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Social disadvantage and the public mobility provision: A socio-spatial GIS analysis of mobility-related exclusion risks in Cologne, Germany

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Abstract

For socially disadvantaged people, public mobility services are a basic prerequisite for social participation. In local politics and public transport planning, issues of mobility-related social disadvantage and the socio-spatial differentiation of participation opportunities have to date received little attention as an approach to reduce social inequalities in cities. This study aims to provide a suitable basis for such an approach. By undertaking a spatial GIS analysis, GTFS timetable data was intersected with socio-spatial data on 100x100-metre grid cells to obtain a high-resolution picture of mobility-related inequalities in Cologne, Germany. Although no evidence of a structural mobility-related under- or overprovision of individual population groups was found, the results show that 31 % of Cologne's population live in urban areas that have an increased potential risk of mobility-related exclusion due to a critical combination of characteristics, including below-average public transport provision and an above-average proportion of the population receiving social benefits. Finally, a total of 49 spatial risk clusters were identified and described in the study area, enabling an individual characterisation of the affected areas and hence providing a possible basis for the development of specific solution strategies as part of further research.

Keywords: Public mobility provision ▪ public transport accessibility ▪ social exclusion ▪ GIS analysis ▪ Cologne

Soziale Ungleichheit und öffentliches Mobilitätsangebot: Eine sozialräumliche Analyse der Risiken mobilitätsbezogener Ungleichheit in Köln

Zusammenfassung

Für sozial benachteiligte Menschen sind die öffentlichen Mobilitätsangebote eine Grundvoraussetzung für gesellschaftliche Teilhabe. Fragen mobilitätsbezogener sozialer Benachteiligung und sozialräumlicher Differenzierung von Teilhabechancen finden im Rahmen kommunalpolitischer Abwägungen und der Verkehrsplanung als Ansatz zum Abbau sozialer Ungleichheiten in Städten bisher nur wenig Beachtung, wofür diese Studie eine geeignete Grundlage bieten soll. Mithilfe einer räumlichen GIS-Analyse wurden GTFS-Fahrplandaten mit sozialräumlichen Daten auf der räumlichen Ebene von 100x100 Meter großen Rasterzellen verschnitten, um ein hochauflösendes Bild der mobilitätsbezogenen Ungleichheiten in Köln zu erhalten. Obwohl keine strukturelle mobilitätsbedingte Unter- oder Überversorgung einzelner Bevölkerungsgruppen festgestellt wurde, zeigen die Ergebnisse, dass 31 % der Kölner Bevölkerung in städtischen Gebieten leben, die aufgrund einer kritischen Kombination von Merkmalen – darunter ein unterdurchschnittliches Angebot an öffentlichen Verkehrsmitteln und ein überdurchschnittlicher Anteil der Bevölkerung, der Sozialleistungen bezieht – ein erhöhtes potenzielles Risiko für mobilitätsbedingte Ausgrenzung aufweisen. Schließlich wurden im Untersuchungsgebiet insgesamt 49 räumliche Risi-

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kocluster identifiziert und beschrieben, die eine individuelle Charakterisierung der betroffenen Gebiete ermöglichen und im Rahmen weiterer Forschung die Grundlage für die Entwicklung spezifischer Lösungsstrategien bilden können.

Schlüsselwörter: Öffentliche Mobilitätsangebote ▪ ÖPNV-Erreichbarkeit ▪ soziale Exklusion ▪ GIS-Analyse ▪ Köln

1 Introduction

Mobility is an important part of social participation and enables social interaction and participation in different spaces such as employment, health services, and educational and cultural facilities (Runge 2005: 5; Daubitz 2011: 183; Ward/Walsh 2023: 1). Various disadvantaged population groups who are restricted in their access to public or private mobility services for different reasons suffer the consequences of this exclusion (Runge 2005: 5; Lucas/Mattioli/Verlinghieri et al. 2016: 355; Collins/Der Wartanian/Reed et al. 2023: 2). Indeed, such a lack of access may not only cause social exclusion, it can also result from it (Daubitz 2011: 183). Lower economic status is associated with a reduced number of journeys, shorter journey times and a lower proportion of car ownership (Lucas/Mattioli/Verlinghieri et al. 2016: 354; Nobis/Kuhnimhof 2019: 27–29, 33; Ward/Walsh 2023: 2, 4), as well as limited participation in social activities and employment options (Ward/Walsh 2023: 4–5). People with limited or no access to a private car or who deliberately refrain from using private cars are often dependent on public transport. However, the mere absence of a private car does not necessarily indicate a general disadvantage. Especially in central and dense urban locations, not owning a car can also be a conscious decision justified by a shortage of parking spaces, attractive public transport connections, cost advantages or other benefits (Church/Frost/Sullivan 2000: 197; Stadt Köln 2017: 175).

Economic aspects play a key role in this context, as they not only determine direct access to mobility options in the form of ticket acquisition (Daubitz/Aberle/Schwedes et al. 2023: 12–13), but also indirectly influence mobility options in form of socio-spatial distribution patterns such as segregation (Beckmann/Bracher/Hesse 2007: 14). In addition to financial barriers to access, the transportation system itself can have other access-restricting effects, such as poor accessibility, service quality or connection quality (Runge 2005: 10). Population groups with specific socio-spatial affiliations thus have different options influencing their choice of transport and exhibit different mobility behaviour (Daubitz 2021: 79–80; Ward/Walsh 2023: 2).

Even though questions of mobility-related social disadvantage and the socio-spatial differentiation of participation opportunities have become an increasing focus in the scientific literature, they have so far received little attention in local political consideration and transport planning (Daubitz 2011: 181) or in publications on mobility-related social reporting (Hausigke/Kruse 2021: 270). For the city of Cologne, serving as the research area of this study, it should be noted that mobility-related and, in particular, public-transport-related aspects of social disadvantage are only briefly mentioned and addressed in Cologne's current local transport plan, in the current guidelines for the creation of the mobility concept "mobil 2025" and in the current city strategy paper "Cologne Perspectives 2030+" (Stadt Köln 2014; Stadt Köln 2017; Stadt Köln 2023).

The objective of this investigation is to utilise the city of Cologne as a case study to determine public mobility provision at a high spatial resolution and to overlay it with the economic status of inhabitants to identify and spatially characterise mobility-related inequalities. A theoretical review of current concepts of transport poverty and social exclusion highlights the importance of mobility for social participation and discusses the connection to mobility-related social exclusion. This theoretical framework constitutes the basis of the socio-spatial analysis. In order to approximate economic status, socio-spatial criteria are spatially located and related to public transport provision. This methodology allows inequalities to be precisely spatially located, and areas for which there is an increased potential risk of mobility-related social exclusion (PRME) are thus identified, suggesting specific needs for action and solution strategies. Consequently, the following research questions emerge:

– How is the proportion of Cologne's population receiving social benefits distributed across the city and how does public transport provision relate to these sub-areas?
– In which sub-areas do low economic status and below-average public transport provision, in combination with additional indicators, suggest a potential risk of mobility-related social exclusion for the resident population?

In the following sections, we discuss the literature on transport disadvantage and mobility-related social exclusion (Section 2). We then present the case study (Section 3) and methods used (Section 4). Finally, we present (Section 5) and discuss the findings (Section 6) and limitations (Section 7) and conclude with implications for subsequent research (Section 8).

2 Theoretical foundations and state of research

2.1 Transport poverty and mobility options

Since the early 2000s, the research field of mobility[1] and social exclusion has become increasingly relevant in the Anglo-American region (Lucas 2012: 105). According to the widely used approach by Lucas, Mattioli, Verlinghieri et al. (2016: 355), four sub-concepts are subsumed under the overarching concept of transport poverty: mobility poverty, accessibility difficulties, lack of transport funding and exposure to external transport impacts.

The term “mobility poverty” refers to a systematic lack of mobility options due to insufficient transport services and infrastructure (Lucas/Mattioli/Verlinghieri et al. 2016: 356; Schwerdtfeger 2019: 45), such as inadequate service coverage, low frequency and poor accessibility of public transport stops (Schwedes/Daubitz/Rammert et al. 2018: 76). The second sub-concept, accessibility poverty, addresses whether people can reach everyday destinations with a reasonable time expenditure, cost and physical or psychological effort (Lucas/Mattioli/Verlinghieri et al. 2016: 356; Schwerdtfeger 2019: 45). The third, transport affordability, concerns the availability of financial resources for mobility, such as the use of private vehicles or public transport (Lucas/Mattioli/Verlinghieri et al. 2016: 355). The fourth, exposure to transport externalities, refers to burdens caused by negative transport impacts. Here, the concept of environmental justice becomes relevant, addressing the social distribution of environmental burdens (e.g. pollution, noise, road severance, accidents) and resources (e.g. green and recreational spaces), and associated health outcomes (Böhme/Franke/Preuß 2019: 28).

To better integrate individual and subjective characteristics, Henkel and Sommer (2024: 152) expand the concept by combining objective indicators (e.g. transport supply) with subjective “mobility options”. These include not only material and monetary resources but also individual abilities and social roles and attitudes. Similarly, Daubitz and Aberle (2020: 7) emphasise the relevance of subjective variables, such as cycling skills or the use of digital mobility platforms, for potential and realised mobility.

The three sub-concepts mobility poverty, accessibility poverty and transport affordability can both result from and cause a lack of mobility options. This connection highlights how a systematic shortage of options can limit individuals’ ability to realise geographical mobility, potentially reducing social participation and leading to social exclusion (Schwedes/Daubitz/Rammert et al. 2018: 79).

[1] The definition of mobility used in the context of this paper only includes short-term and spatial mobility (everyday spatial mobility) according to Hammer and Scheiner (2006: 19). Extended definitions, such as long-term spatial mobility or social mobility, are explicitly not part of the definition used here.

2.2 Mobility-related social exclusion

“The term social exclusion refers to the lower levels in the evolving hierarchies of access to, participation in, and autonomy with regard to, economic life […], political life […], social life […], cultural life […] and health […]” (Schwanen/Lucas/Akyelken et al. 2015: 125). Social exclusion does not describe a state that excludes or includes individuals or groups, but is rather a fluid, dynamic and relative concept (Schwanen/Lucas/Akyelken et al. 2015: 125; Fischer/Rozynek/Henkel et al. 2024: 26). The economic, political and social/cultural dimensions, which are used to define social exclusion in many definitions, are often expanded in the context of mobility research to include other dimensions, such as spatial, temporal, organisational, health and fear-based dimensions (Church/Frost/Sullivan 2000; Cass/Shove/Urry 2005: 550-551; Rozynek/Schwerdtfeger/Lanzendorf 2020: 3). Mobility-related exclusion describes “the process by which people are prevented from participating in the economic, political and social life of the community because of reduced accessibility to opportunities, services and social networks, due to in whole or in part insufficient mobility in a society and environment built around the assumption of high mobility” (Kenyon/Lyons/Rafferty 2002: 210).

However, it is important to note that transport poverty, or the absence of adequate mobility options, does not necessarily lead to social exclusion, as social exclusion can also increase the risk of transport poverty and a lack of mobility options (Runge 2005: 21–22; Lucas 2012: 107). Daubitz (2011: 183) posits that “the absence of physical access to employment, health services, educational and cultural facilities is both a consequence of and a cause for social exclusion” (authors’ translation). This ambivalent process has the capacity to reinforce and reproduce itself (Kronauer 2009: 376), yet it is also capable of being overcome (Church/Frost/Sullivan 2000: 197; FGSV 2015: 9). The explanations show that it is impossible to determine the direction of impact between mobility-related social exclusion and access restrictions. Consequently, this study assumes an undirected relationship.

2.3 Public transport and economic status

While there is therefore broad agreement on the connection between mobility and social exclusion, there is as yet no

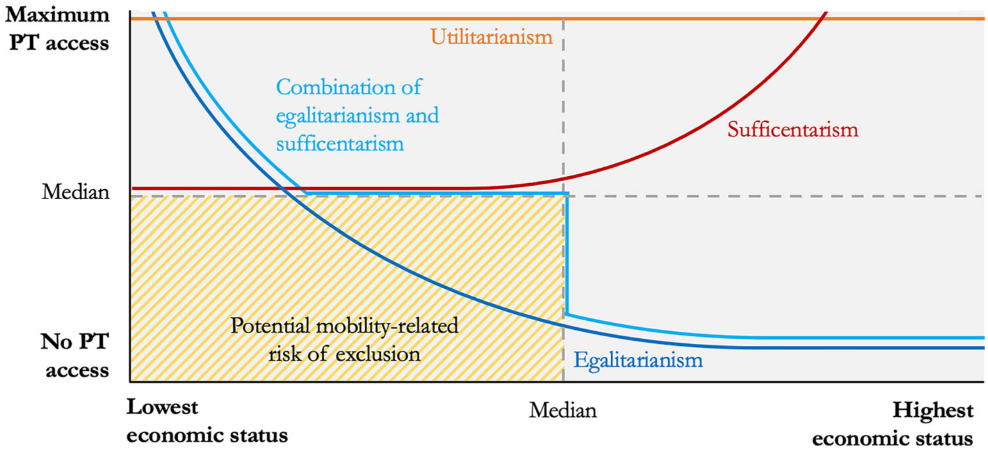

Figure 1 Comparison of the relationship between public transport accessibility and income in different theoretical frameworks. Source: Adli/Chowdhury/Shiftan (2019: 90), modified; PT = public transport

standard for the ideal design of equitable public transport accessibility in terms of economic status. This is due to the complexity of equity considerations in this context and the difficulty of meeting the expectations of all individuals (Collins/Der Wartanian/Reed et al. 2023: 2). However, theoretical approaches can be projected onto the object under consideration (Adli/Chowdhury/Shiftan 2019: 90) (see Figure 1). While some case studies find something approximating an egalitarian distribution curve with a preference towards public transport provision for disadvantaged groups in the study areas (Delbosc/Currie 2011: 1258; El-Geneidy/Levinson/Diab et al. 2016: 302), other research observes the opposite (Aberle/Daubitz/Schwedes 2025: 5; Collins/Der Wartanian/Reed et al. 2023: 6).

A utilitarian understanding of justly distributed public transport accessibility is characterised by maximum accessibility independent of income, thus providing the greatest possible benefit to all income classes. The sufficientarist concept focuses on the provision of a defined minimum level of public transport accessibility. In contrast, the egalitarian approach assumes greater accessibility for low-income groups in order to ensure equal opportunities for disadvantaged groups. Adli, Chowdhury and Shiftan (2019: 90) note that despite good coverage of groups with very low incomes, there may be an undersupply of groups with incomes just below the defined threshold. This is where another theory comes in, which can be understood as an extension of the egalitarian approach and which counteracts the above-mentioned criticism of the possible undersupply of some income groups with an essential element of the sufficientarist approach. The authors view this hybrid approach as extremely useful for local transport planning because it does not fall short of a minimum level of accessibility according to the sufficientarist approach and at the same time makes justifiable a certain inequality in favour of the low-income population groups, those with the most need. While theoretical considerations about the equitable distribution of mobility provision in relation to economic status provide no information on the ideal line along which an optimal distribution should be measured, an area can be identified that is characterised by a potential risk of mobility-related social exclusion (yellow shaded area, Figure 1).

2.4 Disadvantaged urban districts

In urban research, socio-spatial inequalities are often explained as an interplay between complex economic, social, spatial or socio-technical causes (van Ham/Tammaru/Ubarevičienė et al. 2021), resulting from the unequal distribution of resources and opportunities, varying influences of historical and political factors, socio-economic structural change and globalisation, or from segregation and gentrification (van Gent/Hochstenbach 2020: 307–309). Affected urban districts are often characterised by a concentration of population groups with low incomes, high unemployment and below-average education levels as a result of segregation processes (Beckmann/Bracher/Hesse 2007: 12; FGSV 2015: 18; Le Goix 2022). Structural, functional and socio-technical aspects also play an important role (Nelson/Warnier/Verma 2024). The connection between socially disadvantaged neighbourhoods and the potential risk of social exclusion (Stanley/Hensher/Stanley 2022) is based, to some extent, on the structural condition of urban neighbourhoods (Liao/Gil/Yeh et al. 2025). Additional functional quality deficits are caused by high traffic loads, deficits in educational facilities and jobs, or the lack of green and recreational areas. This often leads to multiple burdens on the residential areas, followed by an exodus of wealthier households due to social, structural and functional deficiencies, which can lead to stigmatisation of the urban quarter and its residents and a thinning out of private and public services (Beckmann/Bracher/Hesse 2007: 14; see also Nicoletti/Sirenko/Verma 2023).

2.5 Participation of affected people

In socially disadvantaged groups, participation in addressing mobility-related issues is often low (Daubitz 2021: 91). Even for rail-based public transport projects, where standardised evaluation plays a central political role, cost-benefit comparisons often neglect non-monetizable factors. Thus, many "soft" socio-spatial aspects are insufficiently considered (BMVI 2016). This supports the notion that public transport distribution follows functional and economic rather than social criteria.

In terms of sustainable mobility, Hausigke and Kruse (2021: 271–272) argue that "equal access opportunities to places of general interest and participation in public life for all […] should be given a legal entitlement through legal provisions", while defining mobility "as a merit good in planning" (authors' translation) allows state intervention in market-based mobility systems to better address diverse needs (Hille/Gather 2022: 43).

3 Study area

With around 1,096,000 inhabitants in 2023, Cologne is the largest city in North Rhine-Westphalia and within the regional transport association *Verkehrsverbund Rhein-Sieg* (VRS) (Stadt Köln 2024: 9). The urban area spans 40,500 hectares, stretching 27.6 km east-west and 28.1 km north-south, and comprises 86 districts grouped into nine larger administrative units (Stadt Köln 2024: 9).

18 *S-Bahn*, regional rail and express lines connected Cologne with regional and national destinations (Stadt Köln

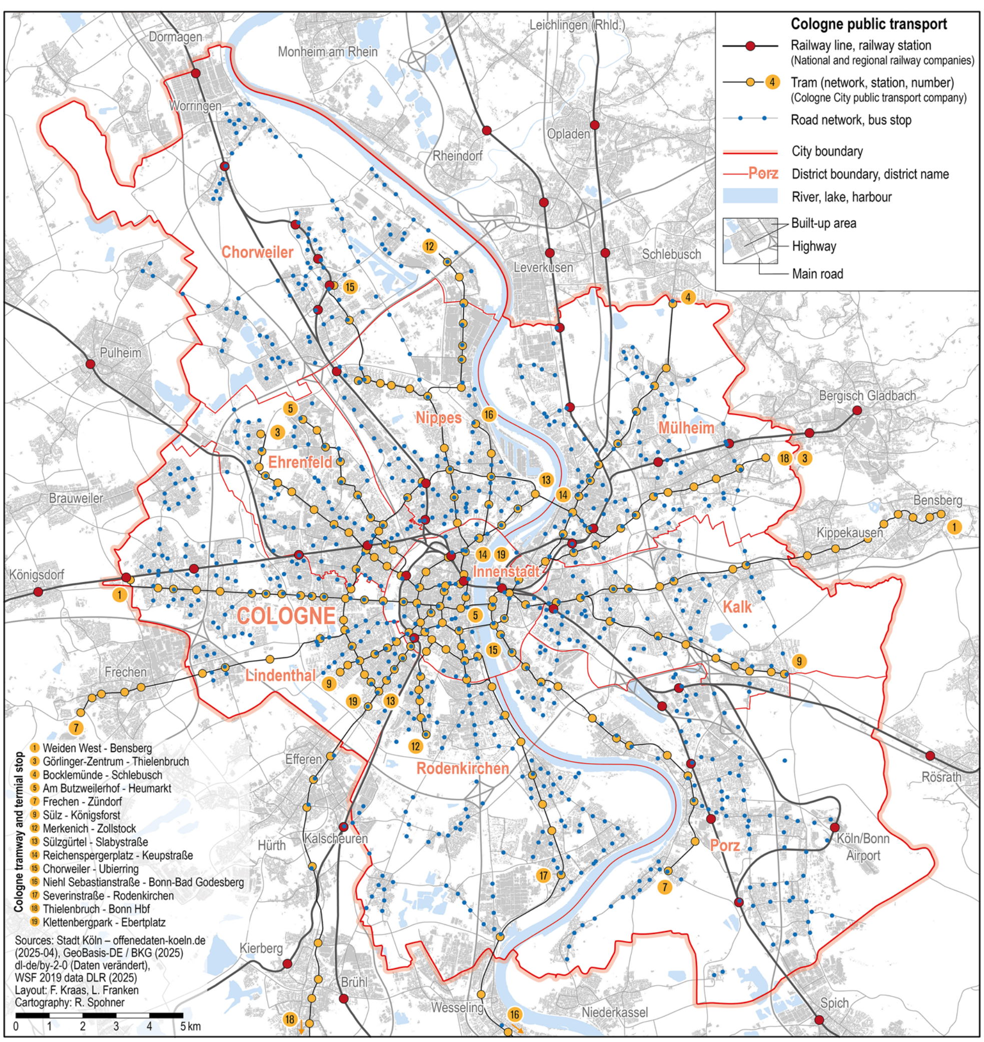

Figure 2 Cologne public transport network

2017: 67–69). These were supplemented by 14 light rail lines and 69 bus routes, 11 of which operated on demand (see Figure 2). In 2019, approximately 286 million passengers were transported (KVB 2021).[2] The light rail mainly serves radial and inner-city ring routes, while buses connect outer districts and serve feeder functions (Stadt Köln 2017: 22). The River Rhine divides the city, with only five of seven bridges carrying public transport routes.

A comparison of 21 German cities showed that public transport ticket prices in Cologne in 2020 were 15 % above the national average, with some categories up to 31 % higher and social tickets slightly below the €40.01 monthly *Hartz IV*[3] standard for transport, but still close to the average of other cities (Bukow/Meinefeld/Schmidt 2020: 20).

Cologne was chosen as an example for four reasons, which are anchored in the “Cologne Mobility Strategy 2025” (Stadt Köln 2014) and, above all, in the principles of the “Cologne Perspectives 2030+” (Stadt Köln 2021). Firstly, the city’s integrated approach demonstrates a strong commitment to improving local public transport (Stadt Köln 2021: 65–67). Secondly, larger urban areas are not yet covered by rail-based local transport. These gaps and disparities in the network are to be closed through targeted intensification of inner-city connections (Stadt Köln 2021: 156–157, 168–169). Thirdly, there are widely varying inequalities across Cologne’s urban districts, including those with particular social challenges (large housing estates, *Großwohnsiedlungen*) (Stadt Köln 2021: 67, 170). In transport-related urban development, a special focus is placed on disadvantaged neighbourhoods (social spaces, *Sozialraumgebiete*), which are disproportionately affected by social disadvantage and poverty compared to the city as a whole (Stadt Köln 2021: 67). Potential is seen in the linking of public transport with eco-friendly transport options (e.g. shuttle services, car sharing, bike stations) (Stadt Köln 2021: 224). Fourthly, Cologne’s transport structure, which is still predominantly focused on the city centre with a significant decline in the mix of uses and density of neighbourhoods towards the outskirts, should be improved to provide better transport links to areas of the outer city with potential for housing development (Stadt Köln 2021: 165–167). Cologne’s geographic, social and infrastructural features clearly make it a suitable study area. Its mix of urban and rural spaces, high diversity and historically shaped transport infrastructure support the research focus. However, mobility-related social disadvantage is barely addressed in key planning documents like the local transport plan, the “Cologne Mobility Strategy 2025” or the “Cologne Perspectives 2030+” strategy (Stadt Köln 2014; Stadt Köln 2017; Stadt Köln 2023). In contrast, public transport provisions for people with physical mobility limitations are more clearly considered in current local transport planning (Stadt Köln 2017: 146–151).

4 Methods and data

The following research design was chosen to investigate the relationship between economic status, public transport provision and their possible impact on a potential risk of mobility-related social exclusion (PRME). First, the spatial distribution patterns of economic status and public mobility provision in the study area were localised in order to demonstrate the socio-spatial prerequisites for a potential risk of mobility-related social exclusion. The degree of potential risk was then identified at a small-scale level using further indicators.

4.1 Bivariate correlation analysis (research question 1)

In order to answer the first research question, which aims to localise spatial distribution patterns of economic status and public transport provision, two methodological steps were taken. First, a descriptive analysis of the spatial distribution of public transport provision and an analysis of data on the receipt of social benefits were carried out to visualise their spatial distribution and correlation. Particularly, the focus was on areas in which below-average public transport provision corresponds to areas with a high proportion of social benefit recipients. In a second step, Spearman correlation analyses were used to identify potential statistical correlations and significances and to assess whether there is a structural undersupply of public transport to financially disadvantaged people in the study area.

4.2 Index formation (research question 2)

The potential risk of mobility-related social exclusion was determined and assessed using an additive and weighted index specifically designed for this analysis, considering additional indicators that can be derived from the theoretical principles in Section 2. An additive index model was chosen over a multiplicative model in order to allow for compensation, “i.e. poor public transport provision can be compensated by high availability of private cars or high economic status” (Bortz/Döring 2006: 145, authors’ translation). In each grid cell, points were awarded for each indicator included. The resulting index value thus reflects the

[2] https://www.kvb.koeln/unternehmen/ (26.09.2025).

[3] Since 2023 the allowance “Hartz IV” has been renamed “Bürgergeld”.

relative potential risk of the mobility-related social exclusion of a grid cell in comparison to all other grid cells considered in the study area. The higher the index value of a grid cell, the higher the potential risk of mobility-related social exclusion for this grid cell. Based on the spatial distribution of the index values, spatial clusters were formed to define potential areas for action.

4.3 Data

4.3.1 GTFS dataset

Due to the highlighted importance of public transport for disadvantaged people, the General Transit Feed Specification (GTFS) dataset served as the basis for the analysis, as it contains complex information about public transport provision in the study area. The GTFS feed was processed in the GIS application QGIS[4] using the object-relational database management system PostgreSQL with the PostGIS extension.[5] As part of the dataset processing, the service frequency for each means of transport (on-demand bus routes,[6] bus, light rail and regional rail) and for each service day examined (Tuesday during schooltime, Saturday and Sunday) was queried from the database and then transferred to the corresponding geo-referenced stop points. For further processing, the point-based departure information had to be transformed into area-based information to do justice to the spatial access function of a stop. The sizes of the access radii, within which residents were considered to be served by public transport and to which the departure data was transferred, range from 300 metres to 800 metres depending on the means of transport and the location within the urban area (core area, peripheral area), and are defined in the strategic plan for the development of local transport (Stadt Köln 2017: 138–139). As stops can be served by more than one means of transport, several access radii of different means of transport can be located around the same stop. To avoid multiple counting of the same departure of a single vehicle in overlapping radii of neighbouring stops, the access radii of the same means of transport were transformed into Voronoi polygons, whereas overlapping areas of access radii of different means of transport (e.g. at transfer stops between bus and light rail) were not affected by this geometrical transformation.

4.3.2 Socio-spatial data on affluence

The second part of the data basis is the socio-spatial dataset with the help of which a spatially differentiated approximation of the social status of the resident population could be achieved. Provided by the City of Cologne, socio-spatial data was available at the spatial level of statistical neighbourhoods (see explanation in Section 4.4). Therefore, the data on the proportion of people entitled to the following social benefits were used: basic income support for jobseekers (SGB II), basic income support in old age (SGB XII), assistance with living expenses (SGB XII) and benefits under the Asylum Seekers Benefits Act.[7] The data was supplemented by the analogously available unemployment rates (Stadt Köln 2021; Bundesagentur für Arbeit 2021), as unemployed persons do not automatically receive SGB II benefits, and simultaneously, unemployment is not necessarily a basic requirement to receive SGB II benefits.

4.3.3 Data on supplementary mobility offers

A dataset on the private car ownership rate was available at the spatial level of "statistical neighbourhoods" (Bundesagentur für Arbeit 2021). As already emphasised in the introduction, this dataset primarily served as an approximation to determine the intentional or forced dependency of car-free households on public transport.

In order to consider overall public mobility provision, additional offers such as the "ISI" on-demand service[8] introduced in 2020 by the local public transport company *Kölner Verkehrs-Betriebe* (KVB) and the KVB bicycle rental system (KVB bike) were included in the evaluation. This was justified by the fact that, unlike numerous other mobility and sharing offers provided by private companies, under certain conditions KVB and VRS subscription customers can use both services at no additional cost to their public transport ticket.[9] Therefore, only the flex zone was considered for the

[4] QGIS Geographic Information System, Version 13.16.7; https://www.qgis.org/ (26.09.2025).

[5] Relational database management system PostgreSQL, Version 13; https://www.postgresql.org/ (26.09.2025).

[6] On-demand bus routes (*Anrufsammeltaxi, Rufbus*) operate on fixed routes with fixed stops with a fixed timetable. However, customers must actively register for these departures, in order to have a vehicle be sent out.

[7] Asylbewerberleistungsgesetz (AsylbLG) in the version published on 5 August 1997 (BGBl. I: 2022), last amended by Article 8(3) of the Act of 23 December 2024 (BGBl. 2024 I No. 449).

[8] In contrast to the aforementioned on-demand bus routes (*Anrufsammeltaxi, Rufbus*), during the time of research, ISI operated in a designated service area without assigned routes, stops or timetables. An algorithm effectively compiles the journeys by bundling journey requests.

[9] https://www.kvb.koeln/mobilitaet/isi/index.html (26.09.2025).

Table 1 Basic structure of the index for determining a potential mobility-related risk of exclusion (PRME)

Subdimension	#	Indicator	Characteristic class	Points	Proportionate weight
PT offer	1*	Absolute number of PT departures (weighted by means of transport)	≤ 0.25 quantile	2 per surveyed service day	34%
			> 0.25 quantile und ≤ 0.5 quantile (median)	1 per surveyed service day	
			> 0.5 quantile (median)	0 per surveyed service day	
	2*	Relative number of PT departures (departures per inhabitant, weighted by means of transport)	≤ 0.25 quantile	2 per surveyed service day	
			> 0.25 quantile und ≤ 0.5 quantile (median)	1 per surveyed service day	
			> 0.5 quantile (median)	0 per surveyed service day	
	3*	PT coverage (location within the access radii)	Yes	0 per surveyed service day	
			No	2 per surveyed service day	
Affluence	4	Proportion of the population receiving social benefits (rates for basic income support for jobseekers (SGB II), basic income support in old age (SGB XII), assistance with living expenses (SGB XII) and the Asylum Seekers Benefits Act (AsylbLG))	≤ 0.5 quantile (median)	0	49%
			> 0.5 quantile (median) and ≤ 0.75 quantile	9	
			> 0.75 quantile	18	
	5	Proportion of the unemployed population (unemployment rate)	≤ 0.5 quantile (median)	0	
			> 0.5 quantile (median) und ≤ 0.75 quantile	4	
			> 0.75 quantile	8	
Supplementary mobility offer	6	Private car density	≤ 0.25 quantile	4	17%
			> 0.25 quantile und ≤ 0.5 quantile (median)	2	
			> 0.5 quantile (median)	0	
	7▲	Location within the ISI on-demand service area	Yes	0 per surveyed service day	
			No	1 per surveyed service day	
	8	Location within the public bike sharing service area (KVB bike)	Yes	0	
			No	2	
TOTAL				53	100%

* Indicator applies for each of the surveyed service days (Tue, Sat and Sun). Thus, a max. of 6 points can be achieved.
▲ Indicator applies if the grid cell is located in the ISI service area on the surveyed service day (Tue, Sat and Sun). 0 points ("yes") or 1 ("no") point can be awarded for each day. Thus, a max. of 3 points can be achieved.

KVB bike,[10] and only the daytime service areas[11] were used for ISI.

4.4 Merging data at the spatial level of INSPIRE raster cells

All datasets were available in non-uniform spatial units and had to be transferred to a uniform spatial level in preparation for the bivariate correlation analysis and index formation. While the geographic INSPIRE grid system "is not an independent data model, but [describes] specifications for the georeferencing of geodata, the use of regular grid cells as a carrier of semantic information [for the representation and analysis of statistical facts] is an established procedure".[12] The merging of public transport data, socio-spatial data and data on supplementary mobility provisions onto the 100x100-metre INSPIRE grid cells was carried out by spatial intersection in QGIS. All input data was transferred from its original geometries (access radii of public transport stops, service areas of supplementary mobility provisions and data from statistical neighbourhoods) to the

[10] At the time of research, a second and station-based zone for KVB Bike in the outer areas of the city was being developed. It was therefore not considered in the data analyses.

[11] The nighttime service area was not considered, as it required a surcharge and therefore fell into the category of paid additional mobility services (mostly provided by private companies) that were not included in the analysis.

[12] https://gdz.bkg.bund.de/index.php/default/open-data/geographische-gitter-fur-deutschland-in-lambert-projektion-geogitter-inspire.html (26.09.2025); authors' translation.

Table 2 Criteria for the weighted public transport departures per means of transport

Means of public transport	Speed[a]	Capacity[b]	Short distance fare[c]	Operational flexibility[d]	Surcharge[e]	Weight factor[f]
	low (1) – high (3)	low (1) – high (3)	not applicable (0) – applicable (1)	low (0) – high (1)	not applicable (0) – applicable (1)	light rail = 1.0
On-demand bus routes	1	1	1	1	0	≈0.7
Bus	1	1	1	1	1	≈0.8
Light rail	2	2	1	0	1	1.0
Regional train	3	3	0	0	1	≈1.2

[a] refers to the average timetable speed achieved by the means of transport in the study area (bus/light rail: Stadt Köln 2017: 73, 81–82; regional train: authors' preparation)
[b] refers to passenger capacity (Schnieder 2015: 61–70)
[c] refers to the possibility of using a cheaper short-distance ticket
[d] refers to operational possibilities in the event of disruptions
[e] refers to additional charges that may apply in addition to the standard rate
[f] results from the ratio of the number of points achieved by the different means of transport, whereby the sum of the points achieved by "light rail" is set to 1

approximately 13,000 INSPIRE raster cells, if the cells' geometric centres lay within the respective source geometry. The dataset was then supplemented by population numbers per grid cell (SSP Consult 2021).

4.5 Sub-dimensions and indicators

As part of the index creation process, specific indicators for capturing the potential risk of mobility-related social exclusion were then derived from the data basis. Reflecting the highlighted importance of dimensions of mobility supply and economic status as manifestations of social inequality, all indicators used in the model could be assigned to one of these dimensions. Application of this theory-based selection of indicators meant that the formation of the index could be described as model-driven (Bortz/Döring 2006: 144–145; de Lange/Nipper 2018: 300).

As part of the index conception, three sub-dimensions were formed out of the two overarching dimensions which constitute the basis of the model for index formation (see Table 1). Within the dimension of mobility provision, the sub-dimensions "PT provision" and "supplementary mobility offers" were formed, economic status was assigned to the sub-dimension "affluence".

The decisive indicator for the "PT" sub-dimension was the absolute number of public transport departures by means of transport per surveyed service day and grid cell. In order to describe all departures of different means of transport with only one value, the individual departure totals of the means of transport were weighted into a common value, which then described the weighted number of public transport departures per grid cell. Assumptions were made for the weighting of departures by means of transport (see Table 2). This indicator was supplemented by the relative public transport departures per inhabitant, which is the quotient of the number of weighted departures in relation to the number of inhabitants living within the access radius of a specific departure. The absolute public transport departures represent the general level of public transport provision, the relative public transport departures can provide information on the proportionality, e.g., the available space in the vehicles. The third indicator of the "PT" sub-dimension was the general public transport coverage status of the grid cell, which is positive if the centre of a grid cell lies within any of the defined access radii (Stadt Köln 2017: 138).

The "affluence" sub-dimension consisted of two indicators that approximate the economic status of the resident population. In addition to the proportion of recipients of basic benefits for jobseekers (SGB II), the indicator for recording the proportion of social benefit recipients also included the proportion of recipients of basic benefits for old age (SGB XII), assistance for subsistence (SGB XII) and assistance in line with the Asylum Seekers Benefits Act, and was already used in the previous methodological description of the bivariate correlation analysis. By considering various transfer payments, people of working age and above were covered. In addition, the unemployment rate was used as the second indicator of the "affluence" sub-dimension and describes the proportion of registered unemployed persons, who are at a particularly high risk of exclusion due to the social significance of employment described above (Daubitz 2011: 183).

The third sub-dimension was made up of indicators for recording supplementary mobility offers that were not included in the "PT" sub-dimension, such as the public bike rental system "KVB bike" and the KVB on-demand service "ISI". Further, the density of private cars was included in order to cover the probability of access to a private car as an alternative significant means of transportation.

4.6 Indicator categories and weighting

As the indicators were available in different units, scales and value ranges, standardisation was achieved by categorising the data (de Lange/Nipper 2018: 302–303). For all indicators used for the additive index, a PRME-favouring characteristic contributed to the index with a higher value (see Table 1). Therefore, for the dichotomous indicators 3, 7 and 8, a location outside the access radii or the service areas ("no") resulted in a high value, while the opposite value ("yes", located within) had a negative effect on potential risk of mobility-related social exclusion and therefore did not increase the index value. For the polytomous indicators 1, 2, 4, 5 and 6, three classes of values were formed using quartiles which represent a special form of quantile (de Lange/Nipper 2018: 77) (see Table 1). The reason for forming classes based on quartiles for the polytomous indicators was that characteristics which particularly contributed to potential risk of mobility-related social exclusion were either above average (e.g. an above-average proportion of social benefit recipients) or below average (e.g. below-average public transport provision) in polarity. The average in this context was the median which divided the sample into two equal parts.

Due to the enormous differences in the number of public transport departures and the availability of the on-demand system on Tuesday, Saturday and Sunday, an index value was calculated for each surveyed day for indicators 1, 2, 3 and 7 instead of determining only the sum of public transport departures of all surveyed service days combined.

The weighting of the indicators and sub-dimensions in the index model was structured so that the combined indicators of the sub-dimensions "PT provision" and "supplementary mobility offers" accounted for 51 % of the maximum possible score, while the sub-dimension "affluence" accounted for 49 %. The objective of this approach was to establish an approximate equilibrium between the sub-dimensions 1 and 3 and subdimension 2, thereby averting misinterpretation resulting from the overrepresentation of a single sub-dimension. This weighting pursued the overarching goal of constructing a high, above-average index value, which could only be achieved through the combined effect of both mobility provision and economic status.

4.7 Cluster formation

To enhance clarity, spatial clusters were formed which were characterised by an increased potential risk of mobility-related social exclusion. To reduce over-interpretation of individual grid cells with a strong outlier index value compared to adjacent cells, an average index value was calculated for each grid cell which included all index values of the maximum of eight adjacent cells. If this averaged value of a grid cell was more than 1.5 standard deviations above the arithmetic mean of all grid cells in the study area, the grid cell was assigned an increased potential risk of mobility-related social exclusion. If at least five contiguous grid cells met this criterion, they were grouped into a spatial cluster. In a further step, the spatial clusters with an average index value above the median of the average index values of all clusters were highlighted and assigned a highly increased potential risk of mobility-related social exclusion.

5 Results

5.1 Public transport and socio-spatial urban structure

Turning to the sum of weighted public transport departures per grid cell for a weekday during schooltime, inner city areas, some outlying district centres and areas along important transport axes had weighted departure totals above the median (see Figure 3). Areas along numerous outbound axes well served by light rail and district centres such as Chorweiler, Porz and Rodenkirchen were also characterised by high numbers of departures. Several sub-centres in smaller and outlying districts were also above the median. In contrast, outlying and less populated areas mostly showed departure totals below the median. While the share of such areas generally increased with distance from the city centre, some central areas with below-average accessibility were identified.

The analyses also showed the proportion of the population receiving basic income support for jobseekers (SGB II), basic income support in old age (SGB XII), subsistence assistance (SGB XII) and benefits under the Asylum Seekers Benefits Act per grid cell (see Figure 3), which served as the basis for indicator 4. Values ranged from less than 1 % to 70.4 %, with half of all grid cells between 9.1 and 15.2 %. Values under 1 % were found in Lindenthal and values well over 50 % in parts of Chorweiler, Ostheim and Meschenich. The superordinated districts of Innenstadt, Lindenthal and Rodenkirchen mostly had a low proportion of social benefits recipients, below the city-wide median of 9.1 %. In contrast, the superordinated districts of Mülheim, Kalk, Porz and parts of Ehrenfeld, Nippes and Chorweiler often had proportions above the median.

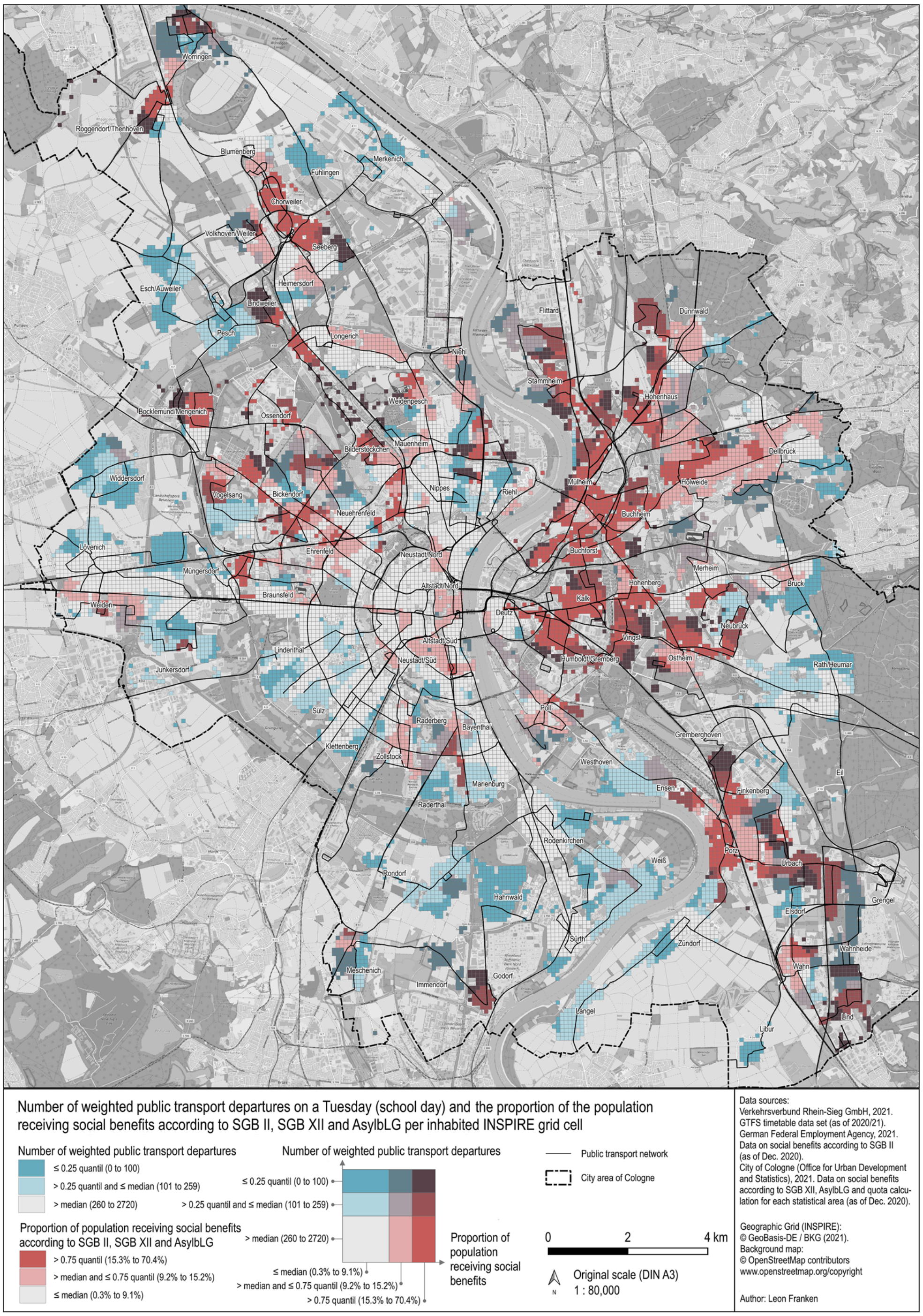

Figure 3 Number of weighted public transport departures on a Tuesday and proportion of the population receiving social benefits per inhabited grid cell

5.2 Correlation between public transport provision and economic status

Building on the previous separate analysis of public transport provision and economic status, the focus of further analysis was on identifying areas characterised by a combination of critical properties relevant to both features in which a total of 21 % of Cologne's population lived (see Table 3). Such areas were particularly located in the districts on the right bank of the River Rhine and the northern districts on the left bank. In particular, peripheral areas of the Stammheim, Mülheim and Buchheim districts and parts

Table 3 Number of grid cells and inhabitants of the four combinations of public transport provision and the proportion of the population receiving social benefits

	Below-average proportion of the population receiving social benefits			Above-average proportion of the population receiving social benefits		
Below-average public transport provision	Grid cells:	3,403	(27 %)	Grid cells:	2,963	(23 %)
Weighted departures (Tuesday)	Inhabitants:	191,331	(18 %)	Inhabitants:	229,309	(21 %)
Above-average public transport provision	Grid cells:	3,102	(24 %)	Grid cells:	3,270	(26 %)
Weighted departures (Tuesday)	Inhabitants:	307,775	(28 %)	Inhabitants:	354,923	(33 %)

of the Gremberghoven, Wahnheide and Lind districts could be cited as examples of this critical combination of characteristics that can promote potential risk of mobility-related social exclusion (see Figure 3). On the left bank of the River Rhine, areas in the districts of, e.g., Godorf, Niehl, Lindweiler, Seeberg and Roggendorf/Thenhoven were increasingly affected by this critical combination of characteristics. The analysis also identified areas with less critical combinations (see Table 3).

The data also provides insights into how the general presence of public transport (grid cell lies within the access radii, as of indicator 3) relates to the proportion of social benefit recipients (see Figure 4). It was found that people in economically highly disadvantaged areas were slightly more likely to have no access to public transport than people in economically disadvantaged and advantaged areas. However, the highest proportion of the population not served by public transport was found in economically highly advantaged areas.

To describe possible statistical correlations between public transport provision and economic status, the weighted public transport departures (as of indicator 1) were initially checked for normal distribution to determine a suitable type of correlation analysis. As no normal distribution could be found, the Spearman correlation coefficient was used as a suitable measure of correlation. Furthermore, the unclear direction of the cause-and-effect relationship between public transport provision and the economic status of the population with social exclusion (see Section 2.3) justifies the examination of an undirected relationship.

The correlation coefficients showed the relationship between the weighted number of absolute public transport departures and the proportion of social benefit recipients (online supplementary material A). It was found that the correlation coefficients of the weighted number of public transport departures on Saturdays and Sundays correlated weakly positively with the proportion of social benefit recipients, with values between $\rho = 0.100$ and $\rho = 0.131$. Thus, with an increasing proportion of social benefit recipients, more weighted public transport departures occur. It was only for the weighted departures on Tuesdays ($\rho = 0.098$) that no significant correlation effect according to Cohen (1988) was found, although the value is just slightly lower than the margin of $\rho = 0.1$. All correlations are two-sided significant at the 0.01 level. No statistical correlation was found between the relative public transport departures

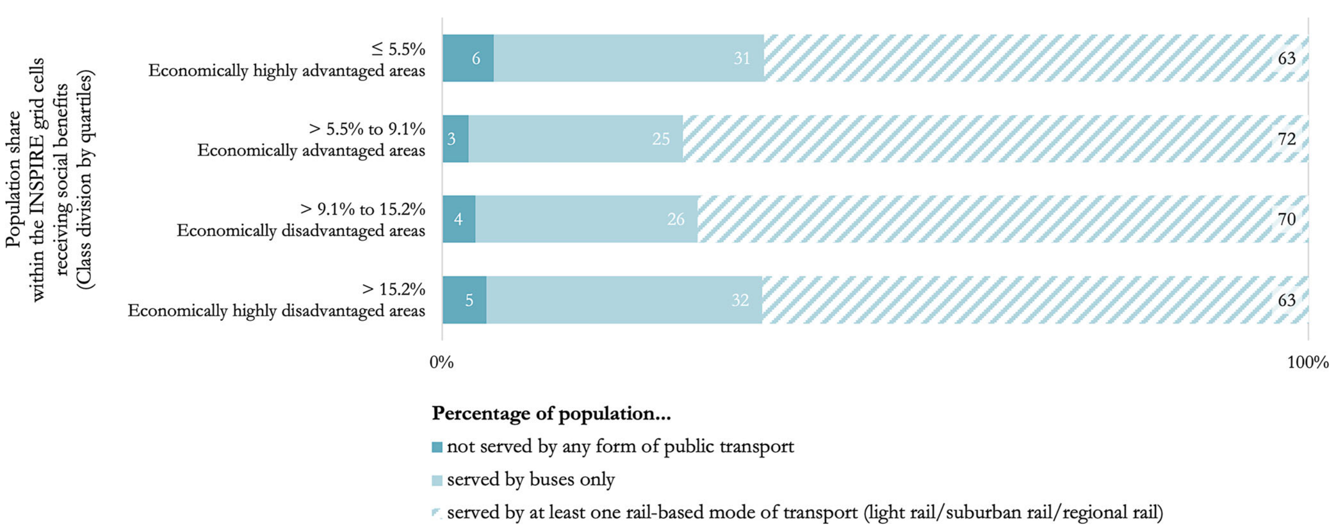

Figure 4 Proportion of the population with no public transport access as a function of the proportion of the population receiving social benefits. Source: authors' compilation, illustration based on Daubitz/Aberle (2020)

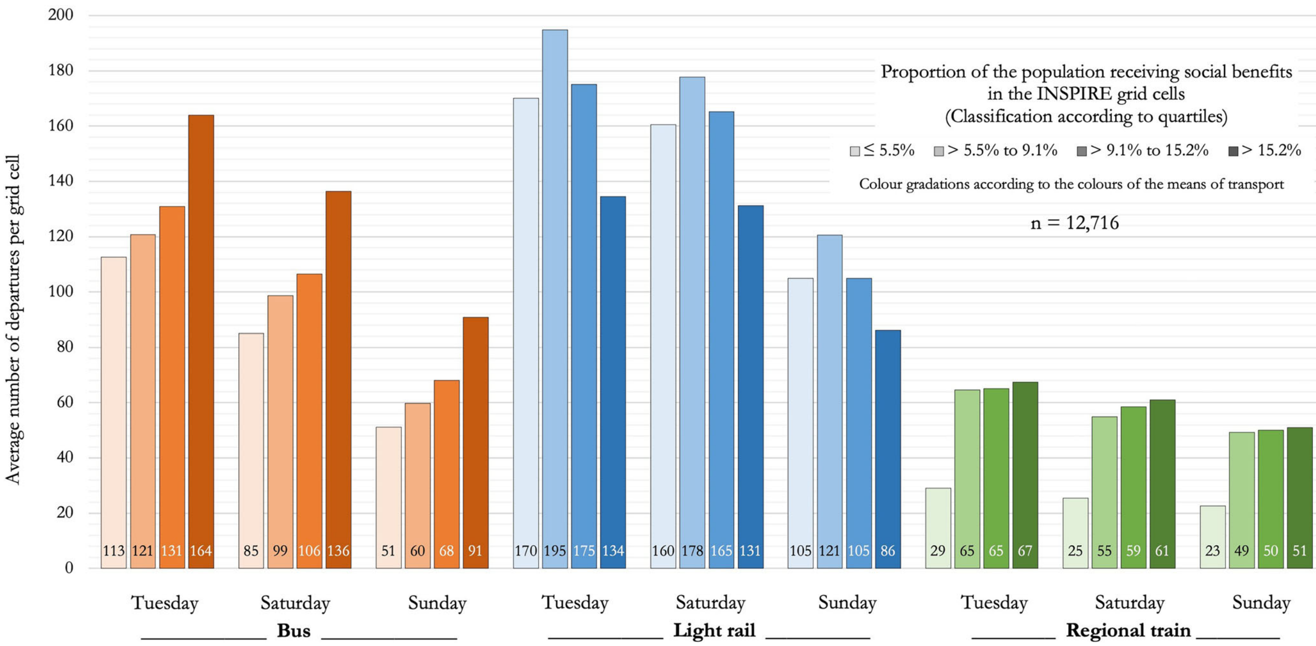

Figure 5 Average absolute number of departures and the proportion of social benefit recipients

per inhabitant and the proportion of social benefit recipients across all surveyed service days.

The analysis also provided insights into the relation between the different means of transport and economic status. When analysing average absolute departures per means of transport as a function of the proportion of social benefit recipients per grid cell, it showed that the average number of bus departures in a grid cell increased with the increasing proportion of social benefit recipients across all surveyed service days (see Figure 5). The same was true, albeit to a lesser extent, for regional train departures. In contrast, areas with a high proportion of benefit recipients had the lowest average number of light rail departures on all surveyed service days.

The correlation coefficients were analysed for a statistical correlation of absolute departures per means of transport in

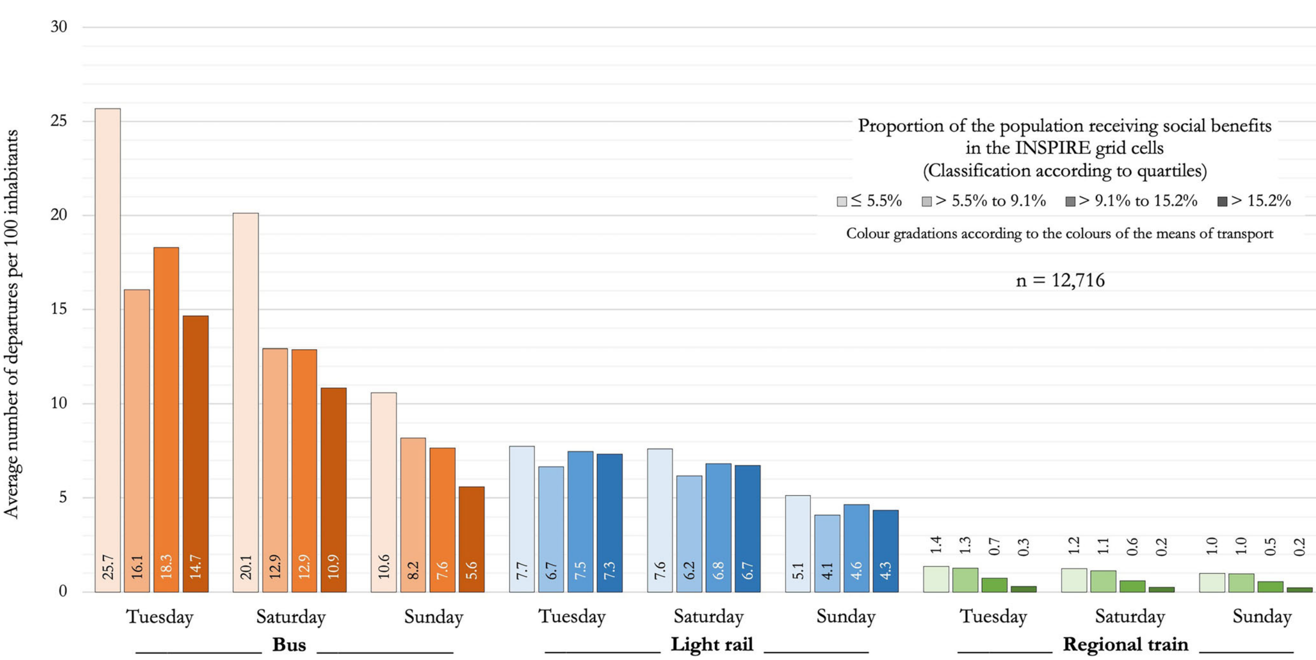

Figure 6 Average relative amount of departures per 100 inhabitants and proportion of social benefit recipients

Table 4 Area and proportion of the population per index class

index value	PRME	grid cells	% of inhabited urban area	population	% of the population	population receiving social benefits	% of the population receiving social benefits
0 – 10	very low	3,622	28.4	313,164	28.9	13,633	9.4
11 – 20	low	3,529	27.7	263,870	24.4	25,382	17.5
21 – 30	medium	2,339	18.4	169,631	15.7	23,413	16.1
31 – 40	high	2,482	19.5	254,941	23.5	64,511	44.4
41 – 53	very high	766	6.0	81,732	7.5	18,337	12.6
		12,738	100.0	1,083,338	100.0	145,276	100.0

relation to the proportion of social benefit recipients (online supplementary material B). The results showed that the absolute number of bus departures and the absolute number of regional train departures on all service days examined correlated weakly positively with the proportion of social benefit recipients, with values between $\rho = 0.146$ and $\rho = 0.212$. However, the absolute number of light rail departures on all service days examined did not correlate with the proportion of social benefit recipients, with values between $\rho = -0.024$ and $\rho = -0.048$, too close to 0 to be classified as a correlation (Cohen 1988).

Looking at the relative departures per means of transport in relation to the proportion of social benefit recipients (see Figure 6), it became clear that residents in economically (highly) disadvantaged areas (classes with higher proportions of social benefit recipients) had the fewest departures per inhabitant for all means of transport on all surveyed service days. In contrast, residents in economically (highly) advantaged areas had the highest average number of departures per inhabitant, also for all means of transport and on all surveyed service days.

Looking at the correlation coefficients of the relative number of departures and the proportion of social benefit recipients (online supplementary material B), the relative regional train departures (values between $\rho = 0.172$ and $\rho = 0.178$) and the Sunday bus departures ($\rho = 0.127$) showed a weakly positive correlation effect. All correlations were two-sided significant at the 0.01 level.

5.3 Index-based potential risk of mobility-related social exclusion

In addition to the bivariate correlation analysis, we created a visualisation of the index values that indicated a potential risk of mobility-related social exclusion at the grid cell level. This contained the results of the additive and weighted index from all eight indicators of the three sub-dimensions. It showed that most areas with a high and very high potential risk of mobility-related social exclusion were located in the superordinated districts of Mülheim, Kalk, Porz, Ehrenfeld and Chorweiler. In contrast, areas with a high and very high potential risk of mobility-related social exclusion were only rarely found in the superordinated districts of Innenstadt, Lindenthal and Rodenkirchen. Larger contiguous areas with a high and very high potential risk of mobility-related social exclusion were also primarily located in the districts on the right riverbank in particular, while such areas were significantly less distinct in terms of size in the districts on the left riverbank. The respective areas and proportions of the population of the identified index classes were compiled (see Table 4).

The analysis showed that 57 % of the social benefit recipients lived in areas with a high or very high potential risk of mobility-related social exclusion, which is significantly more than that of the total population, of which only 31 % lived in such high-risk areas. At the same time, areas with low and very low potential risk of mobility-related social exclusion accommodate only 27 % of the social benefit recipients, which is significantly less than the 53 % of the overall population.

Spatial clusters were formed from the 3,248 grid cells with a high and very high potential risk of mobility-related social exclusion for reasons of clarity and prioritisation and to allow individual consideration. A total of 49 spatial clusters were identified in the urban area that were characterised by an increased risk, of which 24 clusters were highlighted due to a highly increased potential risk of mobility-related social exclusion (see Figure 7). The distribution of the 49 risk clusters showed that they were particularly concentrated in the superordinated districts of Mülheim (13), Porz (10) and Kalk (8) on the right riverbank, while the superordinated districts of Chorweiler (7), Nippes (6), Ehrenfeld (4) and Rodenkirchen (1) on the left riverbank were less affected. Only in the superordinated districts of Innenstadt (Inner City) and Lindenthal were no spatial clusters identified.

The average values of the indicators per cluster with a high potential risk of mobility-related social exclusion were determined (see Table 5 and online supplementary material C) and supplemented by further information on the

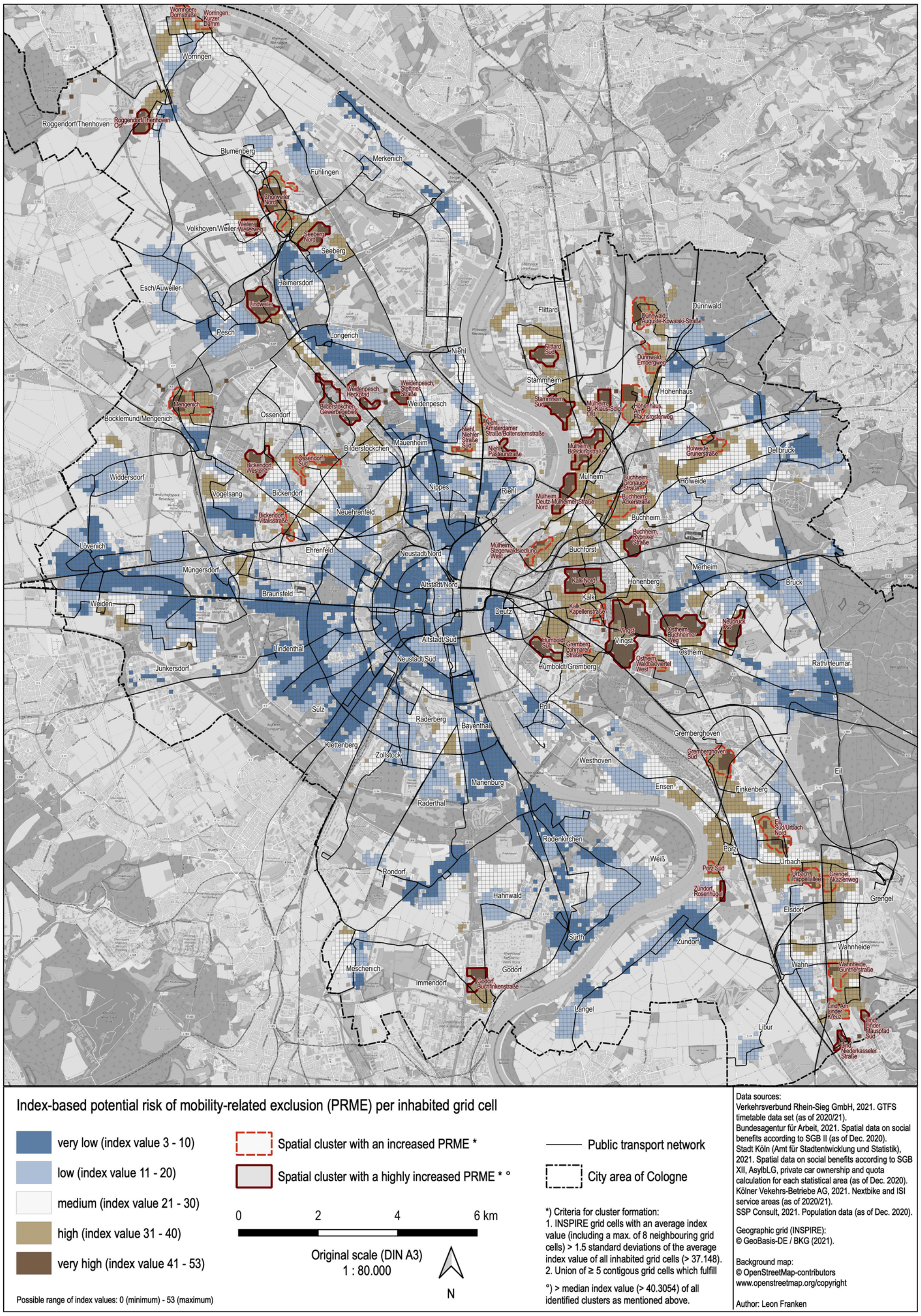

Figure 7 Index-based potential mobility-related risk of exclusion per inhabited grid cell and spatial clusters with increased and highly increased risk levels

area as well as the distinct number of affected residents. The coding of the average values of the polytomous indicators 1, 2, 4, 5 and 6 was based on the quartiles and their contribution to a potential risk of mobility-related social exclusion (***numbers in bold italics*** = most contributing quartile, **numbers in bold** = second most contributing quartile, *numbers in italics* = second least contributing quartile, recte numbers = least contributing quartile). For the dichotomous indicators 3, 7 and 8, the percentage of grid cells in a cluster that lay within the respective area (public transport access radii, on-demand service area, public bike rental service area) was relevant (***numbers in bold italics*** = 0-25 %, **num-**

Table 5 Average index and indicator values per spatial cluster with increased and highly increased potential mobility-related risk of exclusion (5 out of 49 clusters)

No.	Description	Average index value	Inhabitants (rank out of 49)	Area in ha	Indicator 1: Average number of weighted public transport departures			Indicator 2: Average number of weighted public transport departures per 100 inhabitants			Indicator 3: Public transport coverage in percent			Indicator 4: Average proportion of population receiving social benefits	Indicator 5: Average proportion of unemployed population	Indicator 6: Private cars per 100 inhabitants	Indicator 7: Proportionate location in the service area of on-demand traffic in percent			Indicator 8: Proportionate location in the service area of the bike rental system in percent
					Tuesday	Saturday	Sunday	Tuesday	Saturday	Sunday	Tuesday	Saturday	Sunday				Tuesday	Saturday	Sunday	
1	Weidenpesch, Heckpfad	49.00	317 (44.)	10	0	0	0	0.0	0.0	0.0	0	0	0	21.4	12.1	35.7	0	0	0	100
2	Lind, Linder Mauspfad Süd	46.25	249 (46.)	6	27	23	19	5.3	4.5	3.7	17	17	17	15.6	12.3	49.4	0	0	0	0
3	Buchheim, Rybniker Straße	46.21	768 (35.)	14	0	0	0	0.0	0.0	0.0	0	0	0	15.5	8.7	38.5	0	0	0	0
4	Stammheim Süd	45.20	2517 (17.)	26	87	82	57	6.0	5.6	3.7	46	46	46	23.7	13.0	34.1	0	0	0	0
5	Lind, Niederkasseler Straße	45.00	73 (49.)	8	30	0	0	82.2	0.0	0.0	100	0	0	18.8	11.1	54.4	0	0	0	0

bers in bold = 26-50 %, *numbers in italics* = 51-75 %, recte numbers = 76-100 %). Overall, values with numbers in bold and numbers in bold italics therefore had a less favourable effect in terms of a potential risk of mobility-related social exclusion than numbers in italics and recte numbers. The chosen form of presentation thus makes it possible to classify the characteristics of a cluster in relation to the rest of the city and enables a direct comparison of the values between clusters (see Table 5; for the full table, see online supplementary material C).

6 Discussion

6.1 Class-related inequality structures and public transport provision

The results from the correlation between public transport provision and the proportion of social benefit recipients showed that areas with a high proportion of social benefit recipients were not structurally disadvantaged in terms of public transport provision. The pure availability status of public transport was highest in areas with a slightly below-average proportion of social benefits recipients and decreased slightly as the proportion of social benefit recipients increased. However, the areas that were most frequently not served by any public transport were those with a significantly below-average proportion of social benefit recipients, making it impossible to identify a clear trend. Aberle, Daubitz and Schwedes (2025: 7) came to similar conclusions in their analysis of spatial patterns of mobility-related exclusion in Berlin and Hamburg: people living on welfare in Berlin were minimally more likely to be excluded from public transport than the Berlin average, but the difference was minimal; for Hamburg, the opposite was the case.

Delbosc and Currie (2011: 1256) show that public transport services in Melbourne are very unevenly distributed overall: over 70 % of the population receive only 19 % of available public transport. In terms of income classes, low-income residents in inner-city areas benefit more than average from public transport, as this is where the service is concentrated. In central and outer city locations, however, poor households are sometimes significantly underserved, especially if they are not located within well-connected corridors. Thus, a systematic favouring of low-income groups cannot be deduced from this study. Instead, side effects of the urban structure have positive effects for the socially disadvantaged (Delbosc/Currie 2011: 1257–1259).

In contrast, El-Geneidy, Levinson, Diab et al. (2016: 302) find that residents of socially disadvantaged areas in Montreal benefit from more equitable accessibility to jobs using public transport than other groups in the region, even when considering the financial implications of fare costs.

In regard to the public transport provision and economic status, the distribution of absolute public transport departures corresponds most closely to the utilitarian distribution curve, which is characterised by maximum accessibility independent of income and thus provides the greatest possible benefit for all income classes, due to non-existent or weakly positive correlations (Adli/Chowdhury/Shiftan 2019: 90; see Figure 1).

The relative public transport departures also correspond to the sufficientarist approach, as relative public transport provision increases with increasing affluence. However, in the context of high residential densities, where disadvantaged groups are often situated, elements of an egalitarian curve would be desirable for reasons of transport capacity and the frequent dependence of disadvantaged people on public transport. In line with the findings of Aberle/Daubitz/Schwedes (2025) and Delbosc/Currie (2011), no egalitarian distribution curve ("vertical equity" by Delbosc/Currie 2011: 1252, 1256) was found in the Cologne study area. It can therefore be assumed that the distribution of public transport primarily follows functional and economic principles rather than social criteria. Collins, Der Wartanian, Reed et al. (2023: 6) confirm this for southern California and note that before the coronavirus pandemic, there was a strong correlation between poor public transport provision, social disadvantage and ethnic composition. During the pandemic, this inequality was reduced by a stronger focus on disadvantaged urban areas, including the supply of essential workers, before returning to its original state after the pandemic (Collins/Der Wartanian/Reed et al. 2023: 8). Their model shows that racially and socially disadvantaged groups are systematically worse served by public transport – except in exceptional phases such as the pandemic. To address this structural issue, the expansion of public transport would have to specifically address the needs of structurally disadvantaged groups and peripheral areas in order to distribute mobility opportunities in a more resilient, sustainable and fair manner.

6.2 Availability of specific means of transport

In terms of the absolute number of departures differentiated by specific means of transport, the analysis shows that bus services in particular and, to a lesser extent, regional rail services in Cologne increase as the share of social benefit recipients rises. This reflects the egalitarian curve with a stronger provision for economically disadvantaged groups. Only for light rail services, an almost opposite, though weak, trend is observed. Aberle, Daubitz and Schwedes (2025: 7) also confirm that rail-based transport is less available to lower-income groups in Berlin than to others, therefore following an opposite and sufficientarist curve with a preference for higher-income groups.

While the findings of Aberle, Daubitz and Schwedes (2025: 5–7) for Berlin and Hamburg only partially confirm the observations on the absolute distribution of different means of public transport in Cologne, all results showed that the number of relative public transport departures per inhabitant decreased for all means of transport with increasing financial disadvantage. This is probably because financially disadvantaged people, particularly in large cities, often live in high-density neighbourhoods (Beckmann/Bracher/Hesse 2007: 15), which has a negative impact on the relative number of public transport departures per inhabitant. Examples, like the district of Vingst with more than 11,000 inhabitants per square kilometre, show that a high population density can lead to below-average relative public transport provision, even when the absolute public transport provision is above average; this can manifest in the form of fuller stations and vehicles (Daubitz/Aberle 2020: 6; online supplementary material C). Evidently, the provision of quantitatively satisfactory public transport does not necessarily guarantee its suitability in qualitative terms.

The literature focuses mostly on general public transport accessibility and not on quality of transport. Nonetheless, Daubitz and Aberle (2020: 4) state that rail transport is a higher-quality mode and poorer access can lead to mobility-related disadvantages. However, buses and light rails might better meet the needs of socially disadvantaged people (Aberle/Daubitz/Schwedes 2025: 10).

Bus routes in Cologne act as feeders for large parts of the network without direct city centre connections and are mainly disadvantaged in times of travel speed. This structure is reflected in many risk clusters. For example, Kalk-Nord had slightly below-average absolute public transport supply. High population density negatively affected the relative public transport provision. Despite 75 % public transport coverage, the area was served only by buses, whose lower weighting led to a comparatively poor service value. Similarly, in several risk clusters on both sides of the Rhine – such as Stammheim, Flittard and Lindweiler – public transport consisted almost exclusively of buses without transfer-free city centre connections. As a short-term remedy, a planned express bus network in Cologne may optimise public transport services and increase bus attractiveness in areas which are not yet served by rail (Stadt Köln 2017: 215). Express buses can create new direct city centre connections with fewer stops and shorter travel times. Such accelerated bus connections are already used in several major German cities such as Düsseldorf or Hamburg.

6.3 Influence of the spatial settlement structure

The results of the bivariate correlation analysis showed that all bivariate combinations of characteristics were equally present in the study area and that there was no structural under- or over-supply of public transport in areas with an above- or below-average proportion of the population receiving social benefits. However, around 23 % of the inhabited area was characterised by a critical combination of below-average public transport provision and an above-average proportion of the population receiving social benefits, affecting around 21 % of the total population of the Cologne study area (see Table 3).

A comparison of the spatial clusters identified as having an increased potential risk of mobility-related social exclusion with the "social spaces" (authors' translation), mentioned in a framework concept (Stadt Köln 2010: 17) showed large overlaps. These "social spaces" were "based on the 'social situation' index and include the economic, political-cultural and health aspects of disadvantage"[13] (authors' translation). A "settlement-spatial classification [and description] of historical genesis and function" (Stadt Köln 2015: 23, authors' translation) carried out in this context showed that the economic, political-cultural and health-related disadvantage structures focus primarily on three urban fabric types, into which a large proportion of the risk clusters identified in this study could also be classified. Examples include the clusters of the Mülheim, Kalk and Humboldt districts (*Gründerzeit* industrialised suburban belt), clusters of the Buchheim, Gremberghoven and Bilderstöckchen districts (suburban belt of the interwar period), and the Chorweiler Nord and Seeberg Nord clusters (high rise/large estate districts). The large proportion of overlaps indicates that the potential risk of mobility-related social exclusion identified in most cases is accompanied by other problems characteristic of these types of urban fabric, illustrating the interaction between transport and economic, cultural and health aspects as well as employment and education (Beckmann/Bracher/Hesse 2007: 11; Daubitz 2011: 183). This can thus be embedded in explanations on the structural disadvantage of neighbourhoods.

6.4 Impact of financial access barriers

The results of a nationwide comparison of public transport ticket prices showed that public transport in Cologne was among the most expensive (Bukow/Meinefeld/Schmidt

[13] https://www.stadt-koeln.de/artikel/66131/index.html (29.09.2025).

2020: 20). In low-income population groups, transport expenditure accounts for an excessively high share of disposable income. In terms of the *Bürgergeld* (former *Hartz IV*) standard rate and transport costs of €50.49 provided in 2025 (€40.01 in 2021), the concessionary social tickets can be understood as an approximation of the available budget of the people concerned. These concessions are no guarantee for actual affordability, and such offers do not guarantee the individual will of those affected to realise their mobility needs (Daubitz 2021: 82–83).

In contrast, the debate on the introduction of free use of public transport offers the prospect of reducing or completely removing financial barriers to accessing public transport (Cats/Susilo/Reimal 2017; Andor/Fink/Frondel et al. 2020; Kębłowski 2020). In European cities such as Luxembourg (Carr/Hesse 2020: 2) or Tallinn (Sträuli 2024: 686), but also in German cities such as Monheim am Rhein[14] (see Stadt Monheim am Rhein 2022), public transport is already free of charge. In Germany, the "9-Euro-Ticket"[15] introduced in summer 2022 provided users with unprecedented access to public transport services nationwide for just €9 per month. For low-income earners, this temporary offer represented a substantial increase in mobility, providing financial relief and straightforward conditions (Hille/Gather 2022: 2). The *Deutschlandticket*, the successor to the 9-Euro-Ticket, cost €49 per month initially and increased to €58 in 2025. It has enabled the continued use of public transport in an easy and tariff-simplified manner. However, the financial relief it provides is limited (Hille/Gather 2022: 27), considering that the price is almost equivalent to the full €50.49 *Bürgergeld* expenditure rate on transport.

7 Limitations

As part of the merging of input data at the level of INSPIRE raster cells, data from 570 statistical neighbourhoods was disaggregated to around 13,000 cells. Compared to the significantly larger and more heterogeneous 86 Cologne districts, these neighbourhoods are more socio-spatially homogeneous due to their population size and geometry based on settlement structure (Stadt Köln 2021; Stadt Köln 2022). Since many other complex conditions must be met before a (high) risk cluster can be identified, individual inaccuracies have minimal impact on the global results.

Furthermore, the GIS analysis is based on public transport quality using simple, objectively measurable parameters. These measure objective accessibility, without accounting for actual destination relevance or public transport service usability. In addition, social status, as a result of social inequality and disadvantage, is not only measurable via economic indicators, but also via, e.g., health-related, cultural-related dimensions.

As the collective potential risk of mobility-related social exclusion of a raster cell cannot be assigned to individuals to avoid ecological fallacy (de Lange/Nipper 2018: 158–159), the data was interpreted at the spatial unit level. The potential risk of mobility-related social exclusion values reflects the probability that individuals within a cell may be affected and does not reflect a specific risk to each resident.

Despite its relevance, the social and subjective dimension of mobility exclusion has so far received little attention in local political consideration and transport planning (Daubitz 2011: 181), or in mobility-related social reporting (Hausigke/Kruse 2021: 270). A qualitative perspective, involving citizens, local experts and initiatives, would complement quantitative data with subjective insights and allow unequal political participation and the neglected interests of disadvantaged groups to be considered (Böhnke/Groh-Samberg/Kleinert 2023: 62).

8 Conclusion

The analysis provides a comprehensive and spatially high-resolution overview of the spatial distribution of public mobility provision and the economic status of the population in the Cologne study area, placing both dimensions in a spatial context with each other and in a contextual relationship with the concept of social exclusion.

A central finding of the bivariate analysis of the correlation between public transport provision and the proportion of the population receiving social benefits is that people in economically weaker areas of Cologne are not exposed to structurally lower public transport provision, although slight differences are discernible regarding the distribution of specific means of transport. However, considering the number of public transport departures in relation to the number of inhabitants living in the catchment area of these departures, the relative number of departures by all means of transport decreases as the proportion of the population receiving social benefits increases, resulting in fuller stations and vehicles. The high-resolution results also show that 23.5 % of the population in the study area are affected by a high potential risk of mobility-related social exclusion and a further 7.5 % by a very high potential risk of mobility-related social exclusion. Considering only those who receive social benefits, 44.4 % live in areas with a high po-

[14] https://www.monheim.de/stadtleben-aktuelles/stadtprofil/oeffentlicher-personennahverkehr (29.09.2025).

[15] The € 9 ticket and the Germany-wide ticket were not yet available when the GTFS data was collected.

tential risk of mobility-related social exclusion and 12.6% in areas with a very high potential risk of mobility-related social exclusion, which indicates that this vulnerable part of the population has a significantly stronger exposure to a potential risk of mobility-related social exclusion. A total of 49 spatial risk clusters are concentrated in the city area, particularly in the districts on the right bank of the River Rhine. The Innenstadt and Lindenthal districts on the left riverbank have no risk clusters. High population densities and low car ownership in the affected areas increase the negative impact of the below-average public transport provision, which also worsens the relative number of public transport departures per inhabitant.

A high degree of spatial overlap with well-known "problem areas" in the study area underlines that the mobility-related inequalities examined are often embedded in a broader context of disadvantage related to social and settlement structures and that an integrative approach to identifying sustainable solutions is necessary.

In line with the results of other case studies (as mentioned in Section 6.1), the distribution of public transport often primarily follows functional and economic principles rather than social criteria. Other case studies show that socially disadvantaged population groups can also have structurally better access to public transport (see Section 6.1).

Due to the high spatial resolution of the results, this comprehensive socio-spatial analysis allows intra-municipal comparison and thus creates awareness of mobility-related disadvantage structures in the study area. In combination with future further studies, including the qualitative recording of subjective perceptions to complement the objectively determined disadvantage structures, this research can provide an initial basis for the sustainable improvement of corresponding grievances in the previously underrepresented social process of mobility-related exclusion.

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