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Author(s):
Fuhrer, Raphaël

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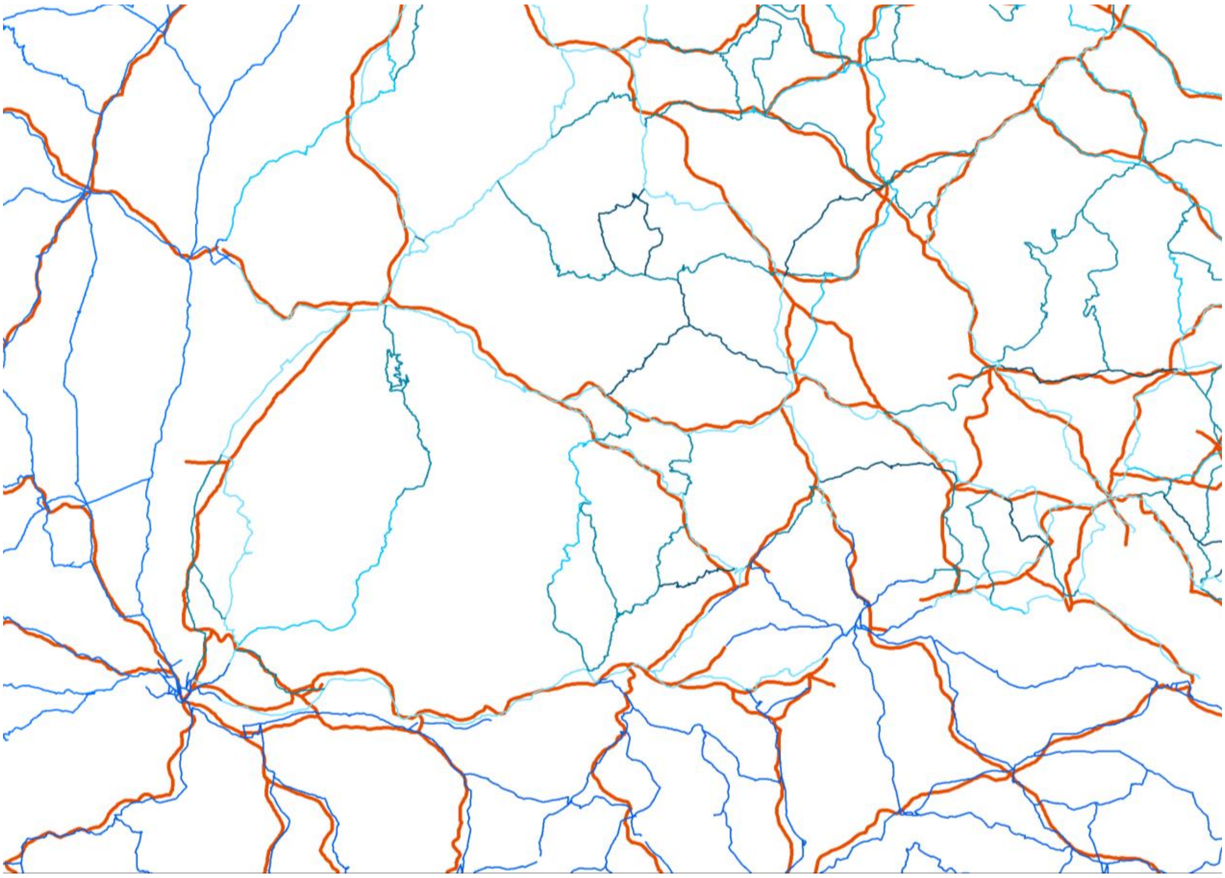

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Raphaël Fuhrer

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Institut für Verkehrsplanung und Transportsysteme
Institute for Transport Planning and Systems

ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Paper

Historical models of least cost paths, travel times and accessibilities of road-based transport in Western Europe 1500 to today

Raphaël Fuhrer
Institute for Transport Planning and Systems
ETH Zürich
Stefano-Franscini-Platz 5
8093 Zürich
Switzerland

Telephone: 0041 44 633 67 37
raphael.fuhrer@ivt.baug.ethz.ch

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Abstract

This research deals with methods to capture, spatially model and quantify changes in the European transport system over the last couple of centuries. Rather than examining one particular region or focusing on a travel pattern of a particular person, the approach captures the changes as a whole and considers transport as a system and as a network. The aim is to obtain a geographic information system (GIS), that includes historical transport infrastructure (h-tGIS = historical transport-GIS). The method is based on what I call Universe of Paths. A further model defines for each year and each territory maximum values of the travel system speed for both, the matrix in between the network as well as for the network and its single categories and links. This maximum value is corrected by the effect of the slope. By overlying the network with the matrix, a graph is constructed that allows to generate least cost surfaces. Finally, if the shortest path is calculated from every cell to every other cell, the resulting list of shortest paths from every cell to every other cell could be summarised using accessibility metrics.

Keywords

Europe; historical GIS; road network; historical travel times; accessibility; least cost surface; transport history

Preferred citation style

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1 Introduction

Today, we live in a mobile and globalised Europe. Many people do not work in their residential municipality and some even live multi-locally, meaning they live and work in several places during the year. Over centuries, this process of growing movement and shrinking distances across Europe and national borders has gone hand in hand with economic and territorial reorganisation. The questions becomes to what degree the transport system has changed, influenced the social and economic environment, and how to capture this development in a spatially meaningful way.

This research deals with methods to capture, spatially model and quantify changes in the European transport system over the last couple of centuries. Rather than examining one particular region or focusing on a travel pattern of a particular person, the approach captures the changes as a whole and considers transport as a system and as a network.

The focus on this paper is on methodical aspects. Related topics are the selection of suitable source materials (maps, written documents, geo-referenced materials), digitalisation, reconstruction of historical transport networks and related infrastructure, modelling of historical travel system speeds, and mapping as well as processing the data in a meaningful way.

The results of such research could be used in the context of any research with spatio-temporal data. How the generated data in this research should be made available has to be defined. It is the aim to cluster similar research results into one platform.

The feasibility of this approach is tested on a perimeter covering Switzerland, parts of France, Germany, Austria and Italy. Currently, the perimeter is expanded to Western Europe.

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2 Method

The far most important source are maps, differentiating in scale, year, and purpose. The general approach and the map processing part have been presented (Raphaël Fuhrer, 2016, 2017; Raphaël Fuhrer and Axhausen, 2018). The project aims in covering Western Europe for the time 1500 until today with the time steps 2010, 1950, 1845, 1720, 1640 and 1510. The time steps are chosen to account for developments in the transport sector, such as technical innovations like the advancement in road construction, or in society, such as the 1848 revolutions. The three most important steps in this process are: First, building of an assessed source (maps etc.) collection. Second, digitising the networks of transport infrastructure. Third, model the speed to overcome space. The spatio-temporal results allow to generate least cost path surfaces and finally calculate accessibility maps. The focus of this contribution is on the third step.

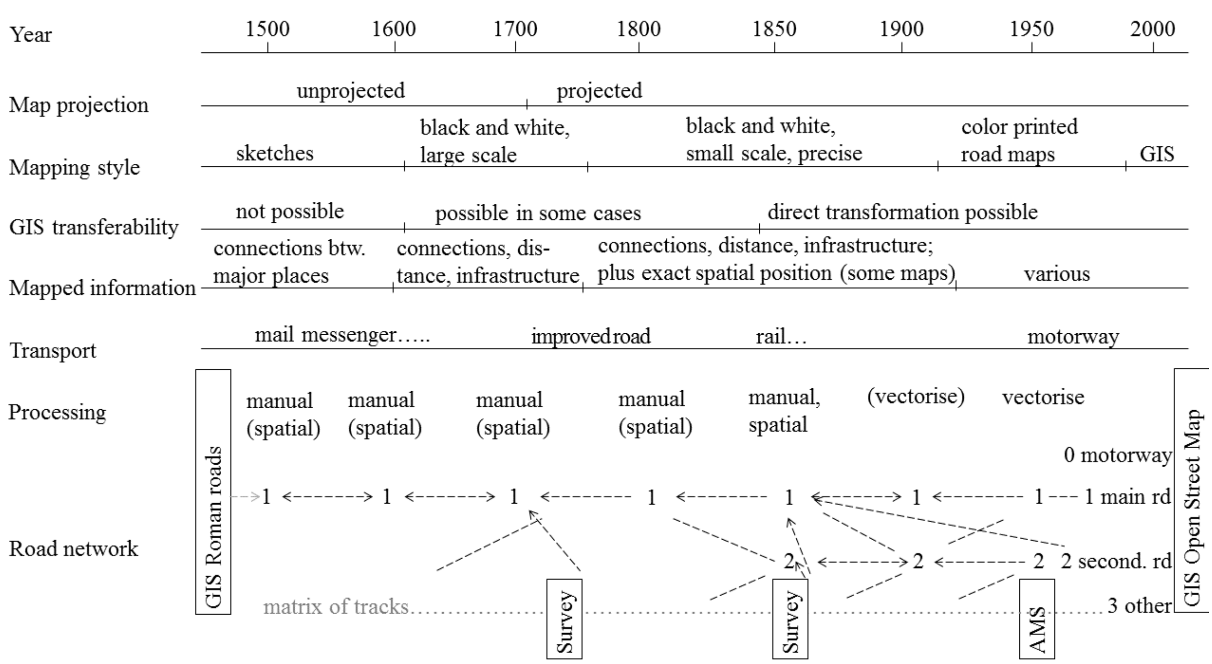
2.1 Summary network digitalisation

The aim is to obtain a geographic information system (GIS), that includes historical transport infrastructure (h-tGIS = historical transport-GIS). The method is based on what I call Universe of Paths. The basic idea is that there always is a form of transport infrastructure between any locations on earth where human activity takes places. This has always been like that. Over time, this network of transport infrastructure can change by extension (adding new connections) and improvement (enhancing existing connections). For both, there has been the opposite too – reduction and decline. In other words, there is strong path-dependency in this system. In combination with considering the development in map making, this approach allows to reconstruct the most likely historical network of transport infrastructure and transport services. This is summarised in Figure 1. Per time step, three (minimum two) inputs are needed: First, information on the existing connections = travel map (for example a mail coach map); second, information on the spatial positions of infrastructure = survey map (for example a topographic map); third a set of reliable GIS data (for example verified GIS data from another time step). By matching all three input information, the most likely network is reconstructed including the different categories of network element, for example the road and service type. In the 1950 case, it is possible to directly digitise the mapped road networks into GIS data using colour US Army American Map Service maps (series 1301). The digitalisation is semi-automated using machine learning (Raphael Fuhrer and Axhausen, 2015); the package is available for R or python[1].

[1] https://github.com/hunzikp/map-classification

The most important sources in network digitalisation are existing transport GIS data, such as OpenStreetMap layers or historical GIS data sets, survey maps on for example Mapire[2], and geo-coded collections of international travel maps[3]. For all three, there are several national and international sources.

Figure 1 The Universe of Paths



Source: (Raphaël Fuhrer and Axhausen, 2018); AMS: Army Map Service map

As shown in Figure 1, the method relies on the interrelation between progress in map making as well as transport infrastructure and transport. There is a mutual dependence, as accurate map information depends on transport infrastructure to survey the land and on the other hand infra-structure construction requires reliable maps and measurement of the territory. Furthermore, both is linked to statehood and territorial aspects, since mapping indicates acquiring title to the mapped land and accessibility allows state presence.

[2] https://mapire.eu/en/

[3] http://search.kartenportal.ch

2.2 Speed

A next important step is to translate the spatial information generated in section 2.1 into reasonable local speed estimates. This allows to calculate the travel time to overcome space in a particular location at a certain time.

Speed values are calculated for each year and for each network element as well as the space in between the network. The identified network represents the mapped connections, but there is always a matrix of tracks in the background. This matrix is not key to the change in speed over time, but omitting all the space off the mapped networks would misrepresent the historical situation since the majority of trips were walking trips.

Speed can relate to different references: The speed of a transport means, for example the vehicle speed of a mail coach (the maximum speed possible the vehicle is able to drive without accident); the speed of a transport service, for example the speed of a diligence service between two cities (the speed deducted from the distance divided by the travel time in the timetable); the speed of the transport system in general, for example the journey time of a person travelling from home to a destination including all time elements, such as access time, in-vehicle time, time for stops (horse changes, meals etc.), and egress time. The model is based on the latter one, the transport system speed. It depends on a lot of factors that vary over space and time: The available horse power (weight of horses, amount of horses, infrastructure to exchange horses, provision of provender), the quality of the road infrastructure (surface, width, weatherability, slope etc.), the quality of the travel infrastructure (inns, guidance etc.), daylight duration or the use of artificial light.

The model in this approach defines for each year and each territory maximum values of the travel system speed for both, the matrix in between the network as well as for the network and its single categories and links. This maximum value is corrected by the effect of the slope. The matrix reflects the general level of transport system speed off the main network and summarises a mixture of different travel styles (walking, riding, driving – depending on the year). The network reflects the investment into higher speeds and depends on the given information about the type of infrastructure and transport service. The travel infrastructure quality influence is not local and depends on the travel duration (e.g. an inn is not needed for short journeys) and thus is captured in the weight functions of least cost and accessibility calculations respectively. As a result, GIS on historical networks and their speed, GIS for cells of a continuous space and their speed, GIS of the travel system speed (as accessibility, i.e. relative to the population distribution) are obtained.

The year 1845 is presented as example. For the perimeter, four main travel maps[4] are used for network connection information and various other travel maps to cross-check the mapped information. The categorisation depends on the travel system in each country, resulting in 16 different mapped categories. This and the corresponding network is presented in Figure 2.**Error! Reference source not found.**

[4] Germany, Switzerland, Liechtenstein: Jügel, Carl (1843) Carl Jügel's Post u. Reise Karte von Deutschland und den Nachbarstaaten bis London, Paris, Montpellier, Nizza, Florenz, Pesth, Warschau und Kopenhagen, Carl Jügel, Frankfurt am Main.
France, some parts of Savoy excluded: Charle, Jean Baptiste Louis (1846): Carte routière et administrative de la France, indiquant les routes de poste avec les distances, les routes royales et départementales, les chemins de fer, les canaux et les rivières navigables ainsi que tous les chefs-lieux de cantons, Dopter, Paris.
Italy, some parts of Savoy included: Cerri, Carlo (1846) Carta stradale e postale dell'Italia disegnata secondo le Carte e le Opere le piu accreditate dei moderni geografi, Artaria, Wien.
Austria: Fried, Franz (1843) Neueste General-Post- & Strassen-Karte der Oesterreichischen Monarchie mit politischer Einteilung der Provinzen und deren Unterabtheilungen, Artaria, Wien.

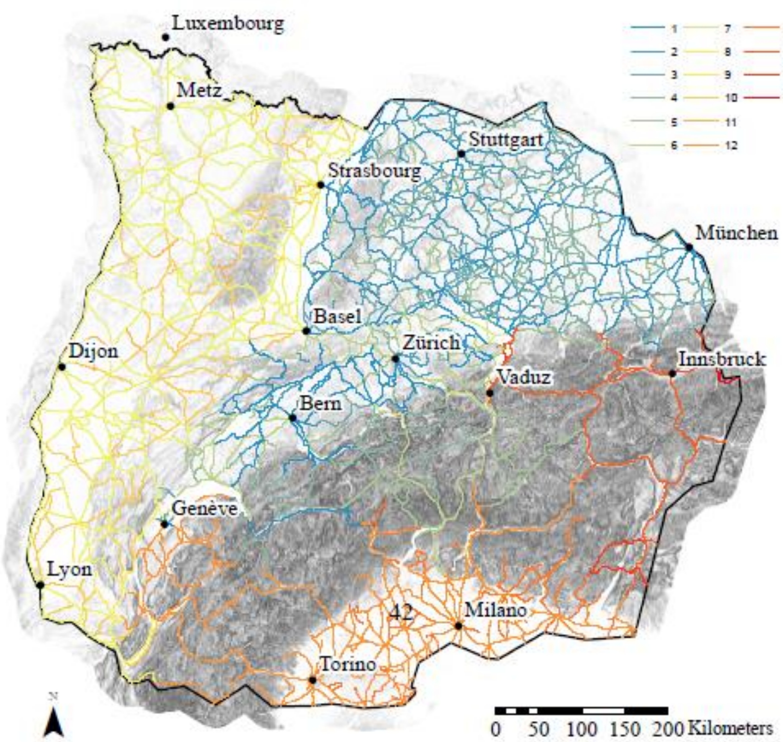
Figure 2 1845 network and road categories

(a) Categories

Note: entries in italic are not described in a legend, but are interpreted in this way.

Category	Legend entry on map
1	Eilwagen, Schnell-, Malle-, Personen-, Briefposten, *[etc.]*
2	Diligencen, Fahrposten, Postwagen, Messagerien
3	Extrapostverbindungen auf Chausseen
4	Extrapostverbindungen auf ordin: Fahrwegen
5	*Other ways [thin black line]*
6	Routen in der Schweiz, die mit Extrapost befahren werden
7	Dampfschiffahrt-Verbindungen
8	Route de Poste
9	Route Royale
10	Route Départementale
11	Chemin Vicinal
12	Strada regie e postali
13	Strade provinciali e commerciali
14	Post roads *[two lines drawn]*
15	Post roads *[single line drawn]*
16	*Ohter ways [thin black line]*

(b) Mapped network



Source: (Raphaël Fuhrer, 2019)

The network is coarser in mountainous areas compared to the lowlands. Connections on lakes are steamship services that complement the road based services. Every connection type is summarised into six travel system types which are given a maximum travel system speed.

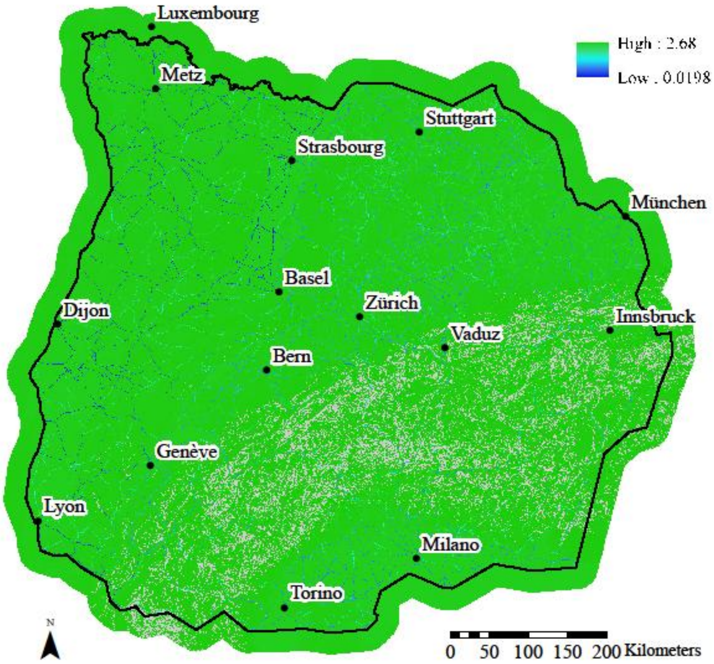
The influence of the terrain on speed is modelled on the network as well as in the space in between. The information on slope is extracted from a digital terrain model. The reduction factor for the maximum speed relative to the steepness of the slope is defined based on the work by Franz Johann Maschek and Eduard Bokelberg (cited in (Schiedt, 2010)), two mid-19th century engineers in the field of optimising draft animal traction. The resulting reduced speed corresponds to the maximum speed multiplied with the term $(1 - 2 \times \sin(\alpha))$, where α is the slope angle.

All other years are processed in a similar way. In 2010, motorways up to secondary roads are included (all without slope factor), the remaining roads are summarised using the in-between space matrix (with slope factor). In 1950, main and secondary roads are included, the remaining roads are summarised using the matrix (all with slope factor). In 1720, the roads and paths with postal infrastructure are included, the remaining roads are summarised using the matrix (all with slope factor). For each year, the maximum speed in the matrix and for each network type is defined using information on the corresponding travel system.

2.3 Least cost path surface and accessibility

The continuous space within the research perimeter is discretised into a matrix of quadratic cells of circa 300x300m. In each year, each cell is attributed a maximum speed; corrected by the slope. By overlying the network with the matrix, a graph is constructed that allows to generate least cost surfaces. Switching from the network to the matrix level does not cost any travel time. This reduces the complexity in the graph (which is necessary to reduce calculation time), however omits to a certain degree the character of schedule based connections. The resulting cost surface, in travel time, shows how costly it is to travel through a location within the perimeter. This cost surface provides information on shortest paths (in terms of travel time) between any two points within the perimeter. The result is presented in Figure 3. One can observe the network elements being faster in general, however the difference between matrix and network decreases due to the slope effect.

Figure 3 Cost surface in 1845 (travel time)



Source: (Raphaël Fuhrer, 2019)

An important limitation to this approach is the omitting of rivers. While main roads usually cross rivers on bridges or fords, this does not always hold for less important roads and tracks. They sometimes stop at rivers. The map in Figure 3 depicts the space in between the network as rather homogeneous, however when zooming into a region the variance becomes larger.

Finally, if the shortest path is calculated from every cell to every other cell, the resulting list of shortest paths from every cell to every other cell could be summarised using accessibility metrics. Not all cells are of equal importance. The amount of population per cell is used to define the importance of a cell. The historical population model is based on a historical population model using larger cells (Klein Goldewijk et al., 2010). The current population distribution pattern within that cells is used to approximate the pattern within smaller cells, i.e. the historical total count of population is distributed to the smaller cells using the current ratio of large to smaller cells. In the accessibility model, only cells with population greater than 3 persons per cell are include. The shortest path algorithm is based on the igraph package in the programming environment R (Csardi and Nepusz, 2006). The equation to calculate the accessibility in every cell *i* is as follows:

$$A_i = \sum_j O_j \times e^{-\beta \times C_{ij}}$$

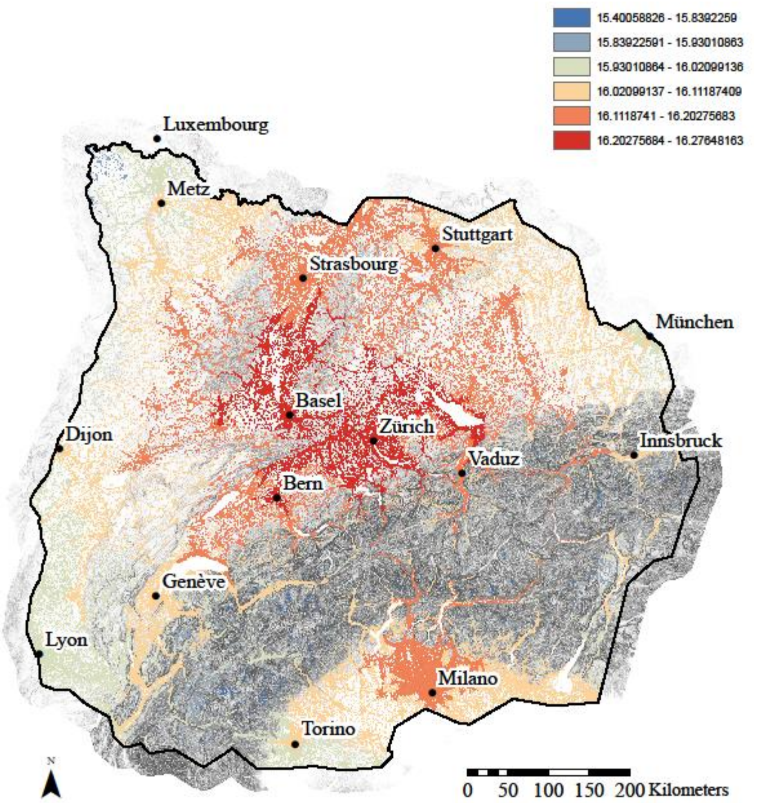
with A_i as accessibility in cell i to all j opportunity cells O_j at generalised costs C_{ij} that are weighted by a negative exponential transformation with factor β (Hansen, 1959). The weight function is chosen in such a way that the limitations due to daylight are captured.

As the result in Figure 4 shows, this metric captures the spatial cost structure based on shortest paths within the cost surface and combines them with the population distribution. The calculated values inform about the ability to reach opportunities (represented by population) in a particular location.

3 Results

In Figure 4, low values (blue) mean low accessibility and thus few opportunities and high values (red) mean high accessibility and thus many opportunities. The majority of population is north of the Alps, where values are higher in general. Higher values occur in areas with dense and fast transport infrastructure, on flat territory, and with population densities above average. The lowest values are found in valleys in the mountains.

Figure 4 Accessibility in 1845



Source: (Raphaël Fuhrer, 2019)

The highest values are located in the centre of the perimeter while the values tend to decrease towards the fringe of the perimeter. This is an artefact of a combination of limits to the model: First, the perimeter is artificial and this means that population counts are cut away from the concentric area around every cell calculated in the model. The radius of the concentric distance to the cell is proportional to the chosen weight factor. Second, some connections are suspended leading to dead road ends. This means higher least cost paths for cells at the fringe. However, overall the results represent the historical situation and capture the historical travel and opportunity landscape well and for most areas within the perimeter.

4 Discussion and outlook

This research shows how to reconstruct historical transport networks and deduct historical travel times, least cost surfaces and finally accessibility values. This spatio-temporal data allows to capture spatial dynamics over long periods of time. It combines information on network dynamics (Raphaël Fuhrer, 2017) and models historical travel times within a continuous space. The results show the historical situation regarding travel and available opportunities. They provide quantitative descriptions on the spatial realities of people living in a particular location, about the area of their mental and everyday space. As in all accessibility calculation, there are border effects in the results. Furthermore, some justified simplifications had to be done in modelling the network, matrix and speed. The bottleneck of this research is the manual work to reconstruct the t-hGIS as well as the computation power to calculate shortest paths and accessibility.

The advantages are manifold. Most importantly, it is possible to produce spatially precise historical networks rather than spatial information on point-to-point connections. The least cost surfaces and accessibility metrics allow to capture spatio-temporal changes not only on local level but on an regional level over long periods of time. This data completes other historical GIS data and could serve as basis for further quantitative and spatially explicit research, for example econometric research, but also as context to qualitative historical research.

Currently, the perimeter is extended. The aim is to capture the whole of Western Europe and data of France, Germany, Austria, Italy and the BeNeLux countries is processed. Also, the scope in time is extended back to 1510 using additional materials.

5 Literature

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