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Public Transport Accessibility and Its Effect on Mode Choice

Fabian Kühnel, Michael Schrömbges, Nora Braun and Tobias Kuhnimhof *

Institute of Urban and Transport Planning, RWTH Aachen University, 52056 Aachen, Germany; fabian.kuehnel@rwth-aachen.de (F.K.); michael.schroembges@rwth-aachen.de (M.S.); nora.braun@rwth-aachen.de (N.B.)

* Correspondence: kuhnimhof@isb.rwth-aachen.de; Tel.: +49-241-8025200

Abstract: The relationship between the service of public transport (PT) and its use is complex but can be simplified through the use of indicators. These indicators should be able to accurately reflect PT use so that improvements in the indicators lead to increases in PT use. Although researchers and planners use similar indicators to describe the access of PT stops, the indicators used to assess the accessibility of destinations differ. Researchers use specific location-based methods to analyze accessibility to spatially dispersed destinations, while practitioners often focus on connectivity to central (business) districts. This raises the question of which approach better reflects the use of PT. By combining the German National Household Travel Survey with nationwide timetable data, we examine the relationship between PT use and two indicators of PT service: (1) travel time to the nearest central district and (2) cumulative opportunity accessibility, both calculated as the ratio of PT to car travel. The results of our binary logit models indicate that the travel time ratio does not have a relevant influence on the choice of motorized transport mode, but the accessibility ratio does. Therefore, we suggest that practitioners should use location-based accessibility methods such as the cumulative opportunity ratio to evaluate and improve PT service planning.

Keywords: public transit; location-based accessibility; connectivity to central business districts; cumulative opportunity; mode choice; binary logit model

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1. Introduction

The past car-centric development of the transport system caused elevated levels of emissions, noise, and land consumption. To reduce car use, German local authorities improve public transport (PT), promote active mobility, and restrict car access. Given its enhanced impact on total kilometers traveled, substituting longer car trips is an efficient way to reduce the environmental impact of transport. Since 90% of walking and cycling trips in Germany are shorter than 5 km [1], PT represents the sole practical alternative to the car for longer distances. Thus, increasing PT use and its mode share are key elements of sustainability measures at local, regional, and federal levels in Germany.

To encourage PT use, planners can reduce fares, improve PT services, and promote transit-oriented urban development. While reducing fares is straightforward, addressing the other two elements is more complex. As a result, planners rely on a variety of indicators to evaluate the transport system. With numerous metrics to choose from, the question arises as to which ones are most effective and should therefore be focused on. To draw the right conclusions for new measures, the indicators should be associated with PT mode choice. Accordingly, an improvement in the indicator values should lead to increased use of PT.

PT indicators can either evaluate daily operations or service planning. This paper focuses on service planning; however, we refer to Redman et al. [2] for insights into the influence of daily operations on mode choice. Ewing and Cervero [3] identify seven dimensions to categorize the built environment. As part of the built environment, they differentiate PT into two components: distance to transit and destination accessibility. Indicators of distance to transit describe the ease of access to the PT system, while indicators of destination accessibility describe the ease of access to activities using PT [3].

Distance to transit indicators are easy to calculate and popular among practitioners and researchers alike. Guidelines in various countries propose targets for maximum access distances to the system (e.g., ref. [4] American Public Transportation Association) or promote such indicators when improving service quality (e.g., ref. [5] Department for Transport). German planning guidelines, as well as regional and local roadmaps for PT improvement, provide guidance on appropriate access distances depending on the type of transport and spatial structure, e.g., refs. [6–8]. In research, such indicators are commonly used to assess PT quality when studying the relationship between built environment and mobility behavior [9,10]. Several studies have already emphasized the relationship between these indicators and PT use in Germany e.g., refs. [11–13], highlighting their relevance for PT optimization.

When analyzing destination accessibility, however, the methods used in research and practice differ. Depending on the task, researchers use a variety of different metrics to evaluate accessibility [14]. In the context of analyzing the relationship between the built environment and mode choice, they typically account for destination accessibility using location-based methods [9,15], which describe the accessibility of spatially distributed opportunities such as jobs [14]. Commonly, these indicators use the total or weighted number of accessible opportunities [14] for a given time frame [16].

When analyzing other aspects of the relationship between the built environment and mobility behavior, several studies use the distance to the city center or central business district as a proxy to control for location-based accessibility [10,17]. In line with this logic, practitioners, planning guidelines, and local transport or urban development plans propose to focus on the connectivity to the city center when evaluating and improving PT, e.g., refs. [18,19]. Consequently, they set out targets to minimize PT travel time to the city center, e.g., refs. [20,21] or to ensure direct connections to these districts, e.g., ref. [22]. As a result, they neglect other destinations and assume that all relevant destinations are located within the central (business) districts.

This raises the question of whether the simplification of complex accessibility indicators in practical applications still reflects the basic association between accessibility and PT use. Are indicators focusing on the accessibility of central (business) districts effective for assessing and improving PT quality? To put the research question in simple words: Do people use PT more often if they reach the city center faster, or is good accessibility of spatially dispersed opportunities more relevant? To address this issue, we review relevant literature on the relationship between PT use and destination accessibility. We then analyze this association based on the German National Household Survey and nationwide PT timetable data using descriptive and multivariate analyses. Finally, this article provides valuable information for practitioners on which indicators should be used to evaluate PT.

2. Literature Review

Numerous studies have already analyzed the relationship between destination accessibility and PT use as part of assessing the association between the built environment and mobility behavior. While not every study accounts for destination accessibility when describing the built environment, those that include accessibility indicators show a higher

theoretical consistency [23]. The hypothesis is that the higher the share of opportunities accessible by PT, the higher the mode share of PT [17]. While many of these studies focused on North America or China, few focused on Europe [24].

Unfortunately, the results of most of these studies are difficult to transfer to Europe and Germany in particular. Due to major differences in settlement and transport infrastructure, the mobility behavior is not comparable. Thus, associations between the built environment and PT use, especially regarding PT service, may differ [11]. Consequently, we limit the literature review to study areas within similar contexts of mobility behavior as Germany. To identify such regions, we rely on a worldwide modal split analysis conducted by Prieto-Curiel and Ospina [25].

Their comparison of different cities indicates that Western European cities, such as those in Germany, show elevated levels of active mobility (walking and cycling) as well as car travel. The share of PT is at around 25% [25]. The mode shares of Northern and Southern European cities are most similar to Western European ones, while Eastern European and Latin American cities tend to have higher PT and lower car shares [25]. In contrast, Northern American cities tend to have very high levels of car use, with almost no use of other modes [25]. As a result, we focus on studies that address Germany, Northern, Southern, or other Western European regions, since their results seem to be the most transferable.

However, the literature addressing the connection between PT use and the built environment in the previously described regions of Europe is sparse [24]. When studies do address this relationship, they often do not consider destination accessibility. Even when studies do include destination accessibility, their findings can be difficult to generalize. They either focus on single user groups e.g., refs. [26,27], specific development projects e.g., refs. [28,29], or selected trip purposes such as commuting or shopping e.g., refs. [30,31]. Therefore, Table 1 shows the assessed relationship between PT use and PT destination accessibility in relevant European studies as well as the context of their analysis, as suggested by Næss [32].

Most studies focus on selected trips, mainly on commuting to work. This selectivity biases the indicators describing destination accessibility. Knowing the exact location of the start and end of the trip, these studies evaluate only the PT service for this specific relation, ignoring other possible destinations. The results of most studies show that PT use decreases significantly as the PT travel time to work increases [27,31,33]. Only Dashtestaninejad et al. [28] could not prove this relationship when evaluating mode choice for two research campuses in Eindhoven.

While the aforementioned studies only consider the PT travel time to work, Lunke et al. [31] compare it with the car travel time. Thus, they capture the competition between the two modes. Their results show that the longer the PT travel time is compared to the car travel time, the less commuters use PT. German planning guidelines already focus on the relationship between the two modes on individual routes and propose equal travel times as a prerequisite for successful PT [18,34].

Unfortunately, local PT improvement plans in Germany usually do not know the spatial distribution of (commuter) trips due to data protection issues. Therefore, home-work connections and relevant origin–destination pairs are unknown. As a result, planners approximate major destinations and focus on the connectivity between home locations and the central business districts. Asensio [35] found that the PT travel time to the central business district, which contains a variety of employment locations, is related to PT use on trips to work for suburban commuters. Since practitioners generalize these findings from work trips to all trip purposes, the question arises whether this association persists.

To assess trip purposes other than commuting, the literature suggests location-based methods to account for destination accessibility. When analyzing shopping trips, research shows that cumulative opportunity indicators are associated with PT use. First, Ronse et al. [36] represented shopping opportunities by accessible population within a given travel time and showed that the higher the accessibility, the higher the PT share. Second, Susilo et al. [37] found that the more supermarkets accessible by PT within a given travel time, the higher the modal share of PT.

Although both studies change the perspective from work to shopping trips, they still only focus on a single trip purpose. Regarding the use of destination accessibility indicators, Ronse et al. [36] focused on the consumer potential of single shopping locations, while Susilo et al. [37] evaluated the potential mobility of the population. Potential mobility in this context refers to ease of access to potentially relevant trip destinations. Evaluating the potential mobility can provide scope for assessing mode choice regardless of the trip purpose, as shown by Papaioannou and Martinez [38].

Based on a sample of 385 respondents from Lisbon, they examined how the accessibility of jobs and trip connectivity affect the mode choice of car captives and non-captives. They proposed a two-stage mode choice process. First, individuals evaluated the PT system based on their potential mobility, calculated as the travel time-weighted number of accessible jobs ("gravity-based accessibility"). Individuals considered PT as an option in their mode choice when PT accessibility was high. Second, individuals decided to use PT for the trip if the connection between the origin and destination of the trip was favorable. Their analysis showed that the potential mobility indicator has a higher impact on mode choice than only those of single trip purposes. Low overall PT accessibility influences the perception of the system, which good connectivity of individual trip relations cannot compensate [38].

Overall, several European studies observed an association between the PT accessibility of place of work and the use of PT for commuting. Information on the association with other trip purposes, especially non-shopping trips, has been scarce. This is a knowledge gap that we are beginning to fill with this study. Furthermore, in the context of improving PT service without knowing the exact trip distributions, the assessment of the service targets potential mobility indicators. Researchers use location-based methods such as cumulative opportunity or gravity-based accessibility to evaluate potential mobility [14]. In contrast, practitioners rely on evaluating travel time to the central business district as a proxy for relevant destinations. Research revealed that such an approximation is feasible for commuting trips. The remaining question is whether this assertion can be generalized to other trip purposes and thus serve as an easy-to-use evaluation of potential mobility in the context of PT improvements.

Table 1. Overview of selected European studies of mode choice and destination accessibility.

Reference	Study Area	Context of Mode Choice	Methodology	Indicator for Destination Accessibility (D5)	Built Environment Dimensions Controlled						Influence on PT Use When Increasing Value for Destination Accessibility
					D1	D2	D3	D4	D6	D7	
Mode choice of selected trips											
Asensio 2002 [35]	Barcelona, Spain	Suburban commuting trips	Nested MNL	PT travel time to CBD	x			x		x	Significant decrease
Mattisson et al., 2018 [33]	Scania, Sweden	Commuting trips	MNL	PT travel time to work location		x		x		x	Significant decrease
Lunke et al., 2021 [31]	Norway	Commuting trips	Binary Logit	PT travel time/car travel time to work location				x		x	Significant decrease
Dashtestaninejad et al., 2023 [28]	Eindhoven, Netherlands	Commuting trips	Binary Logit	PT travel time to work location	x			x	x	x	Not significant
Schiebel et al., 2015 [27]	Luxembourg	Cross border commuting trips	Binary Logit	*a*. PT travel time to work location	x	x		x	x	x	*a*. Significant decrease
				b. Direct PT connection to work location	x	x		x	x	x	*b*. Partly significant decrease
Ronse et al., 2015 [36]	Belgium	Shopping trips	MNL	Cumulative opportunity PT accessibility to population	x				x		Significant increase
Susilo et al., 2013 [37]	UK	Shopping trips	OLS of modal split	Cumulative opportunity PT accessibility to supermarkets	x					x	Significant increase
Papaioannou and Martinez 2015 [38]	Lisbon, Portugal	inner city trips	SEM	Gravity based PT accessibility to jobs		x		x		x	Significant increase
Mode choice with consideration of special contexts											
Paulssen et al., 2014 [39]	Germany	Combination with preferences	Mixed Logit	PT travel time to work location				x		x	Significant decrease
Bamberg 2006 [26]	Stuttgart, Germany	After residential relocation	SEM	Qualitative assessment of PT accessibility of main station						x	Significant increase
Saxe and Denman 2017 [40]	London, UK	After introduction of new metro line	OLS of no. of PT trips	Area accessible by PT							Significant increase

Remarks: MNL = Multinominal Logit; OLS = Ordinary Least Squares; SEM = Structural Equation Modelling. D1 = Density; D2 = Diversity; D3 = Design; D4 = Distance to transit; D6 = Demand management; D7 = Demographics.

3. Research Approach

To assess the suitability of destination accessibility indicators in describing potential mobility, we use timetable data and the results of a nationwide household travel survey. On this basis, we estimate two indicators: (1) the PT travel time to the nearest central business district, a commonly used indicator in German practice, and (2) the location-based cumulative accessibility by PT, a commonly used indicator in research, for each populated 100 m × 100 m grid cell in Germany. Spatial structure, such as the distance to large settlement areas, strongly influences the value of both indicators. This complicates the interpretation of a nationwide analysis across multiple spatial forms. Therefore, we scale the results by calculating the ratio of PT and car travel for both indicators. We call the PT travel time divided by car travel time the travel time ratio, and the accessible population by PT divided by the accessible population by car accessibility ratio (see Section 3.1). Then, these indicators are added to the household survey based on the respondent's place of residence to analyze PT use (see Section 3.2). Our approach focuses solely on destination accessibility. We ignore other potential influences, such as cost and service reliability, due to a lack of nationwide information.

3.1. PT Service Indicators

Different data sets and calculation methods are required to create the two indicators, travel time ratio and accessibility ratio, in order to be able to calculate the travel times by PT and by car. In addition, the spatial context, e.g., the start and destination locations, and the temporal context, e.g., the start time of the calculation, are important. Both aspects influence the PT service and thus the indicators. Such aspects and calculation methods are therefore described below before the two indicators are described in detail.

We are interested in estimating potential mobility as an indication of "usual" PT service at non-work hours. Thus, we derive the off-peak PT travel time for a regular weekday, not accounting for increased service during peak hours or less frequent service at night, on weekends, and on holidays. Based on the analysis of Lindner et al. [41], the chosen time is between 10 a.m. and 11 a.m. on Thursday, 22 September 2022. The nationwide timetable data comes from DELFI [42], who compiles and publishes all timetable data of German regions. Unfortunately, not every region provides timetable data for the selected date. Hence, we identify regions with missing data by comparing the covered PT stops with a nationwide dataset of PT stops [43] and stops from OSM [44]. Finally, we include 367 out of 400 counties (75.7 out of 80.3 million inhabitants in census data [45]) with sufficient timetable data in the analysis. When comparing the distribution of various variables (e.g., age, gender) of the complete data set with the filtered data, we did not find any relevant differences, so we assume that our analyses are representative. Both indicators are calculated for each of the approximately 3 million inhabited 100 m × 100 m grid cell in Germany. As suggested by Peter [46], we use the 1 km × 1 km grid to calculate car travel times for simplification.

The PT travel time consists of accessing the first station, waiting at the station until the departure, traveling with PT, transferring between services (if necessary), and leaving the last station. We consider walking to the first, from the last, and between stations when transferring at a speed of 70 m/min [47]. Since 99% of PT trips in Germany under 100 km trip length consist of a maximum of 2 transfers [1], we set the allowed number of transfers to 2. Furthermore, we consider a maximum walking time to and from the station of 19 min, a waiting time at the first station of 1 min and a minimum of 3 min for transfers between services. We use the R-package tidytransit version 1.7.0 [48] to compute travel times between stations. Furthermore, we use an instance of openrouteservice from Bundesamt für Kartographie und Geodäsie [49] to compute walking distances and to

estimate car travel times between 10 a.m. and 11 a.m. Thereby, we consider a total of 5 min for car access/egress and parking search time.

The travel time ratio (tt_{ratio}) expresses the quotient between PT (tt_{PT}) and car travel time (tt_{car}) to reach the nearest central business district (CBD):

$$tt_{ratio} = \frac{tt_{PT}}{tt_{car}} \text{where tt is travel time to nearest CBD.} \quad (1)$$

We identify these districts by using cluster analysis based on points of interest from OSM [44] and Bundesamt für Kartographie und Geodäsie [50] for medium- and higher-order central cities obtained from Bundesinstitut für Bau-, Stadt- und Raumforschung [51]. The place of residence can affect the results of the travel time ratio. If the place of residence is within the central business district, the travel time ratio cannot be estimated since origin and destination are the same. Therefore, we exclude residents of these areas from the analysis of this indicator (dark gray areas in Figure 1). In addition, there are areas adjacent to the central districts that have exceptionally short travel times to the city center, and the resulting travel time ratio can reach extraordinary values. Furthermore, our assumptions about waiting and parking search time greatly influence the travel time of these areas. Additionally, these inhabitants are unlikely to use motorized modes on their trip to the center, as they can easily walk or bike to the central districts. Therefore, we also exclude inhabitants with car travel times of less than 10 min (light gray areas in Figure 1). Consequently, the travel time ratio can only evaluate selected parts of the PT service.

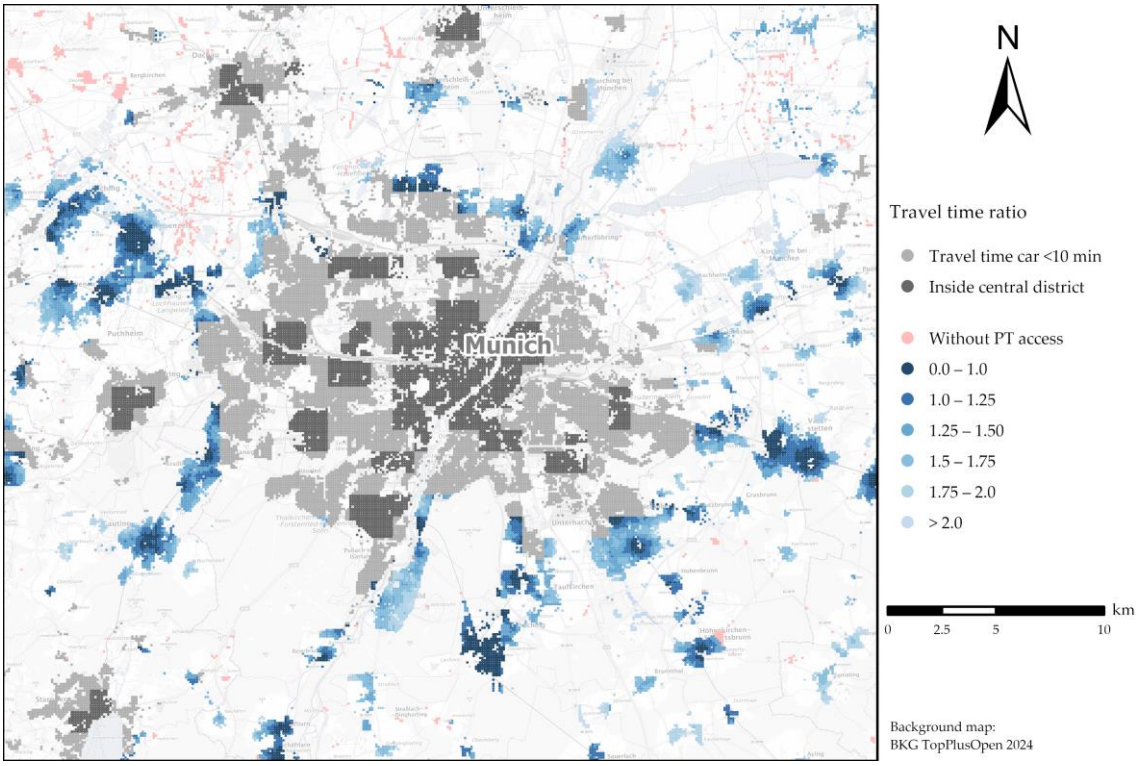


Figure 1. Spatial distribution of the travel time ratio in Munich [42,45,49].

To calculate the location-based accessibility ratio (acc_{ratio}) of each grid cell, we use the cumulative opportunities indicator [14]. Hence, we estimate the population that is accessible within a 30-min travel time by PT (acc_{PT}) and car travel (acc_{car}):

$$acc_{ratio} = \frac{acc_{PT}}{acc_{car}} = \frac{\sum population * resistance_{PT}}{\sum population * resistance_{car}} \text{,where resistance is 1 if tt } \leq \text{ 30 min else 0} \quad (2)$$

We use the population at the 100 m × 100 m level obtained from the census [45] as a proxy for opportunities. Nationwide job locations are not of sufficient quality, as they are either accessible at the municipality level or the POI data lack the desired level of completeness [52,53]. By using population, we overestimate the relevance of high-density residential areas and underestimate commercial districts with low population density. Moreover, unlike the travel time ratio, the accessibility ratio is mathematically and logically capable of analyzing the PT service in the central business districts. Furthermore, the 30-min threshold of travel time resistance excludes long-distance high-speed rail, which is not part of the local and regional PT. In addition, the 30-min threshold isolates the competition between PT and cars, since most of the population will not substitute such long trips with walking or biking. Moreover, about 80% of the motorized trips in Germany (<100 km trip length) have a duration of 30 min or less [1]. Thus, the indicator includes most of the actually selected opportunities.

Figures 1 and 2 show the spatial distribution of the two indicators for Munich. The travel time ratio excludes most parts of Munich, which account for central districts and their surroundings. These excluded areas typically have a higher accessibility ratio. On the outskirts of Munich, there are several settlements with a travel time ratio lower than 1, indicating PT is faster than car. These settlements mostly have close access to rail transit that connects them to the central district. The accessibility ratio of these areas is also higher, but much more limited to the direct vicinity of rail stations. However, even in these areas, PT accessibility cannot reach the level of car accessibility. At most, about half of the opportunities are accessible. Furthermore, there are multiple instances, where there is no PT access at all within the analyzed time interval.

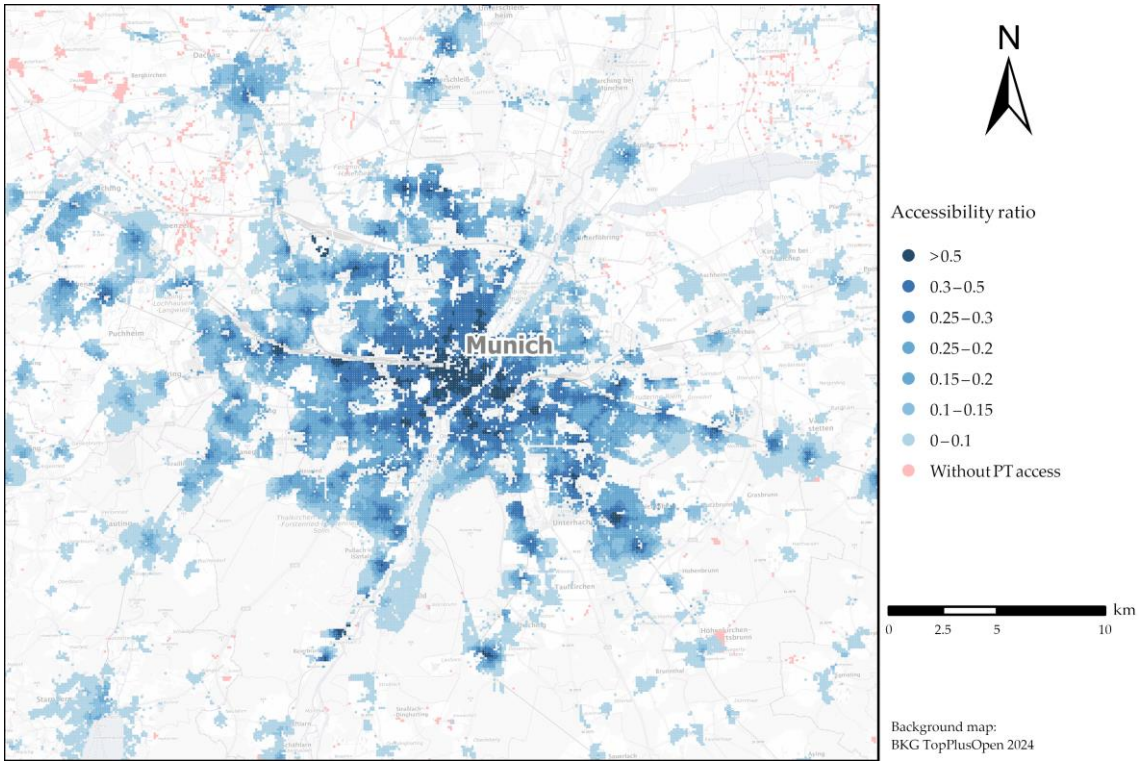


Figure 2. Spatial distribution of the accessibility ratio in Munich [42,45,49].

3.2. PT Use

To link the PT indicators to the PT use, we employ the German national household travel survey "Mobilität in Deutschland 2017" (MID) [1]. We add the PT indicators based on the respondent's place of residence to describe the potential mobility of the respondents.

Thereby, we assume that people with a high PT quality at home use PT more often, even if their trip does not start or end at home. Some respondents did not report their place of residence, and for respondents living in cells with less than 500 inhabitants, the place of residence was withheld for data privacy reasons. In total, residential information is available for 225,000 of the 315,000 respondents at the 1 km × 1 km grid level. The resulting trip dataset consists of 405,000 motorized trips. We assess the PT quality at the 100 m × 100 m grid level, while the residential information is at the 1 km × 1 km level. To add the indicators to the respondent's mobility behavior, we aggregate them by calculating the population-weighted median of each 1 km × 1 km cell.

As a result, we have a dataset that relates both PT indicators and PT use at the place of residence. This dataset is the basis for the following statistical analyses: First, we analyze descriptively the association between each indicator and motorized mode share to determine the relationship between the value of an indicator and PT use. Second, we estimate binary logit models, commonly used in mode choice evaluations (see Table 1), to assess the influence of each indicator on mode choice. Since personal, trip, and built environment attributes also influence mode choice, we control for these variables as suggested in the literature (see Table 1).

4. Results

4.1. Descriptive Analysis of Mode Share

To begin with, we analyze descriptively the relationship between both indicators and the share of PT in motorized trips. Figure 3 shows the relationship for the travel time ratio at the respondent's place of residence, including the areas within or near the central districts. Residents of the central districts use PT for nearly 30% of their motorized trips, which is much higher than people who live outside these areas. Respondents who can reach the central districts within a 10 min drive use PT more often than those who live in the outer parts.

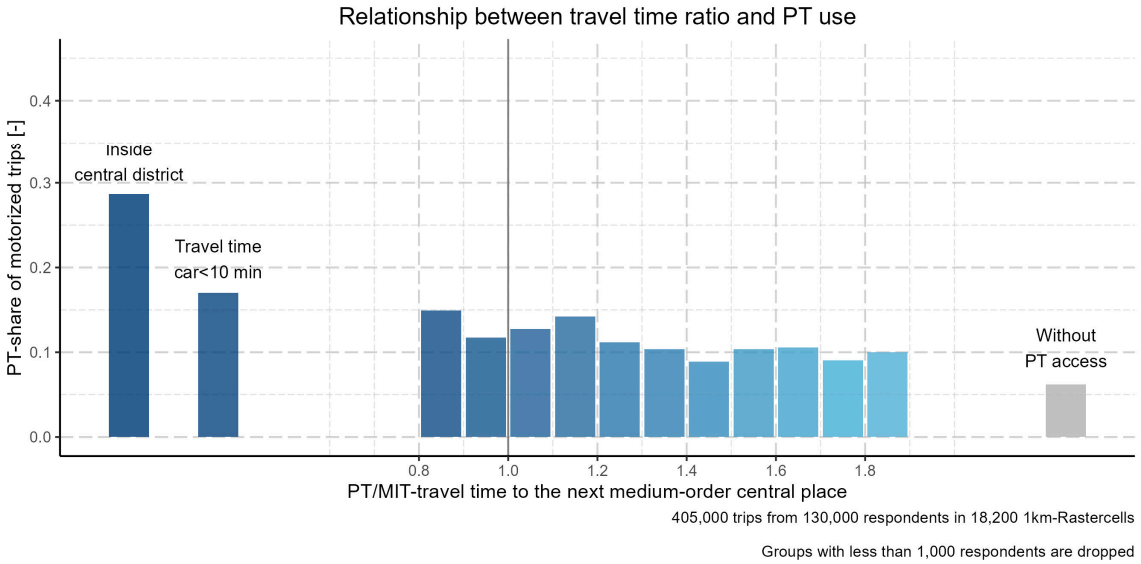


Figure 3. Relationship between travel time ratio and PT use [1,42,49].

Looking at respondents who live further away than a 10 min drive, we see that the share of PT is low. At most, respondents use PT for 15% of all motorized trips, even when PT is faster than driving. As the travel time ratio increases, PT use decreases slightly to a minimum mode share of 9%. Respondents we identify as those without access to PT also use PT, but less than those with access. In areas without access, residents use PT at different

times than the analysis time or travel longer distances to access stops. Overall, respondents who reside in central districts and nearby neighborhoods use PT more often than those from outer parts. Moreover, respondents are slightly more likely to use PT when the travel time ratio favors PT than when the ratio favors driving.

While the travel time ratio cannot assess the PT service inside central districts, and at best can vaguely describe it in nearby areas (see Section 3.1), the accessibility ratio can evaluate all areas. Figure 4 shows the relationship between the accessibility ratio and PT use. When the accessibility ratio is low, people tend to use less PT. As the accessibility ratio increases, so does the use of PT. Between low ratios (0.05) and intermediate ratios (0.35), the increase in PT use appears to be fairly linear. After that, PT use seems to stabilize or increase only slightly. Further analysis shows that 75% of the respondents reside in cells with an accessibility ratio of less than 0.26. Only 10% of the respondents have an accessibility ratio higher than 0.38. This means that the sample size decreases at high accessibility ratios, increasing the statistical noise caused by outliers.

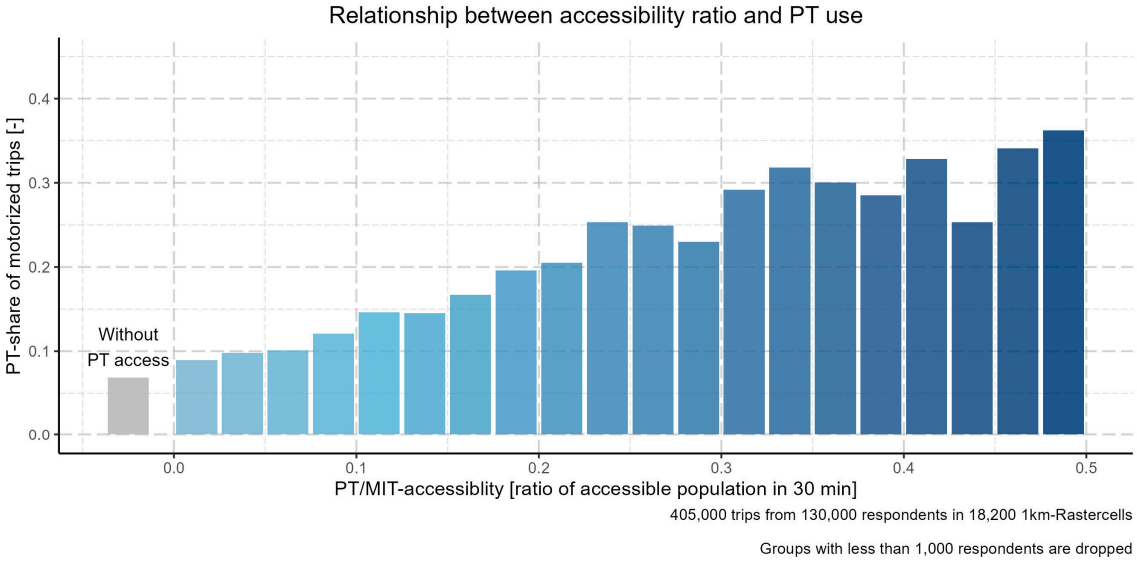


Figure 4. Relationship between accessibility ratio and PT use [1,42,45,49].

Compared to the travel time ratio, the amplitude of the differences in the PT share between classes is greater for the accessibility ratio. The lowest PT share is 8%, when the accessibility ratio is lowest, and around 35%, when the accessibility ratio is highest. Respondents who do not have access to PT correspond to those indicated in the travel time ratio.

In fact, both indicators seem to be related to the PT share on motorized trips and thus to the use of PT. Both show that a better PT service corresponds to a higher PT use. While the travel time ratio can only assess the quality of PT service for outer parts, the accessibility ratio can evaluate the PT service for all areas. Nevertheless, several questions remain regarding the suitability of these indicators. Does the PT service described by these indicators significantly influence PT use, even after controlling for socio-demographic, trip, and built environment characteristics? Can a combination of indicators be useful? Do different user groups react differently? To answer these questions, we describe the results of a multivariate analysis in the following section.

4.2. Multivariate Analysis of Mode Share

Multivariate analysis allows us to assess the impact of the two PT indicators on PT use by controlling for other attributes that influence mode choice. Therefore, we estimate

four binary logit models. These models use the choice of PT or not as a binary dependent variable. Since we only consider motorized trips, the opposite of PT choice is car use. Thus, the models treat car use as the reference. Therefore, an odds ratio of a predictor higher than 1 corresponds to a higher likelihood of PT use as the predictor increases. As mode choice is highly dependent on the modes available, we exclude PT captives from our analysis and assess mode choice for over 18 year olds who possess a driver's license and live in a household with a car. The resulting data set for our multivariate analysis contains 281,000 trips.

To account for factors influencing mode choice besides PT supply, we add respondent, trip, and built environment variables to the dataset. For respondent and trip characteristics, we control for age, gender, money, as well as the trip duration and purpose [1,54]. For the built environment, we add the population density [45] and the intersection density [44] as a microscopic distinction within the city as well as a regional classification (RegioStaR7 [55]) as a macroscopic distinction of the city to account for possible spatial autocorrelation. In addition, we checked all predictors for correlation and multicollinearity. To rule out the interaction of the independent variables, we tested for multicollinearity using the generalized variance inflation factor [56]. All values were less than two, which is below the recommended limit of five [57], allowing the data set to be validly interpreted.

Before analyzing the influence of PT on mode choice, we estimate a reference model (0) using only the respondent, trip, and built environment predictors to evaluate the dataset. Table 2 shows the odds ratios, significance levels, and accuracy for model (0). All predictors have statistically highly significant odds ratios. The in-/decrease in PT usage and magnitudes of the odds ratios are as expected. The odds of using PT are lower when the person is over 30 years old and decrease even more with increasing age. Moreover, respondents with a very low economic status are more likely to use PT. Trip characteristics are also consistent with expectations: Performing a trip with the purpose of education increases the odds of using PT in reference to work trips. On the other hand, the likelihood of PT use declines when the trip purpose is leisure, private business, or shopping. Finally, built environment predictors also match expectations, as PT use decreases in less urban areas and rises with increasing population and intersection density [11,58]. The accuracy of the model is adequate even without any PT indicators. In conclusion, the dataset allows for the evaluation of the influence of PT quality indicators.

For the first evaluation in the model (1*a*), we add the travel time ratio and the corresponding spatial location variables to the base model. Table 2 shows that the model accuracy practically does not change. Of the three added variables, only the travel time ratio has a statistically significant influence on the motorized mode choice but not the spatial location variables. However, the odds of using PT decrease slightly when the travel time ratio increases (e.g., PT performing better in reference to the car), which is not what to expect. Conclusively, the travel time ratio to the nearest central business district does not seem to predict motorized mode choice well. Thus, slight variations in the descriptive analysis (see Figure 3) occur because the travel time ratio is correlated with other spatial attributes of the built environment. In conclusion, the travel time ratio is not suitable for describing the potential mobility when assessing and improving PT service.

Next, we assess the influence of the accessibility ratio on mode choice (see model (1*b*) in Table 2). The results show a slight increase in model accuracy and a highly statistically significant positive influence of the accessibility ratio on PT mode choice, while the magnitudes and significance levels of the other predictors are preserved. Therefore, at best, an increase in the accessibility ratio also increases PT use. This relationship is also visible in the descriptive analysis (see Figure 4).

The results of the two previous models allow us to answer the first question: PT service described by the travel time ratio shows a small and unexpected association with PT use after controlling for other factors. In contrast, PT service, represented by the accessibility ratio, is significantly associated with PT use.

Table 2. Odds ratios and significance levels of the binary logit models.

	Predictors		Dependent Variable: PT Use "Yes"			
			(0)	**(1*a*)**	**(1*b*)**	**(2)**
		Intercept	0.193 ***	0.194 ***	0.152 ***	0.173 ***
Respondent attributes	Age group	18 to 29	--Reference--			
		30 to 49	0.571 ***	0.571 ***	0.572 ***	0.572 ***
		50 to 69	0.574 ***	0.577 ***	0.579 ***	0.579 ***
		≥70	0.611 ***	0.612 ***	0.617 ***	0.617 ***
	Gender	Male	--Reference--			
		Female	1.177 ***	1.179 ***	1.182 ***	1.183 ***
	Economic status	Very low	1.166 ***	1.165 ***	1.169 ***	1.166 ***
		>very low	--Reference--			
	Trip duration	Time in min	1.020 ***	1.020 ***	1.020 ***	1.020 ***
Trip attributes	Trip purpose	Work	--Reference--			
		Education	3.269 ***	3.263 ***	3.318 ***	3.315 ***
		Shopping	0.268 ***	0.268 ***	0.268 ***	0.268 ***
		Private business	0.469 ***	0.467 ***	0.464 ***	0.464 ***
		Leisure	0.620 ***	0.620 ***	0.617 ***	0.616 ***
		Other	0.559 ***	0.560 ***	0.555 ***	0.555 ***
Built environment attributes	RegioStaR7 (macroscopic)	71	--Reference--			
		72	0.582 ***	0.587 ***	0.555 ***	0.555 ***
		73	0.408 ***	0.423 ***	0.441 ***	0.441 ***
		74	0.329 ***	0.366 ***	0.382 ***	0.381 ***
		75	0.287 ***	0.292 ***	0.242 ***	0.242 ***
		76	0.233 ***	0.241 ***	0.229 ***	0.230 ***
		77	0.225 ***	0.249 ***	0.252 ***	0.253 ***
	Density (microscopic)	Population density	1.005 ***	1.005 ***	1.004 ***	1.004 ***
		Intersection density	1.003 ***	1.002 ***	1.002 ***	1.002 ***
	Public transport indicators	Within center		1.005	1.041	0.910 *
		Close to center		1.026	1.141 ***	0.997
		Travel time ratio [1]		0.999 ***		0.999 ***
		Accessibility ratio [1]			1.012 ***	1.012 ***
Quality measures		AIC	114,593	114,046	113,837	113,829
		McFadden Pseudo R^2	0.156	0.156	0.158	0.158

n = 218,000 trips. Note: Statistical significance at *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$, $^{+}$ $p < 0.1$. [1] Predictors scaled: If PT = car, then value of predictor equals 100.

In the next step, we add both PT indicators to the base model and evaluate whether the accessibility ratio should be added to the travel time ratio. Table 2 shows the results of the model (2). The accuracy of the model (2) is comparable to the accuracy of the model (1*b*). In addition, the odds ratios of the two PT indicators do not change between models (1*a*) and (1*b*) to model (2). While the odds ratios and significance levels of the predictors included in the model (0) do not change when both PT indicators are added, the magnitude and significance levels of the location indicators change. The decrease in odds of using PT when residing in the city center is not consistent with the literature, e.g., ref. [59]. In addition to this, the changes in magnitude and significance level of the location near the city center point to a potential interaction between the location variables and the PT indicators. Nevertheless, to answer the question about the combination of PT indicators, Since the effect of the travel time ratio is still small and not plausible, the accessibility ratio should replace the travel time ratio and not be added to it.

Finally, by comparing the influence of the PT indicators and the other indicators, we identify a major influence on mode choice by demographic, trip, and built environment indicators. However, these attributes are not manageable by PT planners.

5. Conclusions

This paper answers the question of which accessibility indicators should be used to analyze and improve the quality of PT. Access indicators to PT stops are used in both practice and research. According to the literature, they are related to the use of PT and are therefore suitable for evaluating its quality. However, when using accessibility indicators, the methods used in research and practice differ, while practitioners only consider central business districts as relevant destinations, researchers use location-based methods to describe the accessibility of spatially distributed opportunities.

Asensio [35] found for Barcelona that the accessibility of central business districts explains the choice of PT for commuter trips. As a generalization for all trip purposes, we could not find this relationship between PT services and PT use in Germany. In contrast, the location-based accessibility relationship used in our study shows a strong, significant correlation with PT use. Hence, the environmental impact of transport can be reduced by a good PT service. For an effective and efficient description and planning of PT services, location-based accessibility indicators should therefore be used in practice.

Because our national analysis includes few respondents from remote areas and sparsely populated cells, the applicability of the results to these specific low-density areas is questionable. In addition, the literature suggests numerous variations for calculating destination accessibility. We assess accessibility by cumulating the accessible opportunities represented by the population. However, more sophisticated methods may better represent the relationship between PT accessibility and use. Further research might address these methods.

In conclusion, our paper shows that location-based accessibility is associated with PT use. While further analysis is needed to define the best indicator of location-based accessibility, basic cumulative opportunity indicators can already represent PT use. However, this does not mean that distance to transit indicators should be removed. Access to transit and accessibility to destinations are both relevant parts of PT service, but improving them simultaneously may be difficult. Therefore, further research is needed to guide practitioners on what to improve first with respect to equity as well as environmental and economic perspectives.

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