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Visualising Transformations of Geographical Time-Space by Transport Systems. The Case of Germany, 1990-2020

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Abstract

By accelerating the overcoming of space on certain relations, transport systems alter the accessibility of places and distort geographical time-space. Particularly in the case of discontinuous and tiered transport systems such as (high-speed) rail networks, effects on time-space can be highly selective and difficult to visualise. This paper compares different methods of operationalisation and visualisation of the effects of new transport systems (infrastructures and services) on time-space, and examines their strengths and weaknesses, using the example of the evolution of the German rail network between 1990 and 2020. The methods are well-known ones such as isochrones, choropleths using measures from network theory, anamorphosis (cartograms) and less-known ones as spring maps and the shriveling model. For the examination of the **readability** of the methods, we present relevant criteria for time-space maps. The results suggest that conventional methods are simpler to interpret, but fail to convey certain criteria, while less frequently used methods may be better at incorporating the criteria at the cost of being more difficult to read.

Keywords: Visualisation, Time-Space, Accessibility, High-Speed Rail

1 Introduction

Distances in space can be covered at different speeds, depending particularly on the presence of transport infrastructures and services. The physical, geographical distances between places and their actual or perceived distances in time differ. These differences and their accelerating development have long led to thinking about creative cartographic solutions that visualise the time-based proximity between places and reveal their accessibility.

Recent innovations in transport technology have again altered the dynamics of differential distortions of time-space geography. Particularly, the development of High-Speed Rail (HSR) systems in the last decades mainly throughout Asia and Europe have transformed temporal proximities by land-based transport systems, by dramatically and abruptly reducing travel times on selected origin-destination pairs. At the same time, travel times between regions not connected to the new transport system remained stable or even increased, as other rail services were sometimes discontinued. However, often-used cartographic renderings of travel-time effects, like isochrone maps or anamorphoses, do not always show these differential effects on varying scales. In this paper, we undertake a comparison of a range of methods of visualisation of the structure and dynamics of such time-spatial geographies, using the evolution of the German rail network in the last decades as a case study.

The paper is structured as follows: After the theoretical background, we introduce five types of maps usable for time-space effects of transport infrastructure systems: isochrone maps, choropleth maps using accessibility indicators such as closeness centrality, anamorphoses, spring maps, and the shriveling map. First, we describe the methodical background for each visualisation type, followed by introducing the case study area. The results section contains examples for each map type, applied on the case study. We then systematically compare the results in the discussion section, before concluding.

2 Theoretical Background

A mode of transport that allows to travel with almost equal speed in all directions and between all places, with no need for heavy infrastructure, e.g. walking, does not distort geographical time-space. Physical and time-based distances are identical. However, from early times on, waterways and highways served as a means to cover certain relations faster than others. The 19th century brought the development of precise topographic maps on the one hand, but also the emergence of new modes of travelling like rail and steamship, which led to a shrinking world (Janelle, 1973), that is, an ever-increasing distortion of geographical time-space as part of globalisation. The visualisation of such shifts within time-space geography is of particular interest. However, this shrinking process occurs unevenly across space (Knowles, 2006): on certain relations, travel times are reduced drastically, while travel times on other relations remain unchanged or even increase. Place A and B along such transport routes can be closer to each other in temporal-relational terms than A and C offside them, although the geographical distance between A and C may be shorter (L'Hostis, 2016). The result is a new landscape of proximities and peripheries, of accessibility and inaccessibility, that differs from the conventional cartographic representations of space we know, and requires innovative approaches to visualisation. Such visualisations may reveal more than just the convenience a certain transport system provides: inherently, they can shed light on power relations in a world system (Friedman, 1986; Sassen, 1994) that increasingly relies on flows between dominant nodes (Castells, 1996).

The task to map this nexus has occupied geography not only since the discovery of the category "time" for the subject (Hägerstrand, 1970). Among the most widespread attempts for visualisation are isochrone maps, anamorphoses, and accessibility maps, which were all already in use in the 19th century (Letaconnoux, 1907). Recently, GIScience has simplified the rendering of such visualisations, and made new visualisation techniques possible, such as shriveling maps. However, a number of particularities make the task a challenging one, inter alia:

- Both complex indicators and unconventional cartographic techniques can aggravate **readability** and interpretability, particularly for lay users,
- the spatially selective nature of time-space compression typically requires more than two dimensions for precise mapping,
- spatial inversion can occur, in the sense that a significant detour, involving a sequence in the opposite direction, can be faster than a direct route (Tobler, 1961; Bunge, 1962)

L'Hostis and Abdou (2021) argue that methods for the production of cartographic time-space maps can be subdivided into two categories: (a) methods where points are moved, and (b) those where edges are drawn in a special way. We extend this categorisation by a third group, in which (c) points or surfaces are drawn in a way that accounts for their accessibility.

In the following, we compare five visualisation types: isochrone maps, choropleth maps using closeness centrality as indicator, anamorphoses, spring maps, and the shriveling model. To compare the visualisation types, we use a set of criteria deemed relevant for the **readability** of maps. Map **readability** in general has been discussed by Stigmar and Harrie (2011) by developing legibility measures, or measurements of clutter, **that is**, excessive amount of disorganized information in a map (Touya and Sidonie, 2016) inter alia. Catered more specifically to maps displaying transport infrastructure, important design rules for manual (Avelar and Hurni, 2006) and (semi-) automatic (Wu and Nöllenberg, 2020) map generations were discussed.

3 Materials and Methods

In this section, we **first briefly** introduce the **evolution of German rail time-space and our used materials**. **Then, we present** different **time-space mapping techniques** and **provide applications to our data set, and finally, give short assessments of the applications**.

3.1 Materials: Evolution of Rail Time-Space in Germany

While a common European HSR network is slowly emerging, up to now, rail infrastructure development has remained largely a national affair in the last 30 years. A plethora of studies exist on the accessibility effects of the pioneering network of France (L'Hostis, 1996) and Japan (Shimizu, 1992), and the fast-growing networks of Spain (Moyano et al., 2018) and China (Cao et al., 2013). However, the evolution of rail time-space in Germany hasn't been studied in detail in the last decades. This is unfortunate, as the German case is characterised by conditions that make a comparison with other countries worthwhile:

- Germany is a polycentric country with a federal political system, which has led to a less radial and more grid-like, but also "patchy" implementation of HSR

- Due to the federal political system, the comparably high bargaining power of local and regional governments has led to the inclusion of more stations in smaller and mid-sized towns in the network
- The German HSR network is fully interconnected with the conventional network, such that HSR, intercity, regional as well as freight trains can and do interchangeably use conventional and most HS tracks
- The similar timing of the inauguration of the first HSR lines in June 1991 and the German reunification in October 1990 led to a double transformation of time-space

Wenner and Thierstein (2020, 2021) analysed the spatial distribution of regional rail accessibility in Germany between 1990 and 2030 by measuring potential accessibility of population and degree centrality. Furthermore, Wenner and Moser (2020) show closeness centrality, betweenness centrality and daily accessibility, which are all displayed as choropleth maps. They also produce time-space analyses in the form of anamorphosis maps. These studies show that there has been a 'shrinkage' of time-space relations along the axes of HSR, but the effects of refurbishment and reconnection of the Eastern German rail network had far stronger overall effects. At the same time, with the abandonment of many regional and local connections, the periphery became disintegrated with the loss of long-distance connections. These results are in light with Spiekermann and Wegener (1994), who predict a shrinking of space across regions in overall, but warn of precisely this kind of polarisation.

However, these studies have not yet harnessed the strengths of spring and shriveling maps. A new synthesis of these methods and a more advanced version of the underlying data will help to understand the actual development of the regional rail accessibility and the change in inter-regional travel times from 1990 to 2020 in Germany, as well as demonstrate the weaknesses and strengths of the various mapping methods.

For the analyses in this article, we constructed a rail network database for Germany and a 4-hours buffer zone around the country by semi-automatically digitising historical and current timetable data. For the historical timetable, we used data provided by Grahnert (2020). The 2020 data was gathered from the website of the German rail operator, Deutsche Bahn, at the time of its application.

As spatial base unit, we used the centres of functional city-regions as defined by the German Federal Institute for Research on Building, Urban Affairs and Spatial Development (BBSR), and NUTS-3 regions in the buffer zone. When destination weights were used, these refer to the residing population.

3.2 Methods: Time-Space Mapping Techniques

Time-space mapping methods are associated with two different types of visualisations. The first one aims to visualise actual tracked movements of one or many individuals over time in space, which is often done by using a time-space cube. We are not concerned with this type in this study, instead, we want to visualise how differing speeds of transport means across different origin-destination pairs in a region, resulting in distinct travel times, shape the travel time distance relations of one, some or all points or areas to all others points or areas in the region. Time-space maps can be used for many different goals as they present techniques that communicate either:

- how fast transport means can travel from an origin point to any other point, (Origin-Specificity from below before)
- or how (relatively) accessible a point or a region is compared to other points or regions,
- or what the underlying network structure for travel routes is,

- or how fast connections between origin-destination pairs compared to others are,
- or, and this resembles the time-space cube idea, in what directions in which chronological order specific routes develop. (Routing from below before)
- or how the use of space distortion and thereby generated geographical discontinuities can increase awareness of differences in time-space relations in a map (Continuity from before)
- or how weighting of some features in the map can shift the map-reader's visual impression, i.e. including population weights in an accessibility indicator. (Weighting from below before)

We chose the techniques portrayed in the following sections as they are, to the best of our knowledge, the most important known techniques (like isochrones, choropleth maps, and anamorphoses), which we extend with the adaptation of lesser-known ones (like spring maps and the shriveling model), that are in overall capable of visualising the most relevant characteristics of geographical time-space, as mentioned above in the bullet points.

3.2.1 Isochrone Maps

Isochrone maps are one of the oldest forms of representing travel times on a 2-dimensional map, with the first examples dating from the 19th century (Letaconnoux, 1907). They show the area(s) one can reach within (a) certain time threshold(s) from a given starting point as "travel time budget indicator" (Schwarze, 2005). The representation of the earth's surface remains topographic. Isochrone maps are relatively easy to comprehend, also due to their widespread use (O'Sullivan et al., 2000). However, a major limitation consists in the necessity to select a single reference location, increasing the effort for spatial and temporal comparisons.

The need to select an origin can be mitigated by overlapping the isochrones for a given time threshold on a map for a set of origins, which effectively highlights those places that are within the most isochrones of other locations. Such a process can be combined with the application of a time-geographical framework (Hägerstrand, 1970), i.e. typical framework conditions of specific travel purposes, such as business travel for meetings. An application example would be a map that shows places that can be reached with a return journey during one day, with the condition that a certain number of hours is spent at the destination ("daily accessibility"). Such information can then be displayed point-wise, network wise (L'Hostis et al., 2017), or using regional areal choropleths, i.e. colours for differentiation.

3.2.1.1 Isochrone Maps from Frankfurt am Main

Figure 1 shows as isochrone maps the destinations that can be reached within certain time thresholds by rail, starting from Frankfurt am Main central station (as the busiest railway station in Germany by passenger numbers) on a typical weekday, for the years 1990 and 2020. Generally, an expansion of the reachable area, with less time needed, can be seen in most directions. The colours in the figure respond to the minutes needed to reach the areas, as indicated in the legend. The expansion is particularly articulated along the axes of HSR infrastructure that have been constructed radially around Frankfurt and the HSR line in France between Paris and Strasbourg that is also used for services from and to Frankfurt. Another marked change is the strong expansion eastwards, which corresponds to the refurbishment and reopening of conventional rail routes across the former inner-German border and between Germany and its eastern neighbours. Interestingly, little change can be observed towards the south, i.e. towards Switzerland and Italy.

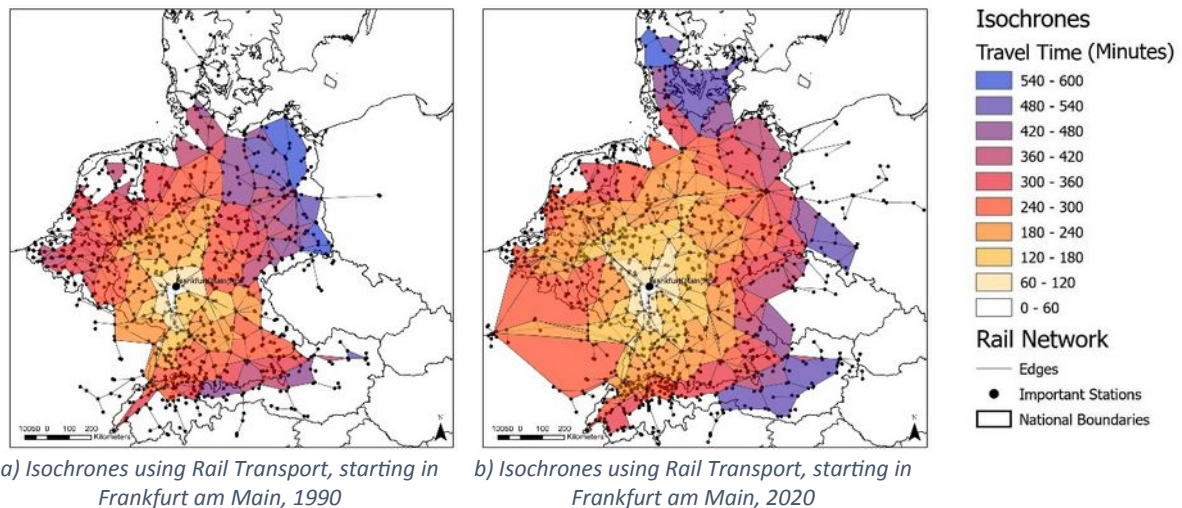


Figure 1: Isochrones

Isochrone maps are relatively easy to interpret also for lay people, however, the necessity to select one origin location restricts its use for more complex analyses of entire networks and regarding inner peripheries. A challenge posed by isochrone maps is the degree of detail: are all locations that make up the areas between access points of long-distance transport means reachable? In figures 1a) and 1b), this is not always true. Instead, the method was chosen as to convey the information how far away transport technology allows passengers to travel. Technically, the isochrone maps in our use case should only colour the stations reachable within the respective time budgets in order to avoid assumptions about further transport possibilities to the hinterland of HSR stations. Isochrones are usually used in local contexts, where detailed mappings are the goal. We follow this approach also to discuss the features of this conventional method.

3.2.2 Choropleth Maps using Closeness Centrality

Having their roots in urban and transport planning (Kansky, 1963), complex accessibility indicators have been developed that can be used to visualise time-space compression. The simplest forms of accessibility indicators are counts per territorial unit, such as the number of stations, the length of track, or the number of departures or lines at a certain stop. Such simple indicators neglect the networked and differential effects of transport infrastructure systems. Advanced indicators are based on networks of nodes and edges, and consider travel time and destinations. In fact, isochrone maps can be considered as a special case of an accessibility map. Finally, complex accessibility indicators show, for all nodes in a given network, the cumulative effort necessary to reach (all or a defined set of) other nodes, i.e. 'Closeness Centrality'. The consideration of destination weights is an important difference to the other forms of visualisation presented in this article. In addition, the effort to reach destinations can be inversely weighted using functions (e.g. exponential or gaussian) together with the inclusion of a buffer zone (for a detailed description of accessibility measurements see Song (1996) and Geurs and van Wee (2004).

Other graph-theoretical measurements, such as betweenness and degree centrality, can also be employed as accessibility indicators. However, we do not include them in our comparison here, as we

focus on travel times as the main factor of time-space compression rather than (non-)directness of connections between nodes.

For this paper, we employ a closeness centrality indicator with weighted nodes but unweighted travel times. Closeness centrality is usually denoted as an inverse value (Erath et al., 2009): the shorter the average travel time to all other regions, the higher the closeness centrality. We consider the non-inverse travel time to other nodes as easier to interpret and hence use the non-inverse 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. 1,

$$C_i = \sum_{j \in G-i} \frac{\sum_{i,j \in G, i \neq j} W_j d_{i,j}}{\sum_{j \in G-i} W_j} \quad (1),$$

where W_j is the weight of destination region j (residing population) and $d_{i,j}$ is the travel time between regions i and j by rail. As accessibility indicators typically yield values for single stations or areas, they can be displayed using point or area symbols (choropleths).

3.2.2.1 Choropleth Maps: Closeness Centrality of German Regions

Figure 2 shows the absolute closeness centrality values for German city-regions for 1990 and 2020. Clearly visible is the bias towards centrally-located regions like Hannover, which always exhibit shorter average travel times to other regions. However, figure 2b) shows that with new infrastructure development, cities further away from the core, like Frankfurt am Main, can also take a central position with regard to closeness. East Germany shows the largest aggregate improvements concerning closeness.

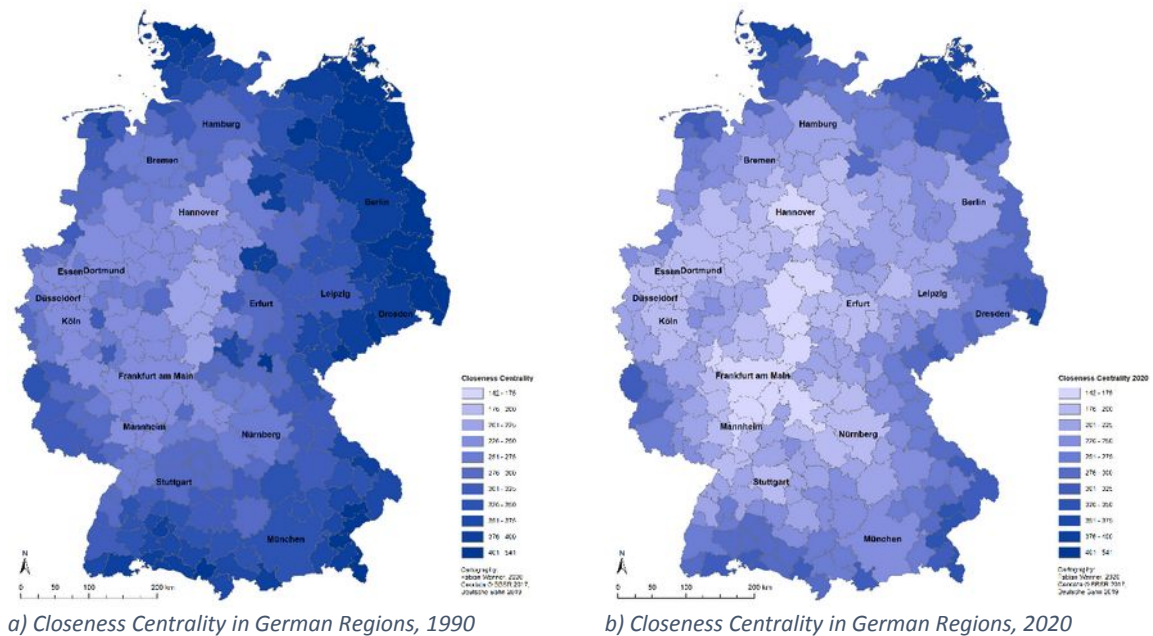


Figure 2: Choropleth Maps using Closeness Centrality

Choropleth maps have the advantage that they usually exhibit administrative regions that readers know and who are thus able to interpret the transmitted values of the mapped metric through the colouring scheme, especially in political and economic contexts with statistical variables such as income. However, they only present aggregated values by adding values of many smaller areas from the bottom up or just assign one value from the top down to all smaller parts of the region. They also neglect visualisation of transport network characteristics, which in the context of time-space maps might be problematic.

3.2.3 Anamorphoses

Anamorphic maps, also called cartograms, use advanced computational methods of multidimensional scaling to rearrange a topographic network according to temporal distance in two-dimensional space, thereby creating 'distorted' maps. Consequentially, the resulting maps have a time-scale instead of a distance-scale. They are a vivid method to illustrate the effects of transport infrastructure, which is represented as a "shrinkage" of space (Spiekermann and Wegener, 1994) and have been employed in geography early on (Tobler, 1961; Bunge, 1962). An exact representation of the time-distances between all points would however require a higher-dimensional coordinate space. Thus, two-dimensional anamorphoses are always only approximate solutions. As a result, they can hide peripheral(ising) and unconnected areas, particularly when they are surrounded by other, well-connected areas (L'Hostis, 1996; L'Hostis, 2009). Acceleration is rendered by combining different maps in a single graphic, with usually the same time-space scale, as in Spiekermann and Wegener (1994). A detailed description on the mathematical background can be found in Spiekermann and Wegener (1993,1994).

To generate time-space maps, we employed a non-metric multidimensional scaling algorithm coded in R. The non-distorted base map is premised on an equal speed of 60 km/h in all directions, the same as in Spiekermann and Wegener (1994), but using more nodes, with Frankfurt am Main as map centre.

3.2.3.1 *Anamorphoses of German Rail Time-Space*

Figure 3 shows time-distance as spatial distance by means of a map distortion. They allow comparing visually the temporal distance in the rail network with the actual topographical distance.

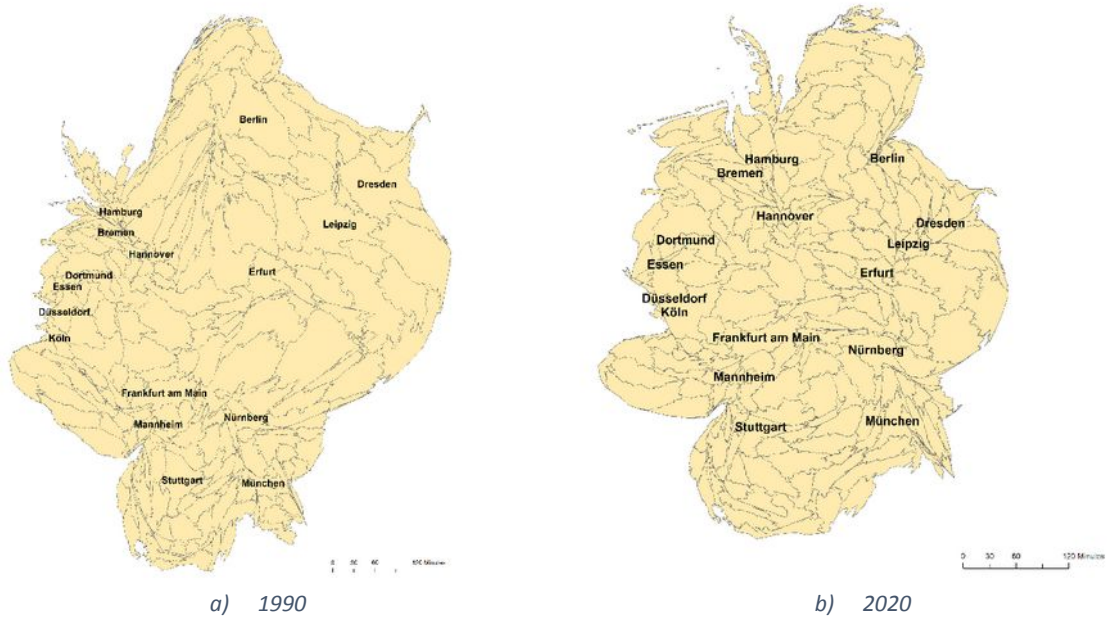


Figure 3: Anamorphoses of German Rail Time-Space

In 1990, the year of German reunification, particularly the strong differences in travel time between East and West become obvious, resulting mainly from the deterioration of the infrastructure in the former German Democratic Republic (GDR), and the lack of connections across the inner-German border. The two economic systems have not only resulted in differences in economic productivity, but effectively in different spatio-temporal regimes and landscapes. This is already observed by Spiekermann and Wegener (1994) 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, i.e. to the south of Köln.

The change between 1990 and 2020 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 times to the cores become visible as “spikes” that radiate outwards from the core area of high integration, i.e. the region northwest of Berlin in figure 3b). On the opposite, peripheral metropolitan cores that benefit from faster access generate “troughs” in the geographical shape, pointing inwards, that express the relative improvement of their accessibility, as is the case for Köln, Frankfurt am Main, München and Berlin.

3.2.4 Spring Maps

Spring maps were invented independently at the same time in France and the USA (Plassard and Routhier, 1987; Tobler, 1997), despite Tobler publishing them ten years later. A spring map shows a transport network where locations remain fixed, while edges take the form of ‘springs’, i.e. ‘zig-zag’ lines. The visual length of the spring expresses the length of the edge measured empirically, usually in hours. Recent developments of the model explored the use of sinusoid curves (Buchin et al., 2014) instead of broken lines, in order to improve the **readability**. For the automatic generation of the sinusoid curves, we use the ratios of distance-to-time and time-to-distance for the amplitude and frequency of the curves. Higher frequencies and higher amplitudes represent worse transport infrastructures, that is, slower average speeds and longer travel times on a relation. The intuition is

The shriveling model, conceptualised by Mathis (1990) and implemented by L'Hostis (1996, 2009), keeps cities fixed at their geographical position, and draws connections between cities with length proportional to travel time, by using the third dimension. The slower road network is attached to the geographical surface, which is then subject to a complex deformation. Recent developments use the cone as the basic shape for describing the terrestrial time-space (L'Hostis and Abdou, 2021).

The model can be developed further by including more modes and different speeds, represented by different cone heights. This would resolve the current 'in-or-out' logic regarding the choice of entry points to the fast transport systems, which are represented by cones with equal height, even if their locational and service characteristics differ. By design, the height of cones depends on the density of nodes; the really significant visual variable being the slope of cones, determined by the ratio of speed road versus the highest available speed.

3.2.5.1 The Shriveling Model of German Rail Time-Space

We based the implementation of the shriveling model of Germany as depicted in figure 5 on a list of 21 major cities. In 1990, conventional rail is the fastest terrestrial speed considered with 90 kph, contrasting with the lower speed on the road at 80 kph. Following the shriveling time-space principle, the ratio for conventional rail and road speed defines the slope of the cones in the representation. In the shriveling model, the maximum available speed of conventional rail generates the straight line of reference. The terrestrial surface, where road transport occurs, is formed by the assemblage of cones generated from the 21 cities, and cut at the borders of the country. The shriveled map of 1990, almost flat, exhibits very gentle slopes because the difference between the fastest transport mode and the road is low. By contrast, the German terrestrial time space of 2020 shows a very pronounced relief, where HSR at 170 kph deforms the road surface at 80 kph. We draw the slower classical train connections above the surface where cities are located, with lengths of curves proportional to the timescale.

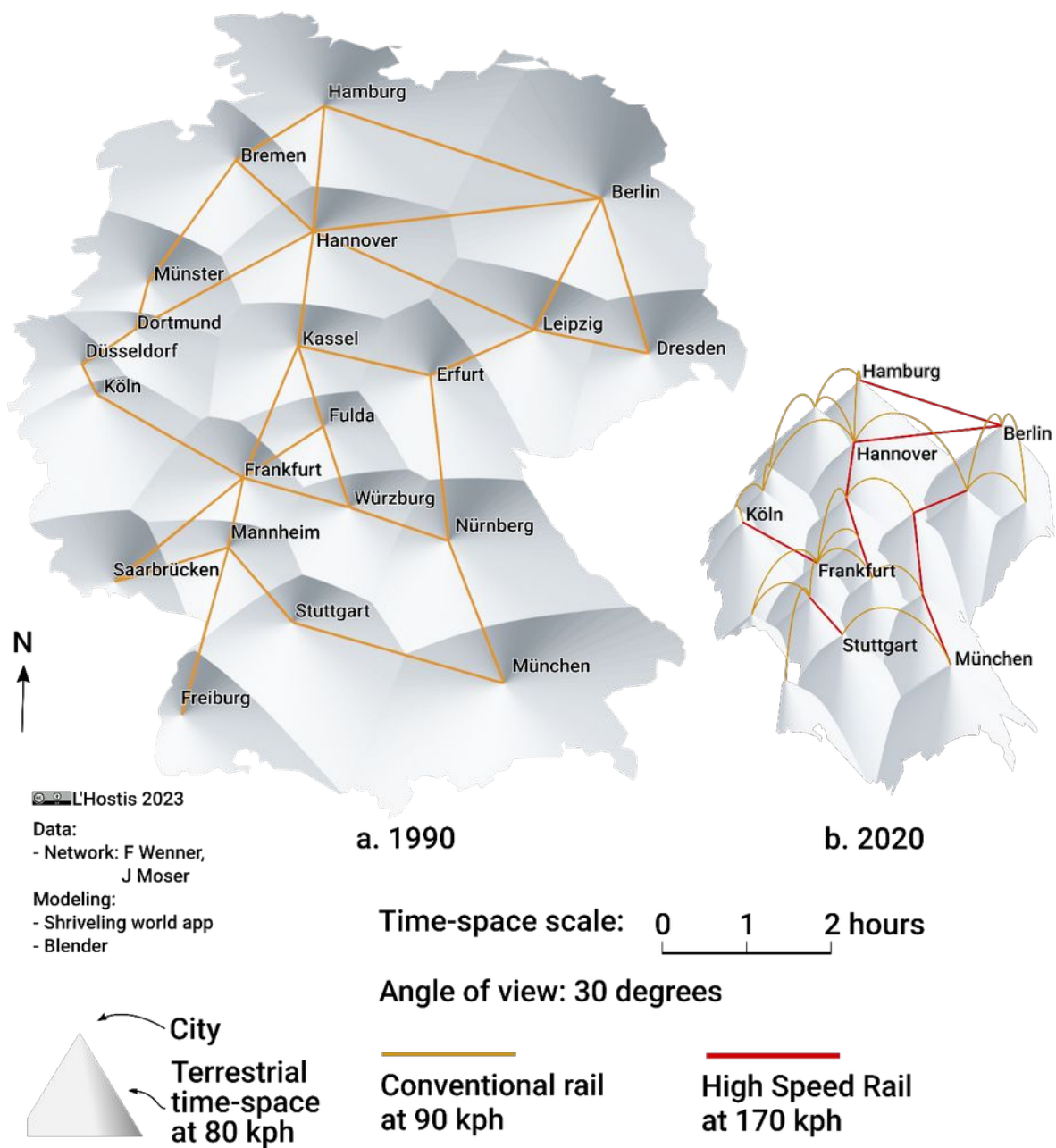


Figure 5: Shriveled Germany, view at 30 degrees, 1990 and 2020 at same time-space scale

As opposed to the conventional cartographic view from the top of sub-figure 6a), the angle of view on sub-figure 6b) reveals the shape of the German time-space. The performance of HSR becomes visible with the long connections between Berlin and Hamburg and Hannover. These long and fast lines crossing spaces with no major intermediary cities generate a marked relief expressing the relative peripheralisation of this intermediate space, despite being located in-between the most accessible cities of the country. This feature of the shriveling map is rendered on no other cartographic representation shown in the paper. While the anamorphosis map generates "blobs" in the periphery, the shrivelled map pushes non-metropolitan spaces below the surface. The area north of Berlin belongs to the 'deepest' parts of German time-space, a position that expresses its relatively low accessibility, as it is expressed as a "blob" similarly on sub-figure 3b). Despite enjoying a favourable intermediate position in the German geography, the region between Berlin and Hannover

lacks direct access to the HSR network and experiences the same fate. Sub-figure 6c) shows the same time-space from an unconventional west position, to further underscore the three-dimensional nature of the representation, and to reveal the effect of north-south HSR connections.

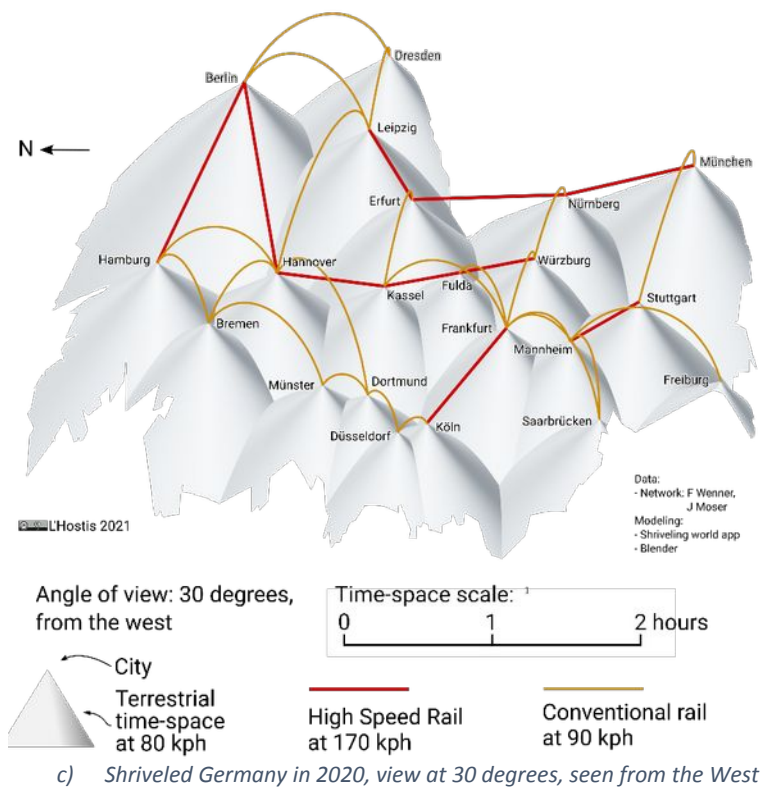
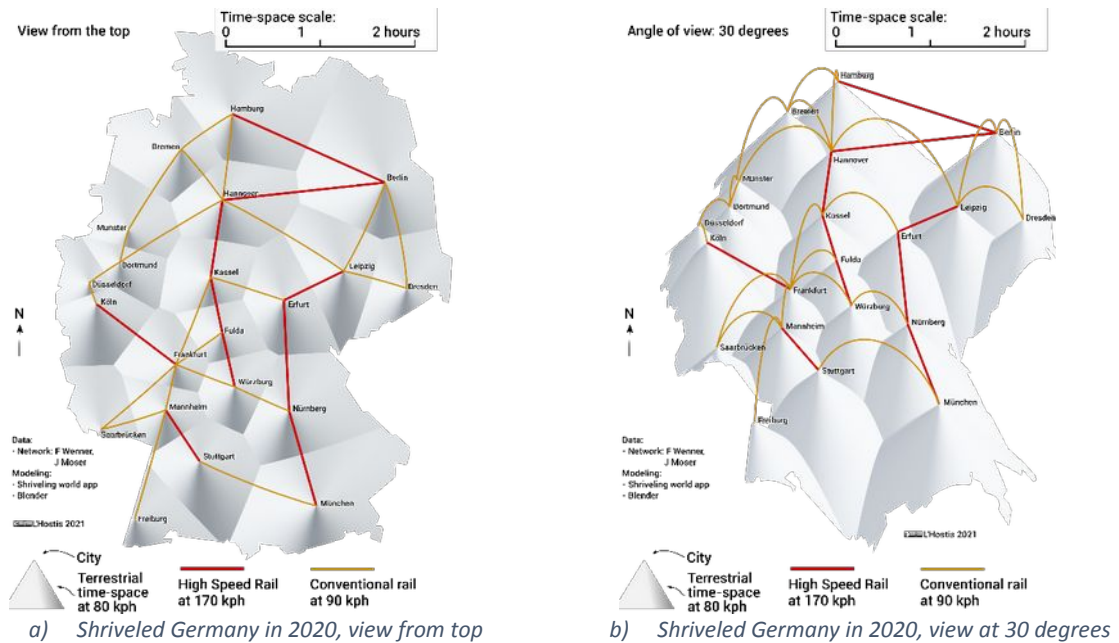


Figure 6: Shriveled Maps of Germany in 2020 with different perspectives

4 Evaluation Design

The assessment of the quality or usability of cartographic visualisations is a contentious point. There are criteria that guide cartographers, as well as lay persons, applying easy-to-use software today, on how to create high-quality maps, which is the task that constitutes the core of the art of cartography. To validate whether maps resulting from the application of the guiding criteria actually convey the intended cartographic message, researchers have developed methods that evaluate the quality of maps outside the realm of the map-maker's own subjective judgement. Three broad categories of such map evaluation designs should be mentioned. Although all three categories are concerned with the evaluation of the usability of a map, they all serve different tasks and are complements rather than substitutes to each other.

The focus of our study is to bring multiple explicit geographical time-space visualisation techniques together, apply them on one data set such that readers can compare visualisations within the same context, with the goal of evaluating their usability in the context of geographical time-space applications. We therefore extend the three map design evaluation categories by a fourth one, drawing on the four properties of geographical time-space by L'Hostis and Abdou (2021), as we deem these properties as a critical requirement to successfully evaluate the maps. As all three authors of this article contributed some of the provided maps, we discussed internally how to assess and evaluate the maps in light of the four properties of geographical time-space. In this sense, our synthesised evaluation consists of three different or external opinions that we report in this article. In the following, the four categories of map evaluations designs will be shortly introduced

First, external cartographic expert assessments are one way of improving maps as they are trained in the field and can give valuable feedback, however, this approach also entails serious disadvantages. Often, it is not a feasible map evaluation approach due to scarce time and monetary budgets of the other experts. More importantly, expert cartographers are usually not the target audience, instead, maps are often designed for lay users as the primary goal of many maps is to inform non-cartographers. Therefore, this approach is more catered to the exploratory, stimulating and idea-generating exchange between cartographers at more fundamental levels of research. In later stages of the research process, other evaluation designs have higher chances to produce constructive evaluative feedback.

The second map evaluation design category involves all approaches that can be subsumed under the term user studies. Within cartographic contexts, user studies aim at generating insights about (lay) map users' understanding and interpretation of maps, while for psychological or cognitive researchers, user studies about maps allow them to reconstruct the brain's processing of visual information absorption. User studies have various design options as they could be conducted in or outside of laboratories, as well as be of qualitative or quantitative kind. Potential methods include interviews, questionnaires, surveys, focus group discussions, inter alia. One of the most popular methods is called eye-tracking, which, with the help of machines, records the test person's eye movements across a projected map. The tracked eye movements facilitate inferences on the map content, i.e. where salient or unobtrusive features are located; as well as the eye itinerary across the map, which helps to establish a map user's train of thought. Subsequently, the information obtained lets map-makers evaluate whether their map design effectuated the intended map-reading behaviour. Eye-tracking is associated with the risk of the inability to generate external validity for especially two reasons. On the one hand, test persons in the user studies are often university students who are not representative of target audiences of some particular maps. On the other hand, a user study is not a real-world scenario, which introduces biases in the estimation of how map users read and interpret maps. Careful design of the user study is therefore indispensable.

While the first two map evaluation designs are based on human assessments, the third one rests on principles of computational automatisisation. The main idea is to devise a set of statistical properties according to which a map-generating algorithm computes and draws map features. This evaluation design stems from the map generalisation literature, which focuses on developing schematised and simplified maps that abstract from highly-detailed reality while still remaining legible. The trade-off is to display as much information as possible without producing clutter, which would inhibit a map's legibility.

The fourth map evaluation design, introduced by L'Hostis and Abdou (2021), suggests an approach based on four properties of geographic time-space with additional complementary criteria. We rearranged the list of properties according to the difficulty to convey them in graphical representation, and we completed this list with a fifth criterion on overall visual readability and on the content of the representation. The first criterion relates to the acceleration of speeds after the introduction of new transport means on certain transport links that lead to geographical time-space shrinkage. This criterion allows to compare two states of the network over time. The second criterion examines whether maps display the transport networks on which alterations of time-space occur. Thus, this property makes intelligible the reasons of why a change in time-space appeared, that is on which components of the transport infrastructure the acceleration of speeds takes place. The third criterion deals with the challenge of the simultaneous depiction of multiple co-existing transport modes that are each characterised by different speeds. This refers to the trade-off between presenting all transport connections or only those of higher hierarchy (fast connections). Omission of too many lower-hierarchy (slow) connections bears the risk of rendering biased or incomprehensible representations. The fourth criterion is associated with spatial inversion (Tobler, 1961; Bunge, 1962), which deals with those connections that first go in the opposite direction in order to reach a distant destination. This is directly related to the third criterion because often passengers have to reach a high-speed transport means with a slower local or regional transport mode, which leads to actual physical detours in space. Finally, we synthesize these four criteria to theoretically assess overall readability and interpretability of time-space maps.

In the following section, we evaluate the mapping techniques using the four criteria of time-space combined with our own assessment whether and how they meet the criteria.

5 Discussion

As indicated in section 2, we assess the maps presented in section 5 first according to features related to transport network maps and second to the list of criteria pertaining to the readability of maps by using the approach suggested by L'Hostis and Abdou (2021). We discuss four features that each of the representations convey and researchers may find important for their own use cases.

The **routing** function of a map implies that it is possible for a reader to establish an optimal route between points. A map permitting routing should exhibit the transport network. Spring and shriveling maps allow for routing, while isochrone maps hint at routes. For choropleth and anamorphosis maps, routing is challenging and requires more domain knowledge.

Not all cartographic methods assume the **continuity** of the geographical surface. Anamorphosis maps sometimes generate "blobs" where the order of proximities is lost, which leads to discontinuous space representations. Spring maps, as network representations, do not explicitly represent

continuous geographical space. On the contrary, the continuity of space is given on the conventional cartography-based representations of isochrones, choropleth and shriveling maps.

Origin-Specificity relates to whether a given point of departure can be identified in a time-space map. This is explicitly the case for isochrone maps. For all others, the relative travel times for the whole area are depicted, and the maps are not origin-specific.

Weighting refers to the option of giving areas more or less importance in the computation of an indicator. This would combine the variable travel time with other variables, like the number of inhabitants in a region. This is frequently done in network science or the accessibility literature. In our case, only closeness centrality allows for weighting of different places in the computation and hence in the representation. However, this does not exclude the option to weight the edges of the network, that is the transport links between two nodes, which could be done in the case of spring maps.

In table 1, we examine how the different map types convey the four geographical time-space properties by L’Hostis and Abdou (2021) and provide a theoretical assessment of their **readability**.

	1 Acceleration	2 Transport networks	3 Co-existence of modes	4 Spatial Inversion	5 Readability
Isochrone Map	Possible	Possible	Tricky	No	Easy
Choropleth Map	Possible	Possible	No	No	Easy
Anamorphosis	Possible	No	No	No	Difficult
Spring Map	Possible	Yes	Tricky	No	Tricky
Shriveling Map	Possible	Yes	Yes	Yes	Difficult

Table 1: How the different types of representation convey the four properties of geographical time-space, and expert assessment of **readability**

Acceleration is rendered by combining various maps representing different points in time in a single graphic, with usually the same time-space scale, as in Spiekermann and Wegener (1994). Therefore, it is possible for all mapping methods.

Transport networks can generally be drawn on the cartographic representations except for anamorphosis maps which would become surcharged. They are displayed by design on spring maps and on the shriveling model.

The two last properties prove difficult or impossible to convey on all types of representations, exception made of the shriveling model. The reader of a map assuming the **co-existence of transport modes** should be able to establish routes through these different networks. Some creative solutions are imaginable for isochrone maps using different colours for different transport modes, but not for closeness centrality maps, except by changing the outcome variable to an aggregate closeness centrality using multiple modes. If the representation is too complex, as in the case of the anamorphosis map, co-existence of modes cannot be depicted. For sparse networks, spring maps could depict multiple transport modes. The basic idea of shriveling maps is to depict more than one transport mode, which makes this method the most suitable for displaying this property.

Spatial inversion has always been considered a major challenge for spatial representation. How to express the inversion of space without tearing or cutting the surface? The design of the shrivelled map allows making clearly understandable the counter-intuitive reverse movement described in the

space inversion. The other map methods only allow for intuitive guessing, but not an exact visualisation of spatial inversion.

However, except for shrivelling maps, travel time can also be replaced by -- or combined with -- other characteristics of a journey into a combined indicator, such as monetary costs, CO2 emissions (Kinigadner, 2020), or comfort.

In summary, the frequently used methods isochrone and choropleth maps have the highest **readability**, but are restricted to visualising more general value distributions of metrics across space. Anamorphosis maps are very creative and impressive in dynamic live presentations, yet they require detailed study and knowledge of the undistorted space to be intelligible. Spring maps are best suited for presenting transport network edge values out of the suggested methods. Finally, the shriveling model is catered specifically to time-space visualisations by allowing for depiction of multiple transport modes and making intelligible the spatial inversion on a map. However, it is designed for advanced use cases and therefore difficult to read.

6 Conclusion

From the thematic point of view, the reunion of five different types of cartographic representations applied to a single dataset, Germany from 1990-2020, provides both a comprehensive and an unprecedented view of the transformation of German time-space over the period. Dramatic point to point improvements between major metropolises, as in the example of Berlin and Hamburg, are expressed by most representations, each with its own unique flavour. The relative time-space disintegration process experienced by several peripheral or more central regions of the country such as Mecklenburg-Vorpommern (north of Berlin) and Saxony-Anhalt (between Berlin and Hannover) is only expressed by the time-space blobs of the anamorphosis image and by the deep valleys of the shrivelled map. This thematic analysis underlines the benefits of applying truly different points of views on the same geographical object.

From a methodological point of view, no visualisation technique is perfect, all have their advantages and disadvantages. Isochrones are the most popular in travel time visualisations, especially in browser-based interactive tools. Accessibility indicators such as closeness centrality on choropleths remain powerful and frequently used, because they are relatively easily understood. Anamorphoses have the appeal of exposing inaccessible places, but they hide important aspects and cannot deal with multiple modes and spatial inversion. Spring maps are most useful for presenting values on edges of transport networks. Shriveling maps incorporate the third dimension and are thus more flexible, but require vast efforts both to produce and interpret them.

Visualisations result from a tradeoff between **readability**, their functionality -- comparing places, the possibility of routing --, and their ability to convey the major properties of geographical time-space. A comprehensive and comparative assessment of the **readability** of these cartographic representations, by means of user tests, still remains to be done.

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Author Contributions

All authors contributed equally to the manuscript.

Data Availability

All data is available upon request.

Declarations

The authors declare that they have no conflict of interest.

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