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Data sources, historical information processing, and first application

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Reconstruction of Western Europe’s Pre-Motorway Road Network Back to 1500: Data Sources, Historical Information Processing, and First Application

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ABSTRACT

This paper presents the construction of a new historical road network data set, capturing conditions between 1500 and 1900, focusing on the 19th and 18th century. It continuous the work presented at TRB in 2015 on Reconstruction of 1950s Global Road Network Using American Army Maps. It covers Western Europe. The main part of this paper reports in detail the heuristics used, which were established based on an assessment of 900 or so collected historical transport related documents, mostly transport maps. Switzerland in 1850 is employed as an example of a geographical information system used to generate historical travel times. As far as the authors can ascertain, such comprehensive and detailed historical transport data has not been available until this point, but it enables examination of various historical and current transport-related research questions using spatial and time-variant data. The purpose of this paper is: first, to report on the reconstruction of these historical road network data and to position it in the existing literature and research tradition; second, to explain how the network is generated; third, to present our approach to model historical generalized travel costs; fourth, show how to use such information by applying it in a Swiss case study.

Keywords: Historical transport data – 1500 to 1900 – Western Europe – Path dependency
INTRODUCTION AND RELATED WORK

There is an increasing interest in historical geographic information systems (GIS) and quantitative transport history in general ((1) and (2)). Some researchers compiled numbers and facts on travel during the Middle Ages, modern times and recent history (for example (3), (4), (5), (6)) to reconstruct historical journeys (e.g. (7), (8), (9)). Other researchers use data on historical transport parameters and patterns to explain and analyze societal and economic developments, such as slavery (10), trade and growth (for example (11), (12), (13), (14)), commuting (15) or migration ((8) and (16)), regional economic or transport policy (for instance (17), (26), (27), (20), (21)).

We are interested in the relation between transport infrastructure, accessibility, and state reach. The main idea is to use accessibility metrics based on transport networks (22) as a proxy of state reach. The transport network captures the presence of the state in its different forms (23); all governmental functions such as law enforcement, public services, etc. require accessibility and thus a fit-for-purpose transport infrastructure. In this spirit, parts of the 1950s global road network were reconstructed using American Army Map Service maps (24). Several studies used this data, for example as an input in spatial models to predict future conflicts due to lacking of state presence (25).

The research presented here continues the work and data set. The main idea stays the same, however the spatial focus is now on Western Europe and the period covers the time back to 1500. Europe has an interesting history regarding territorial changes (see for example (26)). However, it is unclear what the role of transport infrastructure was in this process and whether relationships observed in another context could be transferred to the long-term Western European history. Some researchers linked transport infrastructure and power ((27), (28),(29)), but there have not been any study using European historical GIS. To summarize, the core of this paper is the generation of a spatially explicit historical transport infrastructure model in several time intervals. The future aim is, using this data, to explain the role of transport in European national state evolution. We contribute to an important field of transport history. The data is interesting for other researchers as well, and makes transport history spatial and relates to people’s everyday life at the time.

The paper has the following structure. The second section is the main part of this paper and details data generation and method. It consists of two subsections. The first subsection presents the influence in developments in the history of map making, transport, and travel behavior and how this affects the data source. The second subsection explains the information process using the newly established heuristics. The third section employs the method to the Swiss road network in 1850. The method is applicable to any of the maps covering parts of Western Europe between 1500 and 1900. Switzerland in 1850 serves as an illustrative example for one place within Western Europe at one time between 1500 and 1900 and analyses the method on feasibility and reliability. The fourth and last section concludes.

METHOD: DATA STRUCTURE AND INFORMATION PROCESSING

This main section describes the process from available source materials covering four centuries (1500 to 1900) to corresponding historical transport networks that can be used for various analyses. There are several kinds of documents, such as travel diaries, timetables, or travel guides, but most of these materials are maps. Unlike recent maps back to 1950 or so, the maps used here cannot, for several reasons, be processed automatically using extraction and vectorizing algorithms (30). The researcher needs to establish a more elaborate method, based on different fields and knowledge from transport history. Based on approximately 900 such items, the following two
subsections will explain how these characteristics of pre-1950 transport maps and other materials can be combined and which additional knowledge is necessary.

**Basic Data Model and Fundamental Principles in Modelling Historical Transport Systems**

Pre-1950 maps are 100% man made; this includes data collection, information processing, and map making. It was thus much more costly to produce and possess maps. As a result, even when collecting several hundreds of such maps, every map looks different. This makes it impossible to process them with automated algorithms. There are further aggravating characteristics, such as black and white designs (e.g. the first step in the algorithm presented at TRB 2015 is based on pixel color only), substantial spatial distortions (31), and limited information about the purpose and information source of the map. There have been attempts though to automate this process ((32), (33)), however without success. This was re-confirmed to the authors by several map processing specialists\(^1\). Instead, the authors suggest an approach shown in Figure 1, which combines several heuristics drawing from multiple data sources as well as principles based on the assessment of approximately 900 historical transport maps and related documents.

<table>
<thead>
<tr>
<th>Year</th>
<th>1500</th>
<th>1600</th>
<th>1700</th>
<th>1800</th>
<th>1850</th>
<th>1900</th>
<th>1950</th>
<th>2000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Map projection</td>
<td>unprojected</td>
<td>projected</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mapping style</td>
<td>sketches</td>
<td>black and white, large scale</td>
<td>black and white, small scale, precise</td>
<td>color printed road maps</td>
<td>GIS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GIS transferability</td>
<td>not possible</td>
<td>possible in some cases</td>
<td>direct transformation possible</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mapped information</td>
<td>connections btw. major places</td>
<td>connections, distance, infrastructure</td>
<td>connections, distance, infrastructure; plus exact spatial position (some maps)</td>
<td>various</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transport</td>
<td>mail coach</td>
<td>country road</td>
<td>rail</td>
<td>motorway</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Processing</td>
<td>manual (spatial)</td>
<td>manual (spatial)</td>
<td>manual (spatial)</td>
<td>manual (spatial)</td>
<td>manual, spatial</td>
<td>(vectorize)</td>
<td>vectorize</td>
<td></td>
</tr>
<tr>
<td>Road network</td>
<td>GIS Roman roads</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0 motorway</td>
<td></td>
</tr>
</tbody>
</table>

**FIGURE 1** Basic approach for the input data and heuristics applied to gain continuity in the model. The term matrix of tracks is explained in the section below.

It is important to understand the interplay of the conditions of the three elements of interest here: history of map making, history of transport, and history of state evolution. The focus here is on the first and second element. Figure 1 generalizes the findings and connections based on approximately 900 historical documents. Every map first needs to be assessed (34) regarding its main characteristics. Projection ensures correct relations for the selected elements, say distance, angle etc., in the mapped features and was first introduced by Gerhard Mercator in 1569, however it took a couple of decades until conformal projections became the norm. Possibly the greatest

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\(^1\) Private communications with Yao-yi Chiang, Winfried Höhn, and Lorenz Hurni.
changes have happened in the mapping style. The oldest group are sketch-like maps, of which Erhard Etzlaub’s “Romweg” (Rome to Rome) map is a typical example (35). Dotted lines indicate suitable tracks between major places. Later maps became more similar to current maps, first drawn at large scale (covering larger areas with less precision) and second at small scale (covering smaller areas with higher precision). This corresponded to the mapped information becoming richer. This again was connected to technical and societal changes. In the early 18th century, many regions started to build new country roads. Nevertheless, this required precise measurement techniques, for example correct projection of the data. In most cases the extensive road construction started with a survey of the landscape, the findings of the latter were captured in maps. But also, the increased popularity of travelling – which was in turn enabled by the fact that diligences started to transport passengers in addition to letters – brought a new market for maps and changed their design and content. The introduction and availability of mail coaches and means of transport in general varied widely amongst European regions (3), hence did maps. Surveys sometimes became necessary due to territorial changes. And map makers themselves relied on transport infrastructure to survey the area to be mapped or receive sketched information by local “correspondents”. The metadata has to accommodate for all these complex connections and conditions.

The two crucial points in this research are the reconstruction of the physical network on the one hand side and the modelling of the corresponding generalized travel costs (travel time, monetary costs, and comfort/safety) on the other hand. The bottom part of Figure 1 shows the implications for heuristics to reconstruct the most likely shape of a transport network in Western Europe at any time between 1500 and 1900, given the data and conditions explained in the previous paragraph. The justification for these heuristics are given here. There are two reliable base maps, meaning confirmed spatially explicit data sets of roads (GIS): First the Open Street Map (OSM) network (36), which contains current roads, tracks and paths, and second the Roman Roads (37). In addition, there is the GIS of 1950 main and secondary roads using our algorithm on US Army Map Service (AMS) maps (24); and there are in some cases professional surveys, especially from 1750 and 1800 onwards as the French, English, German and Italian states were mapping there territory. The matrix of tracks is the starting point. It can be thought of as the universe of any type of connecting transport infrastructure. It is based on the assumption that every place used by humans (house, field, etc.) is made accessible, even if it is only a hardly visible trail. This is confirmed by reliable sources through the whole 500 years, be it a current OSM-shapefile, an 1850 or 1730 survey map, a 17th-century map of a monastery and its lands, or a 16th-century painting; they all show a landscape crisscrossed by paths. Over time, some of the paths vanish, some others appear, and some change their alignment/technology. In other words, one can observe network extensions (new roads) and network conversions (road improvements). Typical examples for extensions are the construction of the railway and motorway network, which met different requirements regarding topography than country roads, but they might have an influence on the existing network at the time.

For the time 1500 to 1900, we focus on main roads as we have strong evidence that whether a place was connected to main roads (and suitable infrastructure, see next sub-section) was the crucial point regarding the economic development of this place (18). As the motorway network predominately is a separate network, the 1850 main and secondary road networks have outlasted in most cases. However, they have been extended in the last 150 years. This means that historical main roads have, in general, a current counterpart, whereas not all current main roads have an 1850 ancestor. However, the current network hierarchy alone is not sufficient to derive the historical role of a road and, using further information sources, one is able to identify deviations and likely network developments. The general dependencies are represented in Figure 1 with dashed lines.
(physical conversions) and dashed lined arrows, the latter indicating the information flow during reconstruction of historical networks. In conjunction with the approach based on the conditions of input data – mostly maps –, the indicated processing steps in Figure 1 are needed for materials of a specific year. It is mostly manual work. In this fashion, it is possible to trace developments in the transport network, especially regarding the main and secondary roads, over the entire period. This processing always uses a range of input data of the specific year, but also earlier and later sources, and the researcher has to have profound knowledge on transport as well as map making history. The subsequent sub-section deals with the structured and combined exploitation of these heuristics and data concept.

**Structured Approach Using Essential Tools to Process Sources on Historical Transport**

The introduced data concept is translated into a practical method, explaining the essential tools. It is summarized in Figure 2.

The aim of this research is to reconstruct historical transport networks and to derive generalized transport costs to gain understanding on accessibility values and travelling possibilities in different places at different times. Thus, we need to reconstruct which places were accessible at which costs. It is not possible to calculate exact travel times without the exact journey length; hence the spatially explicit position of the transport infrastructure is needed. The vast majority of people did not travel with their own horse(’es) (38). Apart from the road itself, further infrastructures thus were crucial: horses as “fuel” and coaches respectively for the movement, horse-related infrastructure providing fodder or the service to replace horses, and inns, guesthouses, farms or huts that provided shelter for multiday trips. Without the horse-related infrastructure, you could still use the roads but only as a pedestrian. State-owned or private companies provided such infrastructure, usually related to postal services. Maps with postal routes generally are a reliable source for the information about travelable roads and accessible destinations (Figure 2 and 3, left), an example is (39). They were relatively cheap, widely available and frequently updated (40). However, they only showed which places were connected, but did not show roads in their spatial shape. The shape needs to be defined either based on a current survey map (Figure 2 and 3, middle), an example is (41), that showed all roads regardless of their horse-related infrastructure, or derived from earlier or later confirmed road shapes (Figure 3, right). In combination with further

**FIGURE 2 Structured combination of historical material and essential tools.**
information, either from one of the maps mentioned or from further documents, about the characteristics of the infrastructure (Figure 2, right and Figure 3, left), it is possible to define travel time and travel costs, as they both are defined by the actual journey length, speed, and means of transport. Such further information includes the availability of post offices, express or extra coaches (coaches off the schedule on a larger set of roads and not shared with other passengers), inns, etc. This directly affects the travel comfort that also includes safety aspects.

A problem of this approach is the time before 1750 or 1700 as there were only few spatially explicit transport maps, and map makers were not able to consider individual cases, for example regional characteristics of roads. On the other hand, one can relax these limitations given the fact that travelling at this time was a matter of days and relative imprecision in minutes is of little importance. Decisive elements for speed were rather the journey purpose – communication (letters) versus personal visit versus freight – and the ability to travel – class and travel experience (42). Hence, the most important tool in the concrete work with historical sources is the above explained path-dependency of infrastructure. This means the literally path-dependent developments of the road network out of the matrix of paths. The next section gives an example of the method introduced and evaluates its feasibility.

**FEASIBILITY AND APPLICATION: TRAVEL TIME ANALYSIS 1850**
The method described in the previous section is applied to the collected maps and further documents covering Western Europe between 1500 and 1900. In this section, Switzerland 1850 serves as an illustrative example to prove feasibility as well as to review and confirm the main elements of the method. We can also build on former research at our institute.

**Reconstruction of 1850s Swiss Transport Network and Related Travel Times**
Following Figure 2, three main data sources are used: First, Carl Jügel’s *Post- und Reisekarte* (“Post and Travel Map”) of 1843 (43); second, the so-called Dufour map *Topographische Karte der Schweiz* (“Topographic Map of Switzerland” by General Dufour) of 1855 (44), today published and copyrighted by swisstopo; and third the road layer of Open Street Map of 2017 (36). These sources are presented in Figure 3 left to right; the travel map shows a larger section of the north-south transit route from Lucerne over the Gotthard Pass to Bellinzona, while the other sections show the Gotthard Pass only. It is interesting to notice that the road shape of 1855 and 2017 are identical and on the post map we can see that the first section after Lucerne was travelled by steam ship, the Gotthard Pass was throughout suitable for stagecoaches, but there was no post office until Bellinzona.
Carl Jügel’s map covers most of Western Europe and we can report for Switzerland:
1. There are small errors in the area around Lake Biel and Seeland. This is likely due to repetitive flooding by the river Aare at the time, which changed patterns of marshy and solid ground in this area every year in late spring after the snow melt in the Alps.
2. Apart from Lake Lucerne, there were two other steam ship routes on lakes (Walensee and Zugsee), which served as a road replacement as the road construction on the steep lakeshores would have been difficult.
3. The road hierarchy in Switzerland differed from the categories in the rest of the map. This might be due to the hilly topography and poorly built infrastructure in general, but needs further research.
4. Place names have changed a lot. An illustrative example is the ending point of a stagecoach road called “Neuhaus” (new house) in the Jurassic mountains. However, there is no currently existing place at all in this area with a similar name. With the help of further written documents, it was possible to identify the exact valley of this place. Knowing the valley, it was possible to identify a country road in this valley using the Dufour map. The historical shape of this road is identical with the current road and following it in a current map, it was possible to identify a section called “Zum Neuhsli” as well as an inn called “Restaurant Neuhsli”, i.e. Neuhaus, but dialect inflected, which allowed the exact coordinate definition of this ending point of the stagecoach road.
It was possible to spatially define the whole Swiss network of 1843 as well as the related infrastructure information, such as distances, postal and horse-related infrastructure. The network is depicted in Figure 4 (upper half).
In a second step, a simple travel time model was applied. The model is an approximation at this stage only, since currently the focus is on continuous and comparable European-wide network reconstruction, but such a model shows one potential application. The maximum speeds are derived from map information and sources for the transport means. Two transport modes are considered: walking with a donkey or mule and stagecoach trips. The mode riding on a horse is excluded for two reasons. First, this mode was usually reserved to pure (express) communication (information or document) and there is no corresponding current counterpart, as nowadays information is transmitted electronically. Second, due to the high speed, this mode was substantially more expensive and restricted to a few people only. Thus, we use the maximum speed of the most common transport means at time and compare them to the current counterpart, which is the car. Its maximum speed is defined by speed limits on roads. For now, we summarize normal stagecoaches and extra stagecoaches. The latter one was more expensive, but you not only booked a seat but a whole coach for four people and a driver. Horses were changed at posts as with the other stagecoaches, but you did not stop at every stop and did not have to share the coach with strangers. This reduced generalized costs overall (higher speeds due to fewer stops, higher comfort and safety; higher monetary costs for the coach, but cost savings for omitted stays at inns due to shorter travel times). However, there were only extra, meaning faster, stagecoaches on secondary, meaning slower, roads in Switzerland; the one offsets the other. In a first attempt, one can assume that the difference on roads with postal infrastructure was roughly equal on all mapped roads. Whereas the mapped and unmapped roads and paths without postal infrastructure were much slower as you had to walk, unless you had some kind of privately organized connections to places to feed horses. We consequently assume walking speed on that roads. Correction factors for elevation, gradients, season and weather are not considered for now. To a certain degree, elevation
is captured since very steep and narrow tracks unsuitable for coaches are treated at walking speed, even though they are drawn as roads in the Carl Jügel’s map. But they were identified as bridle paths (“Saumpfad”) in the Dufour map. Snow was less of an issue as the coaches could switch wheels with skids. The resulting travel times are mentioned in Table 1.

### TABLE 1 Infrastructure type and maximum speed 1850 in Switzerland

<table>
<thead>
<tr>
<th>Infrastructure</th>
<th>Transport means</th>
<th>Maximum speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>A few lakes</td>
<td>steam ship</td>
<td>12 km/h</td>
</tr>
<tr>
<td>Country roads (“Chausseen”)</td>
<td>all types of stagecoaches</td>
<td>10 km/h</td>
</tr>
<tr>
<td>Ordinary roads (“ordinäre Fahrwege”)</td>
<td>extra stagecoaches only (“Extraposten”)</td>
<td></td>
</tr>
<tr>
<td>Mapped other roads</td>
<td>walking</td>
<td>3 km/h</td>
</tr>
<tr>
<td>Unmapped paths</td>
<td>walking</td>
<td></td>
</tr>
</tbody>
</table>

Source column 1,2: (43) and column 3: (35); 1 km is 0.621 mi

### Analysis and Comparison Swiss Transport Network 1850 and Today

First, the dynamics in road hierarchy is assessed, and second the result of the simple travel time model is verified. Both analyses evaluate the applied method and hence the reliability and usefulness of the constructed historical networks.

Out of 100% of the 1850 stagecoach road network length (excluding ship routes), which were country roads built until 1850 with horse-related infrastructure,

- roughly 1% became current motorways
- roughly 4% became current hiking trails or alpine paths (“Alpweg”), which are service paths to alpine stables; this transformation mostly occurred with the previously mentioned bridle paths over mountain passes (colored in red in Figure 4)
- roughly 89% became current main roads, mostly “Kantonsstrassen” (state roads)
- roughly 6% became secondary or tertiary roads, mostly in urban areas, where former main roads were converted into “city-friendlier” roads.

Overall, the Swiss data shows a remarkable path-dependency, also visually by comparing the upper and bottom part of Figure 4. In principle, the authors can confirm this finding for other times and areas using visual comparison within the collected documents. However not all of the approximately 900 documents have been compared. Comparing the Swiss case from the other side, only roughly 12% of the current primary road network existed as stagecoach roads in 1850. This number is obtained by an overlay of the 1850 network and the current network (50 and 80 km/h links only). However, there is a high regional variation. This indicates that road construction was more intense after than before 1850 and it was more intense in certain regions, especially the Swiss midlands.
FIGURE 4 Travel time comparison 1850 and today in Switzerland on municipality level. In 1850, only the mapped paths are shown here. Average travel time is the average time needed from a municipality to any other. Change means the percentage reduction in average travel time. 1 km is 0.621 mi.

The second analysis compares travel times at 1850 with current travel times, as shown in Figure 4. The current nearly 3000 Swiss municipalities are taken as spatial reference and mapped. In 1850, the average travel time ranges between 32 and 66 hours. Average travel time means the average of the time needed to travel from a municipality to any other municipality. It is calculated by the total travel time from a municipality to all other municipalities divided by the number of municipalities. As mentioned before, this is a first approach as an example to test the network reconstruction
method; it can be expanded to true accessibility metrics, such as the Hansen accessibility (21). The result for 1850 shows that the ratio between the best accessible and worst accessible place was 1:2. The lowlands and central parts of the country in the triangle Basel (northwest), Bern (west) and Zürich (east) had the lowest travel times. This is confirmed by other research by historians who, rather than modelling as we did here, analyze multiple reported journeys (6). The effects of mountain passes in the Alps and Jurassic mountains are visible too. The result in the comparison shows that the reduction in travel time was around 90% within the period of 150 years. While the reduction overall is that large, regional patterns are not that clear. Nevertheless, the result shows that in mountainous regions, the reduction was higher than in the midlands and that the differences between municipalities in general is much smaller. The first observation can be explained with tourism. Mountains had been sparsely populated and there was no incentive to have stagecoach connections. This changed when most of Switzerland became connected to the European railway network. Based on our data, this happened comparably late in the 1860s and 1870s, but it cut travel costs and time substantially (roughly 48 hours for London to Bern, based on our data). This increased the demand for stagecoaches to the mountains. The second observation can be explained by the founding of the Swiss confederation in 1848. Before, every canton individually built roads. But in the new confederal parliament, the Cantons had equal power in the Ständerat (similar to US Senate) as one of the two chambers where budgets for national roads were adopted.

Overall, the findings of the two analyses do not give reason to question the established and applied method suggested in the previous section.

CONCLUSION AND OUTLOOK
In this paper, a method to reconstruct historical transport networks is developed and tested on the example of Switzerland in 1850. In conjunction with the algorithm presented at TRB in 2015 (24), as far as the authors can ascertain, it is for the first time possible to produce a GIS of a historical road networks covering Western Europe for the period between 1500 and 2000. The paper presents feasible heuristics to overcome data source limitations, such as scarcity of sources, variance in design, monochrome colors, and spatially unprecise features in maps. Approximately 900 transport related documents were collected and assessed. The heuristics applied in the method were developed thereof. Given the developments in the history of map making, transport, and travel behavior, the method is able to reconstruct spatially explicit historical transport networks and adding basic information to them. A crucial element in the method is path-dependency and the approach requires manual work. Hence, reliable data generation is feasible, though costly. On the other hand, the advantages of such a data set are obvious. Time series models become possible and transport models can be traced back in time. Such kind of data makes changes in transport visible and measurable. Existing research in the history of transport means, in history of cartography and era-specific political history is mostly qualitative. It can now be merged in a quantitative model based on transport science.

Future work will need to expand the GIS spatially and temporally; the data set should reach back minimum to 1700, but for some regions 1500 should be feasible. The quality of the infrastructure information needs improvement. Information on elevation as well as on monetary cost elements and for multiday trips (staying overnight) should be added. The GIS data should also account for the class of the travelling person and the purpose of the trip, to capture trade-offs between speed, costs, and comfort. Adding population densities would allow for calculating accessibility metrics. Finally, the GIS data should be used for models on causality between accessibility and territorial dynamics.
Some final thoughts on the presented research in the view of current developments and policies. When postal companies started to separate mail and passengers on their services, communication and passenger transport became separate. During the technological evolution of the last 250 years or so, this separation has become even larger. However, the growing number of server infrastructure to the internet — the main communication network of today — and other communication infrastructure have been following major transport infrastructures (45). Path-dependency still exists in various forms. Another prominent topic in transport planning is the innovation of shared and autonomous vehicles. The questions of rebalancing, fleet management, and profitability however is not new; one of the largest mobility providers called Thurn und Taxis was dealing with it a couple of centuries ago (46). The discussion on future mobility providers might draw from “outdated” models such as horse relays and the debate on advantages of state versus private organized services at the time.

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