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Regional Urbanisation through Accessibility?—The "Zweite Stammstrecke" Express Rail Project in Munich

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Abstract: Transport accessibility is one of the most significant locational factors for both households and firms, and thus a potentially self-reinforcing driver of urban development. The spatial structure and dynamics of accessibility hence have the potential to alter the locational choices of households and firms significantly, leading to concentration and de-concentration processes. In spite of recent innovations in automotive technologies, public transport systems remain crucial for the functioning of metropolises. In this paper, we use the case of public transport in the Munich Metropolitan Region (MMR) in Germany to (1) discuss whether public transport in the past has contributed to regional urbanisation, the blurring of urban and suburban spaces; (2) model future accessibility changes due to the ongoing mega-infrastructure project "second trunk line" ("Zweite Stammstrecke") for suburban trains and their likely effects on processes of regional development; (3) compare the balance of accessibility and functional density at stations in the MMR and (4) recommend a planning strategy based on an integrated urban and transport planning philosophy. We argue that particularly the monocentric design of the project means that it will intensify and extend the scope of suburbanisation and metropolisation, while planning should aim for a greater regionalisation of economic activity.

Keywords: public transport; accessibility; railway stations; integrated urban and transport planning; commuting; metropolisation; suburbanisation; planning strategies

1. Introduction

It is often argued that spatial dynamics in developed countries during the last decades are characterised by new complexities. The seemingly clear-cut and hierarchical inner-regional relationship between urban cores as employment centres and expanding residential suburban areas is increasingly blurring and being supplemented by a new simultaneity of tendencies of employment de-concentration and re-urbanisation of households. "Regional urbanization" [1] or "Zwischenstadt" [2] are some of the labels given to these dynamics. This new parallelism of concentration and de-concentration can be attributed to a range of factors, among them changes in the economic system such as the rise of the knowledge economy [3], as well as demographic developments [4].

New transport technologies and infrastructure are other important drivers of changes in regional settlement structures. For households, transport infrastructure provides accessibility to jobs, services, leisure and retail facilities, while for firms it provides access to (potential) employees, customers and business partners, and hence constitutes an important locational factor. Transport networks can be structured in a monocentric or polycentric way, which influences the regional distribution of accessibility and subsequently settlement dynamics. In this paper, we discuss the relationship of patterns concentration and de-concentration of households and employment with transport infrastructure improvements, particularly public transport infrastructure, in an inner-regional perspective, using the case study of the currently planned major passenger rail project “Second Trunk Line” (“Zweite Stammstrecke”) in the Munich Metropolitan Region (MMR). There has been no analysis of this project with regard to these dynamics in academic literature yet.

First, we briefly discuss the theoretical background of four dynamics—de-concentration and concentration of households and employment—separately and in their relation to transport infrastructure improvements. We then introduce our case study area and project, including previous studies on land use-transport relationships in the region, which mostly conclude that the MMR continues to be a prime example of suburbanisation and metropolisation. We pose four research questions in this paper, which are also reflected in the methods and results sections. (1) First, we ask whether more recent data shows signs of changes for the MMR that point more into the direction of re-urbanisation and regionalisation of economic activity than identified by previous literature. We hypothesize that this is the case, as most of the previous studies on the topic for the MMR have been published a while ago, and they predate the transition to the knowledge economy. Based on the results, we (2) ask which dynamics and patterns of accessibility the “Second Trunk Line” project produces, and which consequences for demand by different users of space are likely to result, using a gravitational accessibility modelling method. Our hypothesis is that accessibility gains will accrue mainly to those locations that already are highly accessible, due to the monocentric alignment of the planned new rail line. We then take a more normative approach that seeks to balance accessibility and functional density and (3) ask whether the current spatial structure still matches the new accessibility opportunities levels in the region. (4) Lastly, we ask what regional planning should do in response to these changing demands, based on recent integrated urban and transport planning philosophies and draw conclusions for metropolitan regions in general. By doing so, we contribute to the growing discussion in academic literature on sustainable urban structures.

We conclude that despite slight tendencies for a dispersion of economic activity and a polycentric development in the immediate surroundings of the city of Munich, the Second Trunk Line is going to reinforce the monocentric alignment of the transport network in the MMR, which will likely cause further suburbanisation and metropolisation. Since construction has already begun, planning should mitigate the consequences using a strategy of transit-oriented development with a greater emphasis on functional mix around the newly emerging accessibility hubs.

2. Theoretical Background

Different strands within the spatial sciences discuss, on the one hand, the continuing de-concentration of population away from urban cores (“suburbanisation”) as well recent indications for its reversal (“re-urbanisation”). With regard to economic activity, both the concentration of economic activities and employment, often between regions (“metropolisation”), and the de-concentration, often within regions (“regionalisation”), are addressed but seldom together. Table 1 shows this categorisation that will be used in this paper, which is based on the literature discussion in the following paragraphs.

Table 1. Dynamics of concentration and de-concentration of households and employment.

	De-Concentration	**Concentration**
Households	Suburbanisation	Re-Urbanisation
Employment	Regionalisation	Metropolisation

2.1. Four Regional Dynamics of Concentration and De-Concentration

Suburbanisation describes the separation of residential location and workplace by a relocation of the residence from an urban core to a less densely populated area in the surroundings [5]. Models that explain suburbanisation with transport costs have a long tradition in spatial sciences. In the monocentric model by Alonso [6], for example, an improvement of transport infrastructure between the centre and the periphery leads in the medium to long run to an increase in city size through an expansion along the infrastructure, leading to suburbanisation and an extension of the commercial zones in the centre. An important precondition in the case of urban land uses is the observation that commuters have a fixed time budget that they are willing to devote to travelling, commonly empirically found to be slightly more than one hour across different spatial and temporal settings [7,8]. Lehner [9] has shown for Berlin that transport improvements and the diameter of built-up space have throughout the 19th and early 20th century indeed been directly correlated, each improvement in mass public transit allowing longer commute distances and opening up new areas around the city for residential development. However, while the (mostly rail-based) public transport infrastructure of this time on a regional scale promoted a structure of discontinuous settlements along a number of axes, only the spread of the car together with the expansion of road infrastructure from the middle of the 20th century on allowed the continuous extension of built-up area around cities. Digitalisation, working from home or while mobile and online shopping might further accelerate the spatial separation of workplace and residential location and deteriorate the importance of urban centres [10]. Even though the assumption of a single employment centre is a too crude simplification even for highly monocentric city-regions [11] (see "regionalisation"), it can be concluded that regional transport infrastructure increases the "daily urban space", the number and scope of activities for its inhabitants, but in the long run also the potential locations for households and firms, potentially causing longer commute distances through suburbanisation and the large-scale separation and upscaling of urban functions.

At the same time, there has been a surge in studies detecting at least a slow-down of suburbanisation and an increased interest of (some groups of) households to remain in or return to the regional centres, and within them to their urban cores, often labelled "re-urbanisation". A stronger appreciation of urban (cultural) amenities [12], a desire to co-locate with others of the same age group in times of demographic change [4] and the advantages of highly-accessible urban locations for dual-income couples and specialised knowledge workers in flexible employment conditions [13,14] are among the reasons identified behind this development in the case of Germany. This is not necessarily related to shorter commutes. Complex and atypical work mobility, especially reverse commuting to suburban workplaces and long-distance commuting between centres, are on the rise [14–16]. Still, real estate rental and purchase prices remain the highest in urban centres compared to their surroundings, at least in most European cities, which is why students, young professionals, high-earners and creatives are so far the main protagonists of re-urbanisation [5,17]. Re-urbanisation also does not necessarily mean a change of lifestyles compared to "suburbia" in terms of dwelling type or mobility, as the examples of "inner-city suburbanization" described by Frank [18] show. New regional transport infrastructure hence increases the opportunities to combine peripheral work and inner-city residential locations, particularly for high-income households, and increases the pool of potential employees for peripherally located firms. Inter-regional and long-distance commuting play a major role for this.

Regarding employment and innovation, the last two decades in regional sciences have brought forth a number of contributions that underscore the role of agglomeration economies, inter-regional competition and the interrelation between cumulative causation processes and network economies, which altogether account for an increasing concentration in particular of knowledge-intensive firms [19–22]. Notwithstanding digitalisation, face-to-face contacts remain the main channel for the transfer of tacit knowledge [23–25]. The strengthened role of knowledge in economic processes means that particularly spatial proximity to similar actors is valued more. "Metropolisation" describes the increasing concentration of economic activity, especially high-paid knowledge-intensive jobs in a few regions that are characterised by high international (air and high-speed rail) and internal connectivity, quality of life and a skilled workforce [26–28] while other regions fall behind. There is hence an implicit connection to re-urbanisation. While the effects of interregional transport infrastructure on this development are ambiguous, as it always goes both ways and can potentially drain newly connected regions of their economic activity, inner-regional infrastructure is generally assessed to be conductive to regional competitiveness [29] and advantages of agglomeration [30]. Aschauer [31] has demonstrated strong multiplier effects of public infrastructure, particularly transport infrastructure, on regional productivity. The boundary between inner- and interregional infrastructure is not always clear, as each new piece of transport infrastructure also expands the (functionally defined) region. This entails the possibility that remote towns become integrated into the hinterland of a neighbouring centre in terms of workplace locations of the local population. While this is often seen negatively by local actors, it can also be seen as a tool to alleviate spatial economic disparities, as every commuting relation implies a reverse stream of income spent locally [32]. Nevertheless, there can also be effects of improved networks on the distribution of functions within regions. Generally, they are found to be in favour of the largest city, especially when it is small in population size ("borrowed size"), even though local population size remains the most important factor for endowment with workplaces and urban functions [33,34]. Particularly, Munich has been found to be a case of borrowing size within its region [35].

While an increased premium for agglomeration means that firms still demand highly urban locations, diseconomies of agglomeration, such as overburdened transport systems, a lack of building space or a scarcity of skilled employees, which receive little attention in spatial sciences [1], are among the most important reasons for firms to relocate to suburban settings ("regionalisation", [36]) or even an overspill to more remote regions, as a study by Prognos just found for Germany [37]. Garreau [38] uses the term "edge cities" to describe new employment centres on the fringes of the suburbanising city—typically with high car-accessibility. Particularly, new hubs of international connectivity outside of cities, such as airports, have been nuclei of these developments, which increasingly provide both agglomeration and (relational) network economies to firms. In the long run, this can give rise to polycentric mega-regions [39] with multiple employment centres and dispersed commuter relations, often difficult for public transport to serve. However, European edge cities are found to have not (yet) reached the size and importance of their American counterparts [5], also due to the greater role of public transport, whose sunk costs exert a preserving influence for existing centres. Even larger shopping outlets are increasingly looking for inner-city locations again as consumer behaviour changes [40].

It seems hence that despite similar tendencies [2], the dissolution of urban and suburban in "regional urbanisation" as described by Soja [1] for the US might not be fully adequate for the European context [41]. Rather, "classical" residential suburbanisation still plays a major role [4,5], albeit in parallel to a selective re-urbanisation to the traditional cores [42], while agglomeration economies mean an increased concentration of employment. Polycentric regions, where they have emerged, more commonly resulted from an already existing urban pattern of cities with similar size and in greater proximity to each other with the advances of transport technology.

2.2. Integrated Urban and Transport Planning as Sustainable Regional Development Strategy

In urban and regional planning, such polycentric, networked regions are often seen as a strategy—a normative potential to sustain a high degree of agglomeration advantages without having to bear too much of the costs of overcrowding ("Decentral Concentration"), [43–47]. It is important to note that such concentration can occur on different spatial scales, from within-city to the regional scale. Such a decentral organisation of space is assumed to entail a range of social and environmental benefits as well, provided the urban areas are functionally and socially mixed, adequately dense, and interlinked by public transport.

Even though the direction of causality between built environment and travel mode choice remains disputed [17], mixing and densification, especially through infill housing, is generally thought to encourage social cohesion and avoid long commutes and hence traffic and should always take precedence before transport infrastructure extensions. Particularly, if low-density areas are connected to urban cores, the "spatial drag" is reduced, which risks urban sprawl, longer commutes, more traffic and a decomposition of uses [48]. Hence, transport infrastructure extensions require cautious planning.

Recent advances in car technology, such as battery-powered cars, car sharing or automated driving will certainly alleviate some of the problems that individual transport causes in metropolitan areas, such as local emissions. The inefficient use of urban public space for (often parking) private cars will most likely, however, not change. Hence, public transport, particularly rail-based, still represents an important element for the functioning of cities and regions for those connections that cannot be covered locally by walking or cycling [49].

Nevertheless, in some cases it might be necessary to extend transport networks. If suburbanisation is happening anyways, it might be more environmentally friendly to channel it towards low-emission rail-based public transport rather than car-dependent settlements. Additionally, at least once that new public transport infrastructure has already been constructed, abandoning the generated urban development potentials would be an inefficient use of resources. In overheated rental and real estate markets, they can alleviate the burden on households.

Nevertheless, this requires a coordinated regional action that involves all affected municipalities, which might reject development for various reasons. Still, many decision-makers take a demand-side view and see mostly the advantages that new transport infrastructure provides for the existing population of a municipality, while too little attention is paid to new development potentials that are created. As a result, "integrated location and transport planning" or "transit-oriented development" [50] are now predominant planning approaches to coordinate settlement development with public transport infrastructure investment to ensure that both residents and employees have at least the option to use public transport and that transport infrastructure is used efficiently where it exists [51] (see also "3. Materials and Methods").

3. Case Study and Context

The Munich Metropolitan Region (MMR), located in the south-east of Germany, is a functionally defined region consisting of the city of Munich as the main employment, business and administrative centre; its surrounding commuter belt and a ring of larger regional centres (among them Augsburg and Ingolstadt). The regional centres are characterised by an own commuter hinterland but exhibit strong functional relations with Munich in terms of business locations or common infrastructure, such as the airport. It has an area of about 26,000 km^2 and a population of about 6 million, while its main centre, Munich, has a population of 1.55 million people in 2019 [52].

The MMR is characterised by a strong local economy, with seven of the 30 firms in the main German stock index DAX located in Munich. Compared with other metropolitan regions in the country, its unemployment rate is low and the purchasing power considerably above average. It also regularly appears on high positions in urban quality of living ratings [53,54]. This has resulted in continuous growth with respect to both population and economy in the last decades, and it is among the few German regions for which strong further population growth is expected in the future [55]. The strong expansion of population and employment means that the MMR now suffers from growing pains. Housing development has not kept up with the pace of immigration to the region, and real estate prices are among the highest in Germany. This is despite strong suburbanisation that has occurred since the 1960s.

3.1. Public Transport in the MMR

In spite of the fact that the car manufacturer BMW is among the largest employers in the region, the modal split shows significantly above average and growing shares for public transport and cycling in both the core city Munich and the commuter belt, compared to other regions in Germany. As a result of rising motorisation rates in the 1950s, actors such as the local chamber of industry and commerce had recognised earlier than elsewhere the detrimental effects of car traffic on public space in the inner city and advocated public transport investments instead [56]. Today, 15% of all journeys in the region and 21% of all journeys in the city occurred using public transport; the figure rises to 51% for journeys to/from the inner city [57]. The figures for car-use (as driver) are 35%, 27% and 8%, respectively. Given the above-average usage of public transport, the system still exerts an influence on locational choices for a high share of the regional population.

The transport system—both road and rail—has largely been constructed in a monocentric alignment; there are few tangential connections, except between the regional centres. This transport network reflects the settlement patterns, and vice versa. The most important regional public transport infrastructure is the "S-Bahn"-network of suburban railway lines. The network was initially constructed as part of the preparations for the 1972 Olympic Games in Munich, which boosted the city's public infrastructure, by consolidating and upgrading varyingly used existing suburban lines and linking them with an east-west tunnel below the city centre. It is now used daily by up to 840,000 passengers [58], near its capacity limits. Besides the S-Bahn, the MMR is served by an extensive regional train network (less frequent than the S-Bahn), local and regional bus lines, as well as underground and tram services in Munich (Figure 1).

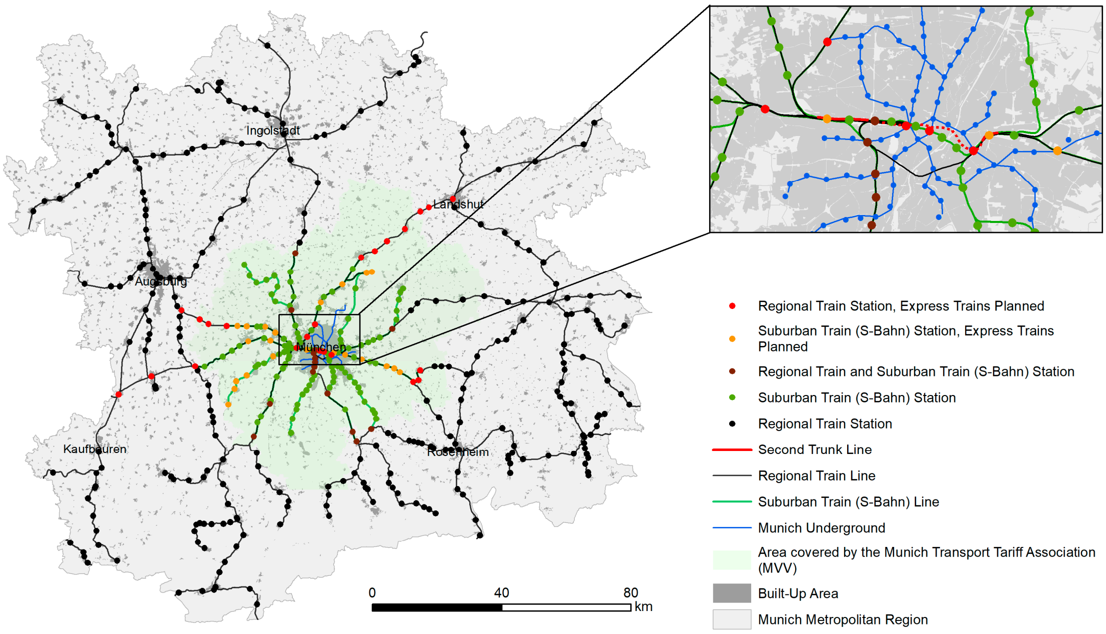

Figure 1. Current and future rail infrastructure in the Munich Metropolitan Region (Source: own work, using geodata by Bayerische Vermessungsverwaltung, Bundesamt für Kartographie und Geodäsie, Deutsche Bahn).

3.2. The "Second Trunk Line" ("Zweite Stammstrecke")

After several decades of only piecemeal additions and improvements of the rail-based infrastructure, construction has now started on a significant alteration of the system, the so-called "second trunk line" ("Zweite Stammstrecke"). The 11.9 km long line—mostly in tunnels—is meant to double the capacity of the existing east-west line across the city centre that is currently used by all S-Bahn train lines. Already envisaged in the 1970s [56], it is scheduled for completion in 2028. The main aim is to improve the reliability and frequency of the S-Bahn system and to allow the introduction of express trains that skip several stations in the inner areas of the MMR. The express network will also stretch farther into the surrounding area than the existing S-Bahn network and will cover more of the metropolitan region, instead of 'only' the narrower city-region of Munich, currently included in the Munich Transport Tariff Association (MVV). The express trains mean that potential commute times to the city centre will be further reduced for a large number of suburban locations. The plan to construct the second trunk line has been strongly disputed by a number of public initiatives, who argue that that upgrading tangential connections would have been cheaper, faster and more desirable (e.g., [59,60]).

3.3. Previous Studies on the Relationship of Transport and Land Use in the MMR

Already the construction of the S-Bahn network had been monitored scientifically with respect to its consequences for settlement patterns. The most important works by Kreibich [61] and Linder [56] from the 1970s will be briefly summarised in the following (own translations). In his assessment of the likely development effects of the S-Bahn, Linder [56] is very critical of the effects of mass transit on patterns of land use and its capacity to reduce car traffic. He sees the S-Bahn as a structuring element of development of region-at-large and an attempt by the (then fully public) German rail operator Deutsche Bundesbahn (DB) to actively participate in the economic development and suburbanisation of Munich (p. 55). He describes the implementation of the then new (first) trunk rail line as "dictate" of segregation of employment, residential and recreational functions for the Munich region by DB, with the aim of a "pyramid construction of large-sized segregated economic spaces" (p. 203) for the sole purpose of economic growth for the region as a whole. Particularly, it encouraged economic concentration through increasing accessibility and locational advantages in central locations, especially when constructed radially (p. 198/203). The displacement of residential uses from the centre to the periphery in favour of commercial uses means displacement of the least with the most traffic-intensive use, creating unnecessary traffic that could be avoided with a closer allocation of spatial functions (p. 195/203). The capacity constraint of transport infrastructure in central locations hence means a real development barrier in the process of urban densification: Where disadvantages of growing congestion offset the advantages of central locations, a growing economy is forced to divert to other centres or the periphery, which might be more desirable in social terms (p. 196).

This view is shared by Kreibich [61]. His analysis of the settlement effects six years after the opening of the S-Bahn strikingly shows its catalysing effects on suburbanisation, with significantly higher population growth rates in towns along the new suburban rail lines. At the same time, he argues that firms are no longer required to operate branch offices in sub-centres, instead being able to service a much wider area from the centre of Munich, reinforcing the monocentric structure of the region and leading to displacement of 50,000 residents from central areas between 1961 and 1974 (p. 294). Like Linder, Kreibich also criticizes the lack of tangential connections (p. 302). In being an instrument of regional economic growth, with detrimental consequences for interregional disparities, the S-Bahn "serves the continuing accumulation of capital in the centre of Munich and the preservation of the capitalist system".

More recent comparable studies have been conducted by Schürmann and Spiekermann [62] for the German Federal Institute for Research on Building, Urban Affairs and Spatial Development (BBSR) and by Thierstein et al. [63].

Schürmann and Spiekermann [62] analyse the effects of four transport infrastructure projects (two rail and two road) in different German city-regions. For the MMR, they analyse the effects of the A96 motorway extension west of Munich completed in 1996. They find that the share of out-commuters to Munich along the corridor is highly correlated with the accessibility level of a municipality within the region, and that there are strong relationships between the accessibility level and the net migration of a municipality as well as the change rate of accessibility and migration surplus. Regarding employment, they find that the relationship between accessibility level and employment development is weakly negative but that improvements in accessibility are correlated with employment growth (particularly for distance- and car-based accessibility indicators). Overall, they identify a strong relation between accessibility levels, land values and urbanisation. Interestingly, their data also shows that the establishment of the new Munich airport north-east of Munich in 1992 seems to have had even stronger effects on employment and population in the respective surrounding municipalities than the A96 corridor.

A study of household, workplace and mobility choices in Munich by Thierstein et al. [63–65] has highlighted the need for differentiation between population subgroups and their motivations for residential and employment location choices. In a sub-project, Zhao et al. [64] demonstrate for example that knowledge-workers show differing patterns of the use of space according to their knowledge-base (as identified by Asheim [66]). While "analytic" knowledge workers—e.g., in the domains of engineering—show a higher willingness to settle in a suburban setting and a preference for car-oriented transportation, "synthetic" and "symbolic" knowledge workers, e.g., in the art and cultural industries, show a stronger preference for urban locations and for active-mode transportation. The study also underlines the need for a better jobs–housing balance in the municipalities of the region as a strategy to reduce commuting distances, as well as an improvement of urban amenities in smaller municipalities [65].

Finally, the Swiss Federal Office for Spatial Development (ARE) [67] has studied the impacts of the opening of the suburban rail network in Zurich 1990, which is comparable to Munich in terms of its economic structure. The study likewise finds evidence for population growth in the area served by the system but even stronger growth in some unaffected municipalities. In terms of employment, areas that have not benefitted from a travel time decrease to the centre have suffered from losses, as well as areas with a strong increase in accessibility in already good starting positions. No clear overall tendencies could be observed. The study highlights the conjecture of three forces influencing local population and employment growth, transport effects, (endogenous) potentials and actors, and recommends stronger collaboration between municipalities, landowners and rail operators to activate building potentials in proximity to stations.

In sum, past studies on the effects of transport infrastructure improvements on settlement structures in Munich tend to find strong relations to suburbanisation, the large-scale segregation and concentration of urban functions and metropolisation but little indications for a connection to re-urbanisation or a regional dispersion of economic activity. The effects seem to weaken with time. The MMR seems, at least until now, as a whole, not to be characterised by the "disappearance of traditional suburbia" or a "blurring of the boundary between urban and suburban" [1], nor have major "outer cities" materialised in low-density suburbs that could rival the traditional urban cores. The studies hint at the conclusion that the monocentric alignment of transport infrastructure, along with other planning policies to protect the traditional urban cores could be responsible for this.

4. Materials and Methods

The fourfold division of the paper is also reflected in the methods. To answer the first research question, we analyse recent commuter data for the MMR between 2005 and 2018 by the German Federal Employment Agency, using descriptive statistics. Commuter data is very useful to identify concentration and de-concentration processes of households and employment, as it always encompasses both residential and work locations [14].

For the second research question, we use a gravitational accessibility model of population. Gravitational accessibility is a measure to describe the cumulative "possibility of interaction" [68] measured through the number of people (or jobs, amenities etc.) that can be reached from a certain location, while more distant destinations in terms of travel time are weighted less than those in greater proximity. We use an exponential distance decay function in the form of

$$Gravity[i] = \sum \frac{W[j]}{e^{\beta \times d[i,j]}} \quad (1)$$

where *Gravity* [*i*] is the Gravity index at location *i*, W[*j*] is the weight of destination *j*, *d*[*i*,*j*] is the travel time between locations *i* and *j*, and β is the exponent for adjusting the distance decay (see [69] for a more detailed description). The gravitational approach has a long tradition in land use-transport interaction modelling and accessibility analysis (e.g., [70,71]), as it is assumed to model interactions and travel likelihood closely.

The distance decay is calibrated using actual commuter data from the MMR for 2018. The share of out-commuters to Munich on all out-commuters in a municipality halves after about 20 minutes of public transport travel distance between the municipality and Munich, resulting in a decay factor of 0.033 for the exponential function (R^2 = 0.78), in line with a range of other studies of regional commuting relations (e.g., [72–74]). The model includes 512 rail stations and their interconnections in the MMR. It encompasses not only the S-Bahn network, which so far covers only Munich and its hinterland but not the regional centres, but also the regional train network that stretches across the entire metropolitan region, and the underground network in Munich. The travel time data was gathered manually from the travel information of Deutsche Bahn [75] for a Tuesday morning in the timetable period of 2019 without construction works. The data for 2028, after the opening of the second trunk line, was estimated based on the currently planned operational programme as published on the official project website [76]. No new stations will be added through the project; the new express lines will only serve—some—existing stations.

Gravitational accessibility modelling has a number of potential weaknesses. To circumvent the self-potential bias in cell-based gravitational accessibility analyses [77], we followed the method of [78] and calculated the average weighted distances from 100 × 100 m population grid cells of the 2011 census [79] to the nearest station included in the model to correct for differing internal population distributions. These population figures are then used as weights of the stations. A common challenge of accessibility models is furthermore a negative bias towards the fringes, unless a buffer zone is included. Hence, we added a buffer zone of 518 stations in a 2-hours travel time buffer around the MMR. In Austria, however, only a 1 × 1 km population grid could be used to derive station weights. The accessibility calculations were carried out for 2019 and 2028, and the results compared. No changes in the distance decay parameter or the population distribution were assumed. An important constraint of the model is that it does not reflect differences in service frequencies of the connections included and that transfer times can only be modelled very crudely. For the model, a fixed threshold of 120 minutes as minimum frequency was chosen to determine whether a connection is included or not, and transfer times were generally assumed to be two minutes, as public transport in the core areas of the region is quite frequent. Here, agent-based modelling provides more realistic results on the level of individual users of the system. Another important qualification must be made regarding the costs used in this paper: It focuses on time-costs only, while monetary costs are important determinants of public transport use as well. In the course of the "Zweite Stammstrecke" project, it is however mainly the temporal aspect that will change. The new lines will be included in the existing transit tariff of Munich. We hence refrained from including monetary costs in our analysis.

For the third step, we gathered additional data on the functions around the 512 stations, namely demographic, employment and land use data in a 700 m radius. Such 700 m radius is typically seen as a distance that residents in urban and suburban settings on average are willing to walk to a higher-order public transport stop like a train station [80]. Where these radiuses overlap, they were cut along the equidistant line between the stations to avoid double-counting. In detail, we collected data for three indicators, the population size, the number of firms, as well as the combined number of retail, leisure and public facilities—henceforth called "facilities". Firms and facilities data originate from the company database Bisnode [81], which lists more than 400,000 firms for the MMR. Facilities were identified according to the SIC classification included in the database (SIC codes 52 to 59 for retail, 78, 79 and 84 for leisure and 91 to 99 for public facilities). In a few cases, the values for shopping and leisure facilities were manually adjusted to adequately represent mass attractors, such as football stadia, large shopping centres and important sights.

It is a basic principle of integrated urban and land use planning that the accessibility a public transport station provides should be in balance with the density of functions around the station. A station with high accessibility (frequent and fast connections to a lot of potential opportunities) should not be surrounded by greenfields—this would be an inefficient use of the public transport resources. Vice versa, dense urban areas should be served by highly accessible public transport stations to avoid car-dependent settlement structures. Hence, planning should not allocate too many functions to stations with low accessibility, or areas far away from public transport, and encourage development around highly accessible but underused transport nodes. A basic conceptual model that describes this relationship is the "node-place-model" by Bertolini [51] that suggests aiming for a balance of "node" (accessibility) and "place" (functional density) at each station. It allows visually to identify "unsustained nodes" and "unsustained places" (stations with an accessibility surplus over the local density of functions and vice versa), as well as "dependent" and "stressed" stations, that are balanced but in danger of inefficiency or overcrowding. The model has been operationalised and tested in various settings (e.g., [82,83]), and several additions have been proposed to derive more detailed station typologies (e.g., [84]). For this paper, we assumed the accessibility values from the second step as node values and the combined functional data (population size, firms and facilities) as place values.

As a fourth step, to derive policy recommendations, we used the indicators and additional data to construct six variables for a cluster analysis:

- Functional Density (or "Place Value", as described above).
- Functional Surplus: The surplus or deficit of local functional density compared to accessibility.
- Residential Surplus: The surplus or deficit of local population size compared to jobs and facilities.
- Accessibility Change (2019–2028).
- Densification Potential.
- New Building Potential.

The densification potential was calculated by determining the area within the 700 m radius around the station that is classified as "built up" in the land use cadastre [85] and dividing it by the place value. The variable hence describes the efficiency of the use of space, i.e., the space needed per point of place value. We assumed as new building potential all areas classified as agricultural or forest, unless they are protected.

The data for all indicators except the new building potential were divided by their maxima and transformed using a square root function to smooth out outliers. For the functional data, this was done separately for population size, firms and facilities and later summed up. All indicators were then normalised on a 1 to 100 scale. The variables were used for a K-means clustering approach to identify groups of similar stations. A solution with seven clusters was chosen as appropriate solution.

5. Results and Discussion

5.1. Structure and Dynamics of Commuting Relationships in the MMR 2005–2018

The first research question deals with the current structure and recent dynamics of commuter relationships. Figure 2 shows the strongest commuting relationships between municipalities in the MMR (250 and more commuters), Figure 3 shows the strongest changes of commuter relationships between 2005 and 2018. No major infrastructure works have been completed during this phase. Aggregate commuting has decreased between 13.5% of all pairs of municipalities, but in these cases only in small absolute numbers. Figure 3 hence shows only relations where the aggregate number of commuters has increased by more than 150.

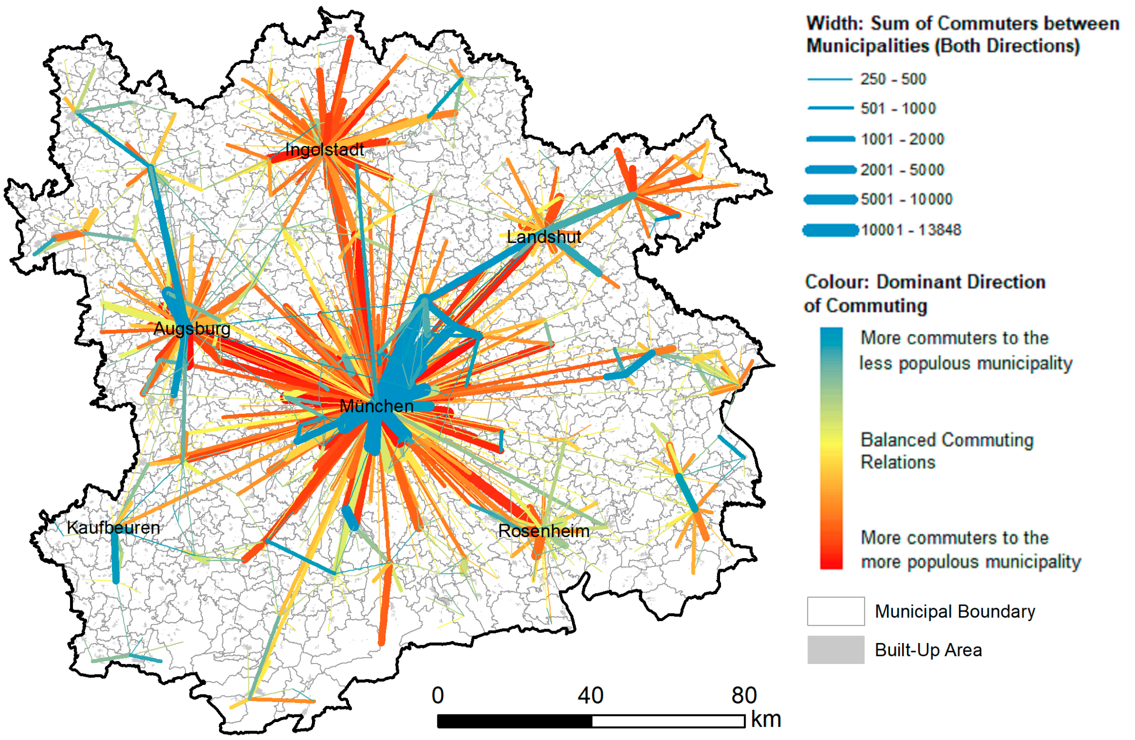

Figure 2. Strongest commuting relations in the MMR in 2018 (Source: own work, using geodata by Bayerische Vermessungsverwaltung, Bundesamt für Kartographie und Geodäsie, Bundesagentur für Arbeit).

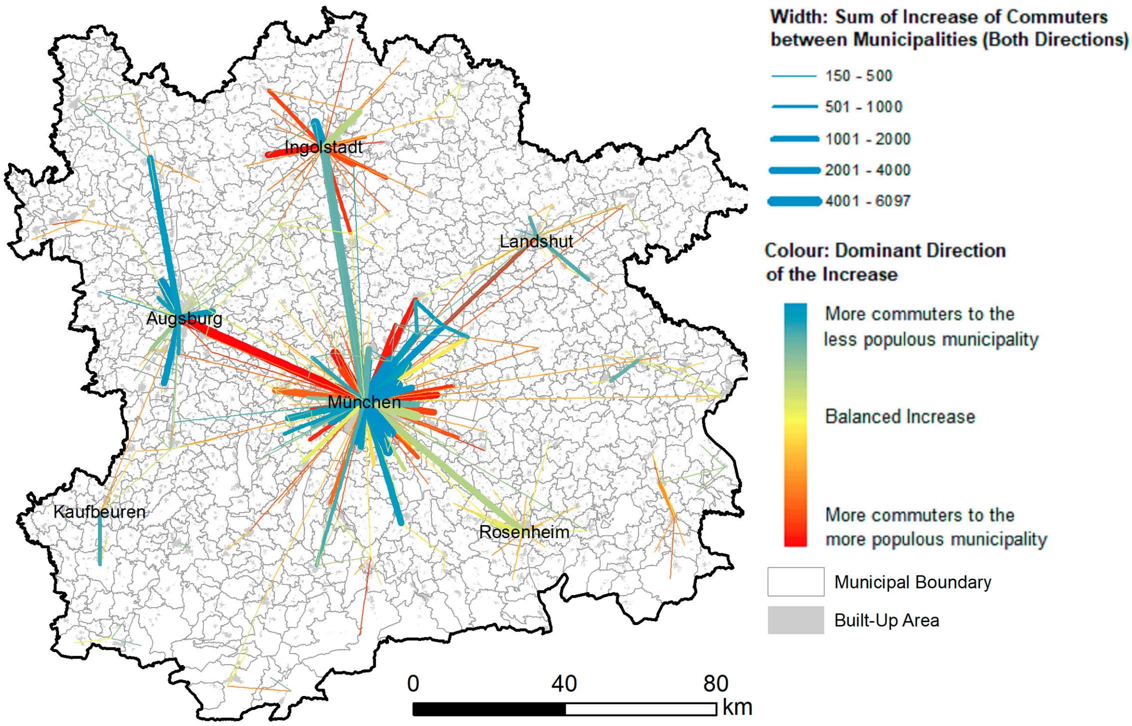

Figure 3. Dynamics of commuter relationships in the MMR between 2005 and 2018 (Source: own work, using geodata by Bayerische Vermessungsverwaltung, Bundesamt für Kartographie und Geodäsie, Bundesagentur für Arbeit).

Commuting relationships in the MMR still show a fairly classical pattern of core–periphery. The city of Munich and, to a lesser degree, the regional centres of Augsburg and Ingolstadt are dominant centres of in-commuting, which shows the degree of metropolisation and suburbanisation in the region. However, some of the municipalities directly bordering on Munich, particularly to the south and north-east, exhibit a commuter surplus from Munich. All these municipalities are well-connected to Munich by rail-based public transport. These relations also show the strongest dynamics during the last 14 years. The most remarkable change has occurred between Munich and its neighbouring municipality Unterföhring to the north-east. The number of out-commuters from Munich to Unterföhring has risen from 6948 to 11,300 in just 14 years, while the reverse direction is only travelled by 2700 commuters a day (2005: 1703). This means that now the strongest commuter flow in the MMR is no longer directed at Munich as in 2005, but away from Munich to one of its suburban neighbours. The change is likely driven by a high number of media and insurance companies located there that have exhibited strong job growth. The town is also located on the axis between Munich and the airport, which is another job motor in the region. It seems however that employees at firms in Unterföhring are not willing or able to relocate there and instead chose to commute from Munich, despite slightly higher rental and real estate prices, which points to an increasing role of urban amenities for employees in knowledge-intensive firms.

The weak position of Augsburg, the second largest city in the region, comes as a surprise: There has been a strong increase in out-commuting to almost all neighbouring municipalities during the last one and a half decades. Augsburg is now the number one commuter origin for Munich and could functionally become a large suburb in the future, as there are no signs of a change in dynamics or an increase of commuting in the reverse direction. Commuting between the other regional centres and Munich has also strongly increased but in a more balanced way. Not included in the figure, but likewise with above-average increases, are commuting relations between the regional centres in the MMR and those of neighbouring regions, particularly between Munich and Ingolstadt, on the one hand, and Nuremberg, on the other, confirming the findings of Pütz [14].

In total, Munich and Ingolstadt still gained new in-commuters from the fringes of their commuter zones, while the commuting relationships with some of their immediately surrounding municipalities are increasingly characterised by a reverse commuting, while overall commuting distances continued to rise. This is in line with previous literature for the Munich case [41,86]. It is thus fair to still speak of a rather monocentrically organised region, with signs of polycentricism immediately around the major regional centres. However, there are two main restrictions to this argumentation: First, the latter can be interpreted as a phenomenon not entirely different from the past, just an upscaling—polycentric development, albeit weak, has happened within the city-limits before (e.g., [87]), and only now that it exceeds the administrative boundaries, it is also visible in the commuter data. Second, and more importantly, tangential commuting relations still play almost no role in the MMR. Among the top commuting relations, there is none that is not directed either to or from one of the major centres Munich, Augsburg and Ingolstadt. These are also still the commuting relations with the strongest growth. Only the 144th relation (Erding–Freising, 1100 commuters) is tangential. This is likely caused by the airport, which is located on the border between the two municipalities and shows its capability to act as nucleus for economic activity.

Regarding our first research question, we conclude that, indeed, commuter relations suggest a growing role of out-commuting from the major centres of the region to municipalities in the vicinity and therewith highly urban and central residential locations combined with suburban employment (re-urbanisation and regionalisation). However, the majority of commuting relations still conform to the traditional regional core–periphery dichotomy. In addition, the new employment centres in the surroundings of Munich, Augsburg and Ingolstadt have so far not been able to attract substantial tangential commuting relations from their other neighbours, which might be due to the monocentric structure of the public transport system.

5.2. Rail-Based Public Transport Accessibility and Accessibility Changes through the Second Trunk Line

Figure 4 shows the clear accessibility gradient by rail-based public transport in the MMR. The most accessible station is expectably Munich main station, from where travel times to most other destinations are shortest (set as 100%). The first 48 of 512 stations in terms of accessibility are located in Munich proper, among them all stations along the first S-Bahn trunk line. Despite the inclusion of a large buffer zone, the stations to the south, close to the Alps and the Austrian border, show the lowest accessibility values, also because often they are located in "dead-ends" of lines. The regional centres Augsburg, Ingolstadt, Landshut and Rosenheim clearly exhibit smaller accessibility maxima, but these do not come close to the values that even suburban stations around Munich show.

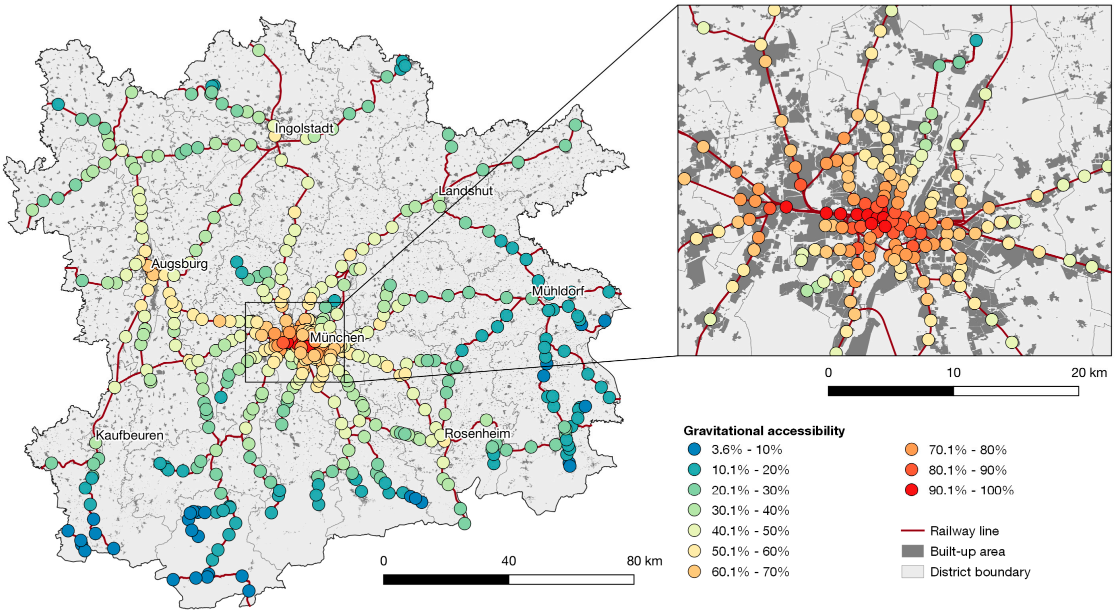

Figure 4. Accessibility of population with rail-based public transport at railway stations in the MMR 2019 (Munich main station = 100%) (Source: own work, using geodata by Bayerische Vermessungsverwaltung, Bundesamt für Kartographie und Geodäsie, Deutsche Bahn).

Figure 5 shows the increases in gravitational accessibility induced by the construction of second trunk line. The east–west orientation of the new infrastructure means that improvements of accessibility are foremost located in these sectors around the city. The stations in the south of the region will profit relatively little, even though they are currently already characterised by low absolute accessibility levels. Nevertheless, it can be seen that all stations in the region profit from an increase of accessibility of at least 22%, even where there will be no direct lines using the new infrastructure, due to trickle-down effects throughout the region. Munich main station is still the point of the highest accessibility, and it is among the stations with the highest absolute accessibility increases, which shows the reinforcing effect of the second trunk line on the monocentric regional structure and confirms our hypothesis. Other stations along the second trunk line can also strongly improve their rank position.

However, in relative terms, suburban stations along four corridors to the west, north and east of the city are to gain most, albeit from a low previous level. Some of the municipalities to the west of Munich, currently showing a strong commuter-deficit, will experience a doubling of their accessibility, higher than some peripheral parts of the city of Munich proper. The strongest accessibility gain was determined for the small town of Weßling, the designated first stop of a planned express line beyond the city centre.

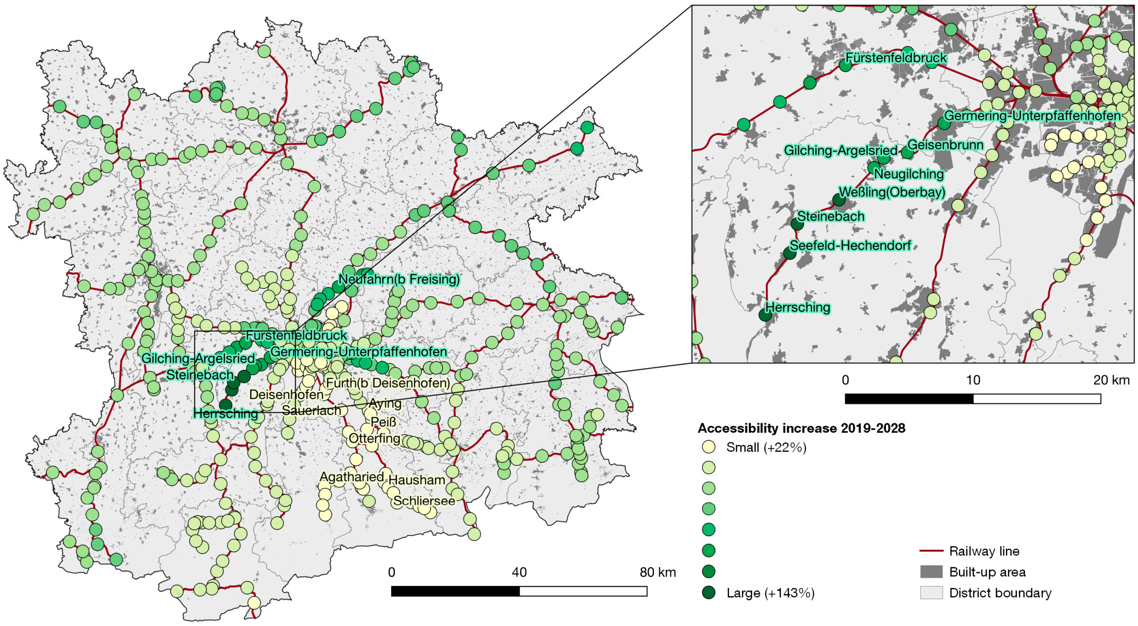

Figure 5. Change of accessibility of population with rail-based public transport at railway stations in the MMR 2019–2028 (Source: own work, using geodata by Bayerische Vermessungsverwaltung, Bundesamt für Kartographie und Geodäsie, Deutsche Bahn).

The analysis shows that the strongest effects are highly selective and affect only some sectors of the public transport network. The effects depend highly on the scheduled services. It also shows that the effects quickly attenuate with distance, assuming a commuting-related distance decay factor. Still, some smaller regional centres that were so far in greater relational distance to Munich, such as Kaufering, Buchloe and Mering to the west of Munich, will receive a direct connection to the very centre of the city and partially fall below the critical commuting time threshold of slightly more than half an hour. Methodologically, the analysis shows the merit of gravitational accessibility analysis for visualisations.

As accessibility and land values are strongly related, the map can also be read as a projection—or at least a spatial perspective—of likely demand changes on the land market. Based on the previous experiences in the region as described in the literature review and the results of chapter 3.1, it can be assumed that particularly the west of Munich will undergo another wave of suburbanisation that will intensify the pressure in the existing commuter belt and extend it further westwards to include the smaller regional centres there. At the same time, the monocentric alignment of the second trunk line means that it will increase the potential customer and employee base of firms in highly central locations, contributing to further segregation of functions and an extension of the commercial zone in Munich.

However, planning can and should set the framework for this development and try to work towards greater regionalisation of economic activity. In the following chapter, we develop a station typology with policy recommendations, which not only includes accessibility but also local potentials and small-scale mix of uses.

5.3. Comparison of Accessibility Levels and Functional Density around Railway Stations in the MMR

Figure 6 compares the accessibility ("Node") and combined functional density of population; firms; and public, leisure and shopping facilities ("Place") for all 512 rail stations in the MMR in 2018. It shows that there is a broad but significant relationship between node and place values (R^2 = 0.41), and a high number of stations can be classified as "balanced" (termed "accessible" in the stricter sense by Bertolini [51]). This means that the larger the number of people that can reach a certain station in a short amount of time, the higher the density of functions around it, which is a characteristic of a sustainable transport system (see "methods"). The stations categorised as in "Stress" are all located in the inner city of Munich, where a combination of high density and accessibility can lead to overcrowding. At the same time, this is a sign for the still highly monocentric transport and settlement structure of the region.

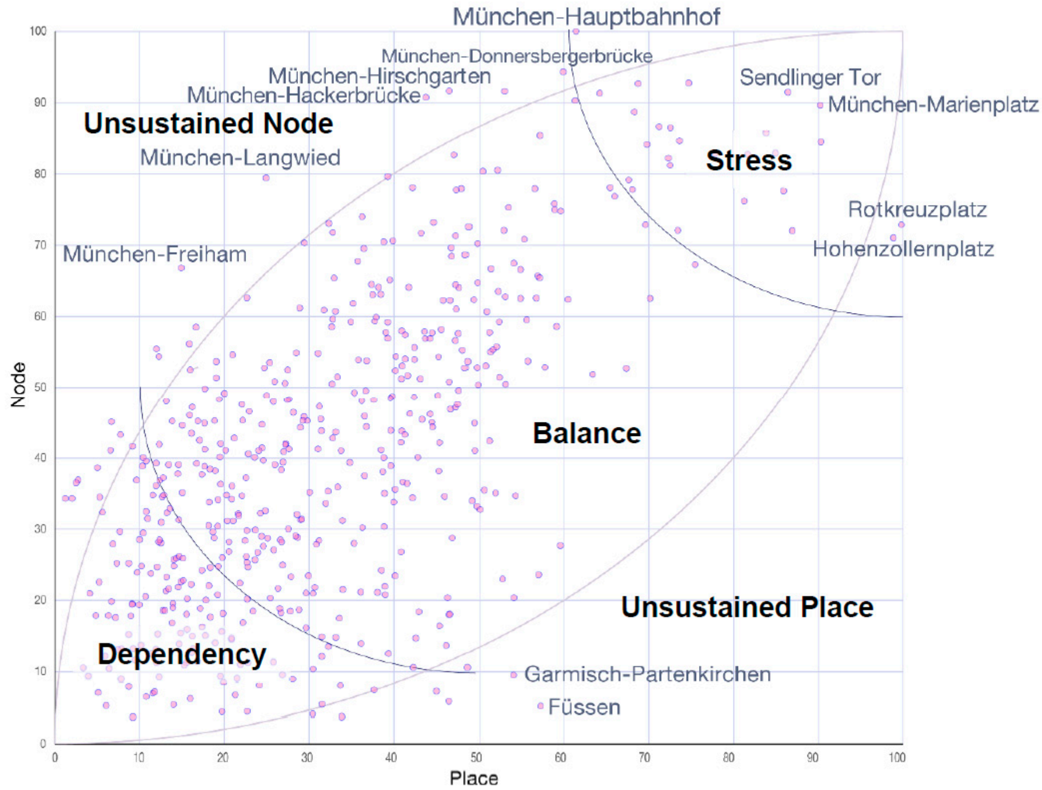

Figure 6. "Node-place diagram" for the Munich metropolitan region in 2019 (Source: own work).

A few stations are located outside of the balanced category. On the one hand, there are "unsustained places", with high functional density but low accessibility. Many of them, such as Garmisch-Partenkirchen and Füssen, are located in the Alpine region south of Munich, where, as described earlier, the difficult topography means that rail lines are not interconnected. However, unsustained places can also be found in the city of Munich proper. Two inner-city sub-centres, Hohenzollernplatz and Rotkreuzplatz, exhibit a much stronger functional density than their accessibility levels would give reason to expect. Within Munich, accessibility levels quickly attenuate with distance from the east–west trunk line. Neither the first nor the second trunk line serves these stations, meaning that they will only profit indirectly from future accessibility increases and not more than other, balanced, stations. This shows that de-concentration of activities into smaller local clusters can at least be identified on a within-city scale and does not necessarily correspond to public transport infrastructure.

The "unsustained nodes", on the other hand, show a less clear pattern. They are distributed across the entire region and are more dependent on individual local conditions, like protected and irreclaimable areas. Figure 7 shows the spatial dimension of the node-place diagram.

The impact of the second trunk line means that a number of stations will move out of the "Balance" into the "Unsustained Node" category, for which an increase of functional densities should accordingly be sought. It should be clear however that the model should never be taken as strict blueprint but that the accessibility-induced development potential must always be harmonised with other local requirements, such as environmental protection or conservation.

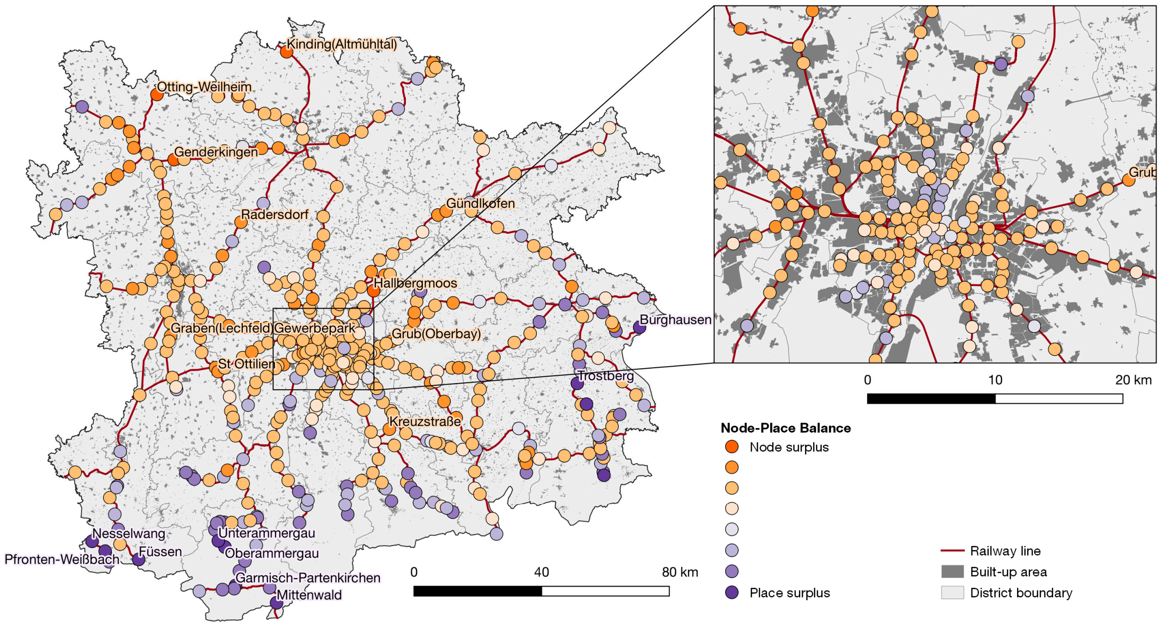

Figure 7. Balance of accessibility ("Node") and functional density ("Place") around railway stations in the MMR in 2019 (Source: own work, using geodata by Bayerische Vermessungsverwaltung, Bundesamt für Kartographie und Geodäsie, Deutsche Bahn).

The fact that the model focuses on railway stations brings with it advantages and disadvantages: On the one hand, railway stations in urban areas are often surrounded by derelict railway land and disused production sites, as a result of the structural change to the knowledge economy. These represent prime building land. The proximity to high-quality public transport means that this land is a convenient location for car-free or car-reduced neighbourhoods. On the other hand, noise from railway lines is a challenge to be adequately dealt with by an appropriate allocation of uses and modern techniques of acoustic protection. For land immediately adjacent to railway lines "urban production" and similar new forms of small-scale manufacturing might also be a suitable use.

Nevertheless, the node-place model in its basic form only uses an aggregate perspective on "Place". However, previous studies point at the importance of small-scale mixing of uses to avoid wasteful commuting and unnecessary traffic (see "Theoretical Background"). Disintegrating the combined place indicator into its sub-dimensions allows to include this dimension into the analysis. A balanced distribution of residential and commercial uses at a station hints at advantageous conditions for local inhabitants to avoid longer commutes.

When comparing residential density at stations with job and facility density (Figure 8), the CBD in the inner-city of Munich can be clearly identified. In the surroundings of the most central stations, Marienplatz, Karlsplatz (Stachus) and the main station, firm locations and facilities strongly outweigh residential locations. Marienplatz, commonly considered the heart of the city and hosting the city hall, is endowed with one of the highest absolute number of firms but ranks only at 237th place in terms of population size. The fact that the stations of highest accessibility correspond with those of the highest imbalance between residential and commercial uses corresponds to classical models of regional land use distributions [6]. Clearly, the S-Bahn serves the hotspots of metropolisation in the region.

Interestingly, a number of stations outside of the traditional urban centres show a strong commercial surplus as well, most noticeable around the airport of Munich, at the major suburban campus of the Technical University of Munich in Garching and at Graben (Lechfeld) Gewerbepark, where a major online retail company has located its regional distribution centre. It seems that mainly strong individual actors, both public and private, are able to initiate and sustain a regionalisation of employment.

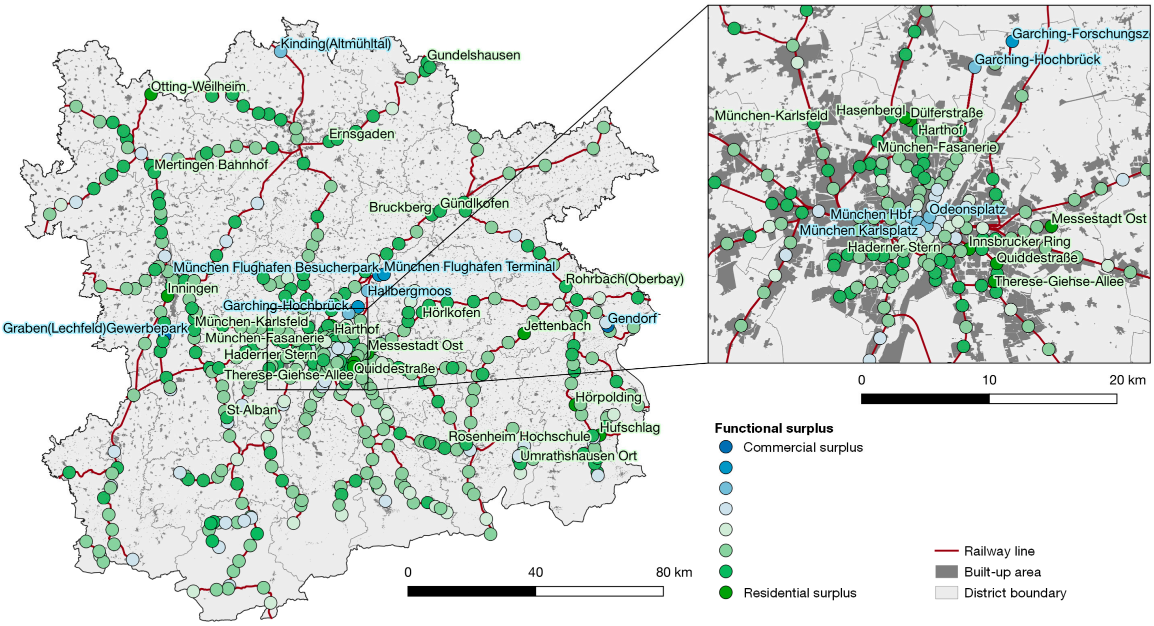

Figure 8. Surplus of residential or commercial (firms and services) uses at railway stations in the MMR 2019 (Source: own work, using geodata by Bayerische Vermessungsverwaltung, Bundesamt für Kartographie und Geodäsie, Deutsche Bahn).

In a few cases, the settlement areas meant to be served by stations are located more than 700 m away from the rail line, e.g., due to technical constraints during the construction phase. In these exceptional cases, the comparison of node and place values yields strong outliers. On the one hand, this can be desired in terms of the model purpose, i.e., it shows the need to establish a new centre around the station. However, in these cases, it might be more useful to try to shift the station in greater spatial proximity to the built-up area.

5.4. Policy Recommendations Based on Cluster Analysis

To integrate the different steps of our analysis, accessibility change, balance of accessibility and functions, as well as balance of residential and commercial uses, and to combine them with densification and new building potentials, we perform a cluster analysis (see "Methods"). We identify seven clusters of stations that show strong similarities with respect to the input variables and that allow the formulation of policy recommendations. Figure 9 shows the spatial distribution of the clusters, Table 2 shows the average values of the variables used for each cluster.

Table 2. Average values of the clustering variables for the seven clusters of stations.

Cluster Name	Number of Stations	Functional Density	Functional Surplus	Residential Surplus	Accessibility Change	Densifi-cation Potential	New Building Potential
Inner-city Situations	88	6053	−1958	2657	1892	2675	136
Suburban Places	130	3194	−3190	4248	2314	3822	1771
Stations in Transition	35	3909	−3544	4649	5729	3564	2050
Rural Areas	145	1531	−4282	4939	2832	3710	6591
Boundary Places	105	3275	5297	2876	2447	3644	3017
Traffic Hubs	5	876	−6794	−4392	4868	2526	1553
Commercial Places	4	1054	−4698	−7067	2153	7361	4356

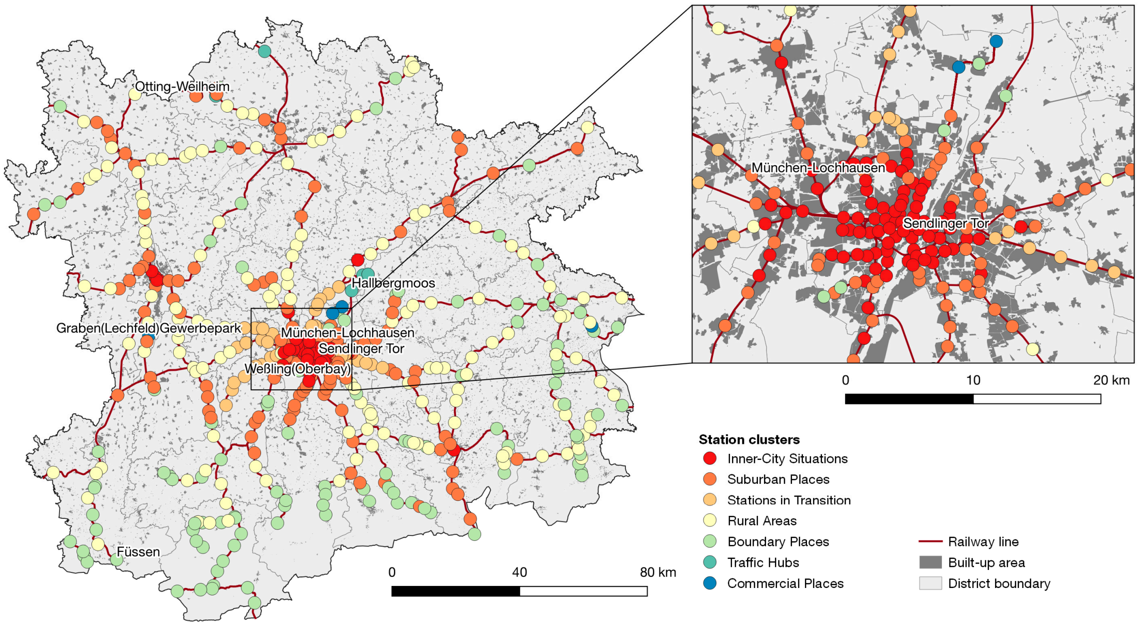

Figure 9. Spatial distribution of the station clusters (Source: own work, using geodata by Bayerische Vermessungsverwaltung, Bundesamt für Kartographie und Geodäsie, Deutsche Bahn).

The clustering results in five groups that can be broadly allocated spatially. (1) Inner-city Situations show the highest functional density, a relatively low residential surplus and almost no new building potential. Since many can be found in the "stressed" category in the node-place diagram, solutions should be sought to relieve congestion in the most affected stations, such as new tangential connections on the city scale. For those stations that show a high functional surplus, the focus should be on transport improvements rather than densification measures. (2) Suburban Places are characterised by a high residential surplus, proximity to a larger city, medium functional densities and average densification and new building potentials. Their mono-functionality means longer than necessary commute distances, indicating a potential to improve the local mix of uses and encourage regionalisation of economic activities. The strongest drivers of such a regionalisation are individual strong public or private actors, such as universities, research facilities, larger firms or cultural facilities that are able to set in motion a self-reinforcing development. (3) The "Stations in Transition" can be seen as a subgroup of Suburban Places but with high accessibility gains until 2028. Despite the potentially negative effects on travel distances, the new development potentials should be used to avoid further car-oriented suburbanisation. A mixing of land uses should be targeted for from the beginning. (4) Rural areas clearly fall short of the functional density in the suburban areas but exhibit the highest residential surplus and new building potential. Despite this potential, further residential densification should not be considered, as overall accessibility is low and distances to employment centres are long. More local jobs would be advantageous but are not to be expected, given the tendency for agglomeration. Stations in this cluster should be considered for relocation where they are further away from the centres of the settlement areas they are supposed to serve or for merging with other nearby stations when no significant disadvantages are to be expected. (5) Boundary Places are stations with a strong surplus of local functional density, compared to the low public transport accessibility. They show a greater mix of housing, jobs and facilities, and a medium functional density. Boundary Places can be addressed as self-sufficient areas that are not strongly integrated into regional transport networks. The focus should be on linking them with each other to improve regional connectivity without risking that they become suburbanised.

While the first five clusters consist of a higher number of stations, two very small clusters with specialised profiles emerge: Transit Hubs and Commercial Places. (6) Transit Hubs are characterised by a very low functional density and, accordingly, a deficit of functional density to accessibility. Typically, they are isolated stations with the main purpose of providing interchanges to connecting bus lines, without serving local uses that could be reached by walking. The lack of functions around them represents a lost opportunity in terms of both an efficient public transport system and an economic use of space, if it means that other areas are developed instead. Stations with little surrounding activities are also often perceived as unsafe. Given their high accessibility to urban centres and in many cases also the airport, transit hubs represent an important untapped reserve for substantial new development. They are candidates for the establishment of regional sub-centres and drivers of a regionalisation of employment. (7) Commercial Places show almost no residential uses in their surroundings and an overall low functional density but high development and new building potentials. Often, they are in the vicinity of a single facility that they are meant to serve. In some cases, this might only be used during certain times of the week, e.g., sports stadia. Where suitable, Commercial Places could be supplemented by local residential uses to reduce commuting distances, as well as smaller businesses to avoid mono-functionality. Where space for this is missing, finding more efficient solutions for the often large parking areas around these stations might provide a way forward. Table 3 sums up the cluster characteristics and policy recommendations.

Table 3. Characteristics, policy recommendations and examples for the clusters.

	Characteristics	**Policy Recommendations**	**Examples**
Inner-city Situations	High functional density Second highest functional surplus Very little new building potential Station overload by transfer passengers	Concentrate on creating new bypasses and tangential connections within the city to reduce pressure on highly congested nodes and increase accessibility at stations with functional surplus	München Sendlinger Tor München Hohenzollernplatz
Suburban Places	Stations with proximity to larger cities Very good accessibility towards neighbouring centres Residential surplus	Improve local mix of jobs, housing and facilities	München-Lochhausen
Stations in Transition	Stations with the highest accessibility gains due to the second trunk line Residential surplus Location attractiveness expected to grow further	Prepare for future accessibility gains by providing space for dense, mixed-use new development, including residential	Weßling Eichenau
Rural Areas	Low functional density High functional deficit and residential surplus High new building potential	Despite high building potentials, refrain from residential densification. Enhancement of land use mix desirable but little demand. Consider relocation of stations towards settlement areas or merging where possible.	Otting-Weilheim Rohrbach (Oberbay.)
Boundary Places	High functional surplus Average mix of uses and development potentials Often overall low accessibility (e.g., stations at end of lines)	Focus on improving accessibility by creating new high-quality public transport/railway links with other Boundary Places	Füssen Bad Tölz
Traffic Hubs	Isolated interchange stations with bus links and car parks Often serve larger surrounding area or airport High accessibility	Settlement should grow towards the station if outside Establish a new sub-centre (shopping, leisure, workplaces, residential)	Hallbergmoos
Commercial Places	High residential deficit Low functional density High potential for densification and new buildings Often greenfield developments with large parking areas	Strengthen residential uses Increase density of functions, establish smaller businesses More compact parking solutions	Graben (Lechfeld) Gewerbepark

6. Conclusions

In this paper, we have reviewed the debate on regional urbanisation, a new complexity and simultaneity of population and employment concentration and de-concentration and a blurring of urban and suburban spaces, in times of economic and demographic change. We have connected this debate with the effects of transport infrastructure extensions, using the "Second Trunk Line" ("Zweite Stammstrecke") express rail project in Munich as a case study.

With respect to recent commuter data, we confirmed the functionally, still relatively monocentric structure of the Munich Metropolitan Region (MMR) despite signs of polycentric development and de-concentration of economic activity in the immediate surroundings of Munich, essentially confirming previous literature on the case. This monocentricity is resembled by the settlement and transport structure and reinforced by the Second Trunk Line project. The Second Trunk Line doubles the existing east–west local train tunnel across the inner city and will allow express train services that skip most of the existing commuter belt around Munich. Instead of focusing on increasing accessibility for areas that are high-density but poorly served, it increases absolute accessibility for those central locations within the MMR that already exhibit high accessibility levels, which gives centrally located firms and shops an even greater locational advantage due to their relational proximity to customers and potential employees. At the same time, relative accessibility of several peripheral, low-density areas will drastically increase as well. Previous studies have already found a strong reactivity of land users in the MMR on (rail-based) public transport extensions, in the form of suburbanisation and metropolisation. Since the pressure on the housing market has only become greater, the second trunk line will likely lead to further polarisation and segregation of land uses and the suburbanisation of residential uses, on the one hand, and the agglomeration of commercial uses in the city centre, on the other. In an aggregate view, it will likely improve productivity in the region, leading to further metropolisation. Another, more tangential and polycentric alignment, as other metropolitan regions in the European context show, would have spread these effects more evenly, encouraging greater regionalisation of economic activity, if desired. Hence, the MMR presents a laboratory situation for other European metropolitan regions with regard to the effects of a heavily monocentric public transport alignment.

However, while new infrastructure in the long run means induced longer commutes and more traffic, settlement structures oriented on rail-based public transport are at least preferable to car-oriented structures in terms of emissions. Refraining from using the generated development potentials would mean an inefficient use of resources, and most inner-city building potentials have already been used. Development around stations should hence be dense and socially as well as functionally mixed, to reduce the necessity for commuting, but tailored to local capacities and restrictions. Such a selective and impact-oriented supply-based strategy, however, requires a common regional commitment and cooperation, which cannot yet be recognised.

Based on a cluster analysis of all 512 rail-based public transport stations in the region, we recommend policies tailored to the capacities and opportunities of seven groups of stations. The recommendations range from deliberate encouraging of sub-centre formation at transit hubs to relocations of stations in rural areas. The cluster analysis furthermore points to the importance of measures not only in the area of urban development but also the further improvement of the transport network, e.g., through gap closures and the creation of tangential connections on different spatial scales. While there are already elementary tangential public transport connections between most of the regional centres, high-performance tangential connections are largely missing in Munich on the city level and city-regional scale. This would also have moderating effects on the strong concentration of employment in Munich, which currently strains both housing markets and transport infrastructure. The categories, while tailored for the Munich MMR, might also be applicable in other metropolitan regions, based on their general characteristics.

Technically, we have proposed a multi-method approach, combining strategies from different strands of spatial sciences: commuter data analysis, accessibility modelling, node-place analysis and cluster-based policy recommendations. Particularly, we have proposed an extension to the node-place model by a perspective that more strongly takes into account a small-scale functional mix. This strengthens the perspective of traffic avoidance to the model that it otherwise mostly focused on efficiency of transit provision and land use allocation. In a further step, it would be useful to also look at areas that are currently still too far away from public transport stations but that would justify a connection based on their functional density. These are commonly not covered by the node-place model in its basic form. It is also important to consider that the node-place model is always relative to the station with the highest node and place values, which might not actually be "stressed" in absolute terms.

Gravitational accessibility studies often use only population as general measure of opportunities; this is also the case in this study. The use of accessibility of firms, shops or cultural amenities could however yield more precise measures regarding the locational advantages of stations for a range of users of space, and hence, it represents an avenue for the future specification of the results.

A major constraint of the results presented here is the fact that they consider only travel time to be decisive for location choices, not other characteristics of the transport mode, particularly the monetary efforts of commuting, which represent a strong spatial drag as well. Often, these are considered to be proportional to commuting time, but this is certainly too simplistic. More in-depth studies should take an integrated view of time and monetary costs of travel and consider relative price levels between different modes of transport. The current reform of the tariff structure in the Munich region would represent a good case to study the differential effects of tariff reductions and increases for single localities in the case study area.

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