TOPOI Mobility: Accessibility and settlement types in the urban rural gradient of Lower Saxony – opportunities for sustainable mobility

Vanessa Miriam Carlow, Olaf Mumm, Dirk Neumann, Nina Schmidt and Thomas Siefer

1TU Braunschweig, Department of Architecture, Civil Engineering and Environmental Sciences, Institute for Sustainable Urbanism (ISU), Braunschweig, Germany; 2TU Braunschweig, Department of Architecture, Civil Engineering and Environmental Sciences, Institute of Transport, Railway Construction and Operation (IVE), Braunschweig, Germany

ABSTRACT
The accessibility of suburban and rural areas presents existential challenges for resident communities. Municipality inhabitants with little access to public transport and structurally weak regions often work in distant urban agglomerations, with long commutes. Widespread monofunctional 'dormitory' villages and suburban areas with low building density and access to public transport, fuelling automobility dependence, are still implemented as planning concepts in Lower Saxony. The objectives of this study are to analyse the quality of public transport accessibility along the urban-rural gradient in relation to settlement types in two regions in Lower Saxony; to identify the interrelations between good accessibility by public transport and population density; to identify opportunities and challenges of urban-rural public transport accessibility. The application of the settlement classification system TOPOI – developed to analyse and define settlement patterns in urban-rural gradients – enabled us to determine the quality of public transport. Furthermore, we newly developed the 'Public Transport Access Score' based on parameters such as available public transport modalities, their catchment areas, operating frequencies, and connectivity and applied it to demonstrate the level of accessibility for different settlement types of similar characteristics (TOPOI). Hence, we localised how sustainable accessibility of public transport can benefit the development of the urban–rural network.

1. Introduction
Urban-rural systems can be understood as spatially interrelated settlement units connected by networks and the flow of people, goods, information, and services (Baccini & Oswald, 1998). They are characterised by high dynamics and transformation processes (Carlow & ISU, 2016; Diener et al., 2005; Koolhaas, 2014), with effects on single...
settlement units and overall settlement patterns. Several approaches to understand urban-rural relations (Diener et al., 2005; Netzstadt (Baccini & Oswald, 1998); Zwischenstadt (Sieverts, 1997); Metacity (McGrath & Pickett, 2011), and Metaplis (Ascher, 1995), offer new insights into urban-rural settlement patterns. However, the lack of sufficient integrated urban-rural planning strategies (Healey, 2002) results in increased land consumption for housing and infrastructure, higher resource and energy demands, increasing and changing mobility needs, and changing commuter behaviour (MSGG, 2013). Moreover, significant interrelations between these phenomena and effects are observable (Akkoyunlu, 2015; Andersson et al., 2009; Tacoli, 2006).

This paper focuses on public transport accessibility within urban-rural regions as a path towards more sustainable mobility. In the EU, the transport sector is responsible for about 25% of total European CO2 emissions (EFTE, 2018). In 2018, the transport sector was responsible for more than 19% of Germany’s greenhouse gas emissions (UBA, 2020). In Germany, the transport sector is divided into road, rail, shipping, and air traffic. Greenhouse gases and air pollutants emitted by the various modes of transport are carbon dioxide, methane, nitrous oxide, sulphur dioxide, nitrogen oxides, carbon monoxide, volatile organic compounds, and particulate matter. In 2018, the total emissions of transport reached 163.6 million t CO2-equivalent 95% of which were caused by road traffic (UBA, 2020). Since 1990, emissions have decreased from all sectors, except transport. Public transport emits comparatively less emission than private motorised transport, per person, per kilometre (UBA, 2020).

Despite the high urbanisation rate in Europe, in Lower Saxony, a German Federal State, many people live in suburban or rural areas, today (Eurostat, 2020; LSN, 2019). In Lower Saxony, 71% of the population live in small towns (< 50,000 Inhabitants), suburban, and rural areas. The accessibility of these areas by public transport can be considered an elementary component of sustainable transformation with a significant impact on CO2 emissions (Carrilero et al., 2018; UBA, 2020). In rural areas of Germany, 90% of households own a car. Comparatively, on average only of 58% of households in metropolitan areas have access to a car. This is also reflected in the modal split, with 70% of all trips in rural areas made by car, whereas, in the metropolitan areas, the proportion of motorised individual transport is 38% (IGES et al., 2020; Nobis & Kuhnimhof, 2018). Public transport thus plays a pivotal role in satisfying daily mobility needs, such as commuting to a place of work or education, while reducing the overall per capita CO2 emissions (UBA, 2020). The length of the average route is 12 km per day in Germany. In 2017, an average of 3.1 trips per person per day were made with a daily average distance of 39 km. The average for persons is 3.7 trips per day and a daily distance of 46 kilometres, thus, higher than the normal average. The mobile inhabitants in large cities cover about 42 km per day, whereas the daily travel distance in rural areas is considerably higher, at 52 km (Nobis & Kuhnimhof, 2018). The development of sustainable public transport in sparsely populated areas is a larger challenge than in densely populated metropolitan regions (Krämer et al., 2019). Nowadays, public transport in rural areas is often limited to school transport during the weekdays (HBS & VCD, 2019; Krämer et al., 2019; Muth, 2018). The number of young people in rural areas is decreasing, significantly. Due to this demographic change, village schools are closing with the consequence that children travel longer distances. Consequently,
collective school traffic has significantly reduced during the last few years (HBS, & VCD, 2019; Krämer et al., 2019; Muth, 2018). In many remote areas, however, school traffic is the only means of public transport, with services limited to school hours, excluding weekends and holidays (Muth, 2018). Mobility patterns during the weekend are not part of this study, since a preliminary analysis proved that the availability of local public transport services is significantly lower in the study regions on Saturday and Sunday. Furthermore, smaller communities often have only one to four connections per day to the nearest larger town, coinciding with the beginning and the end of the school day (IGES et al., 2020). Other municipalities have five to eight connections per day, which equals one trip per hour during rush hours, with no service during off-peak hours. This affects many municipalities with less than 150 inhabitants per km² (1,500 Inh./ha) (IGES et al., 2020). The door-to-door travel time (in comparison to travel by car) and the frequency of connections are especially important to increase the attractiveness of public transport (VDV, 2019). Therefore, the quality of access, of services and of the network are decisive factors (VDV, 2019).

To address the challenges of sustainable public transport in the urban–rural gradient, a precise evaluation of accessibility by public transport in relation to settlement types and their specific characteristics, is required. Some studies have used timetable information data such as General Transit Feed Specification (GTFS) (MobilityData, 2020) to assess the accessibility of metropolitan regions by public transport (Poelman & Dijkstra, 2015). In this research, the authors combined the frequency data with the stop locations, based on which, they developed an assessment matrix with a typology of service frequency, depending on the transport mode and settlement types. Several studies that analysed public transport in less densely populated regions looked for starting points to improve the situation (Becker et al., 2018; Eidam et al., 2012). With our focused analysis of urban–rural settlement patterns and related accessibility, new insights into mobility patterns and needs are offered.

The objectives of this study are as follows: a) to analyse the quality of the accessibility of public transport along the urban–rural gradient in relation to settlement types (TOPOI) in two study regions in Lower Saxony; b) to identify the interrelations between good accessibility by public transport and population density for respective settlement types; c) to identify opportunities and challenges of public transport accessibility in urban-rural regions.

2. The urban-rural settlement system of Lower Saxony

This research focuses on two study regions in Lower Saxony (Germany): (A) Vechta-Diepholz-Verden, and (B) the larger Braunschweig region (see Figure 1). Simultaneous shrinkage and growth in close geographical proximity are characteristic of the recent and current development of Lower Saxony, with often unsustainable effects, such as a high level of sealing of land and dense commuting patterns (Carlow et al., 2021; MSGG, 2013). The study region Vechta-Diepholz-Verden in the west of Lower Saxony can still be described as rural. It is characterised by numerous evenly distributed, mainly prospering
medium-sized and small towns. The study region of the larger Braunschweig region, on the other hand, includes both prospering cities and shrinking municipalities.

To date, the German spatial planning model is still building on the central place theory (BKG, 2020; Christaller, 1933). It differentiates between large cities with more than 100,000 inhabitants, medium-sized towns with a population between 20,000 and 100,000 inhabitants, small towns with up to 20,000, and villages with less than 5,000 inhabitants (BBSR, 2017; BKG, 2020). Furthermore, settlement types are identified as cities (county free), urban counties, rural counties with densification tendencies, and sparsely populated rural counties (BBSR, 2018). In Lower Saxony, only 20% of the population live in large cities (> 100,000 Inh.) and 9% in medium-sized towns. The majority of the population, 71%, lives in small towns (< 50,000 Inh.), suburban, and rural areas (LSN, 2019). Lower Saxony regions show truly diverse spatial development patterns, which the two study regions exemplarily reflect (LSN, 2019). In the study region (B), large cities such as Braunschweig and the medium-sized city of Wolfsburg offer many job opportunities, which the structurally weak regions in the surrounding regions depend on (City of Braunschweig, Department of Urban Development and Statistics, 2019; NIW, 2008; RGB, 2019). This is also reflected in the commuting patterns. Particularly, suburban areas that stem from the deagrarianization of former villages (TI-LR & BMEL 2015; Vogt & Biernatzki), are monofunctional areas with long commuting times and routes (see Figure 2.) (BfA, 2019; Sedrez et al., 2018). Study region (A) is characterised by a more homogeneous distribution of workplaces across different settlement types and the overall positive employment situation in the places of residence.

Figure 1. TOPOI classification of the settlement units in the two study regions: (A) Vechta-Diepholz-Verden, (B) Larger Braunschweig Region (Carlow et al., 2021).
This results in short commuting distances for ‘outward-commuters’; people with their place of residence being their place of work. However, due to the low-density settlement patterns, rather high distances for ‘inward commuters’ arise, for whom the place of residence does not equal the place of work (see Figure 2.) (BfA, 2019; Kreamobil & ZIV, 2017; Sedrez et al., 2018).

Dispersed settlement patterns and segregated, monofunctional settlement structures result in increasing transport demands, often realised through motorised individual traffic in rural and wider metropolitan regions (Holz-Rau & Schreiner, 2005; Kagermeier, 1997; Linder et al., 1975; Motzkus, 2001).

Understanding urbanisation patterns and their relations along the urban–rural gradient is considered a new and promising approach to sustainable development (Carlow et al., 2021; Suarez-Rubio & Krenn, 2018). This requires a holistic approach towards the analysis and planning of urban regions, including cities and their surrounding areas, with manifold interactions, mutual dependencies, spatial linkages, and fluidity between urban and rural lifestyles (Akkoyunlu, 2015; Andersson et al., 2009). The TOPOI method describes the urban-rural settlement system in more detail than the standard planning approach based on size and administrative borders (BBSR, 2017). This unlocks...
opportunities to interpret changes in the physical environment and consequently derive recommendations for a sustainable transition.

This study departs from the analytical framework of the TOPOI method (Carlow et al., 2021). Based on standard planning parameters of form, function, as well as linkages, settlement units of similar characteristics are analysed (see supplemental material Tables S.1, S.2, and S.3) and interconnections are shown. Thus, 13 settlement types were identified in the two study regions. They include isolated and dispersed units, units at the urban fringe, or urban cores. To describe the degree of centrality of the settlements, prefixes such as exo, disseminated, periurban, or node are used (Carlow et al., 2020; see supplemental material Tables S.2 and S.3). In this study, the TOPOI method was expanded to include parameters of accessibility and connectivity, with the goal of revealing the functional interrelations between different settlement types along the urban-rural gradient.

3. Material
3.1. Definitions and legal frameworks

This study uses the definition of mobility as the movement of people, goods, services, or data within a given space (Kirchhoff, 2002). This includes opportunities to participate in movement and the willingness to move (Kirchhoff, 2002). Transport is the sum of movements of persons, goods, energy, or communications. This paper focuses on passenger movements. Changes in location take place along transport routes and occur when a sequence of activities cannot be executed at the same location (Kirchhoff, 2002).

Local public transport, Öffentlicher Personennahverkehr, (ÖPNV) in Germany is divided into local road transport, Öffentlicher Straßenpersonennahverkehr (ÖSPV), and local rail transport, Schienenpersonennahverkehr (SPNV). The SPNV includes railways and suburban rails, and ÖSPV comprises buses, trams, and metro (Bundestag Germany, 2012). Both local public transport systems are regulated by laws and guidelines; local road transport by the Passenger Transportation Act, Personenbeförderungsgesetz, PBefG (BMJV, 1961); local rail transport by the General Railway Act, Allgemeines Eisenbahngesetz, AEG (BMJV, 1993a). The Passenger Transportation Act defines public transport as the generally accessible transport of persons by tram, trolleybus, and motor vehicles in regular service, which are mainly intended to satisfy the demand for urban, suburban, or regional transport (§8 PBefG) (BMJV, 1961). This is the case if most passengers do not travel more than 50 kms or travel time does not exceed one hour. Since the Passenger Transportation Act applies to local road and rail transport, it is incorporated in the Regionalisation Act, Regionalisierungsgesetz, RegG. (BMJV, 1993b). Local road transport includes transport by taxi or rental cars, which replaces, complements, or consolidates a mode of transport such as trams or buses (BMJV, 1961, 1993b). Ensuring an adequate supply of public transport is a public interest task and is regulated in paragraph 1 of the Regionalisation Act, (BMJV, 1993b).
The Association of German Transport Companies (VDV, 2020) and the Road and Transportation Research Association (FGSV, 2020) provide dimensioning recommendations for the quality of service in public transport (FGSV, 2010; VDV, 2020) based on population density and the central place concept applied in federal spatial planning in Germany (BKG, 2020). The guidelines define that contiguous areas are to be serviced if they have more than 200 inhabitants, commuters and/or trainees, or facilities (sites with special functions) with more than 200 inhabitants. If 80% of these people live or are employed in appropriate catchment areas of public transport stops, the area is considered developed (VDV, 2020). Furthermore, the accessibility of the assigned central locations by public transport is defined. The assigned basic centres should be reachable by public transport within 30 minutes, middle centres within 45 minutes, and the nearest regional centres within 90 minutes. Travel time includes the arrival and departure times to and from the stop as well as the waiting and transfer times (FGSV, 2010).

3.2. Data

The analyses in this study are based on the following two data sets:

1. The General Transit Feed Specification (GTFS) (MobilityData, 2020) is a standard transit schedule format used by public transport agencies and service providers to make public transport information available to users. The GTFS dataset consists of stops, routes, trips, stopping times, a calendar, and the executing transport agency (Google Developers, 2020). The GTFS data of Lower Saxony are provided through the Connect OpenData Portal (Connect, 2019a, 2019b). The company combines the services of transport companies and transport associations to create a timetable data pool for the states of Lower Saxony and Bremen.

2. The study applies the TOPOI (Carlow et al., 2021) settlement types as an analytical framework to illustrate connectivity patterns. The data set TOPOI – Urban Rural Settlement Types – Version 1.0 (Carlow et al., 2020), is a geospatial classification of urban and rural settlement types in Lower Saxony, as described in section 2.

4. Methodology

The analysis of mobility patterns was conducted in three steps. First, the timetable data (GTFS) are filtered in accordance with public transport parameters (see section 4.4.). After the superposition of these parameters with the TOPOI settlement types, the latter are analysed to assess their transit accessibility. Based on this, an evaluation matrix for transit accessibility was developed.

4.1 Extraction and generation of key data from the GTFS data

The study data were processed using ArcGIS Pro (ESRI, 2020). Therefore, the GTFS dataset was converted into feature classes and tables using the conversion tool ‘GTFS
To Network Dataset Transit Sources’ (ESRI, 2018) and the plugin ‘Better Bus Buffer’ (ESRI, 2019). Due to the complexity of the data, the analyses were conducted for Wednesday, 25 March 2020 representatively for a regular working day between 6 am and 8 pm. That day was selected because it is not a public or school holiday in Lower Saxony. The period includes early and late rush hours. Consequently, the stops and the corresponding lines of the public transport system are provided in the geospatial context, including information on the operating system and the operating frequency per stop. Based on the spatial intersection of the data sets and the evaluation of the attribute tables, the location, and the number of stops, the public transport operating system for the two study regions was retrieved and their operating frequency per hour was calculated.

4.2. Definition of catchment areas for public transport stops

Based on the VDV and FGSV guidelines, catchment areas are set around public transport stops. Depending on the walking minutes and the operating system, a catchment area with radius $r = 600$ m (10 walking minutes) is set for train stops and $r = 300$ m (5 walking minutes) for tram and bus stops (FGSV, 2010; VDV, 2020). Since people are willing to walk 5 minutes to a tram or bus stop and 10 minutes to a train stop (Poelman & Dijkstra, 2015), three data sets for trains, trams, and buses with the respective catchment areas are created.

Similar standards are applied in the Local Transport Plan (Nahverkehrsplan) of the Regionalverband Großraum Braunschweig, which equals study region (B). The radius for tram and bus stops is 300–500 m and for railway stations up to 1,000 m (RGB, Regionalverband Großraum Braunschweig, 2019). Usage densities are also defined in the VDV and FGSV guidelines (FGSV, 2010; VDV, 2020). The catchment area is described by a defined radius around the stop. The detour factor for the actual footpath length is 1.2 and the speed on foot is 1 m/s (VDV, 2019).

4.3. Superposition of the GTFS data and the generated key data with the TOPOI settlement units

With the Public Transport Access Score we developed a new method to evaluated each areas accessibility by public transport. To calculate the Public Transport Access Score (PTAS) for different settlement units along the urban-rural gradient, we superposed the key data from the GTFS sets with the TOPOI settlement units (Carlow et al., 2020). The following datasets were used for the evaluation of the respective TOPOI settlement units to evaluate public transport accessibility: (a) the number of different operating systems, (b) the average operating frequency per hour, (c) the total percentage of catchment areas around the stops relative to the total settlement area, differentiated by operating system (train, tram, bus), and (d) public transport connectivity (PTC). The PTC is the number of settlement units directly linked to each other by public transport. It can be calculated as $PTC = \sum L_i (L_1 + L_2 + L_n)$, where $L$ is the number of unique settlement units reached by each public transit line that goes
through a TOPOI settlement unit (Carlow et al., 2021). Furthermore, settlement units inaccessible by public transport, are identified.

4.4. Development and application of a Public Transport Access Score (PTAS) to assess the TOPOI settlement types

To evaluate and rank the TOPOI settlement types according to their accessibility, the PTAS, which integrates different indicators of public transport accessibility was developed and applied. For each indicator, classes, distinguished by defined threshold values such as high, medium, low, and no access, are applied. A scoring system determines the values of the indicators (see Table 1). The score integrates different aspects of public transport accessibility uniformly in the evaluation. The scoring system allows different weighting of aspects. The following three indicators form the PTAS:

- Percentage of catchment areas within settlement units accessible by public transport, differentiated by the operating system:
  - Catchment area around railway stations (r = 600 m; 10 walking minutes)
  - Catchment area around tram stops (r = 300 m; 5 walking minutes)
  - Catchment area around bus stops (r = 300 m; 5 walking minutes)
- Average operating frequency within a settlement unit (number of trips per hour)
- Public Transport Connectivity (PTC) (Carlow et al., 2021)

The three indicators represent diverse aspects of public transport accessibility but contribute to the overall quality of public transport. The catchment area of public transport stops relative to the total settlement area, represents public transport coverage. If different operating systems or modes of public transport are offered within a settlement, the quality of accessibility increases further. Operation frequency is the second most important quality factor for public transport accessibility. A high frequency of service shortens waiting times and increases the availability in terms of time. The frequency of operation is considered a decisive factor for accessibility and is given double weighting in the assessment because the willingness is higher to accept a longer way to the stop if the frequency of operation increases (Poelman & Dijkstra, 2015). The third aspect is connectivity, which represents the availability in spatial terms (several lines in one place) and the operating distance of public transport (total length of route).

4.5. Evaluation of the TOPOI settlement types through their Public Transport Access Score (PTAS)

Three evaluation methods are used to identify the accessibility by means of the PTAS for the TOPOI settlement types:

1. Using box plots, the median value for accessibility as well as the dispersion of the values for each TOPOI type is determined.
Table 1. Matrix of the Public Transport Access Score (PTAS) and its thresholds.

| PTAS | Points | Catchment area by operating system | Operating frequency | Public transport connectivity |
|------|--------|----------------------------------|---------------------|-------------------------------|
| High | ≤ 36 – ≥ 25 | Train (r = 600 m) | 66% < x ≤ 100 % | Trips per hour | x ≥ 4 | 9 Points | No access | 0 |
|      |        | Tram (r = 300 m) | 3 Points | x ≤ 20 | 5 Points |
|      |        | Bus (r = 300 m) | 3 Points | 18 Points | 9 Points |
|      |        |                   | 66% < x ≤ 100 % | 1 ≤ x < 4 | 6 Points |
|      | Medium |                   | 33% < x ≤ 66 % | 33% < x ≤ 66 % | 33% < x ≤ 66 % | 3 Points | 5 Points |
| ≤ 24 – ≥ 13 | 3 Points | 3 Points | 1 Point | 1 Point | 1 Point | 1 Point | 5 Points |
|      | Low    |                   | 0% < x ≤ 33 % | 0% < x ≤ 33 % | 0% < x ≤ 33 % | 0% | 0 Points |
| ≤ 12 – ≥ 1  | 2 Points | 2 Points | 1 Point | 1 Point | 1 Point | 1 Point | 0 Points |
| No access | 0 Points | 0 Points | 0 Points | 0 Points | 0 Points | 0 Points | 0 Points |
(2) The TOPOI types are plotted in an evaluation matrix via the PTAS (high, medium, low, and no access). At the same time, the TOPOI types are used to determine the number of inhabitants who enjoy various degrees of accessibility.
(3) The quality of public transport access is mapped for the TOPOI settlement units. The maps can be used to interpret spatial patterns of accessibility.

4.6. Exploring the correlation between the quality of public transport accessibility and the population density of settlement units to assess development potential

By applying a scatterplot, the hypothesis of a dependence between population density and public transport accessibility were tested. First, the correlation between the two variables, Y as the public transport score (PTC), and X as the population density was deduced. From this, the regression formula was calculated, and the corresponding trend line and R² are shown in the scatterplot. The trend line models the linear relationship between X and Y, and R² quantifies the match of the data with the model. R² provides the relative measure of the ratio of the dependent variable variance that the model explains. R² can range from 0 to 1.

5. Results

The analysis of the mobility patterns was conducted in three steps. First, the timetable data (GTFS) was analysed to filter public transport parameters (see section 4.4.). After the superposition of these parameters of public accessibility with the TOPOI settlement types, the latter were analysed to derive an evaluation matrix for transit accessibility by different evaluation methods.

5.1 Evaluation of the GTFS data for the two study regions

Three types of operating systems exist in the two study regions: train (local train, long distance), tram, and bus. In total, there are 84 train stations, 154 tram stops, and 5,925 bus stops.

The train system (red lines) covers the study regions with a coarse mesh network of lines (Figures 3.1(a,b) and 3.2(a,b)). The railway network is structured differently in the study regions. In study region (B), there is a central point with the city of Braunschweig, where all train lines in the region converge (Figures 3.2(a,b)).

However, in study region (A), there is no city where all lines converge. As can be seen in (Figures 3.1(a,b)), two railway lines cross the study region in the west and east. They meet in the north of the city of Bremen and in the south in the city of Osnabrück (both outside of the study region). A reason for this structure may be that there is only one transport association that covers the entire study region (B). Study region (A) has more than one transport association. There are also clear differences in the operation frequency in both areas. The radius indicates the departures per hour; the larger the radius, the more trips per hour are provided. Interlinkages by train exist in study region (B) between the centres of Braunschweig, Salzgitter, and Wolfsburg among themselves and in relation
Figure 3.1. a. Public transport system in the region Vechta Diepholz Verden with different operating systems, stops and connections b. (section of the study region; see Figure 3.1.a.) (Data source: Connect GmbH).
Figure 3.2. a. Public transport system in the greater Braunschweig region with different operating systems, stops and connections; b. (section of study region; see Figure 3.2.a); (Data source: Connect GmbH).
to their neighbouring municipalities. The municipalities at the different lines in the study region (A) are not connected by train with each other. For example, the cities Vechta and Diepholz are only connected by bus (Figures 3.1(a,b)).

Meanwhile, the tram system is limited to the city of Braunschweig (Figure 3.2(a,b)). The pattern shows a radial system connecting the city centre with the city edge and the central station. The tram has a 15-minutes basic frequency on all six lines.

The bus system has a finer mesh and more complex connecting lines. Nevertheless, not all municipalities in both areas are accessible by public transport. The blue stops and lines show the network of bus lines in both study regions in (Figures 3.1 and 3.2(a,b)), where the frequency of operation at the different bus stops varies strongly. This can be seen in larger cities such as Wolfsburg (see Figures 3.2(a,b)). Even where the demand is extremely low, public transport agencies try to provide accessibility to guarantee services of general interest.

5.2 Evaluation of the overlay of GTFS data and indicators of public transport accessibility (integrated in PTAS) with the TOPOI settlement types

The TOPOI settlement types, node city and node town, have railway stations. The existence of a railway station in the TOPOI types in periurban town and (small) periurban village varies between 24% and 75%. For all other types, the presence of a railway station is unlikely. There is no station in any of the exo satellite towns (see Table 2). A tram connection can be found in node city and a few periurban towns and periurban villages, as well as in one exo satellite town. A bus connection is available in 10 of the 13 TOPOI settlement types with a minimum of availability of 97%. However, only 37% to 54% of the three hamlet-TOPOI types have a bus stop (see Table 2).

Since the frequency (number of trips per hour) is a crucial factor for public transport users, a higher frequency indicates a higher probability that people continue to use or switch to public transport. In the node city settlement type, a public transport vehicle stops nearly four times per hour. Node towns have only 2.6 trips per hour. This is equal to an average of 23 min. The top scorer in public transport frequency are the exo satellite towns, where a public transport vehicle departs more often than every 8 min. In periurban towns and periurban villages, a public transport vehicle departs approximately three times per hour, and in exo villages every 30 min on average. In all other villages and hamlets, the frequency tends to be once an hour or every 45 min, if there is a stop at all. The exo industrial zone has an average of 2.91 trips per hour, so the frequency is every 20 min. Additionally, note that all departures are counted. If there are two stops per hour, this can mean that a vehicle only travels in one direction once per hour.

The degree of coverage of public transport catchment areas, as defined in section 4.2, varies strongly between modalities. In 10 of the 13 TOPOI settlement types, the degree of coverage of the catchment areas around bus stops (r = 300 m) is considerably high, between 62% and 78%. In hamlets and exo industrial zones, the value is between 24% and 46%. The catchment areas of the train stops (r = 600 m) is small; for example, the degree of coverage in a node city is only 3%. This is because the node city has only two stations despite its exceptionally large area. To compensate, a node city, on the other hand, has exceptionally good small-scale access by trams and buses. Smaller settlements, such as node towns and (small) periurban villages, due to their medium size areas, are located to a larger extent (10%-17%) in the catchment area of the train station.
Table 2. Matrix of key parameters derived from the GTFS dataset per TOPOS type; e.g. periurban town: 24 settlement units, of which 18 have a train station, 2 a tram connection and 24 a bus connection. Adding up the calculated catchment area overlapping with the settlement unit results in a percentage share of the overall area of the settlement units of the category *periurban towns* of 11% for train stops, 3% for tram and 67% for bus stops. *Periurban towns* have in average 3.02 trips per hour for 1.83 operating systems and a public transport connectivity of 25 (see chapter 4.4 for description of PTAS indicators and scoring).

| TOPOI with railway station (count) | TOPOI with tram stop (count) | TOPOI with bus stop (count) | Train stop (percentage of TOPOS type total) | Tram stop (percentage of TOPOS type total) | Bus stop (percentage of TOPOS type total) | Number of trips per hour (Mean) | Number operating systems (Mean) | Public transport connectivity (Mean) |
|----------------------------------|-------------------------------|-------------------------------|------------------------------------------|------------------------------------------|------------------------------------------|--------------------------------|------------------------------|----------------------------------|
| **Node city**                    |                               |                               |                                          |                                          |                                          |                                |                              |                                  |
| Total count of TOPOI             | Population density (people/ha) | 100%                          | 100%                                     | 100%                                     | 100%                                     | 3%                              | 31%                          | 71%                              |
| **Node town**                    |                               |                               |                                          |                                          |                                          |                                |                              |                                  |
| 7                                | 22.5                          | 100%                          | 0%                                       | 7%                                       | 100%                                     | 10%                             | 0%                           | 74%                              |
| **Periurban town**               |                               |                               |                                          |                                          |                                          |                                |                              |                                  |
| 24                               | 21.4                          | 75%                           | 8%                                       | 24                                       | 100%                                     | 11%                             | 3%                           | 67%                              |
| **Exo satellite town**           |                               |                               |                                          |                                          |                                          |                                |                              |                                  |
| 9                                | 48.2                          | 0%                            | 11%                                      | 9                                        | 100%                                     | 0%                              | 11%                          | 76%                              |
| **Periurban village**            |                               |                               |                                          |                                          |                                          |                                |                              |                                  |
| 42                               | 19.7                          | 64%                           | 7%                                       | 42                                       | 100%                                     | 17%                             | 2%                           | 62%                              |
| **Small periurban village**      |                               |                               |                                          |                                          |                                          |                                |                              |                                  |
| 37                               | 17.2                          | 24%                           | 0%                                       | 37                                       | 100%                                     | 12%                             | 0%                           | 77%                              |
| **Exo village**                  |                               |                               |                                          |                                          |                                          |                                |                              |                                  |
| 524                              | 14                            | 4%                            | 0%                                       | 510                                      | 97%                                      | 2%                              | 0%                           | 71%                              |
| **Small exo Village**            |                               |                               |                                          |                                          |                                          |                                |                              |                                  |
| 73                               | 11                            | 1%                            | 0%                                       | 72                                       | 99%                                      | 0%                              | 0%                           | 81%                              |
| **Disseminated village**         |                               |                               |                                          |                                          |                                          |                                |                              |                                  |
| 160                              | 7.2                           | 11%                           | 0%                                       | 158                                      | 99%                                      | 4%                              | 0%                           | 68%                              |
| **Agri village**                 |                               |                               |                                          |                                          |                                          |                                |                              |                                  |
| 35                               | 5.2                           | 0%                            | 0%                                       | 35                                       | 100%                                     | 0%                              | 0%                           | 78%                              |
| **Disseminated hamlet**          |                               |                               |                                          |                                          |                                          |                                |                              |                                  |
| 1,071                            | 2.3                           | 3%                            | 0%                                       | 573                                      | 54%                                      | 2%                              | 0%                           | 36%                              |
| **Disseminated living agri hamlet** |                             |                               |                                          |                                          |                                          |                                |                              |                                  |
| 4,283                            | 2.3                           | 1%                            | 2%                                       | 1,586                                    | 37%                                      | 1%                              | 0%                           | 24%                              |
| **Exo industrial zone**          |                               |                               |                                          |                                          |                                          |                                |                              |                                  |
| 35                               | 0                             | 9%                            | 3%                                       | 26                                       | 74%                                      | 1%                              | 1%                           | 46%                              |

URBAN, PLANNING AND TRANSPORT RESEARCH
5.3. Evaluation of the Public Transport Access Score (PTAS) in relation to the TOPOI settlement types

In section 4, we describe a method – the Public Transport Access Score – to evaluate the public transport accessibility linked to the geospatial entities of the classified settlement units – the TOPOI. The integrated geodatabase is the basis for three subsequent evaluation steps (see section 4.5: box plot analysis (Figure 4), evaluation matrix (Table 2), and advanced visualisations (Figures 5a,b). The results are as follows. The boxplot (Figure 4) shows that the TOPOI types can be divided into three groups when looking at public transport scores (see supplementary material Table S4 ‘Distribution of scoring points for the TOPOI types’). The first group includes the first two types (node city and node town); here, the median score ranges from 26 to 28 points. The second group includes the types, periurban town to agri village, where the median score ranges from 15 to 24 points. The variance in this second group is extremely high, which makes its clear assignment to an accessibility class difficult. The third group, the hamlets, are at the lower end with 0–7 points. The exo industrial zone has a wide range and cannot be placed in only one of the three groups. Over the entire diagram (Figure 4), the medians of the TOPOI types are resembling a falling exponential curve. The TOPOI types agri village and exo industrial zone are outliers from the trendline \( r^2 = 0.8 \).

More insightful is the second analysis method, in which the TOPOI types are classified in tabular form along the accessibility classes; at the same time, the corresponding population figures are assigned according to the classification (Table 3).

The coverage with public accessibility can be rated as satisfactory for the two study regions, as a whole. The combined population for both study regions, is 1,581,586 people (LSN, 2019). According to the PTAS, 94% of the population has high or medium
accessibility. Thirty-nine percent (621,868) of the people live in settlements with high accessibility. More than half of the population (55%) have medium accessibility, 4% percent low, and only 2% of the inhabitants have no access. People with no access to public transport live outside a catchment area of the train, tram, or bus. A total share of ca. 25% (i.e. 395,344 Inh.) of the population in both study regions are living in exo villages with only medium access. Exo villages are characterised in the TOPOI classification as more remote villages with a relatively high proportion of residents and few public and health services or supplies of daily needs, such as groceries. An improvement in public transport would give residents access to services and supplies located at greater distances.

(Figures 5a,b) show the PTAS in the study region (A) Vechta-Diepholz-Verden (Figure 5a) and in the study region (B) Larger Braunschweig region (Figure 5b). It is
obvious that the region Vechta, Diepholz, and Verden has more settlements with no access to public transport than the larger Braunschweig study region does. Furthermore, it can be observed in (Figure 5a) that high accessibility is concentrated in the larger settlements and settlements in their periphery. The city of Braunschweig and neighbouring municipalities have high or medium accessibility like the cities of Wolfsburg, Salzgitter, and areas in the Harz National Park. Linear spatial patterns with concentrations of high accessibility can be identified along main infrastructures routes (e.g. train lines), for example, between Wolfsburg and Gifhorn. There are settlement units with no
Table 3. Evaluation Matrix: Distribution of Inhabitants per Public Transport Access Score Category (PTAS); e.g. *exo village*: of 524 settlement units of the category ‘exo village’, 24 units with a total number of 41,664 inhabitants reach the PTAS ‘high’, 441 units with 395,344 inhabitants the PTAS ‘medium’, 47 units with 23,742 inhabitants the PTAS ‘low’ and 12 units with 4,844 inhabitants are not connected to the public transport at all.

| PUBLIC TRANSPORT ACCESS SCORE (PTAS) | High | | Medium | | Low | | No Access | |
|---|---|---|---|---|---|---|---|
| Count | Inhabitants | Count | Inhabitants | Count | Inhabitants | Count | Inhabitants |
| Node city | 1 | 159,297 | | - | - | | - | - |
| Node town | 4 | 134,162 | 3 | 66,162 | - | - | - | - |
| Periurban town | 9 | 160,263 | 15 | 156,044 | - | - | - | - |
| Exo satellite town | 3 | 17,535 | 6 | 24,687 | - | - | - | - |
| Periurban village | 18 | 100,134 | 24 | 108,861 | - | - | - | - |
| Small periurban village | 6 | 8,310 | 31 | 32,351 | - | - | - | - |
| Exo village | 24 | 41,664 | 441 | 395,344 | 47 | 23,741 | 12 | 4,844 |
| Small exo village | 2 | 268 | 59 | 10,096 | 11 | 1,669 | 1 | 221 |
| Disseminated village | 1 | 83 | 140 | 56,992 | 19 | 4,646 | - | - |
| Agri village | - | - | 32 | 6,618 | 3 | 191 | - | - |
| Disseminated hamlet | 3 | 45 | 271 | 6,099 | 321 | 9,733 | 476 | 6,892 |
| Disseminated living agri hamlet | 2 | 33 | 516 | 8,931 | 1,106 | 14,428 | 2,659 | 20,851 |
| Exo industrial zone | 5 | 74 | 18 | 300 | 4 | 0 | 8 | 17 |
| SUM study regions A and B | 621,868 | | 872,485 | | 54,408 | | 32,825 | 1,581,586 |
access to public transport in both study regions. This may be related to the fact that remote TOPOI types such as hamlets are widely spread and have a relatively low population density. In study region (A) Vechta-Diepholz-Verden, public transport accessibility is generally lower than in study region (B) larger Braunschweig region. Only a few settlements have high accessibility, whereas most of them are found in the medium accessibility class.

5.4 Evaluation of the correlation between the quality of accessibility by public transport and the population density of settlement units

Figure 6 shows a scatterplot where the 6,301 settlement units of the two study regions are plotted; symbolised by a circle. The colours indicate the TOPOI settlement types. The size of the circles relates to the area of each settlement unit. The scatterplot shows a weak positive correlation between the public transport access score and population density. This can be described by the trendline (see Figure 6). The correlation is weak with a relatively low R² value of 0.30 (see also section 4.6). However, according to the planning guidelines of the VDV and FGSV (see section 3.1), there should be a clear dependence between population density and public transport accessibility. From this, the trend line can be considered an optimum between accessibility and density. Following this thesis, the diagram can be interpreted as follows:

Several settlement units, such as some of the node towns, periurban towns, and periurban villages are located on the left of the trend line. This means that these settlement units have a low population density, given their relatively high PTAS. Other settlement types are situated right of the trendline, for example, exo satellite towns, which have a very low transport score given their high population density. It could be argued that the 2,480 (936,488 Inh.) settlement types with a lower population density in relation

Figure 6. Relationship between population density and Public Transport Access Score (PTAS).
to their accessibility have the potential for urban densification. Settlement types that have a higher density 3,821 (645,098 Inh.) in relation to their accessibility could be better developed with public transport. In this context, individual exceptional TOPOI settlement types can be identified.

6. Discussion

6.1. Summary of the results and conclusions

Public transport is a key factor in making mobility more sustainable. Especially in urban-rural contexts marked by low population density, motorised individual transport dominates. Here, the provision of public transport is not an easy task. The GTFS data and the TOPOI Settlement Types provide a good basis for a fine-resolution analysis of the relationship between the degree of urbanisation and the accessibility of public transport. The evaluation matrix of the PTAS allows the integration of different aspects and qualities of public transport accessibility and is therefore a novel and innovative evaluation tool. The superposition with the TOPOI settlement types allows the evaluation of public accessibility on a regional scale and at the same time helps to locate opportunities to improve public accessibility by increasing the population density or by improving the public transport services. Hence, a number of conclusions can be drawn:

First, regional patterns were identified in the superposition of TOPOI settlement types and the classification of the PTAS. In particular, when comparing the two study regions, patterns of accessibility can be identified through cartographic interpretation (see Figures 5a,b). For example, the study region (A) Vechta-Diepholz-Verden shows a uniformly distributed, primarily medium quality of public transport accessibility, with up to a large number of small settlement units without accessibility. The study region (B) larger Braunschweig, on the other hand, shows clear concentrations of high accessibility, especially in the vicinity of larger TOPOI settlement types. There are also linear patterns with high accessibility.

Second, if the trend line in (Figure 6). is interpreted as the optimum between population density and accessibility, conclusions can be drawn on the settlement units deviating from the trend line. All settlements to the left of the line have the potential for urban re-densification so that the population in those areas could increase utilizing the already existing accessibility. All those to the right of the line show a need to improve public accessibility. For the study regions, this would mean that 59.2% of the area with settlements and 936,488 inhabitants have the potential for urban re-densification. In contrast, 40.8% of the area has the potential to improve public transport accessibility for their 645,098 inhabitants. A number of examples can illustrate the findings in more detail:

One example are the exo villages with their population in both study regions enjoying only medium accessibility in their place of residence. An improvement in public transport accessibility, specifically for this TOPOI settlement type, would have an enormous regional impact and possibly improve the life of roughly 424,000 people in Lower Saxony.
This would allow longer distances to be covered by public transport by providing access to node cities, node towns and periurban towns. Greater accessibility to these TOPOI types would ensure better accessibility to public services and daily needs, improving the quality of life for residents in small towns and villages. Six percent of the total population in the two study regions or roughly 87,000 people have low or no access to public transport, next to exo villages mainly in sparsely populated disseminated living agri hamlets. Also for this population, accessibility could be considerably increased.

With regard to the correlation between population density and PTAS, a weak positive correlation could be identified. Nevertheless, it becomes evident that in larger cities such as the periurban or node towns, public transport services offer considerable potential for optimisation. Given their population number and density, the services currently provided are not in line with the guidelines and do most likely not suffice the needs of the population. This once more underlines the gap between the planning guidelines of VDV, FGSV, and reality.

On the other side there are a number of periurban towns and node cities as well as other settlement units which have a relatively low population density given their good PTAS. In those the population density could be increased without diminishing the PTAS for example, by building new urban quarters or densifying existing.

Our method, allowing for a more fine-grained analysis of settlement networks and their accessibility, is suitable of clearly identifying deficiencies and potentials. This opens up a huge potential for a more evidence-based design of public transport options or urban densification in support of the implementation of existing guidelines.

6.2 Methodical framework conditions

The GTFS data form an exceptionally good basis to analyse and evaluate the quality of public transport. In particular, the evaluation score, PTAS, can be transferred to regions worldwide that have the GTFS data sets available. The assessment score, PTAS, extends the method of Poelman and Dijkstra (2015) in respect of connectivity and dependence on settlement types TOPOI (Carlow et al., 2021). The travel time was not considered for questions on data availability, in this study. However, the travel time between the different transport systems can be a decisive factor in the choice of transport mode and whether people switch from their cars to public transport. This demonstrates potential subjects for future research.

By intersecting the TOPOI settlement types with the evaluation score, PTAS, the method of this study is particularly suitable to evaluate the quality of public transport in an urban-rural context and provide specific results depending on settlement types. The evaluation method we introduced is based on widely available GTFS data, which describes the availability and quality of public transport connections. The aggregated geospatial data provides the potential to assess mobility needs or the development of optimisation strategies if linked to additional, not yet accessible, datasets such as passenger numbers or other commuting data.
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**ORCID**

Vanessa Miriam Carlow [http://orcid.org/0000-0003-0513-9717](http://orcid.org/0000-0003-0513-9717)

Olaf Mumm [http://orcid.org/0000-0001-6628-7874](http://orcid.org/0000-0001-6628-7874)

Dirk Neumann [http://orcid.org/0000-0002-4732-1595](http://orcid.org/0000-0002-4732-1595)

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