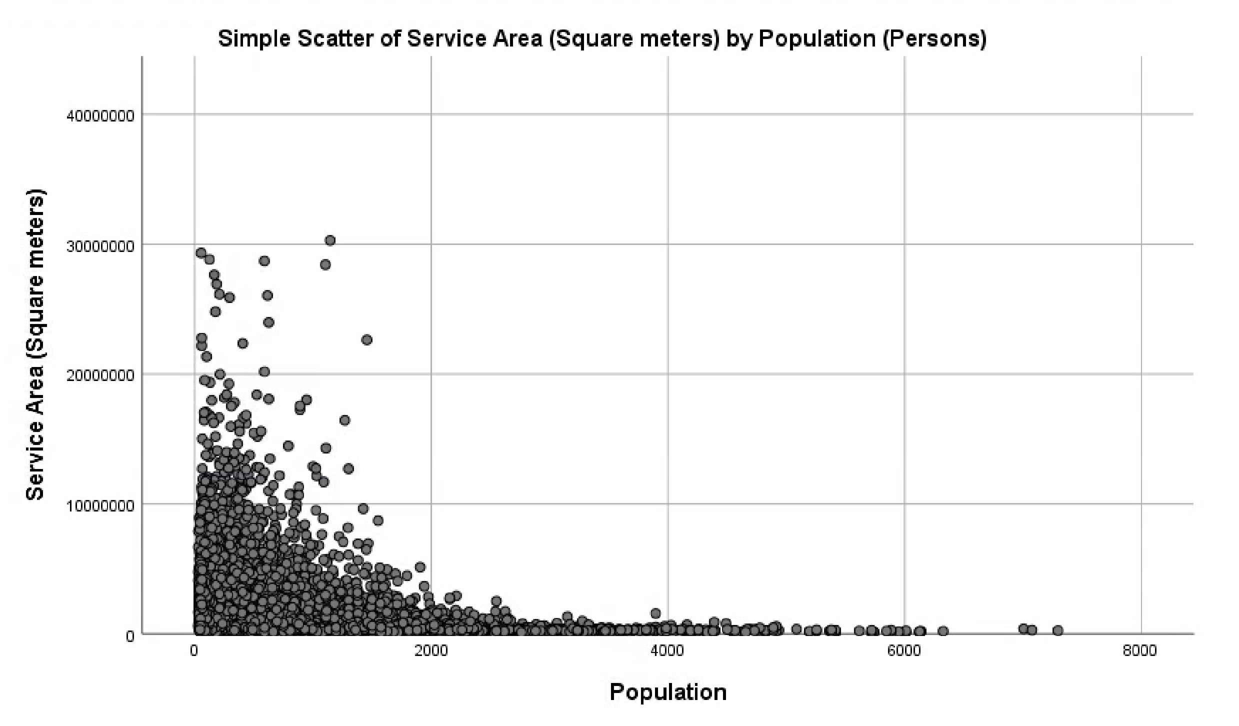

Figure 11. Scatter plot of bus stop service area against population of corresponding square

However, this slope could also be the result of service area and population data being strongly skewed; there are simply more entries at lower population and service area numbers. This issue can be mitigated somewhat by using a logarithmic scale for the Y-axis as opposed to a linear one in order to correct for the strong skewness: the result is shown in Figure 12. For the sake of consistency, the same Y-axis (logarithmic with a base of 3) is used for all the following scatter plots in this section, but all X-axes are linear.

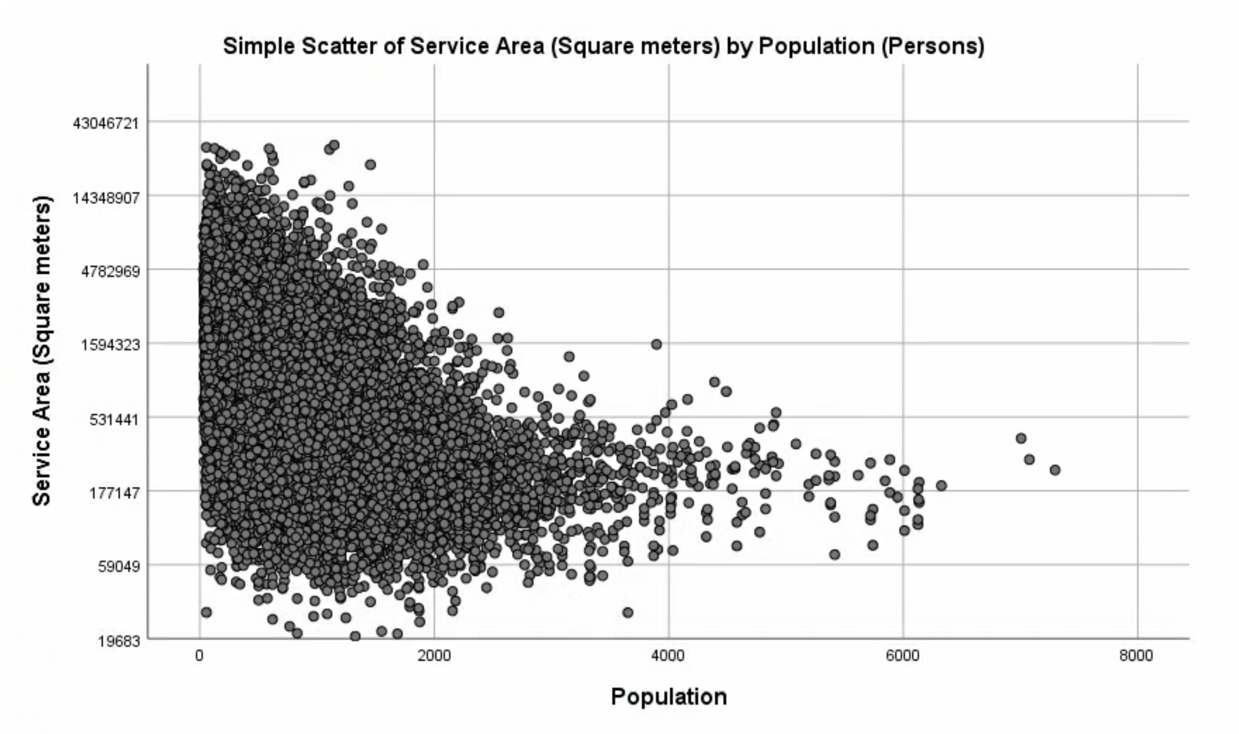

Figure 12. Scatter plot of bus stop service area against population of corresponding square, with logarithmic Y-axis

This graph is comparatively easier to interpret than Figure 11. It suggests that a *monotonic* (i.e. only increasing or decreasing) relationship between population and service area may exist; this would be in line with expectations, as a higher population in a square implies a higher population density, which implies more public transit demand – although service area does not seem to decrease further beyond a local population of around 3,000, which indicates that there may be an upper limit to how public transit demand can be serviced by bus stops placed very close together.

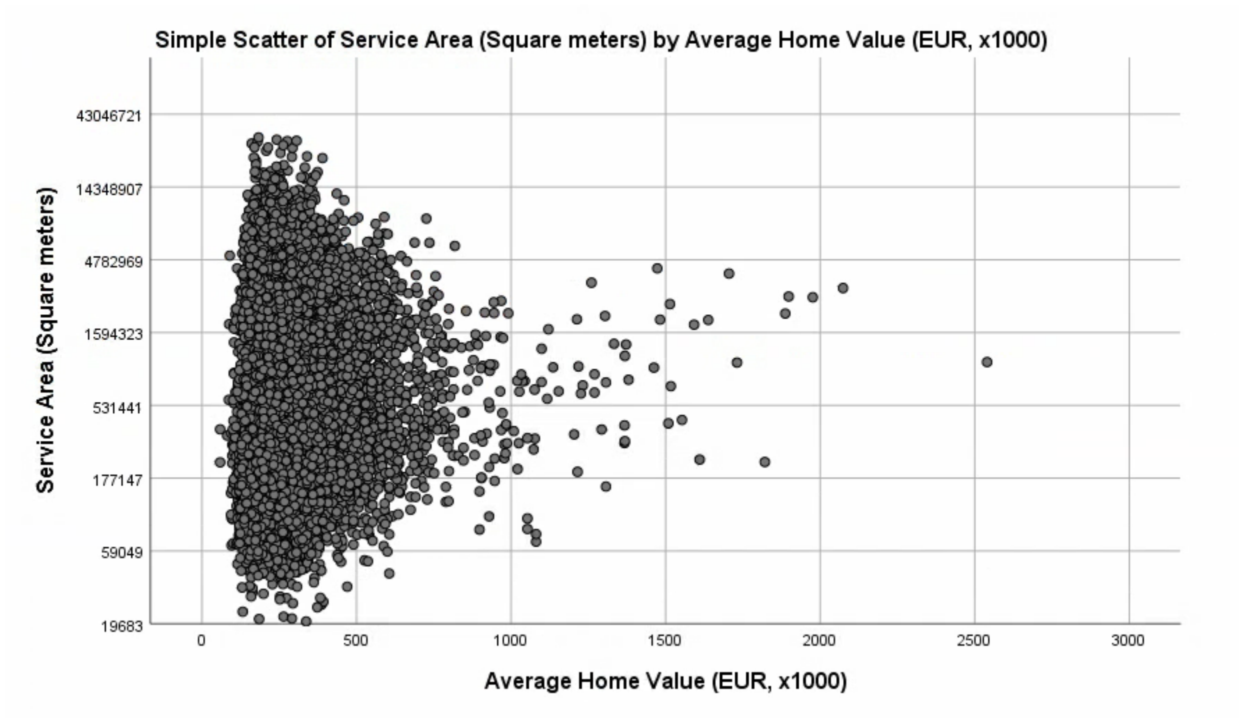

Figure 13. Scatter plot of bus stop service area against average home value (*WOZ-Waarde)*

Figure 13 does not appear to suggest a correlation between average home value and bus stop service area. This scatter plot also shows how strongly average home value is skewed towards the lower ranges.

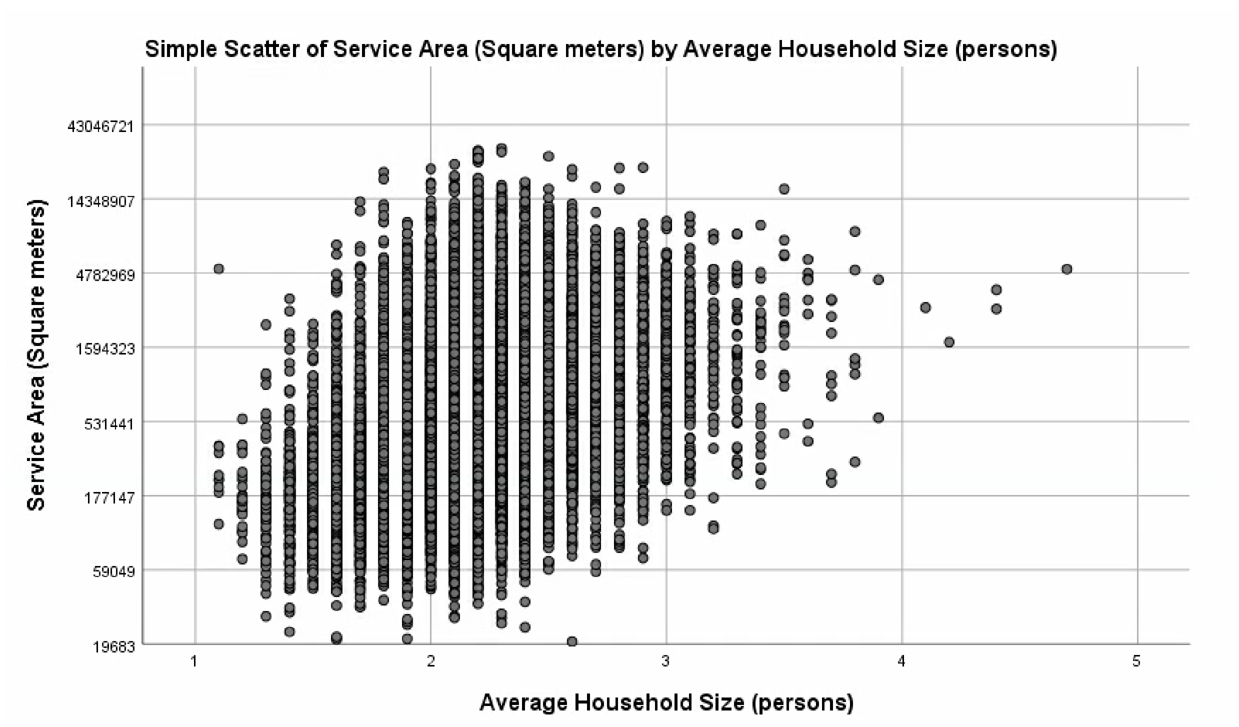

Figure 14. Scatter plot of bus stop service area against average household size.

Figure 14 suggests a positive correlation might exist between average household size and service area. This plot also shows that CBS rounds average household size to one decimal point.

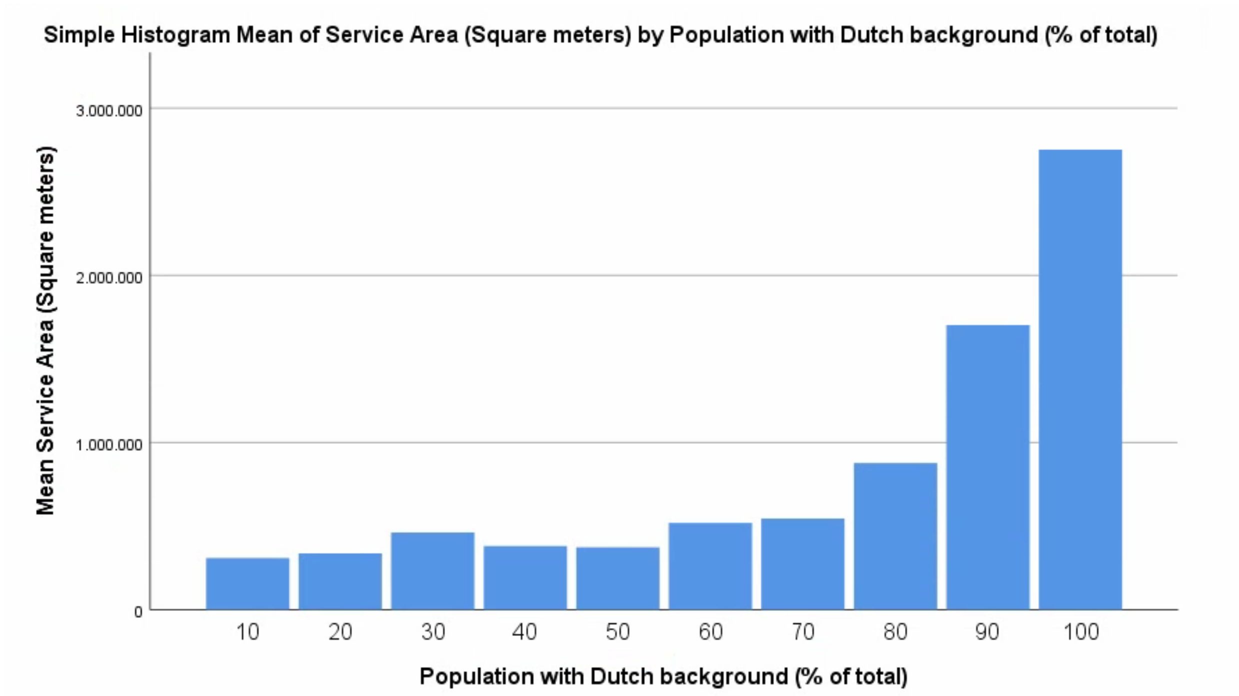

Figure 15. Histogram of mean service area against percentage of population with a Dutch background.

As CBS rounds the percentage of people with a Dutch background to multiples of ten, this variable is considered ordinal – therefore Figure 15 is a histogram. Note that for the histograms, the Y-axis is not logarithmic, as the effect of the skewness of Service Area is not visible here. This histogram strongly suggests the existence of a correlation between service area and the percentage of the population with a Dutch background. However, this may just be showing the influence of an urban-rural split, as cities may have a lower percentage of people with a Dutch background.

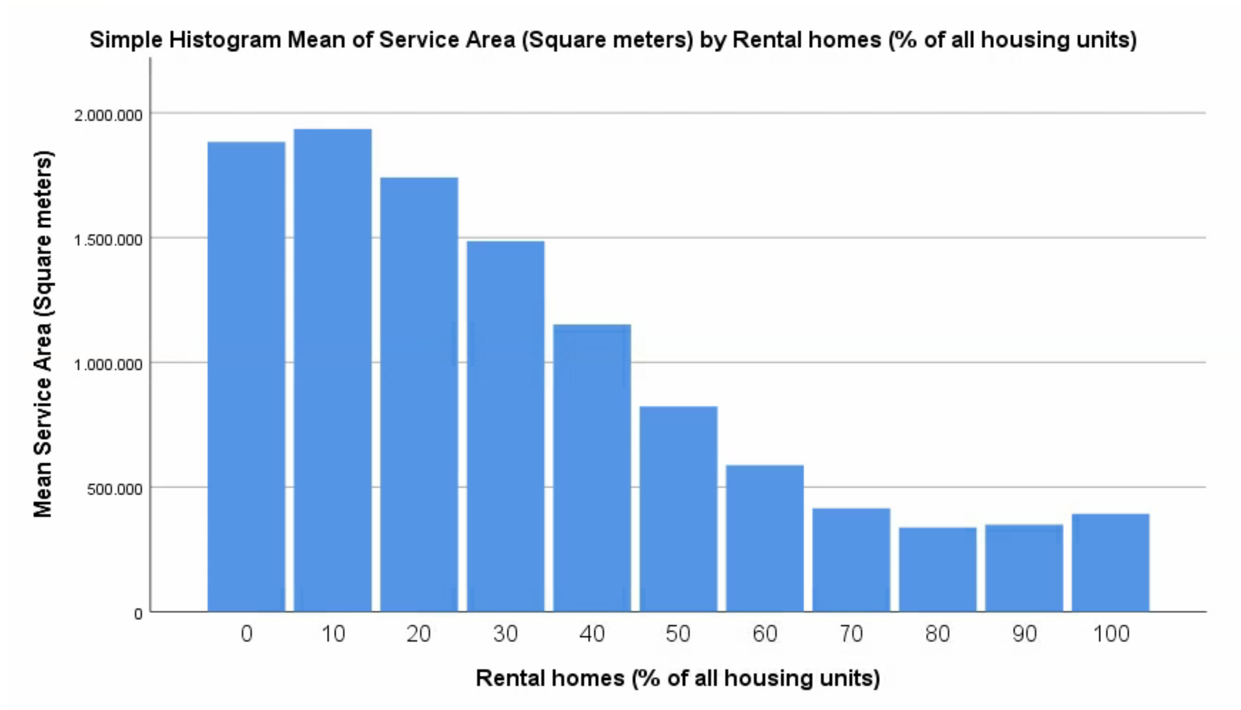

Figure 16. Histogram of mean service area against percentage of housing units that are rentals.

For the same reasons as Figure 15, Figure 16 is a histogram. It similarly suggests a correlation between mean service area and the percentage of rental homes – one which, similarly, may be influenced by an urban-rural split.

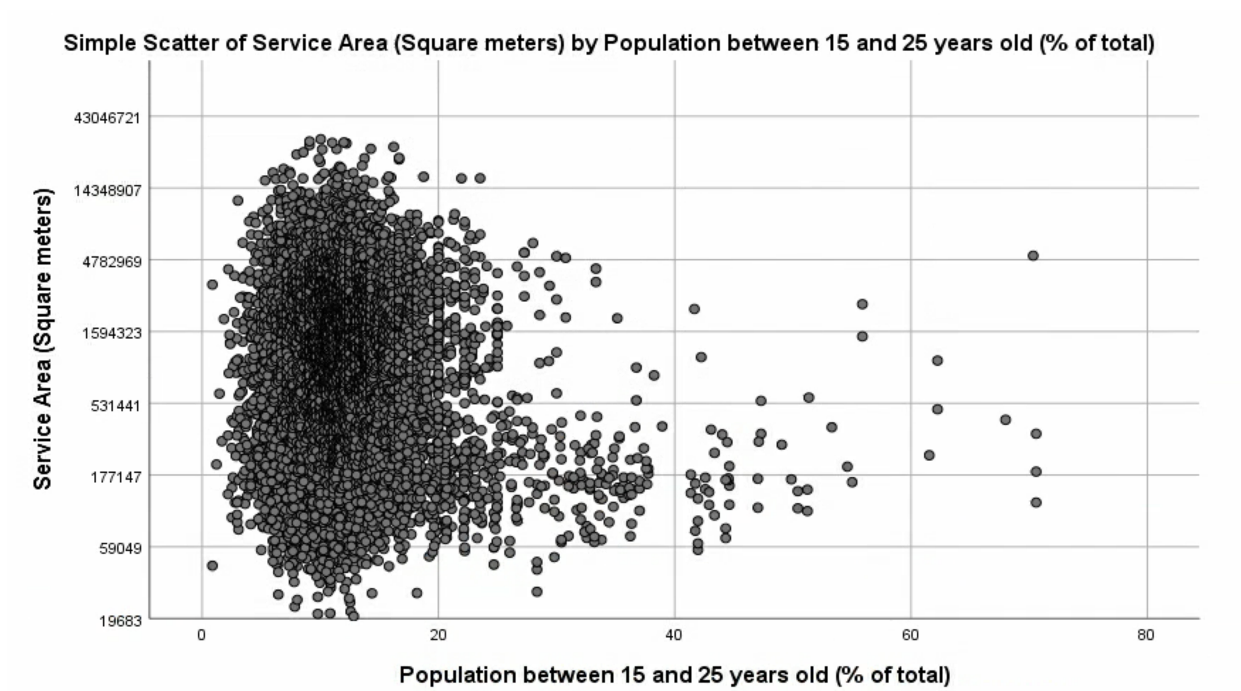

Figure 17. Scatter plot of service area against percentage of the population between 15 and 25 years old.

Figure 17 does not appear to suggest any correlation between service area and the percentage of the population between 15 and 25 years old.

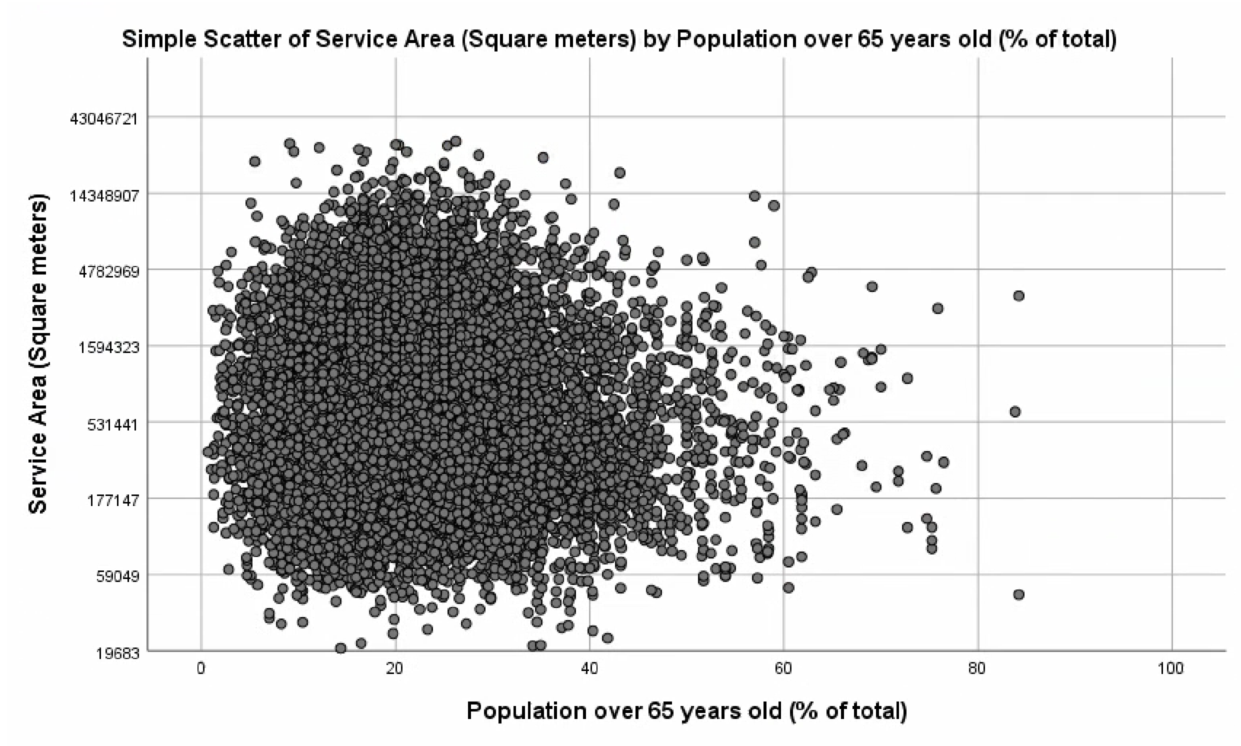

Figure 18. Scatter plot of service area against percentage of the population over 65 years old.

Similarly to Figure 17, Figure 18 does not seem to suggest much of a correlation.

Correlations

A Two-tailed Spearman Rank-Order Correlation is carried out for all variables shown above. For each combination of variables, the null hypothesis is that there is no correlation between them.

Table 2 shows the result of this operation. Only correlations with service area (the first row of the correlation table) are shown.

	Population	Average Home Value	Average Household Size	% Pop. with Dutch background	% of rental homes	% of apartments	% Pop. between 15-25	% Pop over 65
Correlation Coefficient	-0.554	0.135	0.406	0.495	-0.447	-0.529	-0.007	0.036
Significance (2-tailed)	0.000	0.000	0.000	0.000	0.000	0.000	0.390	0.000

Table 2. Correlation coefficients and significance values for correlations between service area and various variables

Table 2 shows that the significance of the correlations with all variables are below the threshold of 0.05 and are therefore at least 95% significant, except for *population between 15-25*.

In line with expectations, it appears that population density is indeed correlated with bus stop service area, as a square's population (analogous to density) has a negative correlation with service area: its correlation coefficient is -0.554, implying a moderate negative correlation. This means that service areas get smaller as population density increases, and therefore accessibility (as outlined earlier) increases.

Average home value seems to have a relatively weak correlation with service area, with a correlation coefficient of 0.135. This implies that service area increases (and accessibility decreases) slightly as home values go up.

Demographics have an effect to a degree, as the percentage of the population with a Dutch background shows a moderate positive correlation with bus stop service area, which means accessibility decreases as the percentage of population with a Dutch background increases. As mentioned earlier, this may be related to an urban-rural split. However, correlations with age are either nonexistent (in the case of the percentage of young adults, ages 15-25) or very weak (in the case of persons over 65, with a correlation coefficient of 0.036). This is not in line with expectations, which list age and cohort effects as possibly being related to bus stop accessibility.

Land use also has an effect, as both the proportion of rental homes and apartments are also negatively correlated with service area (their respective correlation coefficients are -0.447 and -0.529). Bus stop accessibility therefore increases with higher percentages of apartments and rental homes. Of note here, however, is that the proportions of rental homes and apartments are also highly correlated with one another: they have a correlation coefficient of 0.730 with a significance of 0.000, implying a strong positive correlation. It is therefore uncertain whether one of these factors is more important than the other.

Both are also moderately correlated with population (correlation coefficients of 0.547 for rentals and 0.606 for apartments, both with a significance of 0.000) and population is also correlated with the percentage of persons with a Dutch background (coefficient of -0.604, again strongly significant with a significance value of 0.000). This suggests that bus stop density might be correlated with a "cluster" of factors that are all related to urbanity: high population density, high immigrant populations and a high percentage of apartments.

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5. Conclusion and Discussion

Conclusion

This study has investigated the relationship between bus stop accessibility and local demographic, economic and spatial factors. Bus stop accessibility is operationalised through a measure of bus stop service area created using Voronoi polygons. This measure is then correlated with local data around the bus stop. Findings indicate that there exists a correlation between certain local factors and bus stop service area, despite the non-standardised methods adopted by transit planners. While this does not imply that these factors can necessarily serve as predictors and does not imply a direct causal relationship, it does show that the conscious and unconscious parts of the planning process lead to an outcome that produces these correlations. This insight expands on existing literature by providing a backward-looking and country-wide analysis of the effects that the methods of public transit planners have on the distribution of bus stops.

Discussion

One point of discussion is that many of the variables that exhibit a strong correlation are themselves heavily related to urbanity: high population (density), low average household size and a low percentage of people with a Dutch background, all correlated with low bus stop service area, are also all characteristics of cities. It is therefore possible that these correlations can simply be traced back to a relationship between cities and high bus stop density. This context is important to consider in interpreting the results of this research: rather than stating that any one specific factor is strongly correlated with bus stop accessibility, it may be more accurate to state that it is related to a cluster of factors that make up urbanity. This emphasis on urbanity (and its related population density) can be contrasted against the premise of Cooke & Behrens (2017), which suggests moving beyond population density as an indicator for public transit viability. However, this article is mainly focused on expanding transit infrastructure in developing countries (mainly sub-Saharan Africa); it may therefore be less applicable to the Netherlands, which has a developed economy and already has dense public transit infrastructure present.

An interesting observation is the lack of a notable (or existent) relationship between service area and age. Based on this research, it is unclear why this factor appears to be less important relative to other factors. It might not be consciously considered by planners to the extent that other factors are; data on the subject might be less available; or, perhaps, the transit needs of people of different ages do not differ that much from one another. This could be an avenue for further research.

Reflection on Limitations

It may be noted that the frequency and connectivity of transport lines are outside the scope of this research. Because of this, these results may not map directly to the "true" situation. A bus stop may be close and accessible, but still not have much utility for residents as the frequency of transit there is very low. Additionally, physical barriers have not been considered for the calculation of service areas, which impacts their quality as approximations of reality. This is further compounded by the fact that a strongly simplified map of water coverage was used, due to limitations in processing power. This could have distorted service area measurements in areas with much water coverage with complex geometries, such as, for example, the urban core of Amsterdam.

The process of removing cases where CBS does not supply data may have skewed the results – roughly 5,000 cases were omitted. Squares with no or incomplete data are mainly squares with a low population, generally located in rural areas, which may have introduced a bias in this research as rural areas are underrepresented in the dataset. The CBS dataset was also limited in other areas: for example, data for the proportion of rental homes or persons with an immigrant background was given in multiples of 10 percentage points. While the Spearman Rank-Order method should be able to accommodate this data, some information is lost nonetheless.

Recommendations

While this research has aimed to give a very broad overview of the spatial accessibility of bus transit as it is influenced by local factors, the results warrant more work on the subject. More in-depth work could take two directions. One possibility is for research to focus specifically on urban areas and examine the dynamics that exist between different parts of an urban area, such as younger and older neighbourhoods, wealthy and poor neighbourhoods or neighbourhoods with high numbers of immigrants. Limiting research to urban areas would eliminate the factor of "urban-ness" as the main factor influencing accessibility, which may uncover more specific results.

Another avenue would be to do more advanced network analysis in order to measure walking distances or the connectivity of specific bus stops within the broader transit network. Such research may be used to inform planners and policymakers about the dynamics and methods of public transit planning – a topic which, given the mobility transition mentioned in the introduction, will likely be of lasting importance.

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