Technische Universität München

Which Regions Benefit from Rail Accessibility? Germany 1990-2030

A Brief Journey with Maps and Diagrams

Working Paper
Chair of Urban Development
at the Department of Architecture at Technical University of Munich

Authors Fabian Wenner M.Sc.
Johannes Moser M.A.
Chair of Urban Development

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1. Introduction

In two papers currently in preparation, we explore changes in the spatial distribution of rail accessibility in Germany on a regional scale between 1990 and 2020 on the one hand and between 2020 and 2030 on the other, should all planned rail projects of the current German Federal Transport Infrastructure Plan (Bundesverkehrswegeplan, BVWP) be carried out. The papers are part of a larger research project on the effects of rail transport infrastructure projects, particularly High-Speed Rail (HSR) lines, on urban development. In both papers, we have employed two different accessibility indicators: Potential accessibility of population, using an exponential decay function and degree centrality, a graph-theory measure of the number of regions that can be reached without a change of trains. Potential accessibility is widely used in transport studies and urban planning as a measure of location attractiveness and transport benefits (Handy and Niemeier 1997; Geurs and van Wee 2004), and particularly the exponential decay function has been found to be superior to other functions and well matched by empirical observations (Song 1996). Our use of a degree centrality measure was prompted by the anecdotal evidence that decision-makers view direct connections to other cities, rather than potential contacts within a certain time, are decisive for location decisions (Seydack 2015).

On the most general level, our findings for both periods (1990-2020, 2020-2030) are that there has been a tendency towards reduction of accessibility disparities between regions, albeit relatively weak. This is despite a massive investment in HSR infrastructure and services during both periods, which has in other countries been found to induce territorial "polarisation" – an increase in accessibility disparities between metropolitan cores and peripheral regions. The development was most pronounced in the decade immediately after German reunification 1990, and stagnated in the following decades. This was largely due to the upgrading of the deteriorated East German railway network, the effect of which has partly overshadowed the effects of HSR. However, there is also evidence for strong accessibility gains through HSR. If the currently planned rail projects of the BVWP and its sub-project, the "Deutschland-Takt", are implemented, a further balancing of accessibility is to be expected. However, rail investment in the past decades and the next ten years has not been and will not be completely balanced. Particularly the regions in the economically dynamic South and the catching-up Eastern regions which have profited and will continue to do so, while particularly the Northwest region does not attract high levels of rail investment.

As part of our research, we have employed a wider range of accessibility indicators than could be used in the limited scope of these two publications. The purpose of this working paper is to present and discuss these visualisations in the light of the previous findings. Section 1 describes the methods used; section 2 presents results, and section 3 discusses findings and offers conclusions.

2. Methodology

Here, we present four ways to visualise and measure the power of transport infrastructure to “distort” geographic space into a relational landscape of new proximities and peripheries. The rail infrastructure represents nodes and edges in the web of personal interaction and communication, knowledge exchange, and capital flows in the network society (Castells 1996). First, we present a comparison of the potential accessibility of population accessible over the rail network with a “pure” geographical population potential. Next, we show static and dynamic maps for “closeness centrality” and “daily accessibility” for rail travel in Germany. Finally, we show “time-space maps” or time-based cartograms for the German rail network in ten-year intervals between 1990 and 2030.

For all analyses, we use as spatial units 266 functional city-regions (“Stadt-Land-Regionen”) developed by the German Federal Institute for Research on Building, Urban Affairs and Spatial Development (BBSR 2017). They are homogenous, area-covering, non-overlapping areas free of exclaves, based on functional relations between urban cores and their hinterlands. In a buffer zone of four hours around Germany, we use an additional 209 NUTS3 areas as approximation of functional urban areas, which are of a similar extent.

The railway network data was gathered using web-scraping and manual research methods from past and current timetables (DB 2020; Grahnert 2020; DB 1990; DR 1990) and the travel times contained in the current second draft version of the “Deutschland-Takt” project for 2030 (BMVI 2019). For all regions, a main station was defined based on the highest number of departures per day, or, where this was ambiguous, based on centrality and importance in the local context. We then gathered the fastest travel times of all regular train connections between the main stations. A connection is considered ‘regular’ if it runs at least once every two hours over a period of eight consecutive hours on a typical working day.

2.1. Potential accessibility of population: Comparison of rail-based and geographical distance

For the first indicator, we use a potential accessibility of population measure to show the accessibility advantage that the rail network creates in a region, compared to a hypothetical situation of a frictionless space that can be travelled with constant speed in all directions. A potential accessibility indicator measures the number of opportunities that can be reached from a given starting point, with all destinations weighted by the "mass" of their opportunities, but inversely weighted by the travel time to reach them. We use an exponential decay function for the travel time, also called gravitational accessibility, and use population as mass. The formula used has the form of eq. 1,

$$\boldsymbol{P}[\boldsymbol{i}] = \sum_{\boldsymbol{j} \in \boldsymbol{G}-\{\boldsymbol{i}\}\boldsymbol{the}} \frac{\boldsymbol{W}[\boldsymbol{j}]}{\boldsymbol{e}^{\boldsymbol{\beta}*\boldsymbol{d}[\boldsymbol{i},\boldsymbol{j}]}} \qquad \text{(eq. 1)}$$

where P[i] is the potential accessibility of location i, W[j] 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. We use a decay exponent of 0.0057, which translates into a halving of weight after about 120 minutes, representing an interaction likelihood for business purposes.

This measure was calculated twice: Once with the travel times on the railway network, and a second time along direct linear distances between the regional centroids, assuming a constant speed of 60 km/h (for the method see also (BAK Basel Economics AG 2011). A buffer zone of four hours around Germany was included in the calculation to avoid unrealistically low values at the border. The quotient of these two measures shows the advantage in terms of accessibility that a region receives through the rail system, as opposed to the exogenous population distribution.

2.2. Closeness Centrality

A criterion for firm location choice might be the coverage of a national market from a single travel-time minimising location, without any thresholds for maximum distance, but without consideration of neighbouring countries. Closeness centrality measures the average shortest path distance from a node to all other (weighted) nodes in a given network. It is usually denoted as inverse value (Erath, Löchl and Axhausen 2009). The shorter the average travel time to all other regions, the higher the closeness centrality.

We consider the non-inverted average travel time to other regions as easier to interpret and hence use the non-inverted values, which could be better termed as ‘farness’. Hence, lower values represent a shorter average travel time to all other regions and hence a higher accessibility level. The equation is expressed below in eq. 2,

$$\boldsymbol{C}[\boldsymbol{i}] = \sum_{\boldsymbol{j} \in \boldsymbol{G}-\{\boldsymbol{i}\}} \frac{\sum_{\boldsymbol{ij} \in \boldsymbol{G}, \boldsymbol{i} \neq \boldsymbol{j}} \boldsymbol{W}[\boldsymbol{j}] \times \boldsymbol{d}[\boldsymbol{i},\boldsymbol{j}]}{\sum_{\boldsymbol{j} \in \boldsymbol{G}-\{\boldsymbol{i}\}} \boldsymbol{W}[\boldsymbol{j}]} \qquad \text{(eq. 2)}$$

where W is the weight of destination region j and d is the travel time between regions i and j. Again we use population as weight.

2.3. Betweenness Centrality

Betweenness centrality measures “the degree to which a point falls on the shortest path between others and therefore has a potential for control of communication” (Freeman 1977: 35). In our application, again, the functional urban areas act as points in the network. Deviating from standard applications in urban modelling (e.g. Sevtsuk and Mekonnen 2012: 297), all relations are weighted by the product of the weights of their origin and destination, instead of only their destinations weight, to account for the varying importance of origins. If several paths have equal length their weight is distributed equally. The formal expression is eq. 3,

$$\boldsymbol{B}[\boldsymbol{i}] = \sum_{\boldsymbol{j},\boldsymbol{k} \in \boldsymbol{G}-\{\boldsymbol{i}\}} \frac{\boldsymbol{n_{jk}}[\boldsymbol{i}]}{\boldsymbol{n_{jk}}} \times (\boldsymbol{W}[\boldsymbol{j}] \times \boldsymbol{W}[\boldsymbol{k}]) \qquad \text{(eq. 3)}$$

where n_{jk} is the number of shortest paths from origin j to destination k, and $n_{jk}[i]$ is the share of these paths that pass through i, and W is the weight of origins and destinations j and k, respectively.

Importantly, our betweenness measure is based on train stops, not interchanges. This means that a station’s betweenness is increased also if it is a stop on a through-journey – usually just one or two minutes –, without the need for passengers to leave the train. This can already represent an advantage from a regional economic perspective, as regular timetables enable “passersby” to leave the train, interact locally, and continue their journey with the next train; however, only betweenness based on mandatory interchanges shows actual passenger flow at stations, but would require more data.

2.4. Daily Accessibility

‘Daily accessibility’ is another frequently used measure of accessibility in transport studies, which is defined as the number of opportunities that can be reached within a working day. It borrows from the notion of “time geography” (Hägerstrand 1970) that attempts to map the daily routines and activity spaces of persons. It represents a simple contour measure that consists of a count of opportunities within a certain time threshold. For our analysis, we use the threshold of daily return distance for business trips, which is in literature often assumed to be four hours, e.g. (Lutter and Pütz 1993)), (Lutter and Pütz 1993; Vickerman 1995; ESPON 2004; Martín and Reggiani 2007).

2.5. Time-Space Maps

So-called ‘time-space maps’ are a visualisation technique that attempts to map proximity based on travel times in two-dimensional space. They are a vivid method to illustrate the effects of transport infrastructure, which is represented as a “shrinkage” of space (Axhausen 2008). An exact representation of the time-distances between all points would however require a higher-dimensional coordinate space. Thus, two-dimensional time-space maps are always only approximate solutions. It is important to note that this effect can hide inner peripheries between major cities that are moving closer together (L'Hostis 1996; L’Hostis 2009). A detailed description on the mathematical background can be found in (Spiekermann and Wegener 1993, 1994). To generate time-space maps we employ a non-metric multidimensional scaling algorithm in R. The undistorted base map is premised on an equal speed of 60 km/h in all directions, the same as in Spiekermann & Wegener (Spiekermann and Wegener 1994), but using more nodes, with Frankfurt am Main as map centre.

3. Results

3.1. Potential accessibility of population: Comparison of rail-based and geographical distance

Figure 1 shows the quotient of rail-based and geography-based potential accessibility of population. The higher the quotient, the greater is the potential accessibility of population over the rail network, compared to that in a hypothetical frictionless space that can be travelled with 60 km/h in each direction. Table 1 contains the ten regions with the highest and the five regions with the lowest quotients.

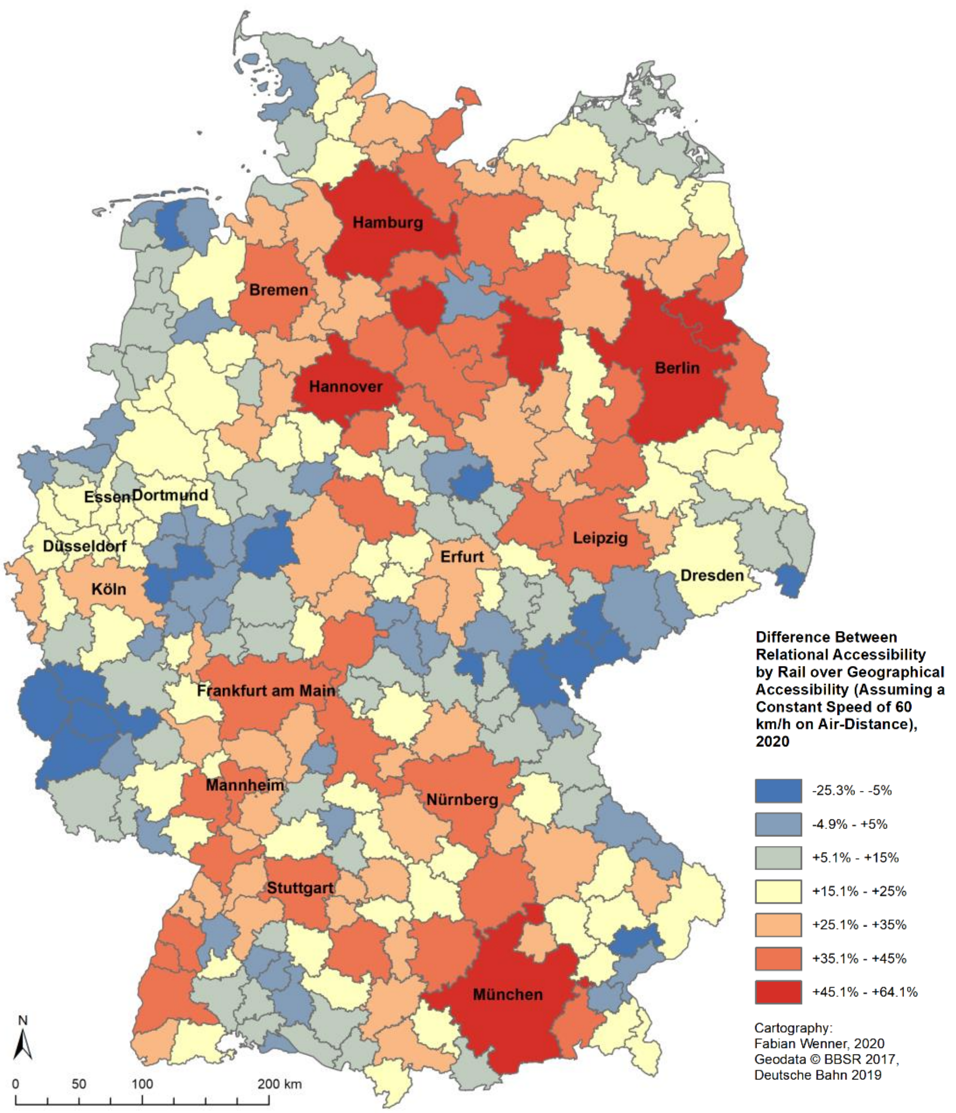


Figure 1: Difference Between Accessibility by Rail over Geographical Accessibility (Assuming a Constant Speed of 60 km/h on Air-Distance), 2020

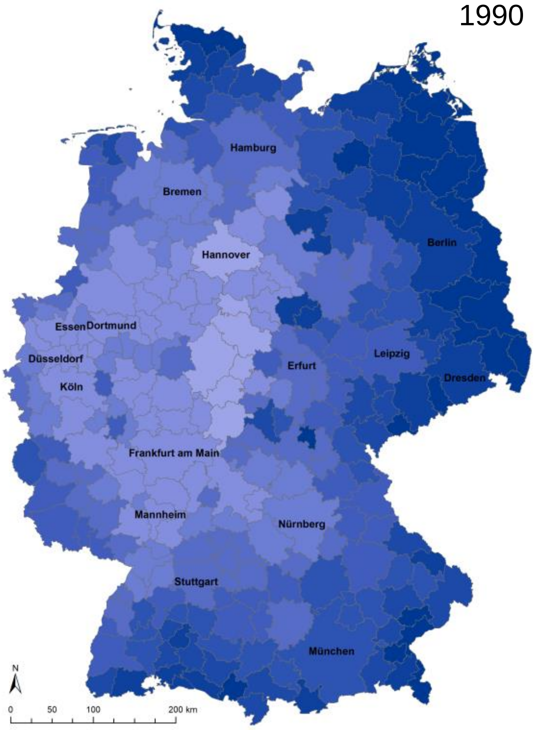
Table 1: Quotients of (relational) rail accessibility and geographic accessibility

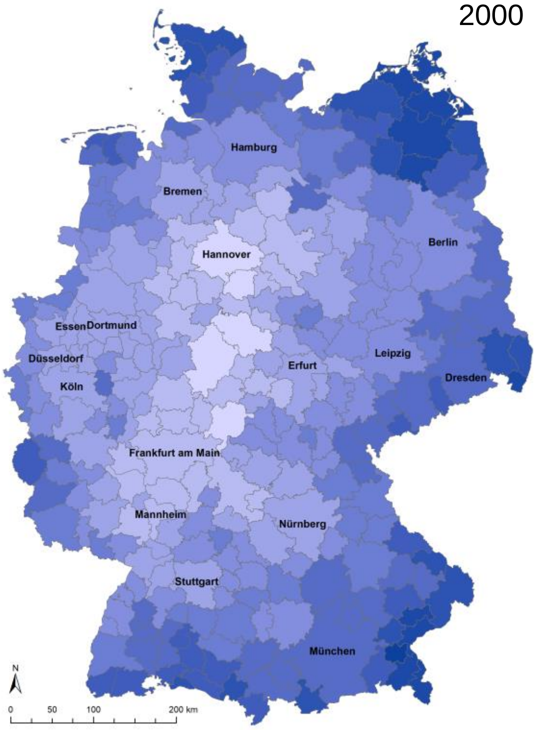
Rang	Region	Quotient of (relational) rail accessibility and geographic accessibility
1	Berlin	+64.1%
2	Hamburg	+51.3%
3	Hannover	+50.3%
4	Stendal	+49.7%
5	Eberswalde	+47.7%
6	Uelzen	+46.7%
7	München	+46.1%
8	Wolfsburg	+44.9%
9	Offenburg	+44.0%
10	Lüneburg	+43.9%
…	…	…
262	Plauen	-12.2%
263	Trier	-12.7%
264	Daun	-18.5%
265	Aue	-22.1%
266	Bitburg	-25.3%

The calculation shows that unsurprisingly the major urban centres Berlin, Hamburg, and Munich get most out of the rail system. Their importance means that over the past centuries, rail lines have been constructed and are still served today in a way that reduces travel times to and from these major centres, and hence give them a locational advantage that their geographical position alone would not afford them with. In addition, in Northern Germany the flat terrain allows the construction of straighter rail lines, which becomes visible in the higher number of regions with a strongly positive coefficient there (e.g. Hannover and Wolfsburg, but also smaller regions like Stendal, Uelzen, and Lüneburg). A notable exception is the Rhein-Ruhr area: despite its high population, the railway network barely allows average air-distance speeds of more than 60 km/h. Frequent stops in this area, that for historical reasons (mining operations) developed in a poly-centric pattern, mean considerably lower average speeds, which puts it in comparably inferior position to other metropolitan areas in the country. This could represent an opportunity for efficiency gains through the introduction of faster trains with less stops. At the same time, some rail connections of peripheral regions are equal to an air-distance speed of significantly less than 60 km/h, which is usually surpassed by individual transport modes, making rail unattractive. This affects both 'outer' and 'inner' peripheries (e.g. Mosel valley and Eifel, South-West Saxony, Sauerland, Eastern Frisia). In 2020, 40 regions are characterised by a quotient of less than 1, which reduces to only 7 in 2030.

3.2. Closeness Centrality

Closeness centrality measures the average time needed to reach all other regions of a given territory, weighted by their population. A lower value hence means better accessibility. Due to the fixed cutoff threshold at the national border, the distribution of values differs signficiantly from potential accessibility measures. Figure 2 shows the regional pattern of closeness centrality in the rail network for Germany in the years from 1990 to 2030 in ten-year intervals. Table 2 shows the regions with the highest and lowest closeness centrality values for the years 1990, 2020, and 2030.





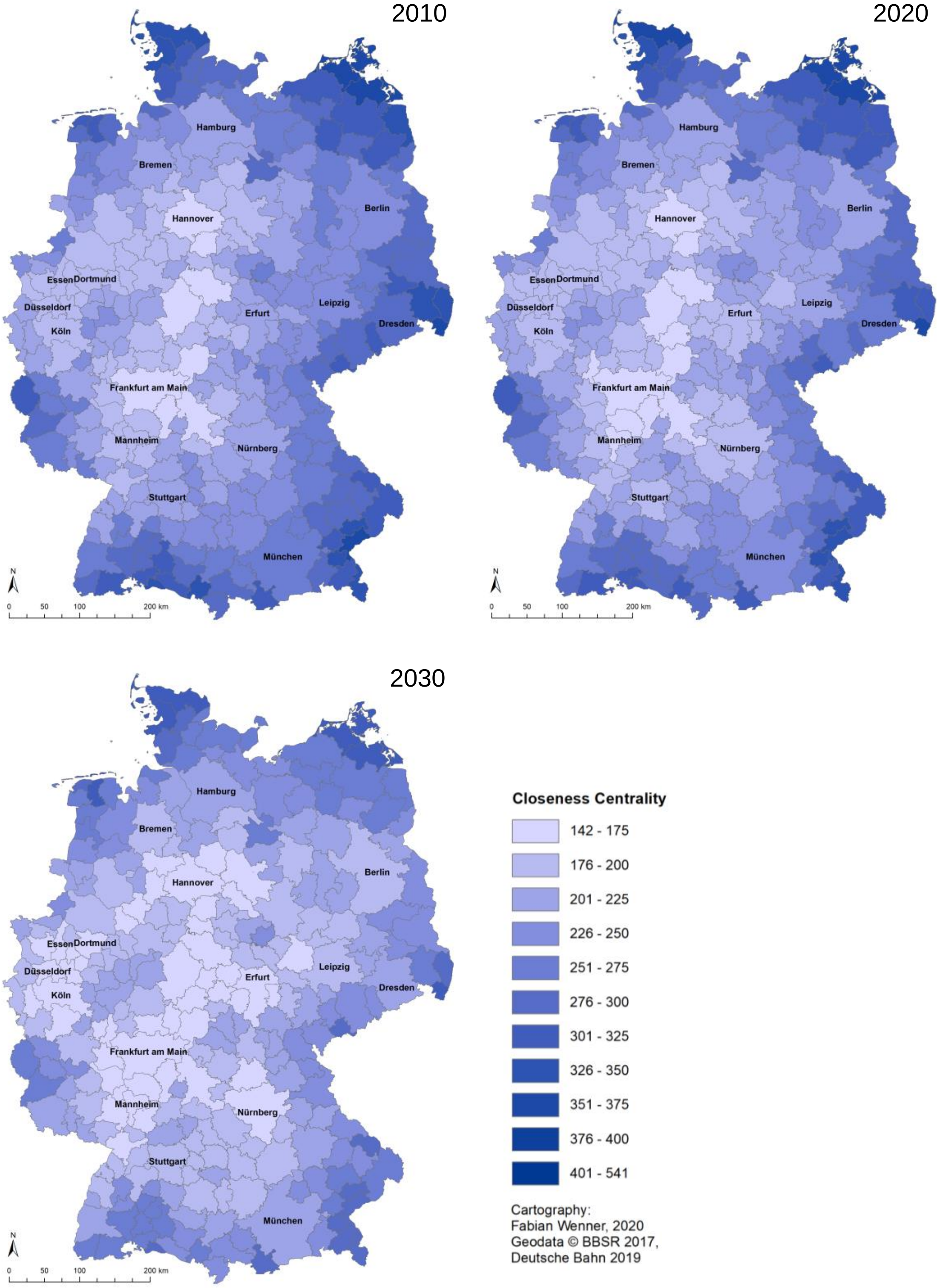


Figure 2: Closeness Centrality 1990-2030

Table 2: Regions with the highest and lowest closeness values in 1990, 2020, and 2030

	1990		2020		2030	
Rank	**Region**	**Closeness**	**Region**	**Closeness**	**Region**	**Closeness**
1	Bad Hersfeld	212.85	Fulda	154.62	Frankfurt am Main	142.29
2	Fulda	214.34	Kassel	160.86	Fulda	147.64
3	Göttingen	216.88	Göttingen	162.96	Aschaffenburg	148.56
4	Hannover	217.78	Frankfurt am Main	163.14	Kassel	149.19
5	Einbeck	218.03	Würzburg	167.75	Darmstadt	149.80
6	Kassel	222.00	Hannover	168.05	Göttingen	150.43
7	Eschwege	223.58	Aschaffenburg	171.19	Mannheim	151.36
8	Frankfurt am Main	228.49	Bad Hersfeld	172.82	Hannover	153.43
9	Würzburg	228.74	Hildesheim	173.43	Bad Hersfeld	154.96
10	Hildesheim	228.93	Darmstadt	174.15	Ludwigshafen am Rhein	155.17
…	…	…	…	…	…	…
262	Torgelow-Ferdinandshof	452.09	Husum	339.13	Aurich	300.23
263	Bautzen	455.28	Flensburg	350.48	Flensburg	309.07
264	Greifswald	457.94	Zittau	353.06	Greifswald	312.32
265	Görlitz	488.67	Stralsund	356.27	Husum	313.55
266	Zittau	540.36	Greifswald	364.20	Stralsund	316.53

The “blue banana” pattern of an arc of high accessibility along the river Rhine cannot be identified here. Instead, closeness centrality depends strongly on geographical location. In 1990, closeness centrality varied between 213 minutes from Bad Hersfeld and 540 minutes from Zittau, a ratio of 1:2.53, which is reduced to 1:2.23 with a range of 142 to 316 in 2030. Regions in the geographical centre of Germany remain on the top places of the list throughout the decades. Nevertheless, a tendency away from geographical determination towards relational centrality can be observed. Bad Hersfeld is the geographically most central region of Germany, and today well-known as a logistics hub, but drops from first to ninth place despite a strong increase of its rail closeness centrality value. Frankfurt am Main, on the other hand, is not geographically remote either, but less central than Bad Hersfeld – nevertheless it takes first place in 2030. Fulda has the most advantageous position in both respects. Many regions that improve their rank positions are located on the HSR network.

On the other end of the scale, the extraordinarily low value of Zittau is improved by 2030, but other regions remain in the last five grouping, e.g. Greifswald. These regions are locked-in by their geographical peripherality. The East-West divide of 1990 (all Eastern regions on the list of highest closeness centrality values) seems to change to a North-

South one, as all regions on the lowest places in the ranking in 2030 are remote coastal regions in the North.

Figure 3 shows the absolute changes in regional closeness centrality for the decades between 1990 and 2030. Table 3 and Table 4 contain a list of these changes for the ten regions with the highest closeness gains (decreased values) and the five regions with the smallest gains. While the map and list for the decade 1990-2000 is dominated by improvements in the conventional rail network in Eastern Germany after reunification (e.g. Zittau, Berlin), with an additional effect for formerly isolated inland border regions (e.g. Sonneberg, Salzwedel), the following decades show a strong impact of HSR construction. Closeness value reductions in regions like Montabaur, Limburg an der Lahn, Ingolstadt and Aachen in 2000-2010 or Bitterfeld-Wolfen and Halle (Saale) in 2010-2020 are clearly induced by the construction of HSR lines in these areas. Particularly in less populous regions that previously had no long-distance rail connections, these effects are stronger since their starting position is lower. But also the upgrading and reopening of conventional and regional rail lines is strongly noticeable in the list, with sometimes similar changes as in the case of HSR, pointing to the importance of an accessibility strategy that takes all modes and speeds into account.

At the other end of the scale there have even been accessibility deteriorations in some regions. This has been particularly strong in the decade 2000-2010, when newly (legally) privatised rail operator Deutsche Bahn reduced services on unprofitable ‘inter-regio’ routes, which particularly affected regional centres away from the dynamic metropolitan areas. The closeness value increase of Saalfeld/Saale in 2010-2020 is due to the discontinuation of long-distance services in the region after the opening of a parallel HSR line without a stop there.

The pattern of closeness centrality change in the coming decade is rather heterogeneous and partly due to service improvements and better timed interchanges and connections. However, several upgrading projects, such as the lines from the Lake Constance to Munich and Stuttgart, as well as the Berlin-Rostock line, can be identified as drivers behind the improvements of the ‘winning’ regions.

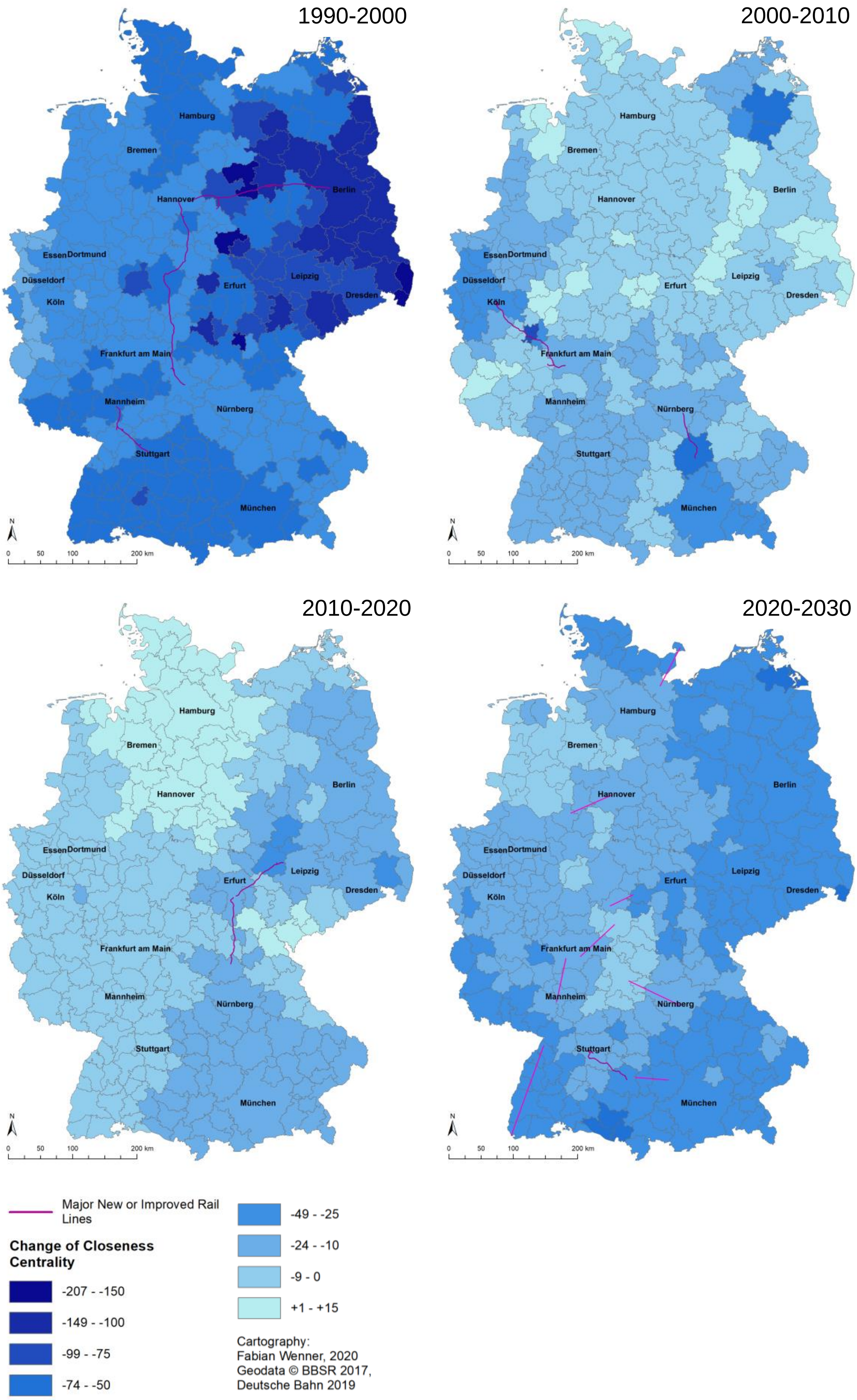


Figure 3: Change of Closeness Centrality 1990-2030

Table 3: Largest and smallest changes in closeness centrality of regions in the decades between 1990 and 2010

Rank	1990-2000		2000-2010	
	Region	**Δ**	**Region**	**Δ**
1	Sonneberg	-175.62	Montabaur	-80.35
2	Zittau	-173.96	Ingolstadt	-56.84
3	Salzwedel	-171.06	Neustrelitz	-53.24
4	Wernigerode	-161.55	Neubrandenburg	-50.04
5	Görlitz	-152.81	Limburg a.d. Lahn	-40.20
6	Berlin	-142.10	Aachen	-39.80
7	Frankfurt (Oder)	-141.98	Gummersbach	-33.70
8	Lübben (Spreewald)	-130.69	Traunstein	-30.83
9	Neuruppin	-129.75	Köln	-30.81
10	Parchim	-128.74	Traunreut	-30.78
…	…	…	…	…
262	Daun	-21.61	Görlitz	+6.76
263	Krefeld	-20.06	Cottbus	+6.86
264	Mönchengladbach	-19.08	Trier	+7.12
265	Bitburg	-18.42	Attendorn	+7.74
266	Kleve	-14.53	Flensburg	+14.21

Table 4: Largest and smallest changes in closeness centrality of regions in the decades between 2010 and 2030

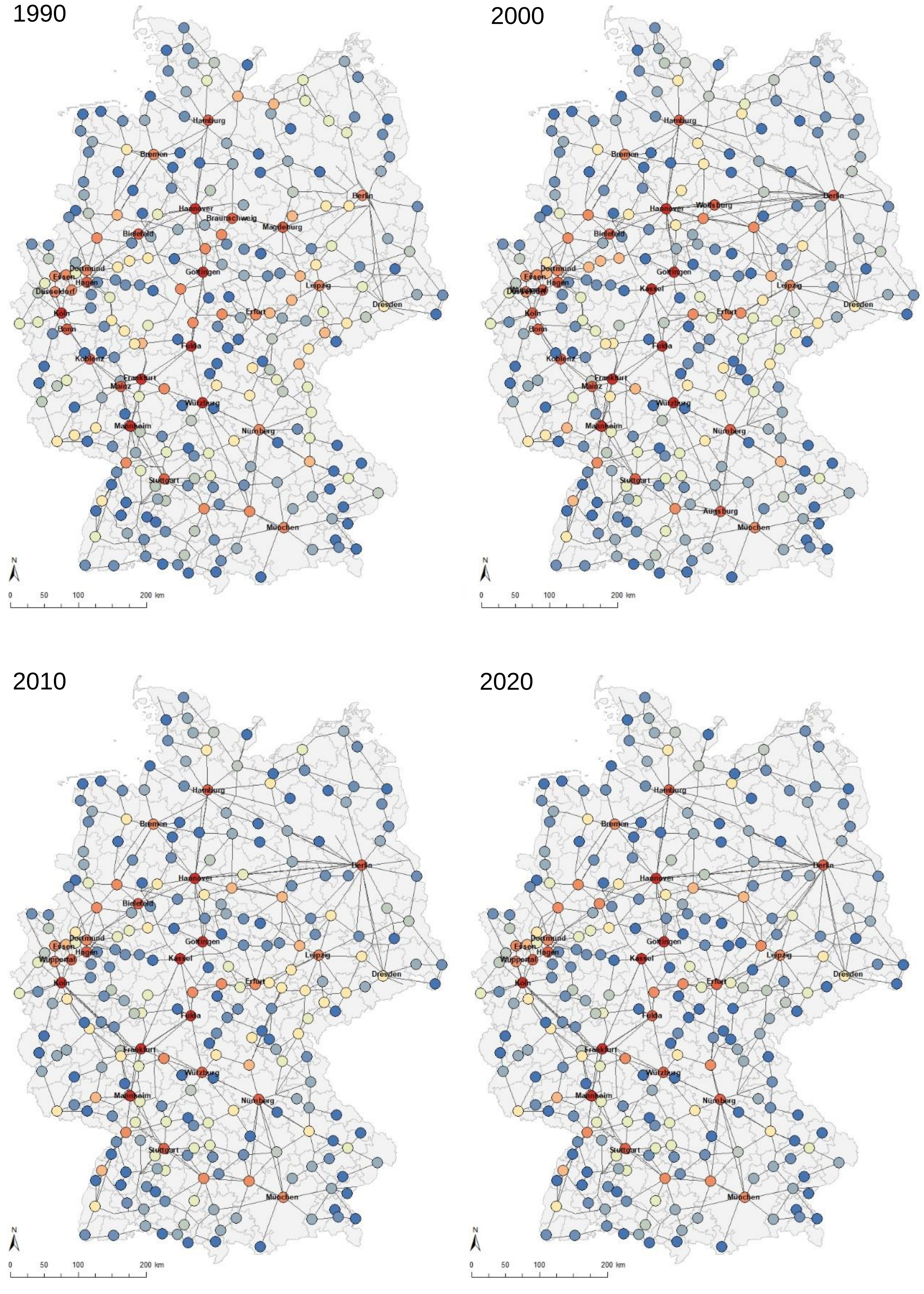
Rank	2010-2020		2020-2030	
	Region	**Δ**	**Region**	**Δ**
1	Bitterfeld-Wolfen	-29.51	Zittau	-52.94
2	Halle (Saale)	-29.10	Wangen im Allgäu	-51.94
3	Dessau-Roßlau	-25.35	Greifswald	-51.88
4	Bautzen	-25.15	Friedrichshafen	-51.72
5	Dresden	-24.10	Ravensburg	-50.08
6	Leipzig	-23.43	Burghausen	-48.49
7	Riesa	-22.47	Freiberg	-48.00
8	Herzberg (Elster)	-21.76	Torgelow-Ferdinandshof	-47.13
9	Gummersbach	-21.19	Waren (Müritz)	-46.67
10	Sonneberg	-20.98	Dresden	-46.09
…	…	…	…	…
262	Zwickau	+0.88	Schweinfurt	-6.21
263	Aue	+0.95	Leer (Ostfriesland)	-5.38
264	Salzgitter	+0.96	Emden	-5.35
265	Hamburg	+1.00	Soltau	-5.09
266	Saalfeld/Saale	+3.02	Bad Neustadt a.d.Saale	-3.46

3.3. Betweenness Centrality

Betweenness centrality measures the extent to which a point serves as a host of through-going traffic within a network. Both the points of origin and destination whose connection produces routes through points in between them are each weighted to account for their relative importance. The betweenness centrality values are normalized via their largest value, Hannover in 2000, which thus becomes 100, meaning that the closer a value to this maximum the more 'in-between' a city has been at that point of time. Equal to the case of closeness centrality, national borders are fixed cutoff thresholds.

Figure 4 displays the degrees of betweenness centrality of Germany's cities in the rail network for the years 1990, 2000, 2010, 2020 and 2030. In all years, the majority of cities has rather low values (blue to yellow). Consistently, bigger cities feature higher values (red circles). The geographical distribution of high betweenness centrality values shows that these are located in more central and western regions. Unsurprisingly, the area with the highest density of cities with large values can be found in the Central West, which has the highest population density within Germany. Germany's rail network's betweenness centrality distribution across cities has become more polarized over time, that is, values shift to the outer ends of the distribution. Bigger cities and important nodes keep the status with high betweenness centrality values, while all others in overall tend to decrease in importance. Another observation, reinforcing this trend, is that many cities in the Central Eastern parts of Germany feature lower values of betweenness centrality in 2020 and 2030 than before. After Germany's reunification in 1990 and with the gradual introduction of HSR lines, the distribution of flows became less widespread and moved on major fast pipelines, that is HSR lines.

Table 5 presents the cities with the most and least pronounced betweenness centrality values in 1990, 2020 and 2030. All the values at the top and bottom end of the distribution in Table 5 exhibit a demonstrative stability – from around 80 percent at position 1 to roughly 40 percent at position 10, while the lowest values linger constantly at around 0.3 to 0.4 percent. A few observations stand out. The top ranks are inhabited by cities that share two common features. First, they belong to the group of the most populated cities in Germany. Second, their geographical locations are by and large in the middle of Germany.


1990
Hamburg
Bremen
Hannover
Braunschweig
Bielefeld
Magdeburg
Berlin
Dortmund
Essen
Hagen
Düsseldorf
Göttingen
Leipzig
Köln
Bonn
Erfurt
Dresden
Koblenz
Fulda
Frankfurt
Mainz
Würzburg
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Stuttgart
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2030

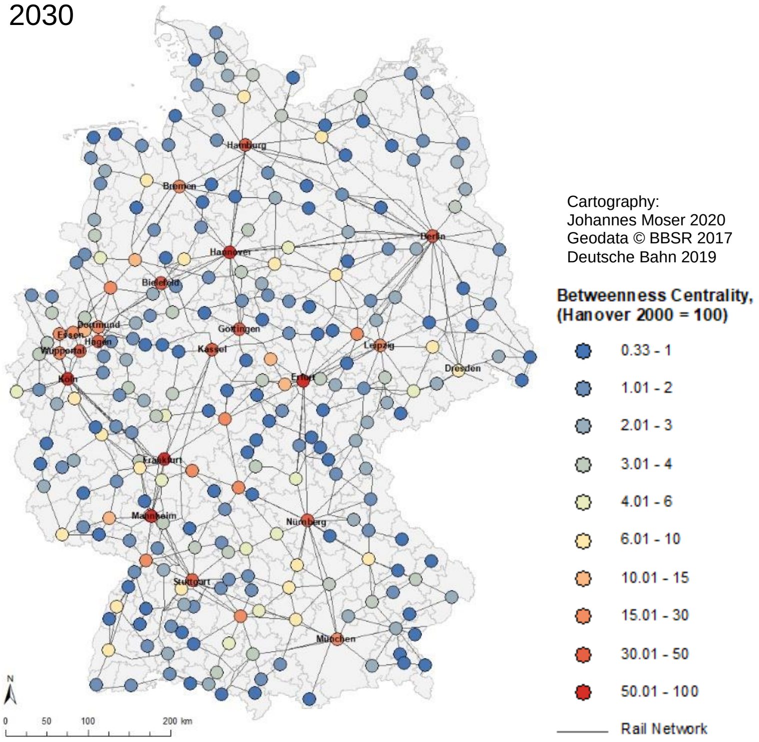


Figure 4: Betweenness Centrality 1990-2030 (Hannover Hbf 2000 = 100)

Taken together, the latter argument appears to dominate. Hamburg and München, Germany’s second and third most populous cities, never show up at the top positions, while Berlin as by far the largest city ranks only as ninth and eighth in 2020 and 2030, respectively. These three are all located towards the outer borders of Germany. As travel relations are more and more international within Europe, this is likely an underestimation of real load due to the limitation on domestic travel only. More central cities along the over decades built HSR line between Hamburg and München such as Hannover, Göttingen, Kassel, Fulda, Würzburg and Nürnberg are all subject to high levels of flows through them. At the other end of the distribution, occupants of the lowest ranks are small towns toward the external borders of Germany.

Table 5: Regions with the highest and lowest betweenness values in 1990, 2020, and 2030 (Hannover Hbf 2000 = 100)

	1990		**2020**		**2030**	
Rank	**Region**	**Betweenness**	**Region**	**Betweenness**	**Region**	**Betweenness**
1	Hannover Hbf	77.40	Hannover Hbf	82.11	Frankfurt (Main) Hbf	79.75
2	Fulda	70.51	Mannheim Hbf	71.02	Hannover Hbf	78.67
3	Frankfurt (Main) Hbf	62.42	Frankfurt (Main) Hbf	65.28	Mannheim Hbf	77.61
4	Mannheim Hbf	58.65	Kassel-Wilhelmshöhe	59.27	Köln Hbf	64.31
5	Göttingen	56.84	Göttingen	55.76	Erfurt Hbf	57.10
6	Würzburg Hbf	53.44	Köln Hbf	52.09	Stuttgart Hbf	49.63
7	Köln Hbf	50.94	Nürnberg Hbf	48.73	Nürnberg Hbf	48.85
8	Braunschweig Hbf	47.13	Stuttgart Hbf	46.13	Berlin Hbf	45.98
9	Magdeburg Hbf	47.09	Berlin (Hbf)	41.59	Göttingen	44.35
10	Koblenz Hbf	41.47	Fulda	40.07	Bielefeld Hbf	36.39
…	…	…	…	…	…	…
262	Hörpolding	0.42	Eggenfelden	0.44	Dannenberg Ost	0.39
263	Eggenfelden	0.41	Dannenberg Ost	0.39	Lübben (Spreewald)	0.38
264	Dannenberg Ost	0.41	Sonneberg (Thür) Hbf	0.38	Norden	0.38
265	Norden	0.34	Norden	0.38	Sonneberg (Thür) Hbf	0.38
266	Pirmasens Nord	0.33	Parchim	0.36	Parchim	0.36

Figure 5 presents the changes of betweenness centrality values between the decades 1990-2000, 2000-2010, 2010-2020 and 2020-2030, including the pink-coloured newly constructed HSR lines during each period. Blue-coloured cities experienced strong declines, while dark-red cities gained the most in terms of betweenness centrality. In the period 1990-2000, many routes of HSR were completed, which markedly improved the North-South connection within Germany. After reunification in 1990, Berlin got access to the North-South connection in Hannover. Also, the two industrial cities Stuttgart and Mannheim were connected with HSR. Almost all cities with stations at the new HSR lines saw increases of their betweenness centrality with the lone exception of Fulda, which had a high starting position in 1990 already due to the Frankfurt-East Germany link. Quite in general, this decade is marked by a broad trend of rising betweenness centrality values. The negative impact of the new lines becomes visible in the cities that 'suffered' by losing direct access to the fastest connections. This was the case for Einbeck, Salzgitter, Braunschweig, Magdeburg and further towns along the route to Berlin. In the next decade 2000-2010, the routes between Ingolstadt and Nürnberg as well as from

Frankfurt to Köln were completed. Again, quite pronounced, the former route from Frankfurt to Köln via Mainz, Koblenz and Bonn exhibits drastic declines in betweenness centrality after it was replaced by the faster and more direct new HSR line. Between 2010 and 2020, the HSR line from Bamberg to Halle (Saale) via Erfurt came into existence, rendering those cities large increases in betweenness centrality. Therewith the rail travel time between Berlin and München decreased from six down to four hours. As before, the formerly sole North-South line Hannover-Würzburg loses in betweenness centrality due to the new line, which shows the (part) redundancy of the two lines. Apart from that the decade in question was rather stagnant concerning change. At last, the decade yet to come, 2020-2030, with many further planned rail network extensions leaves room for an ambiguous interpretation. It is important to keep in mind that changes in the level of service are also included that do not necessarily require extensions in the rail network. Especially the following mechanism is at work: whenever there are a 'winners', there are also 'losers' in neighbouring cities. While the area around Dortmund and Essen and, to the North, Bielefeld will experience an increase in their betweenness centrality values, the cities between them tend to experience a decrease. The same is true in the Central-East with Erfurt, Gotha and Mühlhausen, or in the Central-South with cities along the new HSR line to Stuttgart.

Table 6 and Table 7 show the largest and smallest changes in betweenness centrality within the decades 1990-2030. As opposed to the case of levels in Table 5, the biggest extremes in the case of changes is restricted to either larger cities or more frequently used rail stations. Certainly, the most conflictive case is that of Kassel-Wilhelmshöhe which ranks first in 1990-2000, but at the very bottom from 2020 to 2030. The image created in Figure 5 is corroborated here; the largest decreases are for those cities whose stations become replaced by those along newly built high speed rail lines. This exercise shows that traffic and stops at rail stations, thus their 'betweenness centrality', is very prone to changes in the availability of routes and levels of services offered by rail operators.

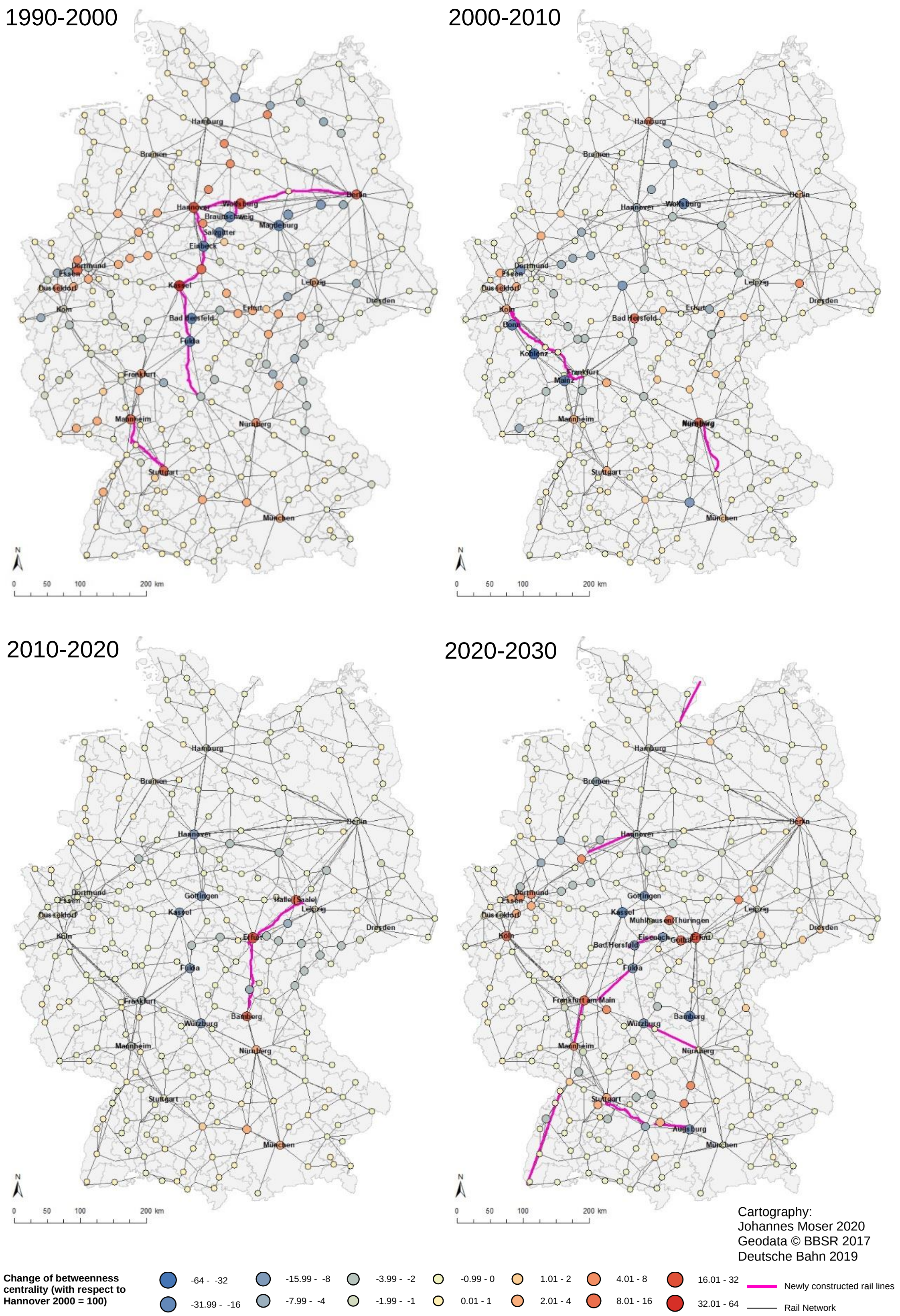


Figure 5: Rates of change of betweenness centrality in decades between 1990-2030

Table 6: Largest and smallest changes in betweenness centrality of regions in the decades between 1990 and 2010

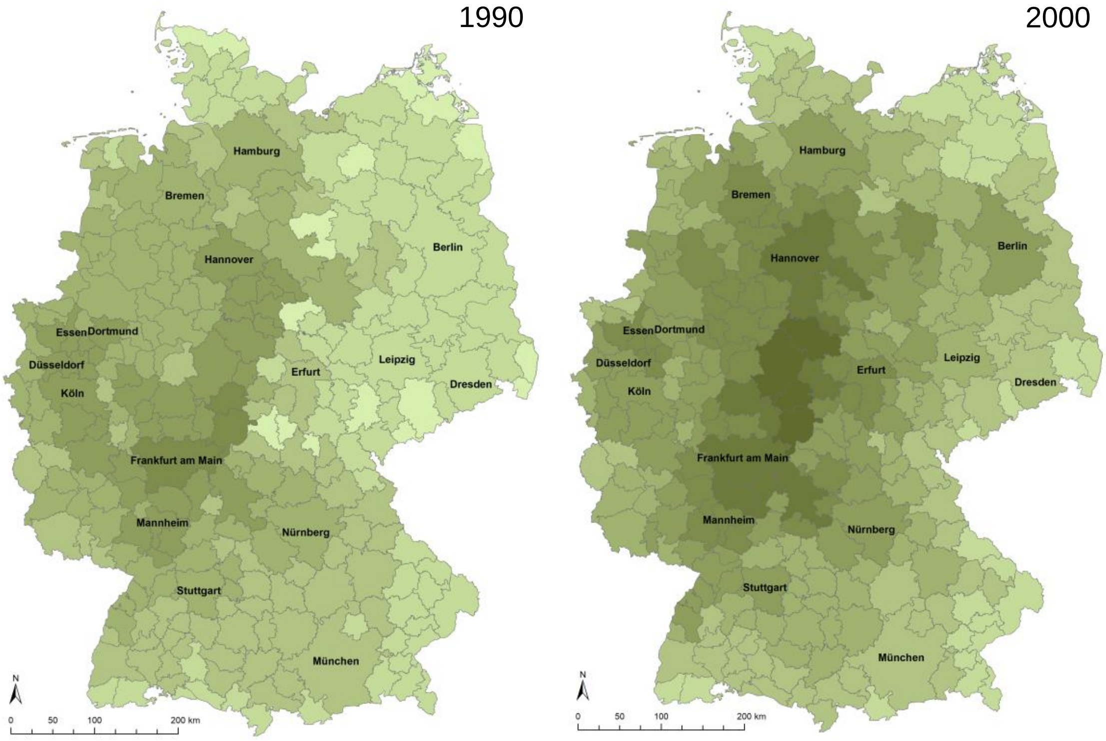
Rank	**1990-2000**		**2000-2010**	
	Region	**Δ**	**Region**	**Δ**
1	Kassel-Wilhelmshöhe	+63.03	Bebra / Bad Hersfeld	+14.67
2	Wolfsburg	+31.51	Nürnberg Hbf	+14.30
3	Hannover Hbf	+22.60	Riesa	+5.33
4	Berlin Hbf (alt) / Berlin Ostbahnhof	+14.84	Düsseldorf Hbf	+4.81
5	Göttingen	+12.67	Hamburg Hbf	+4.07
6	Mannheim Hbf	+11.24	Aschaffenburg Hbf	+3.82
7	Stuttgart Hbf	+10.82	Duisburg Hbf	+3.43
8	Bochum Hbf	+8.79	Mannheim Hbf	+3.38
9	Nürnberg Hbf	+6.81	Köln Hbf	+3.02
10	Frankfurt (Main) Hbf	+5.93	Münster (Westf) Hbf	+2.75
…	…	…	…	…
262	Fulda	-17.69	Augsburg Hbf	-14.03
263	Kreiensen	-18.81	Mainz Hbf	-27.59
264	Bebra	-23.50	Bonn Hbf	-30.07
265	Braunschweig Hbf	-30.95	Wolfsburg / Wolfsburg Hbf	-30.16
266	Magdeburg Hbf	-31.54	Koblenz Hbf	-32.57

Table 7: Largest and smallest changes in betweenness centrality of regions in the decades between 2010 and 2030

Rank	**2010-2020**		**2020-2030**	
	Region	**Δ**	**Region**	**Δ**
1	Erfurt Hbf	+17.14	Erfurt Hbf	+20.26
2	Bamberg	+13.02	Frankfurt (Main) Hbf	+14.48
3	Halle (Saale) Hbf	+8.76	Köln Hbf	+12.22
4	Nürnberg Hbf	+3.64	Gotha	+9.21
5	Augsburg Hbf	+2.52	Mühlhausen (Thür)	+8.93
6	München Hbf	+2.42	Halle (Saale) Hbf	+7.48
7	Ulm Hbf	+1.37	Bielefeld Hbf	+7.27
8	Leipzig Hbf	+0.99	Mannheim Hbf	+6.59
9	Riesa	+0.59	Bochum Hbf	+6.25
10	Mühlhausen (Thür)	+0.33	Treuchtlingen	+5.83
…	…	…	…	…
262	Würzburg Hbf	-8.62	Fulda	-13.98
263	Fulda	-10.35	Bad Hersfeld / Bad Hersfeld (neu)	-14.78
264	Göttingen	-10.96	Würzburg Hbf	-15.92
265	Kassel-Wilhelmshöhe	-11.25	Bamberg	-19.24
266	Hannover Hbf	-11.41	Kassel-Wilhelmshöhe	-23.38

3.4. Daily Accessibility

Figure 6 shows the regional pattern of daily accessibility for regions in Germany in ten-year intervals between 1990 and 2030. Table 8 displays the values for the ten regions with the highest and the five regions with the lowest daily accessibility for 1990, 2020, and 2030 each. Again, as with closeness centrality, the effect of a fixed threshold at the national border becomes clearly visible, as opposed to the potential accessibility measure. Geographically central regions have the highest daily accessibility scores, as a majority of all other regions can be reached within four hours by rail from there. Again, Bad Hersfeld was the most accessible region in 1990, while the regions located directly along the central HSR spine (Fulda, Kassel, Göttingen, Würzburg) have moved up the ranks in 2020 with considerably higher absolute accessibility values. In 2030, Bad Hersfeld takes second place again as the new Fulda-Erfurt HSR line will also feature a stop in the region. For over 78 million people it is possible to reach almost every destination in Germany from Kassel within four hours by rail in 2030. The influence of HSR infrastructure is strongly visible in the list and gradually supersedes simple geographical centrality.



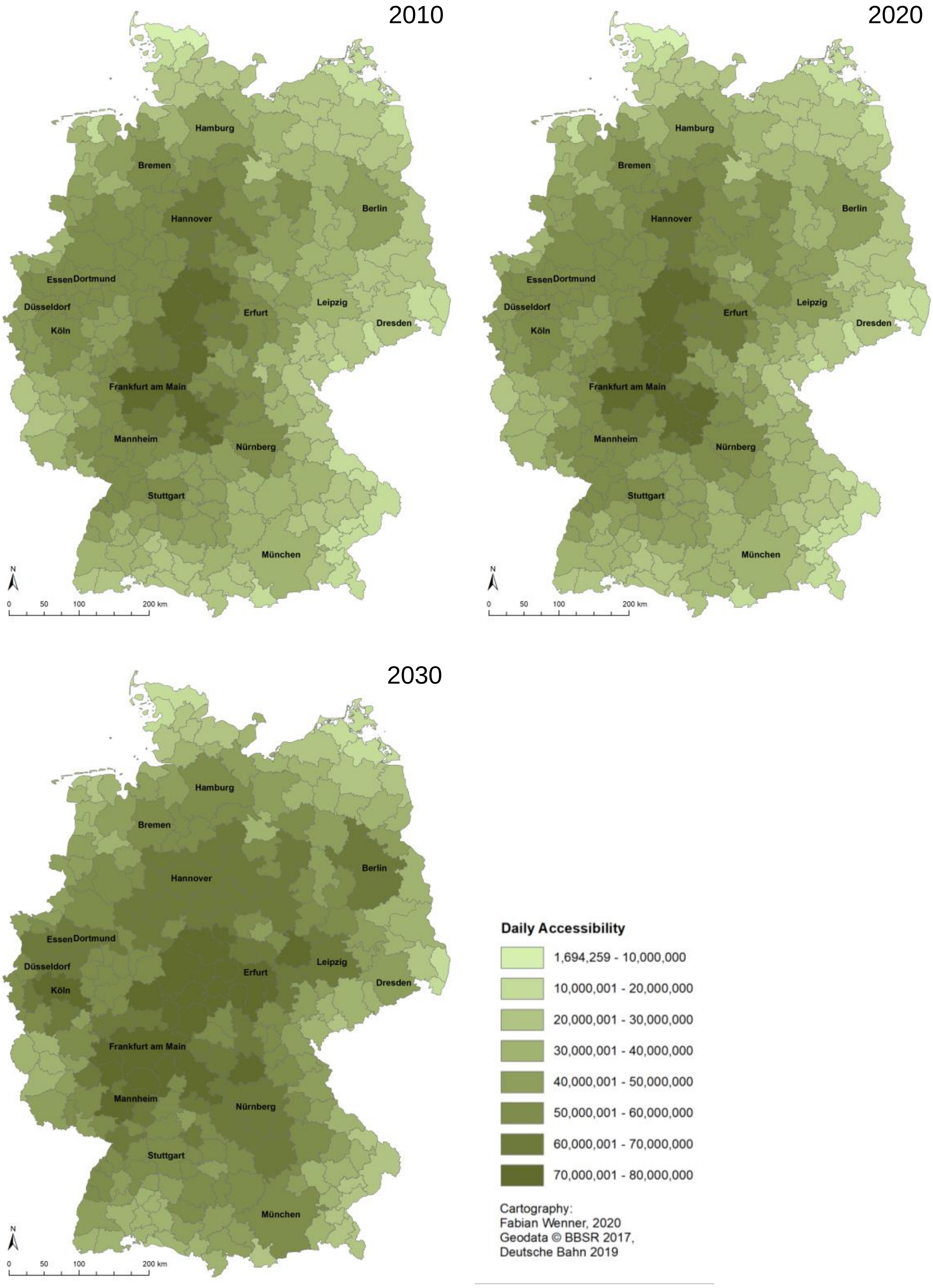


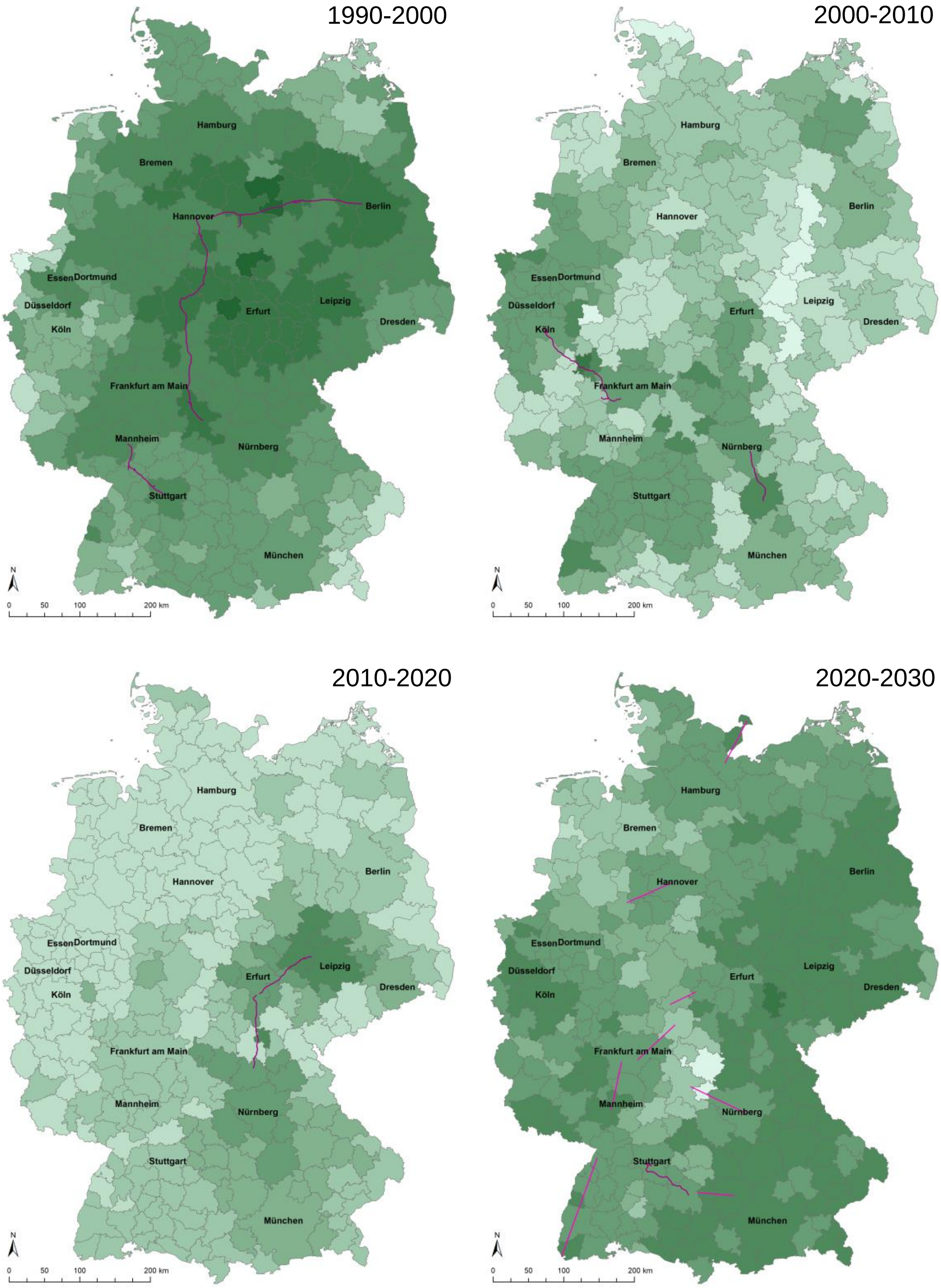
Figure 6: Daily Accessibility 1990-2030

Table 8: Regions with the highest and lowest daily accessibility values in 1990, 2020, and 2030

	1990		2020		2030	
Rank	**Region**	**Daily Acc.**	**Region**	**Daily Acc.**	**Region**	**Daily Acc.**
1	Bad Hersfeld	56,711,952	Fulda	75,429,708	Kassel	78,336,763
2	Fulda	56,693,551	Kassel	73,872,783	Bad Hersfeld	76,677,111
3	Frankfurt am Main	50,287,735	Göttingen	73,419,030	Göttingen	76,427,471
4	Göttingen	49,042,034	Würzburg	73,025,791	Fulda	76,143,765
5	Kassel	48,023,134	Bad Hersfeld	71,863,444	Gotha	75,808,757
6	Hannover	47,936,024	Kitzingen	70,590,045	Eisenach	75,753,009
7	Eschwege	46,914,779	Frankfurt am Main	70,279,545	Frankfurt am Main	75,396,872
8	Gießen	46,620,000	Schweinfurt	70,271,517	Mühlhausen/ Thüringen	75,162,626
9	Aschaffenburg	46,560,350	Lauterbach (Hessen)	70,256,870	Aschaffenburg	75,053,437
10	Einbeck	45,640,679	Eisenach	69,976,195	Eschwege	74,682,289
…	…	…	…	…	…	…
262	Meiningen	6,189,294	Stralsund	13,355,911	Greifswald	19,664,202
263	Salzwedel	6,158,024	Burghausen	12,467,436	Görlitz	18,946,142
264	Wernigerode	5,989,407	Zittau	12,040,938	Husum	18,802,825
265	Zittau	2,443,320	Greifswald	11,521,893	Stralsund	18,154,505
266	Sonneberg	1,694,259	Flensburg	9,993,978	Zittau	14,755,761

On the lowest ranks of the list, we can observe an inversion from internal to external peripheries. Among the regions with the lowest daily accessibility in 1990 are several regions along the former inner-German border, on the Eastern side (Meiningen, Salzwedel, Wernigerode, Sonneberg). These regions had found themselves in a peripheral position within their occupation zone after 1945, and even more so with the continuing deterioration of the railway network, but have since regained a central position after the restoration of rail links with Western Germany and have thus moved up in the ranking. Instead, the regions with the lowest daily accessibility in both 2020 and 2030 are purely geographically very peripheral regions in the North (Flensburg, Husum), North-East (Greifswald, Stralsund), East (Zittau, Görlitz), and South-East (Burghausen).

Figure 7 shows the absolute changes in regional daily accessibility for the decades between 1990 and 2030. Table 9 and Table 10 show the changes in daily accessibility for the ten regions with the largest and the five regions with the smallest increases in daily accessibility during the decades between 1990 and 2030.


1990-2000
Hamburg
Bremen
Hannover
Berlin
Essen
Dortmund
Düsseldorf
Köln
Erfurt
Leipzig
Dresden
Frankfurt am Main
Mannheim
Nürnberg
Stuttgart
München
N
0 50 100 200 km
2000-2010
Hamburg
Bremen
Hannover
Berlin
Essen
Dortmund
Düsseldorf
Köln
Erfurt
Leipzig
Dresden
Frankfurt am Main
Mannheim
Nürnberg
Stuttgart
München
N
0 50 100 200 km
2010-2020
Hamburg
Bremen
Hannover
Berlin
Essen
Dortmund
Düsseldorf
Köln
Erfurt
Leipzig
Dresden
Frankfurt am Main
Mannheim
Nürnberg
Stuttgart
München
N
0 50 100 200 km
2020-2030
Hamburg
Bremen
Hannover
Berlin
Essen
Dortmund
Düsseldorf
Köln
Erfurt
Leipzig
Dresden
Frankfurt am Main
Mannheim
Nürnberg
Stuttgart
München
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0 50 100 200 km

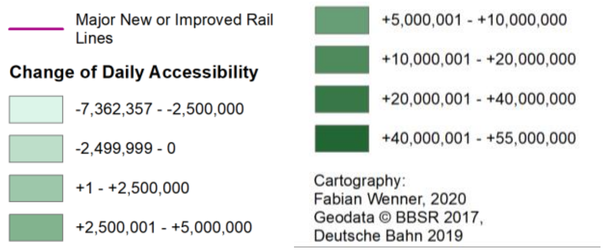

Figure 7: Change of Daily Accessibility

Table 9: Largest and smallest changes in daily accessibility of regions in the decades between 1990 and 2010

Rank	1990-2000		2000-2010	
	Region	**Δ**	**Region**	**Δ**
1	Mühlhausen/Thüringen	+46,794,866	Montabaur	+23,778,106
2	Salzwedel	+43,179,553	Kitzingen	+12,129,148
3	Wernigerode	+40,247,586	Bad Neustadt a.d.Saale	+12,008,783
4	Meiningen	+38,202,999	Bad Mergentheim	+11,568,353
5	Gotha	+35,492,673	Freiburg im Breisgau	+11,211,608
6	Suhl	+34,265,938	Ingolstadt	+11,059,543
7	Stendal	+31,969,199	Lüdenscheid	+10,657,879
8	Erfurt	+31,802,998	Bocholt	+10,366,510
9	Eisenach	+31,321,618	Limburg a.d. Lahn	+10,260,322
10	Sangerhausen	+29,920,235	Wertheim	+10,198,889
…	…	…	…	…
262	Passau	-1,003,523	Gera	-3,037,407
263	Bitburg	-1,261,810	Halle (Saale)	-3,162,479
264	Bocholt	-1,885,283	Dessau-Roßlau	-4,165,553
265	Traunreut	-2,089,999	Naumburg (Saale)	-5,857,390
266	Kleve	-3,198,062	Flensburg	-7,362,357

Table 10: Largest and smallest changes in daily accessibility of regions in the decades between 2010 and 2030

Rank	2010-2020		2020-2030	
	Region	**Δ**	**Region**	**Δ**
1	Halle (Saale)	+13,869,467	Jena	+22,703,914
2	Bitterfeld-Wolfen	+12,567,527	Weißenburg i.Bay.	+19,828,674
3	Leipzig	+10,597,697	Düren	+19,265,884
4	Sonneberg	+10,416,257	Donauwörth	+19,062,282
5	Dessau-Roßlau	+10,270,197	Halle (Saale)	+18,683,888
6	Wittenberg	+9,564,775	Leipzig	+18,192,101
7	Riesa	+9,446,828	Bonn	+17,245,896
8	Ingolstadt	+9,302,077	Bad Salzungen	+17,240,168
9	Neumarkt i.d.OPf.	+8,651,886	Dresden	+17,142,974
10	Ansbach	+8,491,179	Straubing	+16,284,344
…	…	…	…	…

Rank	2010-2020		2020-2030	
	Region	**Δ**	**Region**	**Δ**
262	Hannover	-1,317,784	Fulda	+714,057
263	Minden	-1,323,539	Leer (Ostfriesland)	+436,850
264	Zwickau	-1,420,938	Papenburg	0
265	Hameln	-1,466,605	Kitzingen	-2,901,410
266	Coburg	-1,878,298	Schweinfurt	-3,445,948

The first decade is dominated by the improvement of the Eastern German railway network and the reopening of rail connections across the former inner-German border, which particularly gives regions in proximity to the border in Eastern Germany a boost of daily accessibility. All top 10 regions in this decade can be associated with this type. On the other hand, some smaller peripheral regions in the West lose daily accessibility due to the closure of regional and local lines. In the next two decades, the effects of HSR construction can be seen much more clearly, particularly the Köln-Frankfurt line in 2002 (Montabaur, Limburg a.d. Lahn), the Nürnberg-Ingolstadt line in 2006, and the Nürnberg-Erfurt-Leipzig/Halle lines in 2015 and 2017. The decrease in daily accessibility for Coburg, which is located along the latter HSR line, can be explained with the methodology used: only connections that run at least once every 120 minutes are included. Under these assumptions, the accessibility of Coburg is reduced due to the discontinuation of the slower, parallel IC services that stopped more frequently in the Coburg region. The final decade is more characterised by the effects of service changes than those of infrastructure improvements. It is planned that several long-distance trains will be reintroduced to serve smaller centres in rural areas as well, which will improve daily accessibility of regions like Jena, Weißenburg i. Bay. or Donauwörth. On the other hand, the introduction of a fixed timetable with travel times adjusted to optimal connections rather than fastest speed means the reduction of travel-time based daily accessibility for some regions like Schweinfurt and Kitzingen.

3.5. Time-Space Maps

Figure 8 visualises the ‘shrinkage of space’ through the continuous improvement of transport infrastructure. The cartograms show time distance as spatial distance, which is not always accurately possible and can hide ‘inner peripheries’.

In 1990, particularly the slower average travel speeds on the rail network in East Germany as well as the delays at the former inner-German border become obvious. Delays at the border for identity checks, customs, and change of rail equipment were not necessary anymore after the autumn of 1990, but mostly still scheduled in the rail timetables. This is already observed by (Spiekermann and Wegener 1994)(Spiekermann and Wegener 1994)(Spiekermann and Wegener 1994)(Spiekermann and Wegener 1994)(Spiekermann and Wegener 1994)(Spiekermann and Wegener 1993) in their time-space maps of German rail accessibility. They highlight the particularly slow connections between Bavaria and the former GDR. But also in West Germany several “blobs” of remoteness become visible, particularly in the Mosel valley, the Eifel, and the Sauerland/Siegeland regions.

The change between 1990 and 2000 is most drastic with respect to the former inner-German border, which is hardly discernible anymore. The major metropolitan cores move closer together, hiding the fact that the space in between does not always participate in this development. Geographically peripheral regions with high travel distance to the cores become visible as “spikes” that radiate outwards from the core area of high integration, such as the entire *Länder* (provinces) of Schleswig-Holstein and Mecklenburg-Vorpommern. Superficially, the maps of 2000 and 2010 look similar, but particularly the new HSR rail line between Köln and Frankfurt am Main has stitched together the central west more strongly, while the regions of the Siegerland and Sauerland appear even more bloated and therefore remote than before. The next decade again brings regions closer together through HSR, particularly on the Nürnberg-Erfurt-Leipzig/Halle axis, but also shows the “space-inflating” effect of reduced regional connections in the case of Mecklenburg-Vorpommern, which now appears even larger. Some regions, like Southern Saxony, remain “inflated” throughout the time observed.

Should all projects of the BVWP be implemented as planned, the time-space map of 2030 will again shrink considerably. The reintroduction of long-distance trains in peripheral areas means that several of them move closer to the metropolitan cores. The overall map looks not entirely different from a real map of Germany anymore, signifying a relatively homogenous implementation of rail infrastructure. Nevertheless, some notorious “blobs” of inaccessibility remain.

The time-space maps are a vivid way of visualising time distances in spatial terms, which is often easier to comprehend.

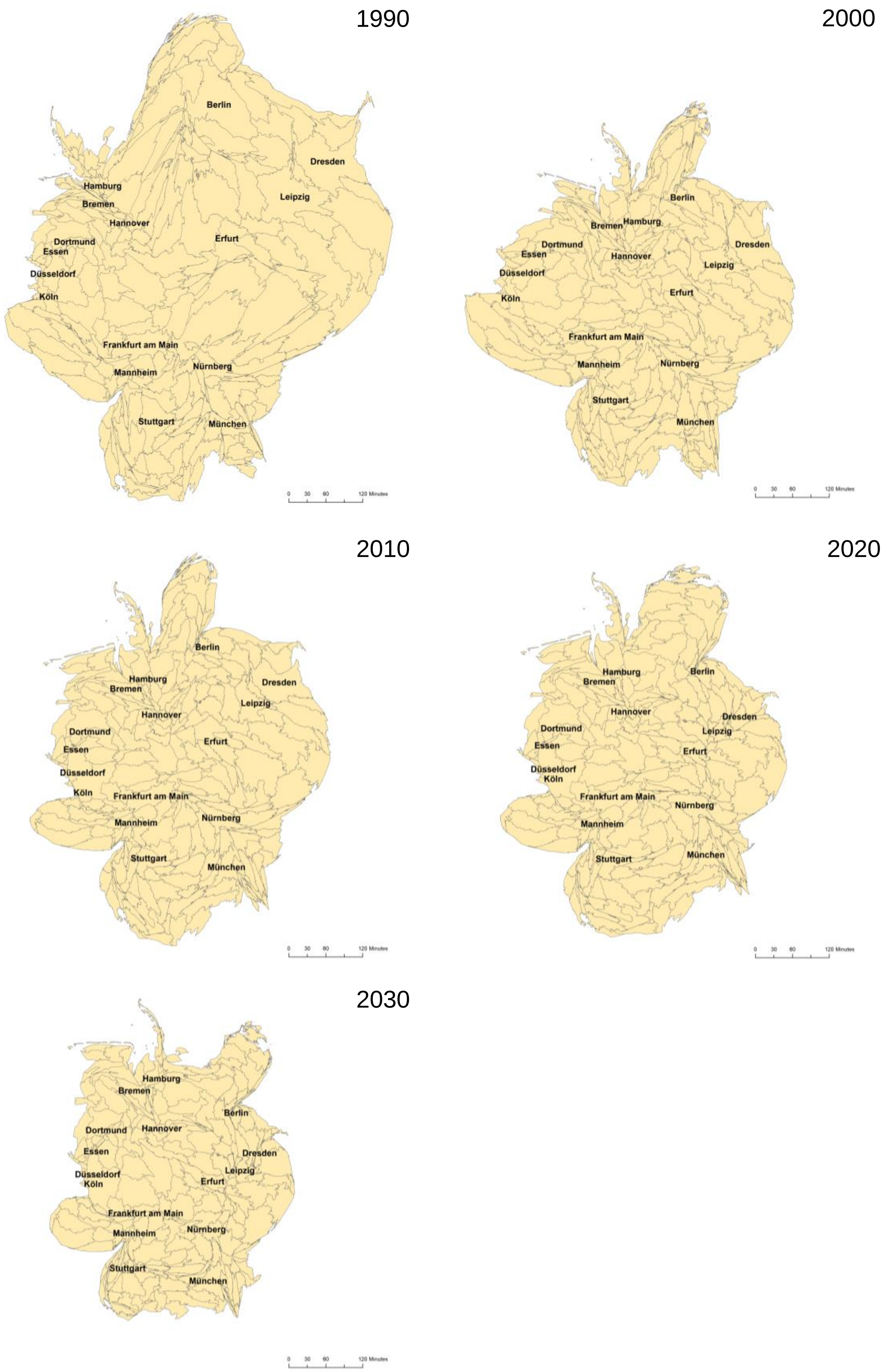

Figure 8: Time-space maps for rail accessibility in Germany, 1990-2030

4. Discussion and Conclusion

In this paper we have presented the results of the application of four different accessibility measures on the development of rail accessibility for regions in Germany between 1990 and 2030 in ten-year intervals. For the year 2030, we have used the currently planned projects in the Federal Transport Infrastructure Plan. The measures used are (1) a comparison between potential accessibility of population, using an exponential decay function, on the rail network on the one hand and in a hypothetical, frictionless space that can be travelled with constant speed in all directions on the other; (2) closeness centrality, i.e. the average travel time to all other regions in the country; (3) daily accessibility, i.e. the number of people that can be reached using the rail network in four hours; and (4) time-space maps.

The comparison of 'geographic' and rail-based accessibility has revealed the importance of sunk costs embodied in the rail infrastructure of the last decades and even centuries. Existing rail infrastructure is aligned to major cities, which gives them an advantage in terms of relational proximity. The analysis has also revealed a potential disadvantage of polycentric regions like the Rhein-Ruhr area, where frequent stops translate into low average speeds, which reduces their accessibility advantage from infrastructure alignment compared to monocentric areas.

Both the closeness centrality and daily accessibility measures have highlighted the importance of geographical centrality if a fixed delimitation of the study area is used. Nevertheless, also with these measures a tendency away from geographical determination of accessibility towards relational creation of it can be observed. While the decade between 1990 and 2000 was overshadowed by the massive improvement of the deteriorated Eastern German rail infrastructure and its effects on accessibility, as well as the disappearance of border checks and the reopening of cross-border lines across the former inner-German border, the following decades allow a clear identification of accessibility gains through HSR lines. Particularly the formerly less accessible rural regions of Montabaur and Limburg are catapulted into a favourable position in terms of accessibility between the major metropolitan centres of Frankfurt am Main and Köln. Accessibility changes in the next decade will be dominated by service changes and upgrading of conventional lines rather than new HSR lines, if the projects of the current BVWP are realised, at least if a national perspective and closeness centrality or daily accessibility indicators are used.

The time-space maps are a very demonstrative way of visualising time-distances and relational proximity, especially across several points in time. It is important to note however that due to the calculation method, low-accessibility regions between major cities can be concealed in these maps, despite the fact that they should appear larger.

The overall conclusion of the paper is that HSR has significantly supported the “shrinking of space” (Spiekermann and Wegener 1994) and the increase of accessibility across regions in Germany, but in comparison, upgrading of conventional lines and service improvements, such as the introduction of express trains on local lines, can often lead to accessibility increases of the same magnitude with less investment volumes. This should be taken into account in the preparation of mobility plans.

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