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Abstract

We exploit exogenous variation arising from the historical rollout of the Swedish railroad network across municipalities to identify the impacts of lowered interaction costs on innovative activity. A network connection led to a surge in local innovation due to an increased entry, productivity, and specialization of independent inventors. As the railroad network expanded, it further led to the emergence of a national market for ideas: inventors in connected areas began to develop ideas with applications outside the local economy, which were subsequently sold to firms along the network. Our findings suggest that the reduced interaction cost between firms, intermediaries, and inventors was a key driver of the historical emergence of a market for ideas.

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1 Introduction

Markets for ideas are central to promote the diffusion of existing technologies and provide incentives to invest in new ideas (Arora et al., 2001). Markets may raise the profitability of developing new technologies (Schmookler, 1954; Acemoglu & Linn, 2004), enable small firms or individuals to specialize in innovation based on comparative advantage (Lamoreaux & Sokoloff, 2001), and ultimately reduce misallocation by enabling firms to draw from a larger pool of ideas (Hsieh & Klenow, 2009; Acemoglu et al., 2018; Akcigit et al., 2016).

Trade in technology, however, involves significant frictions. To develop useful ideas, inventors must be able to identify technology demands of potential buyers. Moreover, the sale of an idea in the form of a patent is complex, plagued by asymmetric information, and typically require face-to-face interaction between buyer and seller. Yet despite beliefs that such frictions are a key barrier in the market for ideas, there is little empirical evidence on how reductions in the cost of exchanges and interactions between firms, intermediaries, and inventors affect innovation and trade in ideas.

This paper leverages the historical rollout of the Swedish railroad to identify the causal contribution of reduced communication and transportation costs to innovation and the emergence of a market for ideas. Between the mid-19th century and World War I, the Swedish state constructed the backbone of a more than 14,000 km long national network that connected previously isolated locations. Notably, the spread of the network coincided with a rise of innovative activity and trade in patents, which made Eli Heckscher (1941) term the period a "technological revolution" that marked Sweden's transition to becoming one of the most innovative countries in the world.[1]

Crucially, the expansion of the Swedish railroad network also provides a unique setting to identify the causal impacts of transport infrastructure on the market for ideas and innovative activity. It was constructed in a country with an "acutely embarassing" lack of a developed highway system (Heckscher, 1954, p.240), and it was designed by a single state planner with the explicit goal of connecting the capital Stockholm with major cities along the shortest possible routes. These features allows us to circumvent the empirical challenge that investments in infrastructure are allocated to places with a higher innovative potential. More concretely, we construct a set of instrumental variables that relies on two sources of variation. First, we identify bilateral least-cost paths (LCPs) between Stockholm and targeted destinations using data on land cover and slope gradients combined with Dijkstra's (1959) optimal route algorithm. Second, we use the *timing* of the construction of the network starting with the

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[1] Today, Sweden ranks second, for example, in both WIPO's Global Innovation Index 2017 and the Bloomberg 2017 Innovation Index, while it was identified as the most innovative European economy by the European Innovation Scoreboard 2016.

completion of the first lines in the 1860s. Ultimately, we exploit the interaction of this cross-sectional and time-series variation in a two-stage-least squares (2SLS) regression framework, where we interact the distance to the LCPs with decadal binary indicators to instrument for network access.

Our main difference-in-differences estimates compare relative changes in local innovative activity after the arrival of a network connection across 2,400 municipalities, while controlling for time-invariant municipality characteristics, regional shocks, as well as potential differential changes due to the local geographic features (determining the cost of railroad construction) and pre-rail economic conditions in each municipality. The estimation strategy rests on the simple idea that, conditional on our rich set of controls, the LCPs traversed many areas that were not explicitly targeted by state-planners due to political pressure or local economic demands. To support this claim, we demonstrate that the instrument passes a balance test of predetermined covariates and that all our outcomes display parallel trends before network connection.

We first establish the causal impact of a network connection on the rate of local innovation using new data on the universe of patents granted by the Swedish Patent and Registration Office (PRV) 1830–1910. After a network connection is established in a municipality, we find large significant increases in patenting activity along both extensive and intensive margins.[2] The increase in patenting activity is mainly driven by an increased entry and output of independent inventors, consistent with an ambiguous impact of reduced frictions on the innovative activity of firms.[3] Additionally, independent inventors on average produced more patents per inventor further suggesting that a network connection enabled individuals to increasingly specialize in innovative activity.[4]

We then show that reductions in interaction costs between firms, intermediaries, and inventors constitutes one important driver of the rise in innovative activity. To support this claim, we provide two sets of empirical results. First, we show that the arrival of a network connection leads inventors to respond to external demand-side influences and produce ideas for an increasingly *national* market. Second, we document that the evolving network facilitated trade in technological ideas by connecting buyers and sellers leading to

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[2] While a key concern is that these localized increases in innovative activity may simply reflect a reallocation across localities, we use several alternative approaches to show that such potentially negative general equilibrium effects are limited in magnitude.

[3] In particular, reduced market frictions may both increase and decrease the incentives to invest in R&D, as lowered transaction costs imply that firms can more cheaply both sell and purchase patents (Akcigit et al., 2016).

[4] Importantly, the increase in patenting output is not offset by a reduction in quality as proxied by patents granted by the USPTO to Swedish residents, patents in "high-tech" sectors, and patents weighted by the payment of renewal fees.

the rise of a market for ideas.

In our first set of results, we document strong and significant effects of network connections also on the development of ideas with applications in industrial sectors that are *not* present in the local economy, as well as in *new* technological fields, leading to a broadening and deepening of the technological profile of connected locations. After a municipality becomes connected to the network, the local distribution of innovation across technology fields and industrial sectors gradually converges with the national distribution. Relatedly, we show that the growth in patenting output is driven by patents registered with a patent agent—a key intermediary that aided inventors in getting their patents through the review process, connected buyers and sellers, and the flow of information regarding new technological developments (Lamoreaux & Sokoloff, 2003).

To establish our second set of results, we collect handwritten data on the buyer and the seller of each individual patent that was sold. We find a significant causal impact of the establishment of a network connection on the extensive and intensive margin of patent transfers. We then show that the increase in transfers is solely driven by: (*i*) inventors selling patents to buyers in other *connected* municipalities; (*ii*) independent inventors selling patents to firms; and (*iii*) patents in industries or technology fields that are *not* present in the inventor's municipality. In contrast, we find no similar increases in transfers to non-connected municipalities, nor any changes in transfers *within* the municipality itself suggesting that improved connectivity, and not a surge in local growth or innovation, is driving the increase in trade.

Taken together, our findings constitute the first causal evidence of how the historical reduction in interaction costs between firms, intermediares, and inventors was key to the emergence and efficiency of a national market for ideas. In particular, our findings suggest that the nascent market enabled independent inventors to pursue economically useful ideas with applications beyond the local economy, even if they lacked the capital or competence to commercialize their inventions themselves. Conversely, reduced frictions in the market for ideas appear to have increased overall innovative activity and enabled firms to rely on technologies developed outside of their organizational boundaries thus ultimately enlarging the pool of ideas that firms could draw upon.

Our paper relates to an influential literature documenting large spatial barriers to the diffusion of ideas and knowledge about new technologies (Jaffe et al., 1993; Comin & Hobijn, 2010; Conley & Udry, 2010). More specifically, our paper contributes to a small but growing literature that empirically and theoretically examines the role of markets for ideas in the innovation process (Akcigit et al., 2016; Spulber, 2015; Lamoreaux & Sokoloff, 1999, 2001, 2003; Arora et al., 2001). In particular, our results are consistent with Akcigit et al. (2016)

who calibrate a search-based endogenous growth model using data on U.S. patent transfers to show that lowering the efficiency in the market for ideas (or closing it down) would have large negative impacts on economic growth and welfare. Consistent with their model, we provide evidence that patents are more likely to be sold the more distant they are to a firm's or a location's industrial structure. Moreover, we document that lowering interaction costs primarily enables independent inventors to specialize in innovation and sell ideas to larger firms, which is consistent with the stylized fact that smaller firms trade more patents (Serrano, 2010; Figueroa & Serrano, 2019).

We also contribute to a recent literature on the impact of transport networks on economic outcomes such as growth, trade, and urbanization (Banerjee, Duflo & Qian, 2012; Duranton & Turner, 2012; Faber, 2014; Donaldson & Hornbeck, 2016; Campante & Yanagizawa-Drott, 2017; Pascali, 2017; Donaldson, 2018).[5] Most directly related to our paper is Agrawal, Galasso & Oettl (2017) showing that interstate highways increased regional patenting in the 1980s and led inventors to increasingly draw upon *local* knowledge within U.S. metropolitan areas.[6] In contrast, we document how transport networks facilitate integration between previously isolated locations, which encouraged inventors to develop ideas with applications beyond the local economy and thus ultimately led to the emergence of a *national* market for ideas.

The remainder of this paper is organized as follows. Section 2 provides an overview of the historical background. Section 3 introduces our data, while section 4 describes the empirical framework and our instrumental variables strategy. Section 5 presents our results concerning the introduction of railroads and innovative activity during the period 1830–1910. Section 6 concludes the paper.

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[5] In particular, our paper is related to Berger (2017) who study the effects of the Swedish railroad expansion during the 19th century on structural transformation. While we use a similar identification strategy, our paper advances their methodology, draws upon considerably more spatially disaggregated data, and focuses on a distinct dimension of economic development, namely innovation, rather than broader measures of structural change. Also see Berger & Enflo (2017) that examine the long-run impacts of the Swedish railroads on the urban structure.

[6] An early contribution to the literature on transport infrastructure and innovation is Sokoloff (1988) documenting a correlation between patenting activity and proximity to waterways in 18th- and 19th-century United States. Similarly, Perlman (2016) documents a positive link between rail access and patenting output across U.S. counties in the 19th century. An important difference to our historical setting that facilitates identification is that Sweden lacked a well-developed transport network, which contrasts the U.S. where substitutes for the railroads were readily available (Fogel, 1964).

2 Historical background

2.1 Sweden's "technological revolution"

Sweden's economic modernization prior to World War I was fuelled by what Eli Heckscher (1941) described as a "technological revolution". This revolution is evident in patenting statistics, which reveal a sustained increase in patented inventions by Swedish firms and individuals (Figure 1A). The rise of patenting activity was underpinned by the establishment of a modern patent law in 1834, which later evolved from a registration system with varying patent length (3-15 years) to a rigorous system of technical examinations, similar to the American and German systems, with uniform patent length (15 years) and an increasing annual fee structure.[7]

Economic historians emphasize that the development of many cutting-edge innovations in this period originated from within the boundaries of industrial firms (Jörberg, 1988). Yet, firms were granted a relatively small share (about 11 percent) of patents (Figure 1A). Instead, the vast majority of patents were granted to individuals, which has led historians to term the latter half of the 19th century as "the era of independent inventors" (Hughes, 1988).

Independent inventors may have been encouraged to develop ideas partly due to the low cost of obtaining a patent in Sweden, as well as the reduced uncertainty of a patent's value after it having passed rigorous examinations.[8] Another potentially important incentive was the opportunity to patent technological discoveries demanded by firms, which could later be traded. Indeed, recent research has suggested that overemphasis on the rise of the Chandlerian firm and in-house corporate R&D neglect the role of such markets for technology (Arora et al., 2001; Lamoreaux & Sokoloff, 2001; Burhop, 2010; Madiès et al., 2014). Instead, large firms used markets for technology as a complement to internal R&D when it was to their advantage. A central role for the opportunity of such transfers of technology has been invoked to explain the continued importance of independent inventors in Japan, Europe, and the United States well into the 20th century (Nicholas, 2010, 2011; Nuvolari & Vasta, 2015).

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[7] The application process was such that: "He who wants to obtain a patent, shall send to the Patent Office a written application and attach two copys of a description of the invention along with the drawings needed to clarify the description, also in two copies, and when needed also models, samples or other material needed.../.../...The description shall be as clear and exhaustive so that an expert should, with its help, be able to practice the invention" (§4, SFS 1884:25, Kongl. Maj:ts nådiga förordning angående patent). When the application was filed at the Patent Office, an examinator (patent engineer) was assigned to the patent to investigate whether the invention was patentable, new and sufficiently useful and important.

[8] In 1885, the applicant had to pay SEK 50 (approximately \$315 in 1998 USD) to file a patent application. In 1893, this cost was lowered by 60% to SEK 20 (\$128). As a comparison, the same cost was around \$437 in the UK and \$795 in the US.

2.2 An emerging market for ideas

Swedish patent legislation played a large part in facilitating trade in technology. Already the patent (or *privilegia exclusiva*) law from 1819 stated that a patent can "as other property be inherited or gifted and also through sale or transaction transferred to another Swedish citizen" (Kongl. Maj:ts nådiga förordning, §6, 1819) , which remained a cornerstone of subsequent 19th-century patent laws. Indeed, the latter half of the 19th century saw a growing trade in patents (Figure 1B). In particular, the increase was driven by the number of patents sold by independent inventors to firms, which were presumably in a better position to exploit and commercialize these inventions. Anecdotal evidence from firm archives demonstrate that the value of such patent transfers from independent inventors to industrial firms could be substantial and economically significant.[9]

Contemporaries, however, stressed that the legal underpinnings of intellectual property rights were not enough for an efficient market for technology to emerge. In the pages of the Swedish Journal of Patents and Trademarks, for example, the Association of Swedish Inventors lamented that:

> "An exchange, a marketplace, where those who wish to acquire or sell inventions can find their customers still does not exist in our nation [...] It is often observed that he who has managed to produce a valuable invention only occasionally possesses the traits required to bring it to the market. It would therefore be of mutual benefit, and foster the industrial life, if these two categories of intellectual workers had a somewhat more secure way to find each other than merely by chance." (Norden, Journal of Patents and Trademarks, May 28, 1886, p. 159)

Inventors in large cities such as the capital Stockholm naturally had access to local networks of intermediaries such as patent agents that facilitated the transfer of patent rights (Andersson & Tell, 2016). Yet, there existed significant barriers to interact with potential buyers and sellers in other locations. Transaction costs were arguably rising given that inventors became increasingly geographically dispersed during Sweden's industrial take off

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[9] One such example comes from Swedish industrial firm AB Separator (today Alfa Laval). In 1886 they paid mechanic Carl August Johansson and his partners SEK 21,000 for five patents, which today would equal approximately $167,000 (Wohlert, 1981, p. 77). Patent transfers were in fact crucial to many Swedish firms. Alfa Laval was founded when famous inventor Gustav de Laval transferred his first milk separator patent to Oscar Lamm to finance the establishment of the firm. Later on, the revolutionary "Alfa"-patent was in fact acquired by the firm from the German inventor von Bechtolsheim. Swedish industrial equipment firm Atlas Copco was partly founded when Rudolf Diesel's Swedish patent was purchased. During the first years of the firm the patent represented 50% of the firm's total value and was valued at SEK 150,000 (approx. $1,114,000 today) (Gårdlund, 1973).

(Figure 1C and 2).[10] One key factor that may have offset these rising costs was the coming of the railroad, which dramatically lowered the costs of exchange and interactions between potential firms, intermediaries, and inventors in the market for technology.

2.3 Expansion of the Railroad Network

Sweden's railroad era began in the mid-19th century. In the *Riksdag* of 1853/54, it was decided that the main parts of the network were to be constructed, funded, and operated by the state. A central role for the state was motivated by the belief that state control was required to align construction with the "public good", while the underdevelopment of the domestic capital market and the widely dispersed population made it impossible to rely on market forces to bring about an extensive national network (Westlund, 1998).

Appointed by the king, Colonel Nils Ericson was designated to be chief planner and was endowed "dictatorial powers" to design the railroad network (Rydfors, 1906). Colonel Ericson presented his proposal in 1856 (see Figure 3 below). It connected the capital Stockholm with the other main trading ports in the West and the South and was to follow the shortest routes between these destinations while avoiding steep terrain, the coastlines due to strategic military concerns, and pre-existing transportation networks to reduce intermodal competition (Heckscher, 1954).

Construction of the network began in the 1850s and in the 1860s the first parts of the network were opened for traffic.[11] Although the backbone of the network had been constructed by the early 1870s, many historically important economic centers were left without a connection (Berger & Enflo, 2017). Against the backdrop of an international railroad boom in the 1870s, the construction of railroads became increasingly driven by private companies establishing additional connections to the network so that most economically important areas had been linked up to the network by the early 20th century (2).[12]

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[10] To estimate the spatial dispersion of inventive activity, we calculate a Herfindahl–Hirschman index (HHI) defined as $HHI = \sum_i s_i^2$, where s_i is the share of inventors, patents, or population in municipality i. As one concern is that changes in the index is driven by a volume effect, we have constructed an alternative HHI by taking 1,000 random draws of 100 inventors/patents in each decade and calculated the index from these draws, which yields a very similar trend as the baseline index. Also see Figure B.1 in the Appendix showing that inventors became increasingly located in non-urban areas over the same period.

[11] Although Ericson's proposal was later rejected in parliament, the government viewed his original proposal as a program that should be constructed in a stepwise manner (Rydfors, 1906, p.99), which resulted in the emerging network shown in Figure 3 closely resembling Ericsson's original proposal (Heckscher, 1954, p.241).

[12] Although private companies increasingly drove the expansion of the network after 1870, the state retained strong control over its evolution due to a strict centralization of the concession process and the setting of fares along joint private-public lines (Nicander, 1980). As these later connections had to be approved by the government, we digitize historical documents that report several of these later line proposals which we use as the basis for a set of placebo tests.

As the railroad network spread throughout the country, it radically lowered travel costs.[13] After a network connection was established, costs decreased by at least half and speed increased manifold (Sjöberg, 1956). The increased mobility depicted in Figure 1D is likely to have raised the diffusion of knowledge, not least by enabling travel at lower cost and thus lowering interaction costs between firms, intermediaries, and inventors. Moreover, it lowered the distribution costs of books, technical journals, and newspapers. Indeed, contemporary observers emphasized the importance of the railroad in these respects, arguing it could compete with the invention of the printed book as a means of spreading new ideas (Rydfors, 1906, p.30).

3 Data

Patents, inventors and transfers. Our main data set is built up by the full universe of all granted Swedish patents during the 19th century up until World War I. The patent data was compiled and digitized from Swedish National Archives (*Riksarkivet*) and the archives of the Swedish Patent and Registration Office (PRV) and include detailed information, such as patent duration, application and grant year, and patent class according to the German patent classification, *Deutsche Patentklassifikation* (DPK). We furthermore manually code these patent classes into the 14 industries used by Nuvolari & Vasta (2015). Moreover, the registers include name, address and occupation of the patent holders and inventors behind each patent.Using the information on the legal nature of the patent holder, we are able to define independent inventors as those inventors that did not grant a firm the property right of the patent.[14]

A total of 18,250 patents were granted by the PRV to individuals or firms residing in Sweden over the period. Approximately 90 percent of granted patents contain non-missing information on the place of residence for the inventor(s) or the patent holder(s) that enables us to geolocate each individual/patent by using the longitude and latitude of the place denoted on the patent. After cross-validating geolocations manually, we obtain 17,309 geolocated patents and the associated inventors. From the PRV patent register, we also collect

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[13] Transportation costs were often prohibitively high prior to the railroad. Notably, while waterways offered cheaper transport than by road, many routes became impossible to travel during winter time. Moreover, the road network was poorly developed, which led Heckscher (1954, p.240) to argue that "[t]he lack of a developed highway system was acutely embarrassing in a country as extensive and sparsely populated as Sweden".

[14] In contrast to the US patent system that stipulated that patents could only be granted to the first and true inventor, the Swedish system (similarly to the German system) allowed firms to receive patents directly for ideas developed within the firm.

data on patent transfers.[15] The patent office recorded everything related to a patent as long as the patentee paid the annual renewal fees. This included for example information regarding the transfer of ownership. This was important information since only the patentee registered as the owner in the patent register had the legal rights to the patent in a court of law. In total, we collect data on the location and legal form of the buyer and seller for all 1,635 patents that were transferred at least once.

In addition to our Swedish patent data, we also collect data from the United States Patent and Trademark Office (USPTO) on all U.S. patents granted to Swedish residents 1872–1910 from the Annual Reports of the Commissioner of Patents.[16] We use Google Patents to collect the citations for all USPTO patents.

Railroads. We digitize the rollout of the railroad network for each decade during the period 1860–1910. We obtain historical maps of the evolution of the railroad network from Statistics Sweden, and create digital versions of these maps using GIS software. We restrict our analysis to railroad lines that connects to the main central network, which we refer to as "network connections" throughout the paper.

Other data. We make use of a rich data set of geographic controls and economic baseline controls. Elevation and land cover are based on data drawn from the GLC2000 and the CGIAR-SRTM obtained through the DIVA-GIS dataservice.[17] Population data from the 1860s are from Palm (2000) and Riksarkivet. Census data for 1880, 1890, 1900 and 1910, which we use to link inventors to individuals in the censuses, are from *Riksarkivet* and the North Atlantic Population Project (NAPP). Manufacturing data for 1865 is digitized from handwritten ledgers obtained from Statistics Sweden and contains information on employment, output, and the geographical location of each manufacturing establishment.

Administrative boundaries and unit of observation. In our main analysis, we collapse our data in ten-year periods and organize them at the municipal level based on historical administrative boundaries based on maps obtained from the Swedish National Archives (*Riksarkivet*). To get consistent borders over time, urban municipalities are collapsed with their adjacent rural municipality (or municipalities) as these borders sometimes changed due to urban expansion. For patents linked to multiple individuals or firms located in different

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[15] In the Appendix, figure C.1 provide an example of the hand-written ledgers that stored information on granted patent and the eventual information on transfers.

[16] 1872 is the first year that the Annual Reports of the Commissioner of Patents starts to report the city of residence for foreign patentees and not just the country of origin.

[17] Available at: http://www.diva-gis.org/.

municipalities, we assign one patent to each municipality. As a consequence, we may interpret our patent variable as the local involvement in innovative activity. We end up with a municipality-level panel with 2,389 municipalities and follow the development of these for each decade during the period 1830–1910.

4 Empirical framework

4.1 Railroads and Innovative Activity

To measure the effect of railroad access on innovative activity, we use two alternative estimation strategies in our main analysis. First, we exploit variation in the final network to identify relative differences in innovative activity during each decade 1830-1900, which allows us to evaluate the existence of pre-trends. Second, we use a standard difference-in-differences approach that allows us to obtain point estimates with meaningful absolute magnitudes.

Our first specification takes the following form:

$$Y_{irt} = \gamma_i + \beta_t Railroad_i^{1900} + \mathbf{G}_i' \delta_t + \phi_{rt} + \varepsilon_{irt}, \tag{1}$$

where Y_{irt} is an outcome such as the number of patents per capita in a municipality i, in region r, and time period t. The key variable of interest on the right-hand-side of equation (1) is $Railroad_i^{1900}$, capturing the access to the completed railroad network in 1900. We include municipality fixed effects, γ_i, to capture any time-invariant effect within a municipality as well as region-by-period fixed effects, ϕ_{rt}, to capture any regional economic shocks. Furthermore, we include a set of time-invariant control variables capturing local geographic conditions, $\mathbf{G}_i$, interacted with time period fixed effects, δ_t, to flexibly capture potential predicted differential changes across municipalities. In our main specification, we include several baseline economic conditions as well. Together they may affect both the demand and supply side of railroad construction. We discuss these controls in detail below.

Our second strategy is a conventional difference-in-differences regression with staggered treatment, which constitutes our main estimating equation throughout most of the analysis:

$$Y_{irt} = \gamma_i + \beta Railroad_{it} + \mathbf{G}_i' \delta_t + \phi_{rt} + \varepsilon_{irt}. \tag{2}$$

Here $Railroad_{it}$ is an indicator variable switching to one in the decade that a network connection is established in a municipality.[18] In both equation (1) and (2), the identifying

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[18] We relax this assumption and adopt a continuous specification where we simply proxy for railroad access by the natural logarithm of the distance to the nearest railroad (see Appendix Table A.2). However, we prefer the indicator specification as the cut-off around 5 kilometers is found to be the driving variation

variation stems entirely from the variation within municipalities over time, after controlling for municipality fixed effects, γ_i, to capture any time-invariant effect within a municipality as well as region-by-period fixed effects, ϕ_{rt}, to capture any regional economic shocks. Again, we include a set of time-invariant control variables, $\mathbf{G}_i$, interacted with time period fixed effects, δ_t, to flexibly capture potential predicted differential changes across municipalities. In our baseline estimations, we cluster standard errors at the municipal level to adjust for heteroskedasticity and within-municipality correlation over time (Bertrand et al., 2004), though we also present alternative standard errors that more flexibly account for spatial correlation in the Appendix Section A.1.

Although the railroads traversed many locations not explicitly targeted by the state planners, the placement of the actual network may still potentially be endogenous. In particular, if the timing of railroad placement is a function of unobservable local economic conditions, OLS estimates of the above equations may be biased. The direction of this potential bias is *a priori* ambiguous, however: it should be negative if declining economic areas were targeted and positive if areas with a high growth potential were targeted. To address these potential concerns, we therefore proceed with an instrumental variables strategy.

4.2 Instrumenting for the Railroad Network

In designing our instrumental variables strategy, we exploit unique features of the rollout of the network, described in section 2. In particular, we use methods from transport engineering to calculate cost-minimizing routes between the destinations targeted by state planners to identify municipalities that "accidentally" were traversed by the network. We next describe the construction of these LCPs.

Guided by historical documents, we start by singling out four nodal cities (Gothenburg, Malmö and Östersund in Sweden, and Kongsvinger in Norway) that were deemed to be particularly important to connect with the capital Stockholm. In a next step, we calculate least-cost paths (LCPs) between Stockholm and each of these destinations. More precisely, we use data on land cover and slope gradients to calculate the construction costs associated with each cell between Stockholm and our destinations. When creating the cost function, we reclassify the cost to increase monotonously with increasing slope values, while assigning the highest cost to cells that are covered by water to reflect the prohibitively high cost of traversing major water bodies. Then, we run Dijkstra's (1959) algorithm to identify the bilateral cost-minimizing routes between Stockholm and the target destinations using the cost layers derived from the land cover and slope data.

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behind our results, as envisaged in Appendix Figure A.2, where we study a flexible specification for different cut-offs.

Figure 3 depicts the LCPs in red. As seen in the figure, our predicted network mirrors the early phase of railroad expansion in the period 1860 to 1880 as depicted in Figure 2. Importantly, it is further evident that several of the lines in Colonel Ericson's proposal (that were subsequently constructed) are located approximately along the LCPs, lending support to the anecdotal evidence concerning Ericson's approach when designing the network.

While the LCPs capture a static network, we are ultimately interested in studying a dynamic relationship as given by equation (2). We therefore proceed by interacting the LCPs with a time period indicator for each decade after construction. This results in four instruments: the predicted railroad network interacted with an indicator for the decades starting with 1870, 1880, 1890 and 1900. As such, the instruments can be thought of as capturing the predicted development of the network during each decade.

Importantly, since slope and land cover are crucial for calculating the LCPs, the existence of a predicted railroad in a municipality is likely to be correlated with local geographic features. As such, we condition for the local geography of each municipality by controlling for the following variables: the mean slope, the mean elevation as well as the standard deviation of the elevation, the area, and the mean cost of construction based on the land cover and slope data.[19]

Moreover, as the distance to the LCPs may be mechanically correlated with the distance to the targeted destinations, we explicitly control for the distance between each municipality centroid and the nearest targeted destination. Additionally, to exclude municipalities with enhanced probability to get connected to the network for mechanic reasons or due to political pressure, we exclude directly targeted destinations as well as urban municipalities in all our main regressions. In the Appendix, we present results including urban locations.

Formally, the first-stage relationship for our main difference–in–differences equation (2) takes the following form:

$$Railroad_{irt} = \gamma_i + \sum_{d} \lambda_d ln(Distance\ to\ LCP)_i + \mathbf{G}_i'\psi_t + \phi_{rt} + \varepsilon_{irt}, \tag{3}$$

where λ_d is an indicator variable taking the value of one if the time period is equal to $d = 1870, 1880, 1890, 1900$ and zero otherwise. As such we have four instruments, one for each decade after the introduction of the railroad.[20]

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[19] We take the natural logarithm of all these variables. In practice, since the controls we use are time-invariant, we interact the controls with a full set of time period fixed effects.

[20] When instrumenting the fixed railroad in 1900 interacted with time period fixed effects in equation (1), we let $d = 1840, 1850, 1860, 1870, 1880, 1890, 1900$ to have as many excluded instruments as instrumented variables.

4.2.1 Identifying Assumptions and Balance Tests

The λ_d's in equation (3) capture the effect of the distance to the LCP for each decade after railroad introduction. Thus, the identifying assumption is that the distance to these predicted LCPs is quasi-random only when conditioning on local geographic features and the distance to the nearest targeted endpoint of the network as well as municipality and region-by-year fixed effects. To explicitly test for quasi-randomness, we perform a balance test by regressing potentially related variables on the cross-sectional variation of our instruments, conditional on the local geographic conditions. To be precise, we run the following type of cross-sectional regressions:

$$E_{ir} = \alpha + \rho ln(Distance\ to\ Predicted\ Railroad)_i + \mathbf{G}_i'\psi + \xi_r + u_{ir}, \tag{4}$$

for a municipality i and region r. The outcome variables, E_{ir}, are either levels or changes in baseline economic conditions before railroad construction.

We present the results in Table 1. The balance test suggests that there are no observed differential levels or trends in economic conditions before the construction of railroads between municipalities receiving a network connection and municipalities that do not.[21] Nevertheless, we control for a set of pre-rail economic controls in our main specifications by including the following variables interacted with time period indicators on the right-hand side of the regression equations (1)-(3): the population at the baseline (1865), the distance to the nearest town, an indicator for whether a municipality had any granted patent prior to 1860 or not, the number of manufacturing firms per capita and the share of manufacturing workers in 1865, as well as the latitude and longitude of the municipality centroid to capture potential local economic features related to geographic location.[22]

4.2.2 First Stage Results

We start by visualizing the first stage by plotting the non-parametric relationship between network access and our instrument, conditional on region fixed effects as well as our set of local geography and baseline economic controls, for each separate decade 1870-1900. As seen from Figure 4, the negative relationship is evident in all four post-railroad construction decades, thereby suggesting that our instruments are highly relevant.

Proceeding to the difference-in-differences specification, Table 2 documents the first-

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[21] While the balance test exploits cross-sectional variation, we additionally present pre-trends in innovative activity using decade-to-decade variation in our main panel regressions below.

[22] As some of the outcome variables used in the balance tests have a considerable number of missing observations (in particular, mortality in the 1850s as well as mortality and population changes) we do not use them as controls in our main specifications.

stage regression results.[23] The first column displays the effect when controlling for our set of local geography controls interacted with time period fixed effects as well as controlling for municipality fixed effects. The second column adds our set of local pre-railroad economic controls interacted with time period fixed effects, while the third column additionally adds region-by-year fixed effects. As seen from the table, the coefficients remain stable when adding controls in column 2 and 3, thereby suggesting that our instrument, conditional on local geography, have no or limited correlation with potential baseline economic determinants of railroad access. In other words, it suggests that the local geography controls, including the distance to the nearest nodal point, do a good job in ensuring the quasi-randomness of the instrument.

5 Analysis and results

5.1 Network connections and local innovative activity

In this section we document that the establishment of a network connection leads to increases in local innovative activity along two distinct margins: an higher rate of entry of new inventors and an increased number of patents produced per inventor. In particular, the effects are evident among independent inventors. Moreover, besides being quantitatively more productive, inventors also produce more high-quality inventions after they gain access to the emerging network, all together suggesting an increasing specialization in innovation.

5.1.1 Local patenting output

We start our analysis by showing that the establishment of a network connection in a municipality leads to significant increases in local innovation as measured by patents granted by the Swedish Patent and Registration Office. Figure 5, panels A and B, present OLS and 2SLS estimates based on equation (1) where the outcome is either a binary indicator for whether a municipality has at least one patent in a given decade (A), or the number of patents per 1,000 inhabitants (B). We condition on municipality fixed effects, region-by-period fixed effects as well as controls for the local geography and pre-rail economic conditions interacted with period fixed effects in all regressions.

Panel A documents a sustained increase in the probability that a connected municipality exhibited any innovative activity as the network was rolled out. The OLS estimates show that a connected municipality was approximately 15 percentage points more likely to have at least one patent in the early 20th century relative to baseline. We also present 2SLS estimates

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[23] Appendix Figure B.1 displays the decadal relationship in a figure.

where we use, as excluded instruments, the natural logarithm of the distance to the LCPs with a full set of time period fixed effects. The 2SLS estimates suggest a relative increase in the probability that a municipality has at least one patent by roughly 30 percentage points by the end of our period, which corresponds to an increase of 1.4 standard deviations (SDs). These patterns are virtually identical when turning to the intensity of patent activity at the local level in panel B: OLS estimates show that the number of patents per 1,000 inhabitants in connected municipalities increased by an additional 0.76 patents relative to baseline, while the 2SLS estimates indicate a relative increase of about 1.90 patents (or about 1.5 SDs) by the early 20th century.

Importantly, there is no evidence in Figure 5 of any differential pre-trends prior to the major parts of the network is finalized in the 1860s. Thus, local increases in innovation in areas connected to the network after the 1860s do not reflect pre-existing trends in innovation.[24]

We next present more standard difference-in-differences estimates focusing on the same two outcomes. Table 3 presents OLS (panel A) and 2SLS (panel B) estimates based on equation (2), where we condition on the full set of controls as above. Column 1 displays the effect of a network connection on the probability of having at least one patent; the chance of patent activity increases by 16.2 percentage points according to the 2SLS estimates (panel B). Similarly, the 2SLS estimates in column 2 reveal an average increase of 0.78 patents per 1,000 inhabitants in the decades following access. Taken together, these estimates thus suggest that the establishment of a network connection increased both the probability that a municipality was involved in innovative activity as well as patenting output per capita.

5.1.2 The entry of independent inventors and the specialization in innovation

We proceed to document an increase in the total number of inventors per capita in a municipality after a network connection is established. Figure 5, panel C, presents OLS and 2SLS estimates based on equation (1) where the outcome is the number of active inventors in each decade and municipality. Reassuringly, there is no evidence suggesting that areas that eventually would become connected to the network had more inventors prior to the major parts of the network being finalized in the 1860s. After construction of the major lines is finished, however, we see a divergence: by the early 20th century, the number of inventors per capita has increased by 0.38 in a connected municipality according to our OLS

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[24] To further reduce concerns of pre-existing trends, we display the corresponding reduced form estimates with different measures of innovative activity regressed on the full set of time period interactions with the natural log of the distance to the predicted railroad networks in Appendix Figure B.1. The non-parametric reduced form relationship is additionally depicted in Figure B.1 for each separate decade. It is clearly seen that the negative relationship between the instruments and innovative activity increases over time and that there is no evidence of any pre-existing trends.

estimates. Again, 2SLS estimates are substantially larger, suggesting a relative increase of 1.17 inventors per capita. The corresponding difference-in-differences estimates reported in Table 3 similarly documents a relative increase in the number of inventors per capita of 0.50 after a network connection is established (panel B, column 3).

What type of inventors are affected the most by network access? To study this question, we distinguish inventors by the legal form of the patent holder at the time of grant: independent inventors and firms, respectively. While the possibility to sell ideas should increase with reduced market frictions, also the possibility to purchase ideas should increase. The latter may be particular valuable to firms, in contrast to individual independent inventor. Thus, network access may differentially affect independent inventors and firms.

In fact, we show in Table 3 that the increased number of inventors per capita in a municipality after a network connection is established is mainly driven by an increased entry of independent inventors, rather than firms. The 2SLS estimates in columns 4 and 5 suggest a statistically significant increase of 0.48 in the number of independent inventors per capita, and a non-significant increase in the number of firm inventors of 0.02. One potential intermediary that could convey information along the network to indenpendent inventors was the patent agent. Although one central role of the agent was to provide administrative services, such as the drafting and filing of patents at the patent office, anecdotal evidence suggests that patent agents also developed close business relations with clients, acted as consultants and advertised patented inventions for sale (Andersson & Tell, 2016). In fact, Appendix Table B.5 documents that the increase in innovative activity, in particular by independent inventors, is driven by patents with a patent agent.

We next document that the evolving network enabled independent inventors to increasingly specialize in innovation, as proxied by the number of patents produced per inventor. Figure 5, panel D, documents that the number of patents per inventor increases in connected municipalities as the network was rolled out.[25] We present difference-in-differences estimates in Table 3 documenting that independent inventors on average produced 0.25 additional patents per inventor after a connection was established (column 7), but a weaker response among firm inventors (column 8).

While inventors on average produced more patents after a network connection was established, the increase in quantity could potentially be driven by lesser quality patents. To study such concerns, we use three complementary ways to measure the value of patents. First, we infer the economic value of inventions in different technological fields based on

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[25] Inventor productivity is measured as the average decadal number of patents per inventor in each municipality. When constructing patents per inventor, we assume that all municipalities have a residual inventor by setting patents per inventor equal to zero for municipalities without patents in a specific decade.

the number of years patentees paid renewal fees.[26] Second, we isolate technologically more advanced—that is, presumably more valuable—patents by using the classification scheme of Nuvolari & Vasta (2015) to identify "high-tech" patents.[27] Third, we use patents granted by the USPTO to inventors residing in Sweden as a proxy for quality, which additionally allows us to use citation counts as a proxy for patent quality.[28] In Appendix Table B.6, we document that network connections increased inventive output also when proxied by these different quality measures.

In sum, these results suggest that the establishment of a network connection led to an increase in local innovative activity both by encouraging new independent inventors to enter the innovation sector and by enabling them to specialize in innovation and produce more inventions per inventor. The increase in productivity is not coupled with a reduction in quality as high-quality patents increased with connectivity. Moreover, the effects are mainly driven by independent inventors, while firms are less affected. A weaker response among firms is consistent with an ambiguous impact of reduced market frictions on their innovative activity: enabling firms to sell ideas may increase incentives to invest in R&D, yet the flipside is that the lowering of transaction costs means that firms can also more cheaply purchase patents that may reduce returns to partake in R&D activities (Akcigit et al., 2016).[29]

5.2 Network connections and the emerging market for ideas

In this section, we proceed to document that the arrival of the railroad led to an increase in innovation within a wide range of sectors, in novel technology classes with respect to the patenting history of a municipality, and that inventors developed ideas for a national market. We then provide direct evidence of such a market by documenting an increase in the buying and selling of patents between *connected* locations, that traded patents were more distant from the technology fields existing in the inventor's location, and that the increase in patent transfers is driven by independent inventors developing ideas that are subsequently sold to firms.

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[26] Renewal fees are often argued to be a good proxy for the economic value of patents as the patentee needs to decide upon renewing his or her patent based on the expected economic return from extending the patent right (see e.g. Schankerman & Pakes, 1986; Streb et al., 2006; Burhop, 2010; Hanlon, 2015). We calculate the mean number of years that renewal fees were paid for 89 distinct technology classes; the maximum number of years a patent could be in place was 15 years. We then assign each patent the average number of years based on its technology class.

[27] High-tech sectors include: chemicals, electricity, machinery and metals, steam engines, and weapons.

[28] While renewal fees may be considered as a better measure of the economic value of patents, citations are a widely used indicator of the inventive quality of a patent.

[29] On the production side, it is also consistent with the argument that the R&D of firms to a larger extent relies on knowledge produced within the boundaries of the individual firm (Agrawal, Galasso & Oettl, 2017).

5.2.1 Network connections and the production of new ideas

We first document that inventors in many cases produced ideas with applications beyond their locality after they became connected to the national railroad network. First, to provide a comprehensive picture, we estimate our baseline difference-in-differences specification in equation (2) separately for 14 individual sectors.OLS and 2SLS estimates for each individual sector are reported in Appendix Figure B.1. Estimates show that patenting output increased in a wide range of sectors—including agriculture, food and beverages, machinery, as well as textiles—which is an indication that inventors developed ideas in areas that may not have a local use.

Second, we more directly study the development of novel ideas with respect to the patenting history of the inventor's municipality of residence. We define "novel" patents as belonging to technology classes in which no inventor in a particular municipality has previously been granted a patent in. We then make use of detailed establishment-level data at the municipality-industry level to establish the local economic structure of each municipality before the major parts of the railroad network was finalized in the 1860s. In particular, we define a patent as a patent from a "(non-)existing" industry if the patent is (not) related to an industry that existed in 1865. Similarly, we define a patent in a "(non-)leading" industry if the patent is (not) related to the industry with the largest share of output.[30] Table 4 presents OLS and 2SLS estimates from our baseline specification in equation (2) using these measures of novel ideas as outcomes. It shows that a network connection increased patents both within novel technology fields and in industries that were not represented locally and in fields that were represented in the municipality, thus, both broadening and deepening the technological profile of connected locations.

As the network spread across municipalities, the market for ideas potentially became increasingly national in scope. If inventors developed ideas for an emerging national market, we would expect to see that the distribution of innovation across technology fields became increasingly similar to the national distribution after a municipality became connected to the network. To study this, we use Jaffe's technical proximity measure (Jaffe, 1986) and construct the uncentered correlation between a municipality's share of patents in each technology class and the corresponding national shares. Letting $\rho_{i,N}$ denote the technological proximity between municipality i and the national distribution, it is defined as:

$$\rho_{i,N} = P_i P_N' / \left[(P_i P_i')(P_N P_N')\right]^{1/2}, \tag{5}$$

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[30] As agriculture is not documented in the industrial statistics, we assume that it is an existing industry in all non-urban municipalities.

where P_N is a vector of shares of patents of each class at the national level and, similarly, P_i is a vector capturing the shares for municipality i. A high value implies that the technical profile in a municipality is similar to the national distribution.[31]

Figure 6 presents estimates from equation (1) showing that patents granted to inventors in connected municipalities became increasingly similar to the national distribution of patented inventions. The estimates from our main difference-in-differences specification confirms this. Column 7 in table 4 documents that a network connection increased the technical proximity with 0.06 on the scale between 0 and 1, which corresponds to a 0.9 standard deviation increase. As seen in column 8, results are similar when we, instead of technological classes, use the shares in each of the 14 industrial sectors (see above) when defining our technical proximity measure.

Thus, consistent with the notion that railroad access benefited both the diffusion of knowledge and the workings of a market for ideas, patents also became more similar to the national distribution, suggesting that inventors increasingly responded to demands from a larger market. We next provide direct evidence that ideas were developed for other markets after a network connection was established by studying the trade in patents.

5.2.2 Network connections and the transfer of patents

To more directly establish that inventors developed ideas for markets beyond the local economy, we start by documenting an increase in patent transfers after a network connection is established. Table 5 presents OLS (panel A) and and 2SLS (panel B) estimates of equation 2 where the outcome is a binary indicator for whether a municipality has at least one patent transfer in a given decade or the number of transfers per capita. The OLS and 2SLS estimates reported in column 1 suggests that a network connection increased the probability of a patent transfer by roughly 2 and 4.4 percentage , respectively.

To establish that this increased trade in technology takes place along the network, we separately study transfers between a buyer and a seller that are both located in a municipality connected to the network, and transfers where at least one of them is located in a non-connected municipality. In columns 2–4, we document that the increase in patent sales is entirely driven by transfers between buyers and sellers that are both located in connected municipalities. Notably, we find no evidence that transfers increase to non-connected locations, nor any increase in transfers within the municipality itself. Thus, our results likely reflect improved connectivity of buyers and sellers, rather than a local increase in patenting activity.

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[31] It has the attractive feature that $0 \leq \rho_{i,N} \leq 1$: it is zero when the two vectors are orthogonal and one when they are identical.

Moving from the extensive to the intensive margin, the number of transfers per capita follows the same pattern. As shown in columns 5–8, a network connection led to a subsequent increase of 0.09 transfers per 1,000 inhabitants. While this may seem as a small effect, it corresponds to 0.5 SDs. Figure 7 documents the increase by decade.

Not only the extent of transfers, but also the speed of such transfers increased after an inventor's municipality became connected to the network. We document that the increase in transfers is only evident for patents that are transferred within three years of their grant date (see Appendix Table B.9). To contextualize this time frame, one can note that patents granted in the late-20th century by the USPTO were on average transferred within 5.5 years of being granted (Akcigit et al., 2016). Among Swedish patents granted by the Swedish Patent and Registration Office, the average time is approximately 2.5 years.

As shown by Akcigit et al. (2016), a patent is more likely to be sold the more distant it is from the inventor's technology space. Thus, assuming that connectivity increases the efficiency on the market for ideas, we would expect the positive effect on transfers to be more pronounced for patents not related to the local economy of the municipalities. As above, we separate between patents that belong to (non-)novel technology fields based on the patenting history of municipalities, as well as patents in (non-)existing or (non-)leading industrial sectors based on whether a sector is represented in the local economy. Table 6, columns 1–6 show that patent transfers are only evident for novel fields as well as non-existing and non-leading industries. That is, only those patented inventions that were presumably not useful in the local economy were subsequently sold to outside buyers. Conversely, there is no evidence that patents that are more likely to have been useful in the local industry are sold.[32]

These patterns provide an interesting contrast to the results presented in Table 4 above, showing that patenting output increased in *both* novel and non-novel technology fields as well as existing/leading and non-existing/non-leading industries after a network connection was established. A straightforward interpretation is, thus, that a network connection leads inventors to increasingly pursue ideas with potential applications in the local and national economy, but that only those inventions that have no local connection are subsequently sold.

An active market for innovation enables inventors that have useful ideas to develop those even if they lack the competence or capital to exploit and commercialize these inventions. To study the type of transactions, we categorize all transfers by the legal status of the buyer/seller in Table 7. The OLS estimates show that given a connection to the railroad network a transfer was more likely to occur from independent inventors to firms or between

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[32] Appendix B.8 documents a similar pattern for the extensive margin.

two independent patentees.[33] In the 2SLS, the effect disappears for transfers between individual, but becomes stronger for individual to firm transfers. We find no effects on transfers between firms or from a firm to an individual patentee. Thus, the entire increase in transfers is driven by independent inventors developing ideas that are subsequently sold to firms located in other areas along the network.

In sum, these estimates provide direct evidence of how the evolving railroad network led to the creation of an increasingly national market for ideas. The growing market enabled individuals to specialize in the production of new ideas, which could then be sold to firms that were presumably better placed to develop and commercialize them.

5.3 Additional estimates and robustness

Spatial reallocation. A sharp increase in the rate of innovation and trade in technology in areas that become connected to the network raises the important question whether these gains reflect truly "new" innovative activity or whether it is simply driven by a spatial reallocation of inventive activity from other municipalities. Understanding whether such general equilibrium effects are empirically relevant is important because it would suggest a smaller contribution of the railroads to aggregate innovation. We use four distinct approaches to gauge the extent of such reallocation in our data.

First, we follow Moretti & Wilson (2014) and create a spatial measure of network access for municipality i, by taking the sum of the weighted railroad access in all other municipalities j:

$$\textit{Spatial Network Connections}_{it} = \sum_{j \neq i} w_{ij} \times \textit{Network Connection}_{jt}, \tag{6}$$

where w_{ij} corresponds to a set of weights that are constructed based on the inverted geodesic distance between municipality i and j and satisfy $\sum_{j \neq i} w_{ij} = 1$.[34] We scale this measure so that a higher value of "spatial network connections" corresponds to neighboring municipalities having better access to the network. In the case that additional connections in the vicinity of a municipality have beneficial effects, we would expect the coefficient to be positive, whereas a negative sign would indicate that there are negative spillovers.

We report OLS and 2SLS estimates of our baseline difference-in-differences specification in

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[33] Anecdotal evidence suggests that transfers between two independent inventors were made when one party possessed better complementary assets to exploit and commercialize the patented invention. For example, patent no. 10494 and 20606 are example of transfers when the profession of the buyer, i.e. "banker" or "wholesaler", indicates that the buyer most likely was in a better position to bring the invention to the market.

[34] An alternative approach would be to calculate market access measures similar to Donaldson & Hornbeck (2016). Unfortunately, information on municipal-level population required to calculate similar measures is not available for the entirety of our study period.

equation 2 when including the spatial network connections-measure in the Appendix (Table A.13).[35] In all specifications, we find that our baseline estimates of the impact of network connections on innovative activity remain stable, while the spatial network connections-measure itself is relatively small in magnitude and not statistically significant.

Second, in the Appendix, we also display difference–in–differences OLS estimates of equation (2) where we allow the treatment effect to vary flexibly across 5 km bins of distance to the railroad network (Figure A.2). As seen in figures, nearby non-connected areas do not exhibit relative reductions in inventor entry (panels B–C), nor in patenting output (panel A). This suggests that inventor migration or a reallocation of innovative activity at most accounts for a small share of the overall increase in entry that we observe.

Third, we exclude nearby untreated areas (i.e., without a network connection) from the control group and re-estimate our baseline difference-in-differences model in equation (2).[36] Appendix Figure A.3 displays OLS and 2SLS estimates from seven individual regressions where we sequentially exclude plausibly untreated areas. Although estimated magnitudes decline somewhat when omitting areas in proximity to the network (i.e., 5-20 km), they remain stable in magnitude and statistical precision when omitting more distant areas.

Fourth, to more directly study mobility patterns of inventors, we link individual-level data on a subset of the inventors in our data to the decadal population censuses 1880–1910.[37] While inventors were more mobile than the population average in terms of leaving their municipality of birth, they are surprisingly non-mobile when following them across time: of the 1,055 individual inventors that we can match to at least two census rounds, only about two percent of them change their municipality of residence. Again, this suggests that inventor migration unlikely accounts for our results.

While we cannot fully disregard potential positive or negative spillovers along the network, these results taken together suggest that spatial reallocation is unlikely to be important in driving our results.

Alternative extended sample and heterogeneity To exclude municipalities with enhanced probability to get connected to the network due to political pressure or local demand-driven reasons, we have excluded urban municipalities in all our main regressions. Given that

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[35] To instrument for spatial rails in our 2SLS regressions, we create an additional instrument where we interact time period indicators with a spatial rail measure constructed using the least-cost path instead of the actual railroad network.)

[36] As pointed out by Redding & Turner (2014), the treatment effect corresponds to the compound effect of growth and spatial reallocation corresponding to $\beta = 2d + a$, where d is the amount of activity that is reallocated between the treated and untreated area and a is the pure growth effect. Stable estimates when limiting the control group to residual areas suggest that $d \approx 0$ and that the estimated impacts mainly reflect growth rather than spatial reallocation.

[37] We describe this procedure in more depth in Appendix Section C.2.

patents are over-represented among urban municipalities, the main fear is that these urban locations should bias our estimates upwards. In Appendix Table A.7, we extend the sample and include all urban locations except those at the nodes of the network. While most coefficients are similar in magnitude, in general they are slightly larger in the non-urban sample, despite our endogeneity concerns, as well as more precisely estimated. In particular, this is the case for patent transfers. A potential explanation is that rural localities had comparatively less scope for using the patent in production within the municipality. As such they are relatively more affected by network connection compared to urban locations. To study this potential heterogeneity further, we introduce an interaction term between an indicator for urban and the network connection indicator. Although, we find that the interaction coefficient is negative for the regressions on the patent transfer outcomes, in line with the argument above, it is positive for the regressions on the number of patents and inventors per capita, and in general non-significant for all our main outcomes.

Innovation in the railroad sector. One potential concern is that our results stem from that the arrival of the railroad induced inventors to develop technologies directly related to the railroad (e.g., machinery). As direct evidence against such explanations driving our results, we provide estimates in Appendix Table A.8 where we restrict our outcomes to (non-)railroad-related patents, which reveal a very similar increase in local innovation not directly linked to the railroad.[38]

Alternative forms of protection of intellectual property. Other mechanisms for protecting intellectual property—most importantly, secrecy—may have become less useful relative to patent protection after a network connection was established. If inventors prior to the coming of the railroad, for example, relied on secrecy to protect their inventions, the external integration of the local economy may have increased the incentives to protect their intellectual property using patents. Thus, one concern is that the increase in patenting output that we document above reflects an increase in patenting activity, but not necessarily an increased rate of innovation.

To explore whether such mechanisms are likely to drive our results, we rely on evidence by Moser (2005) that the effectiveness of non-patent forms of protection vary across industries. Based on exhibitions by American and British inventors at the Crystal Palace World's Fair in

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[38] We define railroad-related patents as patents belonging to specific DPK subclasses directly related to the railroad sector, or where a patent contains one of a set of rail-related keywords (e.g., "rail*", "loco*", etc.). In particular, we search for the Swedish terms "*jernvä*" OR "*järnvä*" OR "*räls*" OR "*järnvagn*" OR "*jernvagn*" OR "*spår*" OR "*loko*" OR "*syll*". We manually review each individual match to confirm that the invention is related to the railroad sector.

1851, she documents that the fraction of inventions (exhibits) that are patented vary sharply across industries in both Britain and the United States, despite their vastly different patenting systems. If the fact that patents may have become necessary to protect (pre-existing) inventions after an inventor's municipality is integrated with external markets explains the increase in patenting output, we would expect to see larger increases in industries where alternative forms of protection (e.g., secrecy) are less effective.

We present estimates in Appendix Table A.9 showing that patented inventions increased both in industries where alternative forms of protection is most and least important.[39] Thus, it is unlikely that an increased propensity to patent explains the local surge in patent output after a network connection is established.

Functional form In our main specification, we present results where the outcome variables is specified either as an indicator variable or as the number of patents, inventors or transfers, per 1,000 inhabitants. In Appendix Tables A.3 and A.4, we show that our results are similar when using alternative transformations of our outcome variables, such as the natural logarithm or the inverse hyperbolic sine function.[40]

We have throughout our main analysis defined network connection as an indicator variable equal to one if the railroad network is within 5 km of the municipality centroid. In Appendix Table A.2, we document that our results are robust to measuring network access as a continuous measure by using the natural logarithm of the distance to the network.

Standard errors. To adjust for potential correlation of the error term within municipalities, we cluster standard errors at the municipality level throughout our analysis. In the Appendix Table A.5, we report bootstrapped standard errors alongside our analytical standard errors. As seen in the table, the errors are only marginally affected. Furthermore, to document that our results are robust to allowing for spatial dependence at different cutoffs, we display Conley standard errors in Appendix Table A.6.

OLS vs. IV. Consistently, we obtain 2SLS estimates that are larger in magnitude than the corresponding OLS estimates in all our main specifications. One explanation for the discrepancy between OLS and 2SLS estimates is that network connections are allocated

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[39] Based on data supplied in Moser (2005), we define sectors with high patenting rates (where secrecy is presumably a less effective protection relative to patents) to include machinery (including metals, steam engines, and weapons), scientific instruments, and manufactures, while sectors with low patenting rates (where secrecy provides relatively more effective protection) include chemicals, food and beverages, mining, and textiles.

[40] As we have several municipalities with zero innovative activity in certain decades, we add 1 before taking the logarithm.

to less favourable regions, which induces a downward bias in the OLS estimates. Yet, an alternative interpretation may be that the difference in magnitudes could stem from the fact that the 2SLS estimates may capture a local average treatment effect (LATE), as opposed to the average treatment effect (ATE) in the OLS.[41] However, the small increase in the coefficient when adding the pre-rail economic controls, as evident in Appendix Table A.14, is consistent with the notion that economically less developed locations are in general more likely to receive public transport infrastructure (Baum-Snow, 2007; Duranton & Turner, 2012; Redding & Turner, 2014).[42]

To further mitigate concerns regarding a LATE, Appendix Table A.10, documents our main results using an alternative instrumental variables strategy based on the network plans by Colonel Ericson.[43] The Ericson plan is pictured in Figure 3. As discussed in Section 2, Ericson's overarching aim was to connect Stockholm with a limited number of destinations, rather than to connect rapidly growing municipalities. While the coefficients are generally smaller in magnitude then those using the least-cost path as instruments, they are larger than their OLS counterparts. Taken together, the most plausible explanation, in our view, therefore involves network connections being allocated to areas with lower unobserved propensities for innovation.

Placebo tests. One concern is that network connections were allocated to areas based on unobserved factors that may subsequently have shaped innovation outcomes. As described above, the original network proposed by Colonel Ericson was altered through subsequent parliamentary decisions, which resulted in parts of the intended network never being constructed.[44] We estimate the effects for these unbuilt lines as well as lines that were part of another major proposal put forth in 1870, which consisted of additional lines proposed by a state committee and municipalities, respectively. We show in the Appendix that there are

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[41] This could, for example, be the case if our IV strategy captures the main trunk lines rather than the average rail line. Moreover, it may be the case that the effect for *always takers*, in the jargon of a potential outcome model, is smaller than for the *compliers* of the instrument. In our setting, this could be the case if the marginal effect of railroads for municipalities, such as densely populated areas, that would obtain a railroad at least at some point in time, disregarding the cost of passing the network through those municipalities, is smaller than the effect on municipalities that heavily rely on accidentally being located in the proximity of the predicted network.

[42] Only two of our main outcomes presented in Appendix Table A.14 have slightly lower coefficients when including our pre-rail economic controls.

[43] After measuring the distance to the Ericson plan for each municipality, we proceed with the instrumental variables strategy in a similar fashion as when using the least-cost path.

[44] A notable deviation occurred due to the decision to shift the main line connecting Stockholm and Malmö eastward. While this alteration served to raise the construction costs, it was mainly motivated by the fact that it shortened the distance between the two major cities and was thus presumably exogenous to characteristics of locations along this route (Rydfors 1906, p.86). Additional minor changes were the result of more detailed surveys, which identified cheaper ways of routing segments of different lines.

no increases in local innovation or patent transfers in areas that were assigned a network connection, but where no connection was ultimately established (Tables A.11 and A.12). To the extent that the allocation process underlying the planning of these lines did not differ from those lines actually built, these results reduce concerns about potentially different fundamentals in areas that received network connections.

6 Concluding remarks

We study the causal impact of reduced communication and transportation costs on local innovative activity by exploiting the staggered rollout of the historical Swedish railroad network across municipalities. We document three key findings. First, the establishment of a network connection increased the pace of local innovation, by encouraging new inventors to enter the innovation sector and by increasing the output of inventors. Second, the unfolding railroad network enabled inventors to increasingly develop new ideas with applications beyond the local economy leading to an increased technological proximity between local and national innovation. Third, by connecting inventors to potential buyers, the emerging network enabled independent inventors to sell their patented ideas to firms, which were presumably better positioned to develop and commercialize these new technologies.

Are these results also relevant to understand the link between transport infrastructure and innovation today? The period that we study was an era of rapid globalization and technological change, which shares many similarities to recent decades. To further provide motivating evidence that transport networks constructed during this period still today shape spatial innovation patterns, Figure 8 documents persistent differences in inventive activity across the municipalities in our sample over the 20th century. Today, patenting output is substantially higher in places where network connections had been established a century before. Moreover, areas where network connections were opened or closed down during this 100-year period experienced an increase and reduction in patenting output respectively.[45]. While these correlations are not necessarily causal and thus should be interpreted carefully, in our view they constitute suggestive evidence that historical transportation networks still remain a key determinant of the local rate of technological progress today.

Our results suggest that communication and transportation costs are an important determinant of spatial patterns of innovation and trade in technological ideas. While prior research has emphasized the role of R&D tax credits, increasing the supply of college graduates in STEM fields, or expanding mentorship programs (Bell et al., 2018, 2019; Bloom et al., 2019), our findings suggest that investing in transport networks may be an important policy

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[45] See Appendix Table B.10

lever to increase innovation, partly by connecting firms, intermediaries, and inventors in the market for innovation. Another potentially important channel is that the integration of a market for innovation reduces the misallocation of ideas across firms as they can increasingly draw on technologies that originate outside their organizational boundaries by purchasing patents. An important avenue for future work is to analyze the extent to which an increased trade in technology improved the allocation of ideas across firms and the impacts this has on growth, innovation, and welfare.

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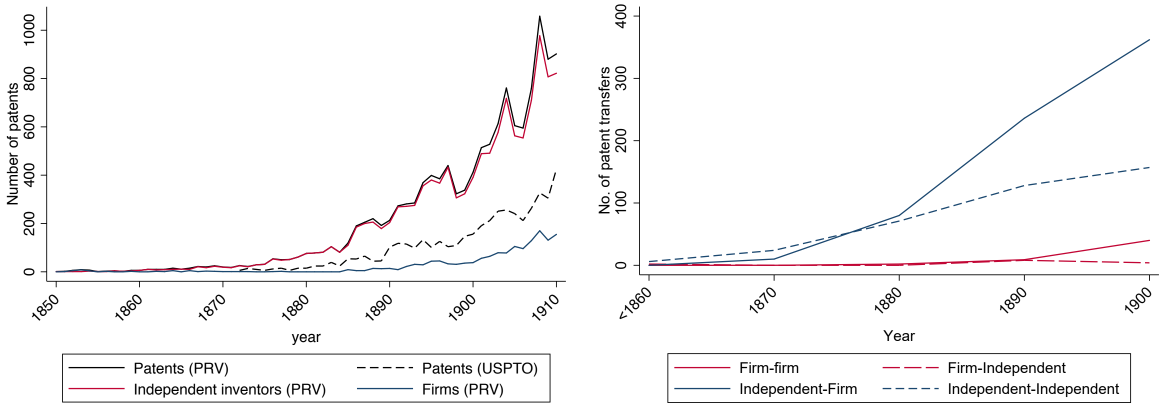
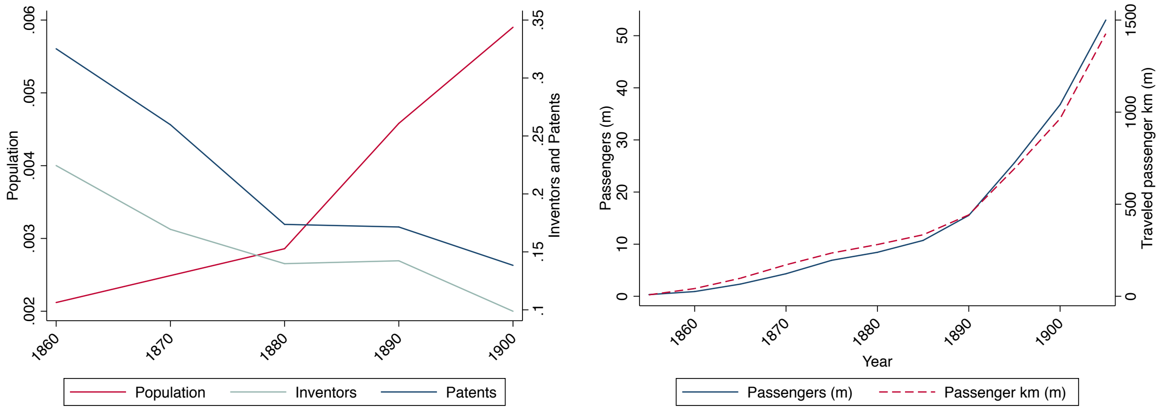
7 Figures



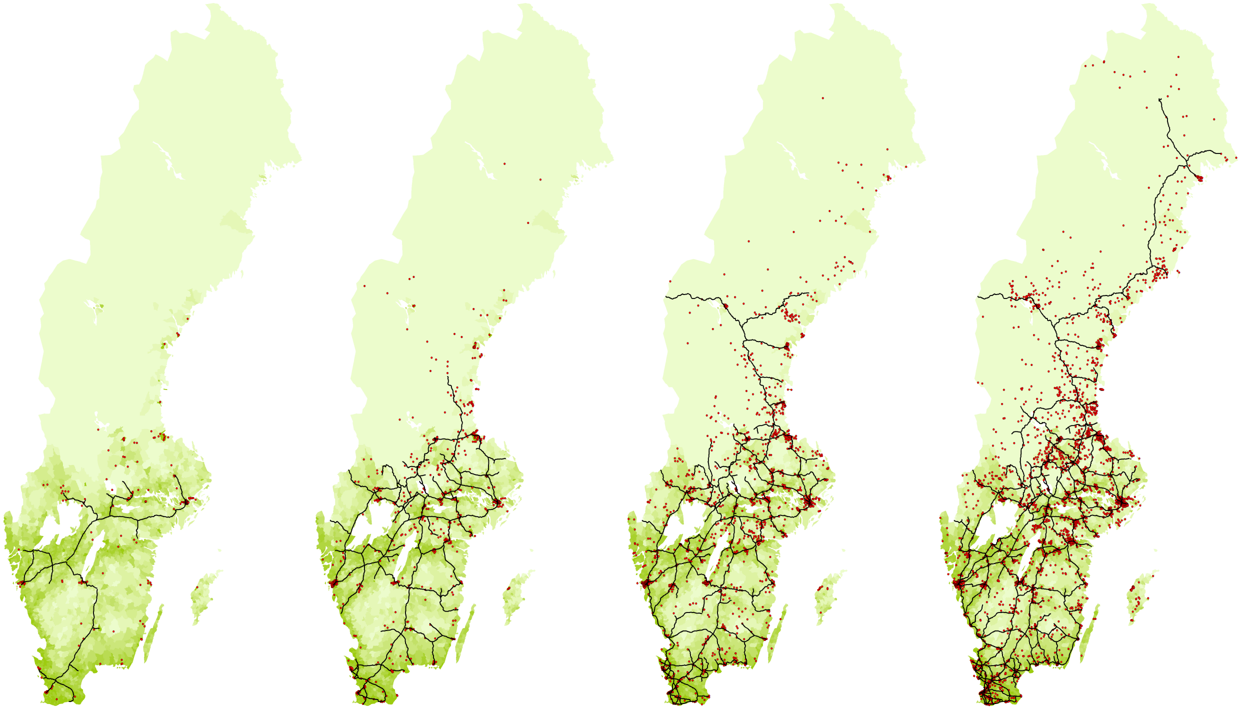
(A) Patents (B) Patent Transfers



(C) Herfindahl–Hirschman Index (D) Traveling by Rail

Figure 1:
The rise of innovation in Sweden

Notes: Figure A shows the number of patents granted to Swedish inventors by the PRV and the USPTO. Figure B displays the number of transfers by legal category. The legal category of a patent is defined as a firm if a patent was granted to a firm and otherwise as an independent patent. Figure C shows a Herfindahl–Hirschman Index for the number of inventors, patents, and population across municipalities. Figure D displays the number of passengers and passenger kilometers (both in millions) traveled on the railroad network from Historisk Statistik för Sverige (1960, Table 47).



(A) 1870 (B) 1880 (C) 1890 (D) 1900

Figure 2:
Inventors and the Rollout of the Railroad Network 1870–1900

Notes: This figure displays the railroad network for the years 1870, 1880, 1890 and 1900 depicted in black and the location of each inventor. Each dot corresponds to one unique inventor patenting at least once in the subsequent decade. Also shown shaded in green is the population density in 1865 divided into deciles where darker shades correspond to higher density.

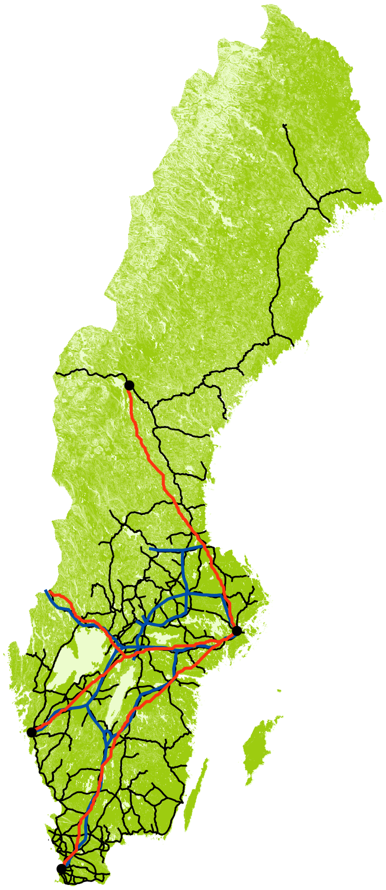
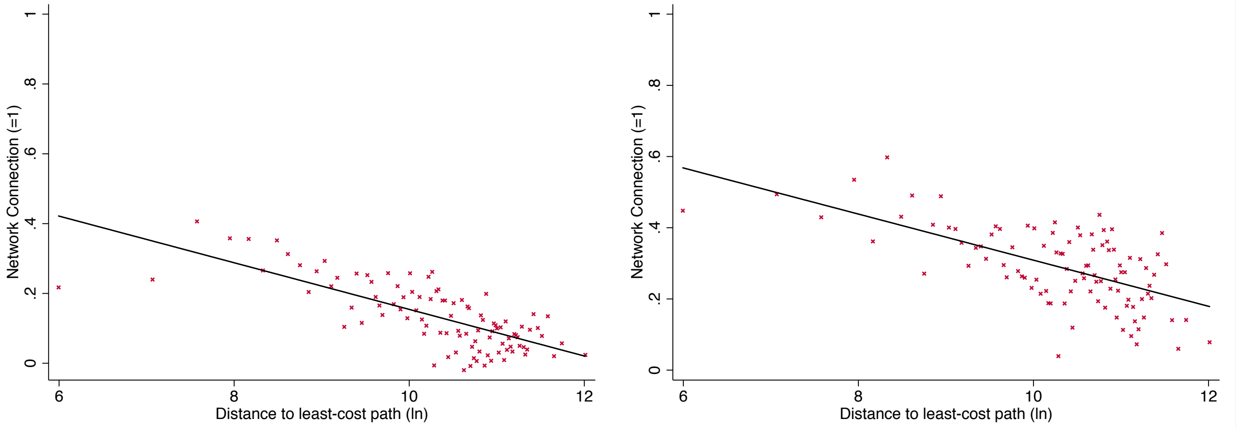
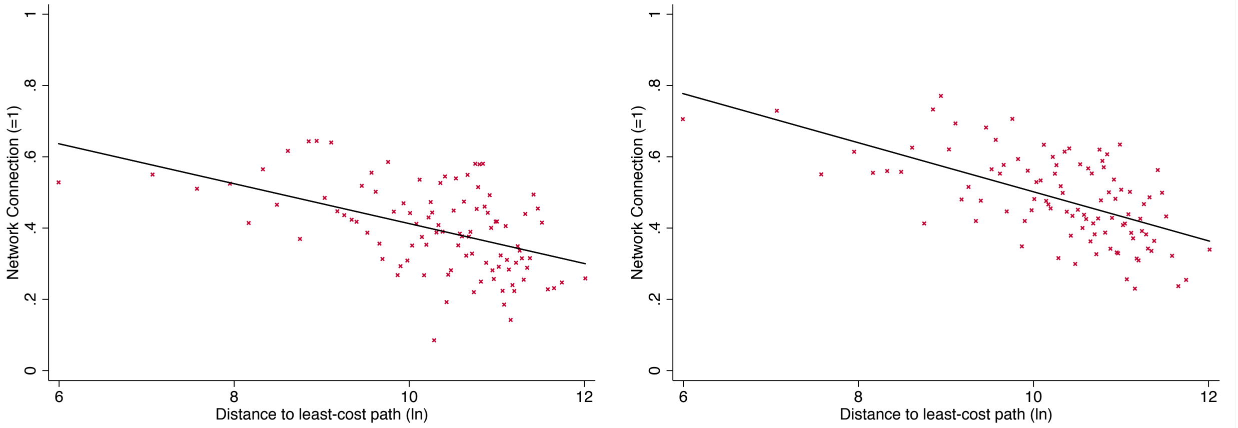


Figure 3:
The railroad network, the LCPs and the Ericson plan

Notes: This figure displays the railroad network (in 1900) in black, the LCPs in red and Colonel Ericson's proposal in blue.



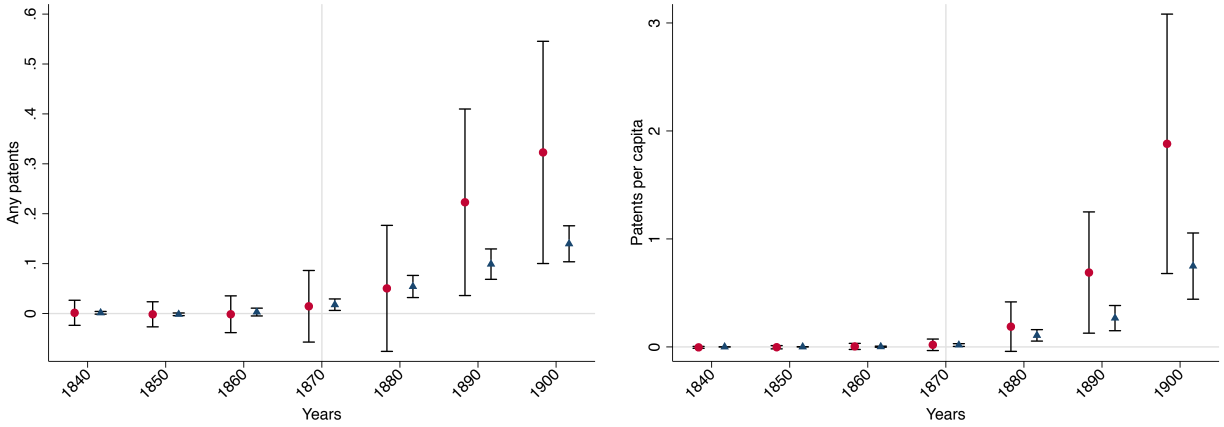
(a) LCP 1870 (b) LCP 1880



(c) LCP 1890 (d) LCP 1900

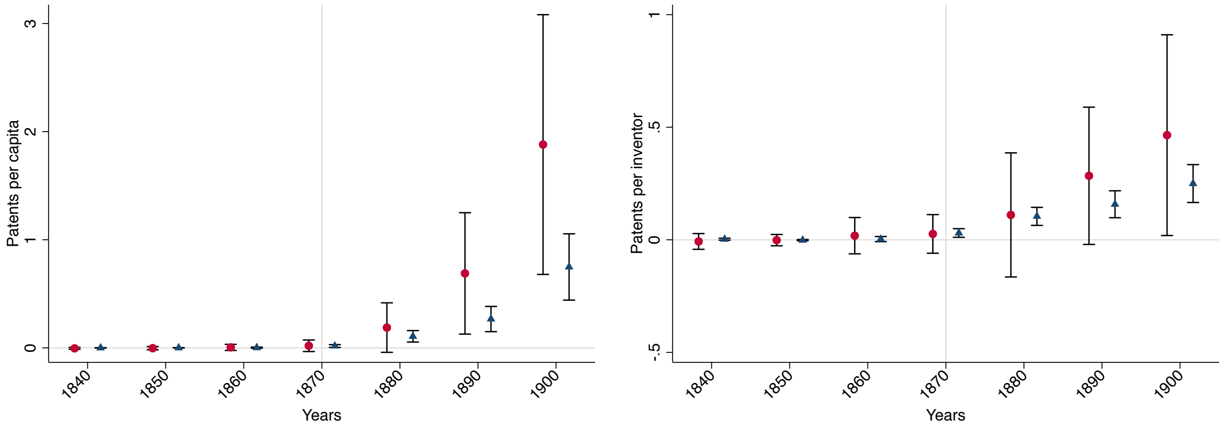
Figure 4:
First-stage relationship – Railroads and distance to the LCPs

Notes: The figures display the non-parametric relationship between network access (i.e., an indicator capturing whether a municipality is located within 5 km of a railroad) and our instrument by decade. All variables have been residualized using local geography and pre-rail covariates as well as region fixed effects. Local geography covariates include: the mean slope, the mean elevation as well as the standard deviation of the elevation, the area, and the mean cost of construction based on the land cover and slope data (all in logs). Pre-rail covariates include: log population in 1865, the log distance to the nearest town, an indicator for whether a municipality had any granted patent prior to 1860 or not, the number of manufacturing firms per capita and the share of manufacturing workers in 1865, the latitude and longitude of the municipality centroid. Observations are sorted into 100 groups of equal size and the dots indicate the mean value in each group. A linear regression line based on the underlying (ungrouped) data is also shown.



(A) Any patent

(B) Patents per capita



(C) Inventors per capita

(D) Patents per inventor

Figure 5:
Rollout of the railroad network and the spread of innovative activity

Notes: The figure displays OLS estimates (blue diamonds) and 2SLS estimates (red circles) of the effect by decade of access to the railroad network on: a binary variable indicating whether a municipality has at least on patent in a given decade (A), the number of patents per 1,000 inhabitants (B), the number of inventors per 1,000 inhabitants (C), and the number of patents per inventor (D). Bars indicate 95 percent confidence intervals. The grey solid vertical line denotes the year when the first parts of the network were in operation. All regressions include local geography-by-year controls, pre-rail-by-year controls, municipality fixed effects and region-by-year fixed effects. Local geography controls include: the mean slope, the mean elevation as well as the standard deviation of the elevation, the area, and the mean cost of construction based on the land cover and slope data (all in logs). Pre-rail controls include: log population in 1865, the log distance to the nearest town, an indicator for whether a municipality had any granted patent prior to 1860 or not, the number of manufacturing firms per capita and the share of manufacturing workers in 1865, the latitude and longitude of the municipality centroid as well as region fixed effects. Standard errors are clustered at the municipality level.

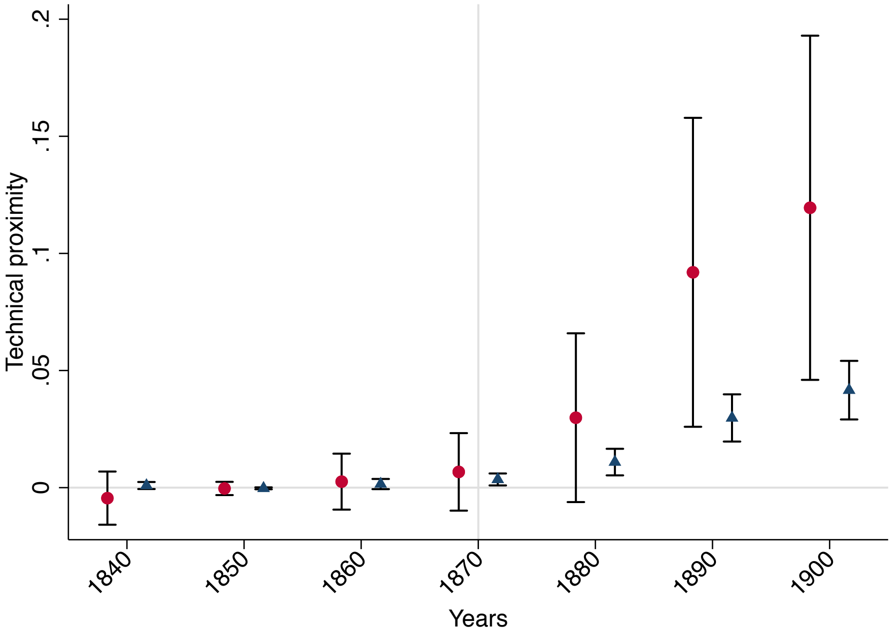


Figure 6:
Rollout of the railroad network and technical proximity to national patents

Notes: The figure displays OLS estimates (blue diamonds) and 2SLS estimates (red circles) of the effect by decade of access to the railroad network on the technical proximity to the national distribution. Bars indicate 95 percent confidence intervals. The grey solid vertical line denotes the year when the first parts of the network were in operation. All regressions include local geography-by-year controls, pre-rail-by-year controls, municipality fixed effects and region-by-year fixed effects. Local geography controls include: the mean slope, the mean elevation as well as the standard deviation of the elevation, the area, and the mean cost of construction based on the land cover and slope data (all in logs). Pre-rail controls include: log population in 1865, the log distance to the nearest town, an indicator for whether a municipality had any granted patent prior to 1860 or not, the number of manufacturing firms per capita and the share of manufacturing workers in 1865, the latitude and longitude of the municipality centroid as well as region fixed effects. Standard errors are clustered at the municipality level.

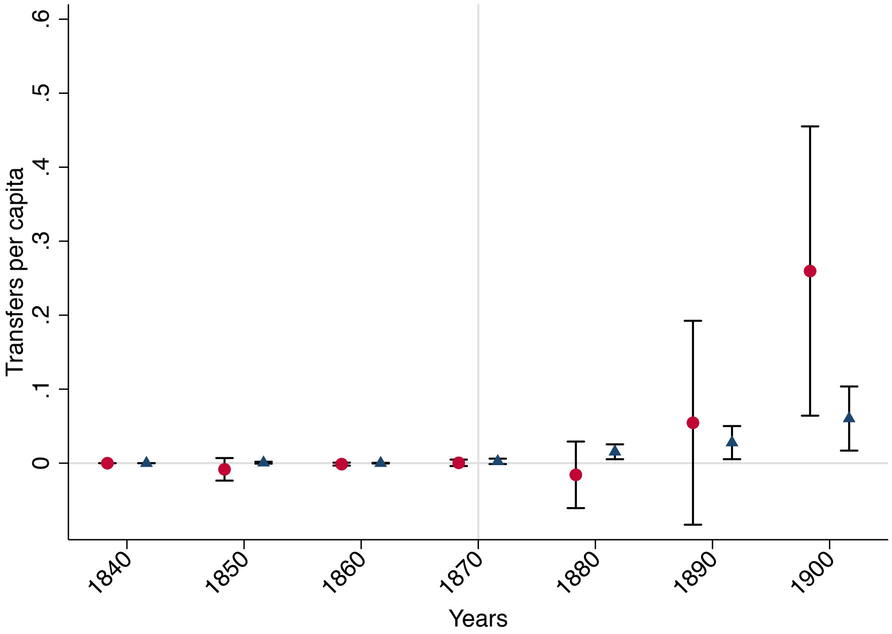


Figure 7:
Rollout of the railroad network and patent transfers

Notes: The figure displays OLS estimates (blue diamonds) and 2SLS estimates (red circles) of the effect by decade of access to the railroad network on the number of patent tranfers per 1,000 inhabitants. Bars indicate 95 percent confidence intervals. The grey solid vertical line denotes the year when the first parts of the network were in operation. All regressions include local geography-by-year controls, pre-rail-by-year controls, municipality fixed effects and region-by-year fixed effects. Local geography controls include: the mean slope, the mean elevation as well as the standard deviation of the elevation, the area, and the mean cost of construction based on the land cover and slope data (all in logs). Pre-rail controls include: log population in 1865, the log distance to the nearest town, an indicator for whether a municipality had any granted patent prior to 1860 or not, the number of manufacturing firms per capita and the share of manufacturing workers in 1865, the latitude and longitude of the municipality centroid as well as region fixed effects. Standard errors are clustered at the municipality level.

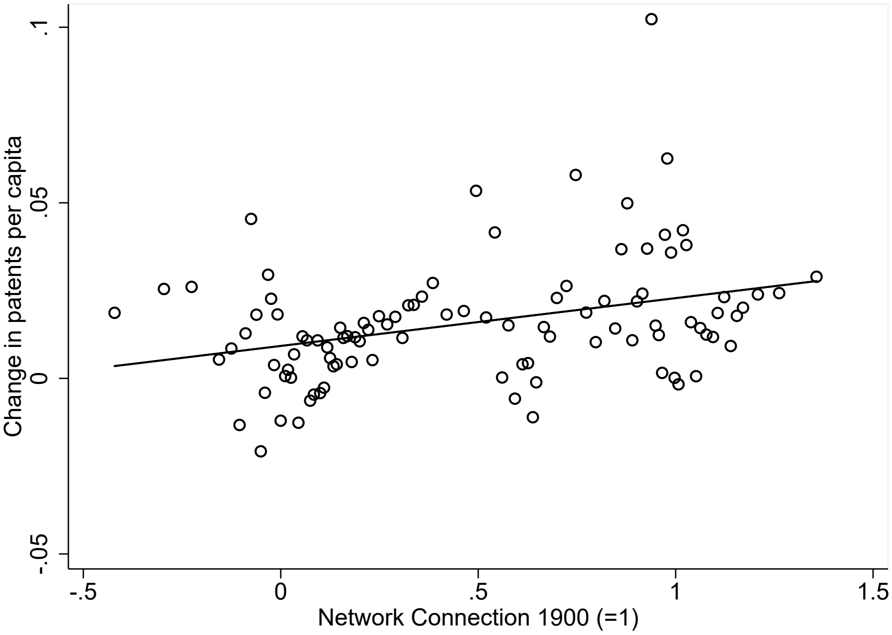


Figure 8:
Non-parametric relationship of innovative persistence

Notes: Non-parametric relationship between railroad access in 1900 and the difference in the number of patents in 2005–2014 and 1900–1910 per 1,000 inhabitants in 1865. Both variables have been residualized using local geography and pre-rail covariates as well as region fixed effects. Local geography covariates include: the mean slope, the mean elevation as well as the standard deviation of the elevation, the area, and the mean cost of construction based on the land cover and slope data (all in logs). Pre-rail covariates include: log population in 1865, the log distance to the nearest town, an indicator for whether a municipality had any granted patent prior to 1860 or not, the number of manufacturing firms per capita and the share of manufacturing workers in 1865, the latitude and longitude of the municipality centroid. Observations are sorted into 100 groups of equal size and the dots indicate the mean value in each group. A linear regression line based on the underlying (ungrouped) data is also shown.

8 Tables

Table 1: Balance test of instrument

	(1) ln(Distance to Least-Cost Path)	
ln(Population 1865)	-0.035	(0.034)
ln(Longitude)	0.007	(0.009)
ln(Latitude)	-0.000	(0.001)
ln(Distance to town)	0.034	(0.021)
Any patent before 1860	-0.002	(0.002)
Technical university	-0.011	(0.007)
Mfg. firms p.c. 1865	-0.000	(0.000)
Share mfg. workers 1865	-0.000	(0.000)
Mortality 1850s	-0.000	(0.000)
Change in Population 1810-65	-0.004	(0.006)
Change in Mortality 1850-60	0.000	(0.000)

Notes: OLS regressions. Each row is a separate regression with the indicated dependent variable regressed on the distance to the nearest LCP, in logs, as well as local geographic controls and region fixed effects. Column (1) displays the coefficient of ln(Distance to Least-Cost Path). Standard errors are given in parenthesis and are clustered at the region level. All regressions include the mean slope, the mean and the standard deviation of elevation, the area, the mean cost of construction based on the land cover and slope data (all in logs) and region fixed effects. *** - $p < 0.01$, ** - $p < 0.05$, * - $p < 0.1$.

TABLE 2: FIRST-STAGE ESTIMATES

Dependent variable:	Network Connection (=1)		
	(1)	(2)	(3)
ln(Distance to Least-Cost Path)×Year 1870	-0.069***	-0.067***	-0.076***
	(0.008)	(0.008)	(0.009)
ln(Distance to Least-Cost Path)×Year 1880	-0.078***	-0.066***	-0.065***
	(0.009)	(0.009)	(0.010)
ln(Distance to Least-Cost Path)×Year 1890	-0.062***	-0.052***	-0.062***
	(0.009)	(0.010)	(0.010)
ln(Distance to Least-Cost Path)×Year 1900	-0.071***	-0.063***	-0.074***
	(0.009)	(0.009)	(0.010)
Local Geography×Year FE	Yes	Yes	Yes
Pre-Rail Controls×Year FE	No	Yes	Yes
Region FE×Year FE	No	No	Yes
Observations	18152	18152	18152
Mean dep. var.	0.163	0.163	0.163

Notes: OLS regressions. The table displays the effect of the distance to the nearest LCP (in logs) interacted with four separate indicator variables for the decades starting in 1870, 1880, 1890, 1900 on an indicator for railroad access (within 5 km). All regressions include municipality fixed effects and year fixed effects. Local geography controls include: the mean slope, the mean elevation as well as the standard deviation of the elevation, the area, and the mean cost of construction based on the land cover and slope data (all in logs). Pre-rail controls include: log population in 1865, the log distance to the nearest town, an indicator for whether a municipality had any granted patent prior to 1860 or not, the number of manufacturing firms per capita and the share of manufacturing workers in 1865, the latitude and longitude of the municipality centroid as well as region fixed effects. Standard errors are given in parentheses and are clustered at the municipality level. *** - $p < 0.01$, ** - $p < 0.05$, * - $p < 0.1$.

Table 3: The Effect of Network Connections on Local Innovative Activity

Dependent variable:	Any patent	Patents per capita	Inventors per capita			Patents per inventor		
			All	Independent	Firm	All	Independent	Firm
Panel A: OLS	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Network Connection (=1)	0.085***	0.319***	0.178***	0.169***	0.009***	0.150***	0.144***	0.024***
	(0.010)	(0.066)	(0.033)	(0.031)	(0.003)	(0.020)	(0.020)	(0.008)
Panel B: 2SLS	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Network Connection (=1)	0.159***	0.751***	0.489***	0.471***	0.018	0.228**	0.246**	0.070*
	(0.054)	(0.234)	(0.130)	(0.123)	(0.015)	(0.102)	(0.101)	(0.040)
Municipality FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Region FE×Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Local Geography×Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Pre-Rail Controls×Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
First-Stage F-stat	26.48	26.48	26.48	26.48	26.48	26.48	26.48	26.48
Observations	18152	18152	18152	18152	18152	18152	18152	18152
Mean dep. var.	0.056	0.115	0.073	0.070	0.003	0.083	0.081	0.010

Notes: OLS and 2SLS regressions. The table displays the effect of an indicator for network access (within 5 km) on whether a municipality has any patent (column 1), the number of patents per 1,000 inhabitants (column 2), inventors per capita by legal category (columns 3–5), and patents per inventor by legal category (columns 6–8). Numbers of inhabitants are from 1865. Local geography controls include: the mean slope, the mean elevation as well as the standard deviation of the elevation, the area, and the mean cost of construction based on the land cover and slope data (all in logs). Pre-rail controls include: log population in 1865, the log distance to the nearest town, an indicator for whether a municipality had any granted patent prior to 1860 or not, the number of manufacturing firms per capita and the share of manufacturing workers in 1865, the latitude and longitude of the municipality centroid as well as region fixed effects. Standard errors are given in parentheses and are clustered at the municipality level. *** - $p < 0.01$, ** - $p < 0.05$, * - $p < 0.1$.

Table 4: The Effect of Network Connections on the Local Technical Profile

Dependent variable:	Patents per capita						Technical proximity	
	Technology fields		Industrial sectors				Technology fields	Industrial sectors
	Novel	Non-novel	Existing	Non-existing	Leading	Non-leading		
Panel A: OLS	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Network Connection (=1)	0.235***	0.084***	0.046***	0.273***	0.043***	0.276***	0.024***	0.039***
	(0.040)	(0.030)	(0.010)	(0.062)	(0.010)	(0.062)	(0.003)	(0.005)
Panel B: 2SLS	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Network Connection (=1)	0.579***	0.170**	0.167***	0.584***	0.167***	0.585***	0.064***	0.076***
	(0.178)	(0.080)	(0.056)	(0.206)	(0.055)	(0.206)	(0.017)	(0.029)
Municipality FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Region FE×Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Local Geography×Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Pre-Rail Controls×Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
First-Stage F-stat	26.48	26.48	26.48	26.48	26.48	26.48	26.48	26.48
Observations	18152	18152	18152	18152	18152	18152	18152	18152
Mean dep. var.	0.095	0.021	0.021	0.095	0.020	0.096	0.014	0.024

Notes: OLS and 2SLS regressions. The table displays the effect of an indicator for network access (within 5 km) on patents per 1,000 inhabitants by category (columns 1–6) and technical proximity to the national distribution based on either 98 technical (DPK) patent classes (column 7) or 14 industrial sectors. A non-novel (novel) technology field refers to patents in DPK patent classes with a (no) prior patent in the municipality. A (non-)existing industrial sector refers to if the patent is (not) related to an industry that existed in 1865. A (non-)leading industrial sector if the patent is (not) related to the industry with the largest share of output. Numbers of inhabitants are from 1865. Local geography controls include: the mean slope, the mean elevation as well as the standard deviation of the elevation, the area, and the mean cost of construction based on the land cover and slope data (all in logs). Pre-rail controls include: log population in 1865, the log distance to the nearest town, an indicator for whether a municipality had any granted patent prior to 1860 or not, the number of manufacturing firms per capita and the share of manufacturing workers in 1865, the latitude and longitude of the municipality centroid as well as region fixed effects. Numbers of inhabitants and workers are from 1865. Standard errors are given in parentheses and are clustered at the municipality level. *** - $p < 0.01$, ** - $p < 0.05$, * - $p < 0.1$.

Table 5: The Effect of Network Connections on patent transfers along the network

Dependent variable:	Any transfer				Transfers per capita			
	All	Connected	Non-connected	In-municip.	All	Connected	Non-connected	In-municip.
Panel A: OLS	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Network Connection (=1)	0.020***	0.017***	0.002	0.002	0.030***	0.027***	0.001	0.001
	(0.004)	(0.004)	(0.001)	(0.002)	(0.008)	(0.007)	(0.001)	(0.002)
Panel B: 2SLS	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Network Connection (=1)	0.044**	0.035**	0.006	0.005	0.087**	0.059*	0.004	0.018
	(0.021)	(0.017)	(0.008)	(0.012)	(0.041)	(0.031)	(0.004)	(0.020)
Municipality FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Region FE×Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Local Geography×Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Pre-Rail Controls×Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
First-Stage F-stat	26.48	26.48	26.48	26.48	26.48	26.48	26.48	26.48
Observations	18152	18152	18152	18152	18152	18152	18152	18152
Mean dep. var.	0.008	0.005	0.001	0.002	0.009	0.007	0.001	0.001

Notes: OLS and 2SLS regressions. The table displays the effect of an indicator for network access (within 5 km) on whether a municipality has any transfer (columns 1–4) and the number of transfers per 1,000 inhabitants (columns 5–8) by category. All refers to all categories of transfers, (Non-)Connected to transfers where the buyer AND the seller have (not) a network connection and In-municip. refers to transfers within the municipality. Numbers of inhabitants are from 1865. Local geography controls include: the mean slope, the mean elevation as well as the standard deviation of the elevation, the area, and the mean cost of construction based on the land cover and slope data (all in logs). Pre-rail controls include: log population in 1865, the log distance to the nearest town, an indicator for whether a municipality had any granted patent prior to 1860 or not, the number of manufacturing firms per capita and the share of manufacturing workers in 1865, the latitude and longitude of the municipality centroid as well as region fixed effects. Numbers of inhabitants and workers are from 1865. Standard errors are given in parentheses and are clustered at the municipality level. *** - $p < 0.01$, ** - $p < 0.05$, * - $p < 0.1$.

TABLE 6: THE EFFECT OF NETWORK CONNECTIONS ON TRANSFERS BY DISTANCE TO THE LOCAL ECONOMIC STRUCTURE

Dependent variable:	Transfers per capita					
	Technology fields		Industrial sector			
	Novel	Non-novel	Existing	Non-existing	Leading	Non-leading
Panel A: OLS	(1)	(2)	(3)	(4)	(5)	(6)
Network Connection (=1)	0.039***	0.004*	0.007***	0.022***	0.006***	0.023***
	(0.008)	(0.002)	(0.002)	(0.007)	(0.002)	(0.007)
Panel B: 2SLS	(1)	(2)	(3)	(4)	(5)	(6)
Network Connection (=1)	0.123***	0.014	0.002	0.086**	0.004	0.084**
	(0.040)	(0.011)	(0.008)	(0.038)	(0.008)	(0.038)
Municipality FE	Yes	Yes	Yes	Yes	Yes	Yes
Region FE×Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Local Geography×Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Pre-Rail Controls×Year FE	Yes	Yes	Yes	Yes	Yes	Yes
First-Stage F-stat	26.48	26.48	26.48	26.48	26.48	26.48
Observations	18152	18152	18152	18152	18152	18152
Mean dep. var.	0.011	0.001	0.002	0.007	0.001	0.007

Notes: OLS and 2SLS regressions. The table displays the effect of an indicator for network access (within 5 km) on transfers per 1,000 inhabitants by category. A non-novel/novel technology field refers to patents in DPK patent classes with a/no prior patent in the municipality. A (non-)existing industrial sector refers to if the patent is (not) related to an industry that existed in 1865. A (non-)leading industrial sector if the patent is (not) related to the industry with the largest share of output. Numbers of inhabitants are from 1865. Local geography controls include: the mean slope, the mean elevation as well as the standard deviation of the elevation, the area, and the mean cost of construction based on the land cover and slope data (all in logs). Pre-rail controls include: log population in 1865, the log distance to the nearest town, an indicator for whether a municipality had any granted patent prior to 1860 or not, the number of manufacturing firms per capita and the share of manufacturing workers in 1865, the latitude and longitude of the municipality centroid as well as region fixed effects. Numbers of inhabitants and workers are from 1865. Standard errors are given in parentheses and are clustered at the municipality level. *** - $p < 0.01$, ** - $p < 0.05$, * - $p < 0.1$.

Table 7: The Effect of Network Connections on patent transfers by legal category

Dependent variable:	Transfers per capita				
	Independent (I) – Firm (F)	Other combinations			
		I–I	F–F	F–I	All
Panel A: OLS	(1)	(2)	(3)	(4)	(5)
Network Connection (=1)	0.021***	0.008***	-0.000	0.001	0.008***
	(0.006)	(0.003)	(0.000)	(0.001)	(0.003)
Panel B: 2SLS	(1)	(2)	(3)	(4)	(5)
Network Connection (=1)	0.072**	0.011	0.002	0.001	0.014
	(0.032)	(0.012)	(0.002)	(0.002)	(0.013)
Municipality FE	Yes	Yes	Yes	Yes	Yes
Region FE×Year FE	Yes	Yes	Yes	Yes	Yes
Local Geography×Year FE	Yes	Yes	Yes	Yes	Yes
Pre-Rail Controls×Year FE	Yes	Yes	Yes	Yes	Yes
First-Stage F-stat	26.48	26.48	26.48	26.48	26.48
Observations	18152	18152	18152	18152	18152
Mean dep. var.	0.006	0.002	0.000	0.000	0.002

Notes: OLS and 2SLS regressions. The table displays the effect of an indicator for network access (within 5 km) on transfers per 1,000 inhabitants by category. Independent (I)– Firm (F) refers to transfers from an independent inventor to a firm (column 1). The other combinations (columns 2–5) are either (I)– (I), (F)– (F), (F)– (I) or all three combined. Numbers of inhabitants are from 1865. Local geography controls include: the mean slope, the mean elevation as well as the standard deviation of the elevation, the area, and the mean cost of construction based on the land cover and slope data (all in logs). Pre-rail controls include: log population in 1865, the log distance to the nearest town, an indicator for whether a municipality had any granted patent prior to 1860 or not, the number of manufacturing firms per capita and the share of manufacturing workers in 1865, the latitude and longitude of the municipality centroid as well as region fixed effects. Numbers of inhabitants and workers are from 1865. Standard errors are given in parentheses and are clustered at the municipality level. *** - $p < 0.01$, ** - $p < 0.05$, * - $p < 0.1$.

Appendix to Making a Market: Infrastructure, Integration, and the Rise of Innovation

A Robustness

A.1 Specification checks

Table A.2: Specification check of instrumented variable - Distance to railroads

Dependent variable:	Any patent	Patents per capita	Inventors per capita	Patents per inventor	Technical proximity (fields)	Any transfer	Transfers per capita		
							All	Indp–Firm	Non-exist. industry
Panel A: OLS	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Network Connection (=1)	0.085***	0.319***	0.178***	0.150***	0.024***	0.020***	0.030***	0.021***	0.022***
	(0.010)	(0.066)	(0.033)	(0.020)	(0.003)	(0.004)	(0.008)	(0.006)	(0.007)
Panel B: 2SLS	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Network Connection (=1)	0.159***	0.751***	0.489***	0.228**	0.064***	0.044**	0.087**	0.072**	0.086**
	(0.054)	(0.234)	(0.130)	(0.102)	(0.017)	(0.021)	(0.041)	(0.032)	(0.038)
Municipality FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Region FE×Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Local Geography×Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Pre-Rail Controls×Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
First-Stage F-stat	26.48	26.48	26.48	26.48	26.48	26.48	26.48	26.48	26.48
Observations	18152	18152	18152	18152	18152	18152	18152	18152	18152
Mean dep. var.	0.056	0.115	0.073	0.083	0.014	0.008	0.009	0.006	0.007

Notes: OLS and 2SLS regressions. The table displays the effect of the log distance to a railroad on our main outcomes. Local geography controls include: the mean slope, the mean elevation as well as the standard deviation of the elevation, the area, and the mean cost of construction based on the land cover and slope data (all in logs). Pre-rail controls include: log population in 1865, the log distance to the nearest town, an indicator for whether a municipality had any granted patent prior to 1860 or not, the number of manufacturing firms per capita and the share of manufacturing workers in 1865, the latitude and longitude of the municipality centroid as well as region fixed effects. Number of inhabitants is from 1865. Standard errors are given in parentheses and are clustered at the municipality level. *** - $p < 0.01$, ** - $p < 0.05$, * - $p < 0.1$.

Table A.3: Specification check of main outcome variables - the natural logarithm

Dependent variable:	Patents	Inventors			Transfers			
		All	Independent	Firm	All	Connected	I–F	Non-exist.
Panel A: OLS	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Network Connection (=1)	0.121***	0.096***	0.092***	0.008***	0.020***	0.016***	0.014***	0.016***
	(0.014)	(0.011)	(0.011)	(0.003)	(0.005)	(0.004)	(0.004)	(0.004)
Panel B: 2SLS	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Network Connection (=1)	0.284***	0.242***	0.241***	0.025	0.055**	0.044**	0.045**	0.061**
	(0.083)	(0.067)	(0.066)	(0.015)	(0.025)	(0.019)	(0.021)	(0.025)
Municipality FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Region FE×Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Local Geography×Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Pre-Rail Controls×Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
First-Stage F-stat	26.48	26.48	26.48	26.48	26.48	26.48	26.48	26.48
Observations	18152	18152	18152	18152	18152	18152	18152	18152
Mean dep. var.	0.066	0.056	0.053	0.004	0.007	0.005	0.005	0.006

Notes: OLS and 2SLS regressions. The table displays the effect of an indicator for network access (within 5 km) on the natural logarithm of patents (column 1), inventors by category (columns 2–4) and transfers by category (columns 5–8). We add 1 to the number of patents/transfers before taking the log. Local geography controls include: the mean slope, the mean elevation as well as the standard deviation of the elevation, the area, and the mean cost of construction based on the land cover and slope data (all in logs). Pre-rail controls include: log population in 1865, the log distance to the nearest town, an indicator for whether a municipality had any granted patent prior to 1860 or not, the number of manufacturing firms per capita and the share of manufacturing workers in 1865, the latitude and longitude of the municipality centroid as well as region fixed effects. Number of inhabitants is from 1865. Standard errors are given in parentheses and are clustered at the municipality level. *** - $p < 0.01$, ** - $p < 0.05$, * - $p < 0.1$.

TABLE A.4: SPECIFICATION CHECK OF MAIN OUTCOME VARIABLES - THE INVERSE HYPERBOLIC SINE

Dependent variable:	Patents	Inventors			Transfers			
		All	Independent	Firm	All	Connected	I–F	Non-exist.
Panel A: OLS	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Network Connection (=1)	0.154***	0.123***	0.118***	0.010***	0.026***	0.021***	0.018***	0.021***
	(0.018)	(0.014)	(0.014)	(0.003)	(0.006)	(0.005)	(0.005)	(0.006)
Panel B: 2SLS	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Network Connection (=1)	0.358***	0.311***	0.309***	0.031	0.071**	0.056**	0.058**	0.078**
	(0.105)	(0.086)	(0.084)	(0.020)	(0.032)	(0.025)	(0.027)	(0.031)
Municipality FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Region FE×Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Local Geography×Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Pre-Rail Controls×Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
First-Stage F-stat	26.48	26.48	26.48	26.48	26.48	26.48	26.48	26.48
Observations	18152	18152	18152	18152	18152	18152	18152	18152
Mean dep. var.	0.084	0.071	0.069	0.005	0.010	0.006	0.006	0.008

Notes: OLS and 2SLS regressions. The table displays the effect of an indicator for network access (within 5 km) on the inverse hyperbolic sine of patents (column 1), inventors by category (columns 2–4) and transfers by category (columns 5–8). We add 1 to the number of patents/transfers before taking the log. Local geography controls include: the mean slope, the mean elevation as well as the standard deviation of the elevation, the area, and the mean cost of construction based on the land cover and slope data (all in logs). Pre-rail controls include: log population in 1865, the log distance to the nearest town, an indicator for whether a municipality had any granted patent prior to 1860 or not, the number of manufacturing firms per capita and the share of manufacturing workers in 1865, the latitude and longitude of the municipality centroid as well as region fixed effects. Number of inhabitants is from 1865. Standard errors are given in parentheses and are clustered at the municipality level. *** - $p < 0.01$, ** - $p < 0.05$, * - $p < 0.1$.

A.2 Standard errors

Table A.5: Alternative standard errors

Dependent variable:	Any patent	Patents per capita	Inventors per capita	Patents per inventor	Technical proximity (fields)	Any transfer	Transfers per capita		
							All	Indp–Firm	Non-exist. industry
Panel A: Robust	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Network Connection (=1)	(0.042)***	(0.179)***	(0.098)***	(0.080)***	(0.014)***	(0.019)**	(0.031)***	(0.026)***	(0.029)***
Panel B: Cluster by municipality †	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Network Connection (=1)	(0.054)***	(0.235)***	(0.131)***	(0.102)**	(0.017)***	(0.021)**	(0.041)**	(0.032)**	(0.038)**
Panel C: Bootstrap (robust)	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Network Connection (=1)	(0.061)***	(0.243)***	(0.124)***	(0.114)**	(0.020)***	(0.024)*	(0.042)**	(0.033)**	(0.040)**
Panel D: Bootstrap (cluster by municip.)	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Network Connection (=1)	(0.059)***	(0.252)***	(0.140)***	(0.106)**	(0.018)***	(0.023)*	(0.042)**	(0.033)**	(0.040)**
Municipality FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Region FE×Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Local Geography×Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Pre-Rail Controls×Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Notes: This table displays various standard errors of the coefficient of network connection on our main outcome variables. Bootstrapped standard errors are obtained using 1,000 draws with replacement. The † denotes our standard specification. *** - $p < 0.01$, ** - $p < 0.05$, * - $p < 0.1$.

Table A.6: Reduced Form Results with Standard Errors Robust to Spatial Correlation

Dependent variable:	Any patent	Patents per capita	Inventors per capita	Patents per inventor	Technical proximity (fields)	Any transfer	Transfers per capita		
							All	Indp–Firm	Non-exist. industry
Panel A: Spatial corr. 50 km									
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
ln(Dist. Least-Cost Path)×1870	(0.003)	(0.011)	(0.005)	(0.004)	(0.001)	(0.001)	(0.002)	(0.001)	(0.002)
ln(Dist. Least-Cost Path)×1880	(0.004)	(0.011)	(0.005)*	(0.009)	(0.001)**	(0.002)	(0.002)	(0.001)	(0.001)
ln(Dist. Least-Cost Path)×1890	(0.006)***	(0.015)***	(0.010)***	(0.008)**	(0.002)***	(0.002)	(0.004)	(0.003)	(0.004)
ln(Dist. Least-Cost Path)×1900	(0.007)***	(0.048)***	(0.023)***	(0.015)**	(0.003)***	(0.004)***	(0.007)***	(0.006)***	(0.007)***
Panel C: Spatial corr. 100 km									
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
ln(Dist. Least-Cost Path)×1870	(0.003)	(0.010)	(0.006)	(0.004)	(0.001)	(0.001)	(0.002)	(0.001)	(0.001)
ln(Dist. Least-Cost Path)×1880	(0.004)	(0.010)	(0.005)*	(0.009)	(0.001)**	(0.002)	(0.002)	(0.002)	(0.001)
ln(Dist. Least-Cost Path)×1890	(0.006)***	(0.015)***	(0.010)***	(0.008)**	(0.003)***	(0.003)	(0.003)	(0.003)	(0.003)
ln(Dist. Least-Cost Path)×1900	(0.006)***	(0.047)***	(0.024)***	(0.014)**	(0.003)***	(0.005)**	(0.007)***	(0.006)***	(0.007)***
Panel C: Spatial corr. 200 km									
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
ln(Dist. Least-Cost Path)×1870	(0.003)	(0.011)	(0.006)	(0.004)	(0.001)	(0.001)	(0.002)	(0.001)	(0.001)
ln(Dist. Least-Cost Path)×1880	(0.004)	(0.011)	(0.005)*	(0.007)	(0.001)**	(0.002)	(0.002)	(0.002)	(0.001)
ln(Dist. Least-Cost Path)×1890	(0.007)**	(0.015)***	(0.011)***	(0.009)**	(0.003)**	(0.003)	(0.003)	(0.002)*	(0.003)*
ln(Dist. Least-Cost Path)×1900	(0.006)***	(0.053)***	(0.026)***	(0.014)**	(0.003)***	(0.005)**	(0.009)**	(0.007)**	(0.008)**
Municipality FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Region FE×Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Local Geography×Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Pre-Rail Controls×Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Notes: This table displays standard errors robust to spatial correlation up till 50 km in panel A, 100 km in panel B, and 200 km in panel C. *** - $p < 0.01$, ** - $p < 0.05$, * - $p < 0.1$.

A.3 Municipality samples

Table A.7: Extending the sample to include urban municipalities

Dependent variable:	Any patent		Patents per capita		Inventors per capita		Patents per inventor		Technical proximity		Any transfer		Transfers per capita					
													All		I–F		Non-exist. industry	
Panel A: OLS	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)
Network Connection (=1)	0.085***	0.086***	0.312***	0.321***	0.178***	0.176***	0.150***	0.153***	0.024***	0.023***	0.020***	0.019***	0.029***	0.030***	0.022***	0.023***	0.021***	0.023***
	(0.009)	(0.010)	(0.067)	(0.069)	(0.033)	(0.034)	(0.020)	(0.020)	(0.003)	(0.003)	(0.005)	(0.004)	(0.008)	(0.008)	(0.006)	(0.006)	(0.007)	(0.007)
Network Con.(=1)×Urban		-0.019		-0.188		0.042		-0.054		0.020		0.031		-0.030		-0.021		-0.056
		(0.049)		(0.351)		(0.179)		(0.100)		(0.021)		(0.037)		(0.046)		(0.039)		(0.045)
Panel B: 2SLS	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)
Network Connection (=1)	0.153***	0.156***	0.731**	0.719***	0.459***	0.453***	0.150	0.166	0.068***	0.065***	0.021	0.028	0.063	0.069*	0.055*	0.063*	0.059	0.066*
	(0.053)	(0.053)	(0.294)	(0.268)	(0.152)	(0.147)	(0.114)	(0.112)	(0.018)	(0.017)	(0.025)	(0.025)	(0.041)	(0.042)	(0.032)	(0.033)	(0.038)	(0.039)
Network Con.(=1)×Urban		0.010		0.203		0.203		-0.812		0.036		-0.208		-0.087		-0.078		-0.084
		(0.225)		(1.131)		(0.618)		(0.605)		(0.074)		(0.186)		(0.091)		(0.060)		(0.071)
Municipality FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Region FE×Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Local Geography×Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Pre-Rail Controls×Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
First-Stage F-stat	28.47	12.12	28.47	12.12	28.47	12.12	28.47	12.12	28.47	12.12	28.47	12.12	28.47	12.12	28.47	12.12	28.47	12.12
Observations	19056	19056	19056	19056	19056	19056	19056	19056	19056	19056	19056	19056	19056	19056	19056	19056	19056	19056
Mean dep. var.	0.069	0.069	0.152	0.152	0.097	0.097	0.103	0.103	0.019	0.019	0.012	0.012	0.011	0.011	0.007	0.007	0.009	0.009

Notes: OLS and 2SLS regressions. The table displays the effect of an indicator for network access (within 5 km) and its interaction with an indicator for if a municipality is urban on our main outcomes using an extended sample including urban municipalities. Local geography controls include: the mean slope, the mean elevation as well as the standard deviation of the elevation, the area, and the mean cost of construction based on the land cover and slope data (all in logs). Pre-rail controls include: log population in 1865, the log distance to the nearest town, an indicator for whether a municipality had any granted patent prior to 1860 or not, the number of manufacturing firms per capita and the share of manufacturing workers in 1865, the latitude and longitude of the municipality centroid as well as region fixed effects. Number of inhabitants is from 1865. Standard errors are given in parentheses and are clustered at the municipality level. *** - $p < 0.01$, ** - $p < 0.05$, * - $p < 0.1$.

A.4 Railroad-related patents

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Table A.8: DiD estimates - Rail and Non-Rail Patents

Dependent variable:	Any patent		Patents per capita	
	Rail	Non-rail	Rail	Non-rail
Panel A: OLS				
	(1)	(2)	(3)	(4)
Network Connection (=1)	0.011***	0.081***	0.009***	0.410***
	(0.003)	(0.009)	(0.002)	(0.073)
Panel B: 2SLS				
	(1)	(2)	(3)	(4)
Network Connection (=1)	0.032*	0.151***	0.025*	0.726***
	(0.017)	(0.053)	(0.014)	(0.228)
Municipality FE	Yes	Yes	Yes	Yes
Region FE×Year FE	Yes	Yes	Yes	Yes
Local Geography×Year FE	Yes	Yes	Yes	Yes
Pre-Rail Controls×Year FE	Yes	Yes	Yes	Yes
First-Stage F-stat	26	26	26	26
Observations	18152	18152	18152	18152
Mean dep. var.	0.00	0.06	0.00	0.11

Notes: OLS and 2SLS regressions. The table displays the effect of an indicator for network access (within 5 km) on whether a municipality has any patent (column 1–2) and the number of patents per 1,000 inhabitants (columns 3–4), both by different categories. "(Non-)Rail" refers to a (non-)railroad-related patent. Local geography controls include: the mean slope, the mean elevation as well as the standard deviation of the elevation, the area, and the mean cost of construction based on the land cover and slope data (all in logs). Pre-rail controls include: log population in 1865, the log distance to the nearest town, an indicator for whether a municipality had any granted patent prior to 1860 or not, the number of manufacturing firms per capita and the share of manufacturing workers in 1865, the latitude and longitude of the municipality centroid as well as region fixed effects. Number of inhabitants is from 1865. Standard errors are given in parentheses and are clustered at the municipality level. *** - $p < 0.01$, ** - $p < 0.05$, * - $p < 0.1$.

A.5 Alternative forms of IP protection

Table A.9: DiD estimates - Patents with More/Less Effective Non-Patent Protection

Dependent variable:	Any patent		Patents per capita	
	Secrecy	Non-Secrecy	Secrecy	Non-Secrecy
Panel A: OLS				
	(1)	(2)	(3)	(4)
Network Connection (=1)	0.052^{***}	0.041^{***}	0.099^{***}	0.108^{***}
	(0.007)	(0.007)	(0.024)	(0.031)
Panel B: 2SLS	(1)	(2)	(3)	(4)
Network Connection (=1)	0.118^{***}	0.087^{**}	0.261^{***}	0.174^{*}
	(0.039)	(0.041)	(0.097)	(0.094)
Municipality FE	Yes	Yes	Yes	Yes
Region FE×Year FE	Yes	Yes	Yes	Yes
Local Geography×Year FE	Yes	Yes	Yes	Yes
Pre-Rail Controls×Year FE	Yes	Yes	Yes	Yes
First-Stage F-stat	26.48	26.48	26.48	26.48
Observations	18152	18152	18152	18152
Mean dep. var.	0.026	0.024	0.035	0.035

Notes: OLS and 2SLS regressions. The table displays the effect of an indicator for network access (within 5 km) on whether a municipality has any patent (column 1–2) and the number of patents per 1,000 inhabitants (columns 3–4), both by different categories. (Non-)Secrecy refers to patents within industries where alternative forms of protection was most (least) important based on the data supplied by Moser (2005). Local geography controls include: the mean slope, the mean elevation as well as the standard deviation of the elevation, the area, and the mean cost of construction based on the land cover and slope data (all in logs). Pre-rail controls include: log population in 1865, the log distance to the nearest town, an indicator for whether a municipality had any granted patent prior to 1860 or not, the number of manufacturing firms per capita and the share of manufacturing workers in 1865, the latitude and longitude of the municipality centroid as well as region fixed effects. Number of inhabitants is from 1865. Standard errors are given in parentheses and are clustered at the municipality level. *** - $p < 0.01$, ** - $p < 0.05$, * - $p < 0.1$.

A.6 Alternative instrument and placebo test

Table A.10: Alternative Instrument - The Ericson Plan

Dependent variable:	Any patent	Patents per capita	Inventors per capita	Patents per inventor	Technical proximity (fields)	Any transfer	Transfers per capita		
							All	Indp–Firm	Non-exist. industry
Panel A: OLS	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Network Connection (=1)	0.085***	0.319***	0.178***	0.150***	0.024***	0.020***	0.030***	0.021***	0.022***
	(0.010)	(0.066)	(0.033)	(0.020)	(0.003)	(0.004)	(0.008)	(0.006)	(0.007)
Panel B: 2SLS	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Network Connection (=1)	0.113***	0.433***	0.254***	0.198***	0.040***	0.018*	0.041	0.033*	0.043*
	(0.032)	(0.145)	(0.081)	(0.060)	(0.011)	(0.011)	(0.025)	(0.020)	(0.023)
Municipality FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Region FE×Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Local Geography×Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Pre-Rail Controls×Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
First-Stage F-stat	75.52	75.52	75.52	75.52	75.52	75.52	75.52	75.52	75.52
Observations	18152	18152	18152	18152	18152	18152	18152	18152	18152
Mean dep. var.	0.056	0.115	0.073	0.083	0.014	0.008	0.009	0.006	0.007

Notes: OLS and 2SLS regressions. The table displays the effect of an indicator for network access (within 5 km) on our main outcomes. The 2SLS regression uses the log distance to the Ericson plan interacted with the set of 4 decadel indicator variables as excluded instruments. Local geography controls include: the mean slope, the mean elevation as well as the standard deviation of the elevation, the area, and the mean cost of construction based on the land cover and slope data (all in logs). Pre-rail controls include: log population in 1865, the log distance to the nearest town, an indicator for whether a municipality had any granted patent prior to 1860 or not, the number of manufacturing firms per capita and the share of manufacturing workers in 1865, the latitude and longitude of the municipality centroid as well as region fixed effects. Number of inhabitants is from 1865. Standard errors are given in parentheses and are clustered at the municipality level. *** - $p < 0.01$, ** - $p < 0.05$, * - $p < 0.1$.

TABLE A.11: PLACEBO - NEVER REALIZED LINES A

Dependent variable:	Any patents					Patents per capita					Inventors per capita					Patents per inventor				
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)	(20)
Network Connection (=1)	0.085***	0.085***	0.085***	0.086***	0.086***	0.319***	0.318***	0.319***	0.319***	0.318***	0.178***	0.177***	0.179***	0.178***	0.178***	0.150***	0.149***	0.149***	0.150***	0.149***
	(0.010)	(0.010)	(0.010)	(0.010)	(0.010)	(0.066)	(0.066)	(0.066)	(0.066)	(0.066)	(0.033)	(0.033)	(0.033)	(0.033)	(0.033)	(0.020)	(0.020)	(0.020)	(0.020)	(0.020)
Placebo line (Ericson's proposal)		-0.028			-0.027		-0.141			-0.141		-0.071*			-0.070*		-0.073*			-0.073*
		(0.033)			(0.033)		(0.086)			(0.086)		(0.041)			(0.041)		(0.043)			(0.043)
Placebo line (1870 committee proposal)			0.013		0.013			0.018		0.017			0.066		0.066			-0.025		-0.026
			(0.044)		(0.044)			(0.072)		(0.072)			(0.074)		(0.074)			(0.046)		(0.046)
Placebo line (1870 municipality proposal)				0.105	0.105				-0.040	-0.041				-0.032	-0.032				0.102	0.101
				(0.103)	(0.103)				(0.053)	(0.053)				(0.037)	(0.037)				(0.091)	(0.091)
Municipality FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Region FE×Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Local Geography×Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Pre-Rail Controls×Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	18152	18152	18152	18152	18152	18152	18152	18152	18152	18152	18152	18152	18152	18152	18152	18152	18152	18152	18152	18152
Mean dep. var.	0.06	0.06	0.06	0.06	0.06	0.12	0.12	0.12	0.12	0.12	0.07	0.07	0.07	0.07	0.07	0.08	0.08	0.08	0.08	0.08

Notes: OLS regressions. The table displays the effect of an indicator for network access (within 5 km) on four main outcomes. Local geography controls include: the mean slope, the mean elevation as well as the standard deviation of the elevation, the area, and the mean cost of construction based on the land cover and slope data (all in logs). Pre-rail controls include: log population in 1865, the log distance to the nearest town, an indicator for whether a municipality had any granted patent prior to 1860 or not, the number of manufacturing firms per capita and the share of manufacturing workers in 1865, the latitude and longitude of the municipality centroid as well as region fixed effects. Number of inhabitants is from 1865. Standard errors are given in parentheses and are clustered at the municipality level. *** - $p < 0.01$, ** - $p < 0.05$, * - $p < 0.1$.

Table A.12: Placebo - Never Realized Lines B

Dependent variable:	Transfers per capita					Connected					Non-connected				
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)
Network Connection (=1)	0.030***	0.029***	0.030***	0.030***	0.029***	0.027***	0.027***	0.027***	0.027***	0.027***	0.001	0.001	0.001	0.001	0.001
	(0.008)	(0.008)	(0.008)	(0.008)	(0.008)	(0.007)	(0.007)	(0.007)	(0.007)	(0.007)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Placebo line (Ericson's proposal)		-0.016*			-0.016*		-0.013			-0.013		-0.001			-0.001
		(0.009)			(0.009)		(0.009)			(0.009)		(0.000)			(0.000)
Placebo line (1870 committee proposal)			0.002		0.002			-0.000		-0.000			0.000		0.000
			(0.006)		(0.006)			(0.005)		(0.005)			(0.001)		(0.001)
Placebo line (1870 municipality proposal)				-0.000	-0.000				0.001	0.001				0.001	0.001
				(0.007)	(0.007)				(0.007)	(0.007)				(0.001)	(0.001)
Municipality FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Region FE×Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Local Geography×Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Pre-Rail Controls×Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	18152	18152	18152	18152	18152	18152	18152	18152	18152	18152	18152	18152	18152	18152	18152
Mean dep. var.	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00

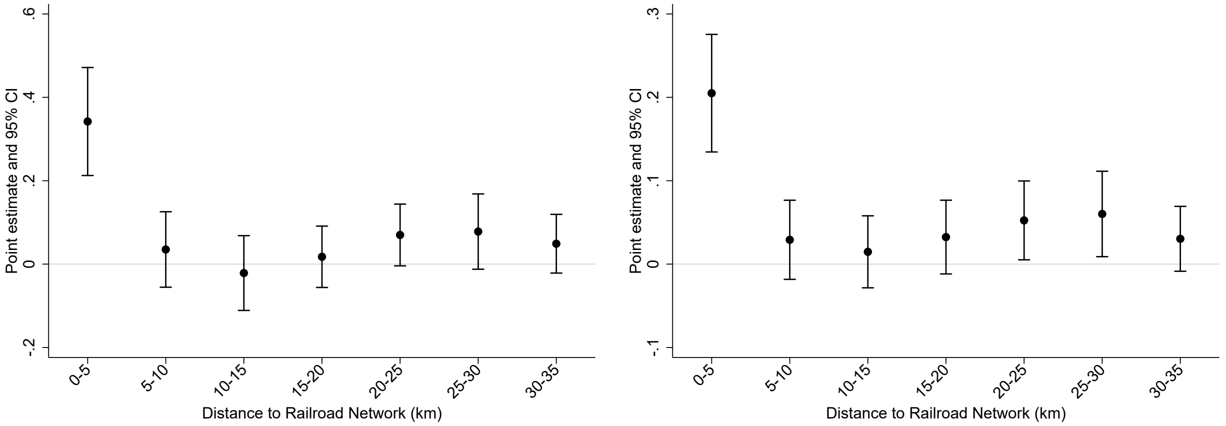
Notes: OLS regressions. The table displays the effect of an indicator for network access (within 5 km) on three main outcomes. Local geography controls include: the mean slope, the mean elevation as well as the standard deviation of the elevation, the area, and the mean cost of construction based on the land cover and slope data (all in logs). Pre-rail controls include: log population in 1865, the log distance to the nearest town, an indicator for whether a municipality had any granted patent prior to 1860 or not, the number of manufacturing firms per capita and the share of manufacturing workers in 1865, the latitude and longitude of the municipality centroid as well as region fixed effects. Number of inhabitants is from 1865. Standard errors are given in parentheses and are clustered at the municipality level. *** - $p < 0.01$, ** - $p < 0.05$, * - $p < 0.1$.

A.7 Reallocation

Table A.13: Main results controlling for spatial reallocation

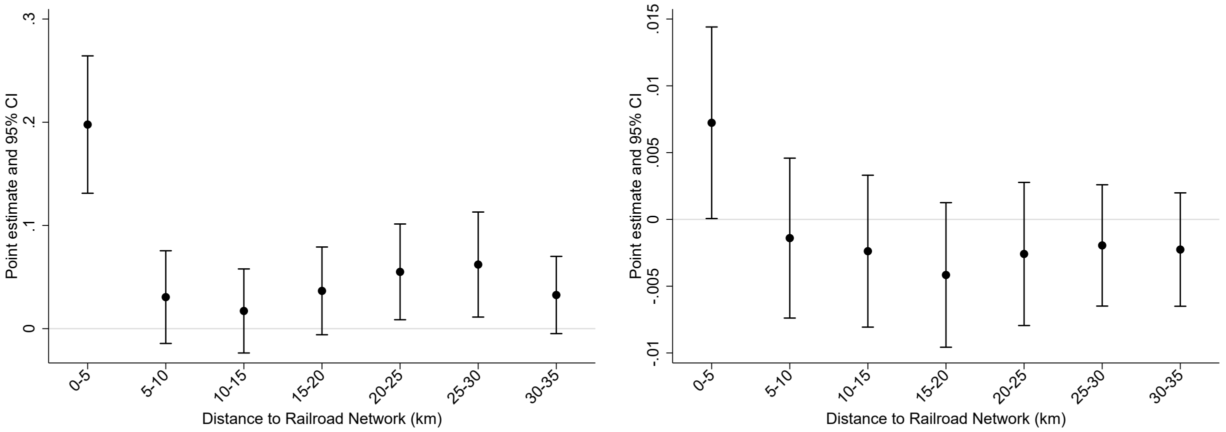
Dependent variable:	Any patent	Patents per capita	Inventors per capita			Patents per inventor		
			All	Independent	Firm	All	Independent	Firm
Panel A: OLS	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Network Connection (=1)	0.084***	0.322***	0.169***	0.160***	0.009***	0.153***	0.148***	0.023**
	(0.010)	(0.073)	(0.033)	(0.032)	(0.003)	(0.022)	(0.022)	(0.009)
Spatial Network Connections	0.033	-0.105	0.414	0.390	0.024	-0.127	-0.158	0.047
	(0.115)	(0.638)	(0.346)	(0.329)	(0.027)	(0.254)	(0.251)	(0.106)
Panel B: 2SLS	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Network Connection (=1)	0.121**	0.716***	0.350**	0.334**	0.015	0.189*	0.208**	0.062
	(0.057)	(0.271)	(0.149)	(0.140)	(0.019)	(0.105)	(0.105)	(0.038)
Spatial Network Connections	0.109	-0.388	0.860	0.860	-0.001	0.029	0.015	0.005
	(0.216)	(1.293)	(0.802)	(0.744)	(0.089)	(0.417)	(0.410)	(0.204)
Municipality FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Region FE×Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Local Geography×Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Pre-Rail Controls×Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
First-Stage F-stat	10.94	10.94	10.94	10.94	10.94	10.94	10.94	10.94
Observations	18152	18152	18152	18152	18152	18152	18152	18152
Mean dep. var.	0.056	0.115	0.073	0.070	0.003	0.083	0.081	0.010

Notes: OLS and 2SLS regressions. The table displays the effect of an indicator for network access (within 5 km) and its interaction with a measure of spatial network connection on whether a municipality has any patent (column 1), the number of patents per 1,000 inhabitants (columns 2), inventors per capita by legal category (columns 3–5), and patents per inventor by legal category (columns 6–8). Numbers of inhabitants are from 1865. Local geography controls include: the mean slope, the mean elevation as well as the standard deviation of the elevation, the area, and the mean cost of construction based on the land cover and slope data (all in logs). Pre-rail controls include: log population in 1865, the log distance to the nearest town, an indicator for whether a municipality had any granted patent prior to 1860 or not, the number of manufacturing firms per capita and the share of manufacturing workers in 1865, the latitude and longitude of the municipality centroid as well as region fixed effects. Number of inhabitants is from 1865. Standard errors are given in parentheses and are clustered at the municipality level. *** - $p < 0.01$, ** - $p < 0.05$, * - $p < 0.1$.



(A) Patents per capita

(B) Inventors per capita

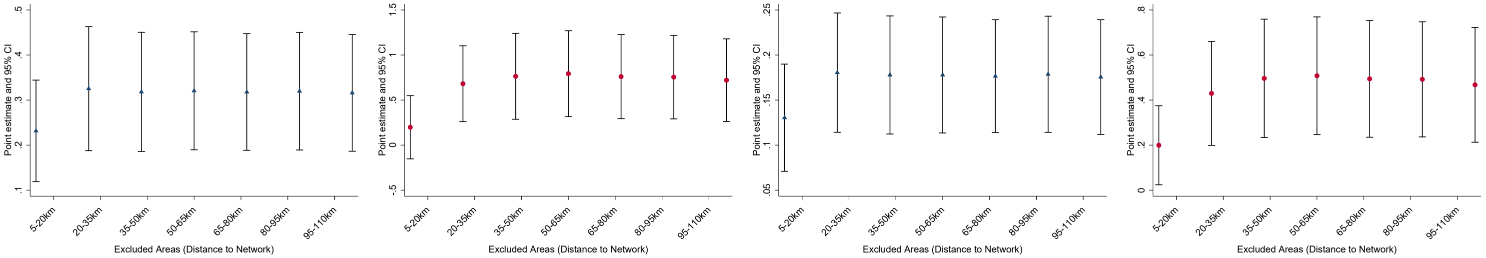


(C) Independent inventors per capita

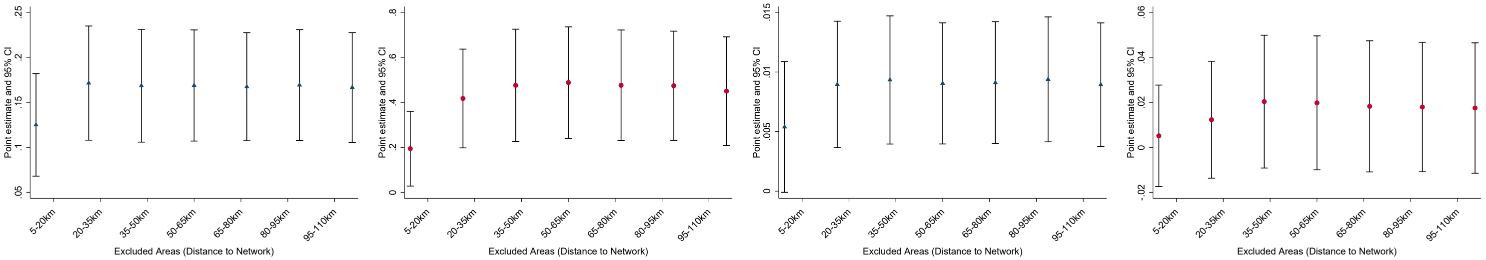
(D) Firm inventors per capita

Figure A.2:
Spatial reallocation of innovation – Flexible distances

Notes: OLS regressions. The figures display estimates of a modified version of equation (2) where we include separate dummy variables for 5 km bins of distance to the railroad network in each decade on our outcomes: the number of patents per capita (A), the number of inventors per capita (B), the number of independent inventors per capita (C), and the number of firm inventors per capita (D). All regressions include local geography-by-year controls, pre-rail-by-year controls, municipality fixed effects and region-by-year fixed effects. Local geography controls include: the mean slope, the mean elevation as well as the standard deviation of the elevation, the area, and the mean cost of construction based on the land cover and slope data (all in logs). Pre-rail controls include: log population in 1865, the log distance to the nearest town, an indicator for whether a municipality had any granted patent prior to 1860 or not, the number of manufacturing firms per capita and the share of manufacturing workers in 1865, the latitude and longitude of the municipality centroid as well as region fixed effects. Standard errors are clustered at the municipality level.



(a) Patents p.c. (OLS) (b) Patents p.c. (2SLS) (c) Inventors p.c. (OLS) (d) Inventors p.c. (2SLS)



(e) Ind. inv. p.c. (OLS) (f) Ind. inv. p.c. (2SLS) (g) Firm inv. p.c. (OLS) (h) Firm inv. p.c. (2SLS)

Figure A.3:
Spatial reallocation – Dropping municipalities within distance windows

Notes: OLS and 2SLS regressions. The figures display coefficients for the effect of network access on the number of inventors and patents per capita. Each coefficient is a separate regression, where municipalities within a specified distance from the railroad network has been omitted. All regressions include local geography-by-year controls, pre-rail-by-year controls, municipality fixed effects and region-by-year fixed effects. Local geography controls include: the mean slope, the mean elevation as well as the standard deviation of the elevation, the area, and the mean cost of construction based on the land cover and slope data (all in logs). Pre-rail controls include: log population in 1865, the log distance to the nearest town, an indicator for whether a municipality had any granted patent prior to 1860 or not, the number of manufacturing firms per capita and the share of manufacturing workers in 1865, the latitude and longitude of the municipality centroid as well as region fixed effects. Standard errors are clustered at the municipality level.

A.8 Additional robustness checks

Table A.14: Main results with and without local economic controls

Dependent variable:	Any patent		Patents per capita		Inventors per capita		Patents per inventor		Technical proximity		Any transfer		Transfers per capita					
													All		I–F		Non-exist. industry	
Panel A: OLS	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)
Network Connection (=1)	0.094***	0.085***	0.332***	0.319***	0.182***	0.178***	0.168***	0.150***	0.026***	0.024***	0.022***	0.020***	0.031***	0.030***	0.023***	0.021***	0.022***	0.022***
	(0.010)	(0.010)	(0.068)	(0.066)	(0.034)	(0.033)	(0.021)	(0.020)	(0.003)	(0.003)	(0.004)	(0.004)	(0.007)	(0.008)	(0.006)	(0.006)	(0.006)	(0.007)
Panel B: 2SLS	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)
Network Connection (=1)	0.177***	0.159***	0.758***	0.751***	0.471***	0.489***	0.269***	0.228**	0.069***	0.064***	0.050**	0.044**	0.086**	0.087**	0.072**	0.072**	0.084**	0.086**
	(0.049)	(0.054)	(0.218)	(0.234)	(0.122)	(0.130)	(0.094)	(0.102)	(0.016)	(0.017)	(0.020)	(0.021)	(0.036)	(0.041)	(0.029)	(0.032)	(0.034)	(0.038)
Municipality FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Region FE×Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Local Geography×Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Pre-Rail Controls×Year FE	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes
First-Stage F-stat	30.49	26.48	30.49	26.48	30.49	26.48	30.49	26.48	30.49	26.48	30.49	26.48	30.49	26.48	30.49	26.48	30.49	26.48
Observations	18152	18152	18152	18152	18152	18152	18152	18152	18152	18152	18152	18152	18152	18152	18152	18152	18152	18152
Mean dep. var.	0.056	0.056	0.115	0.115	0.073	0.073	0.083	0.083	0.014	0.014	0.008	0.008	0.009	0.009	0.006	0.006	0.007	0.007

Notes: OLS and 2SLS regressions. The table displays the effect of an indicator for network access (within 5 km) on our main outcomes. Local geography controls include: the mean slope, the mean elevation as well as the standard deviation of the elevation, the area, and the mean cost of construction based on the land cover and slope data (all in logs). Pre-rail controls include: log population in 1865, the log distance to the nearest town, an indicator for whether a municipality had any granted patent prior to 1860 or not, the number of manufacturing firms per capita and the share of manufacturing workers in 1865, the latitude and longitude of the municipality centroid as well as region fixed effects. Number of inhabitants is from 1865. Standard errors are given in parentheses and are clustered at the municipality level. *** - $p < 0.01$, ** - $p < 0.05$, * - $p < 0.1$.

B Additional material

B.1 Figures

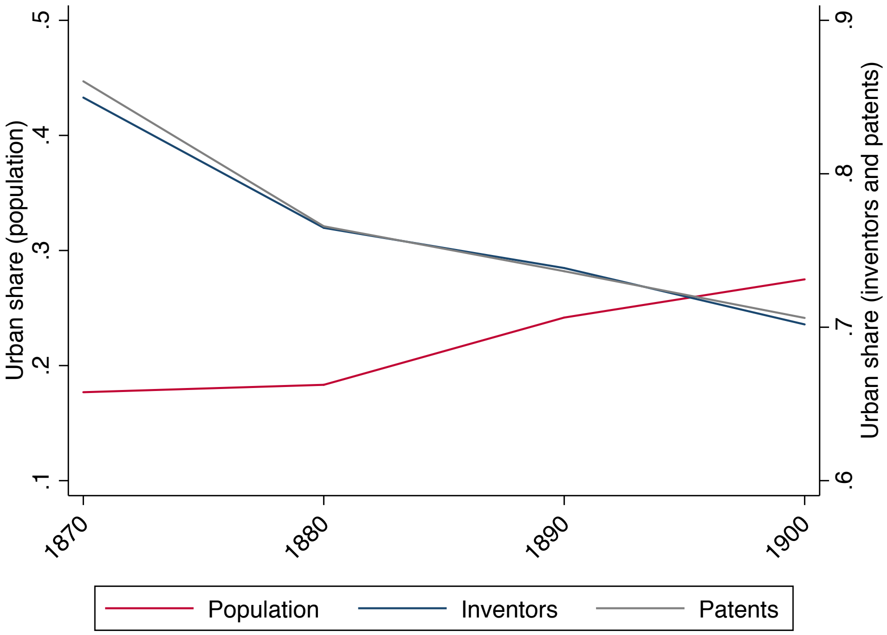
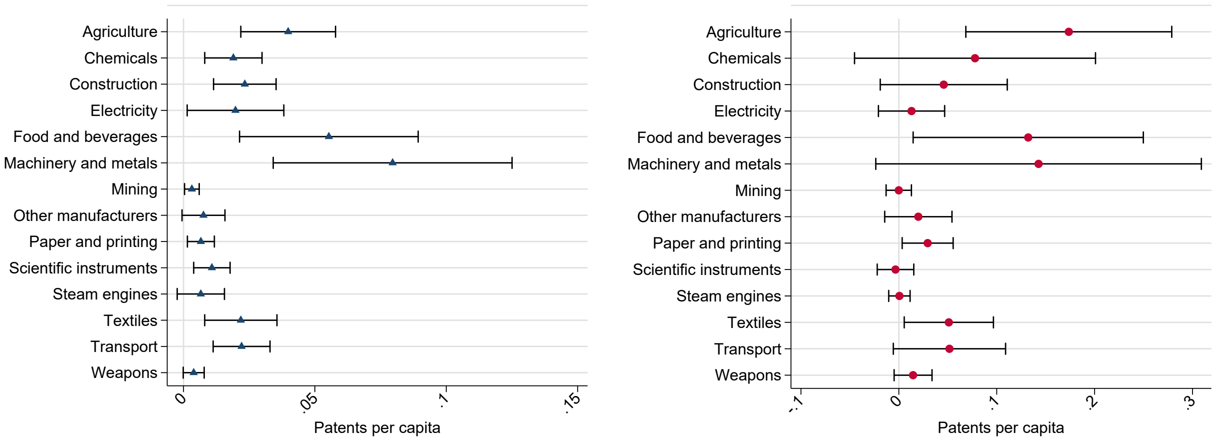


Figure B.1:
Share of innovation and population in urban areas.

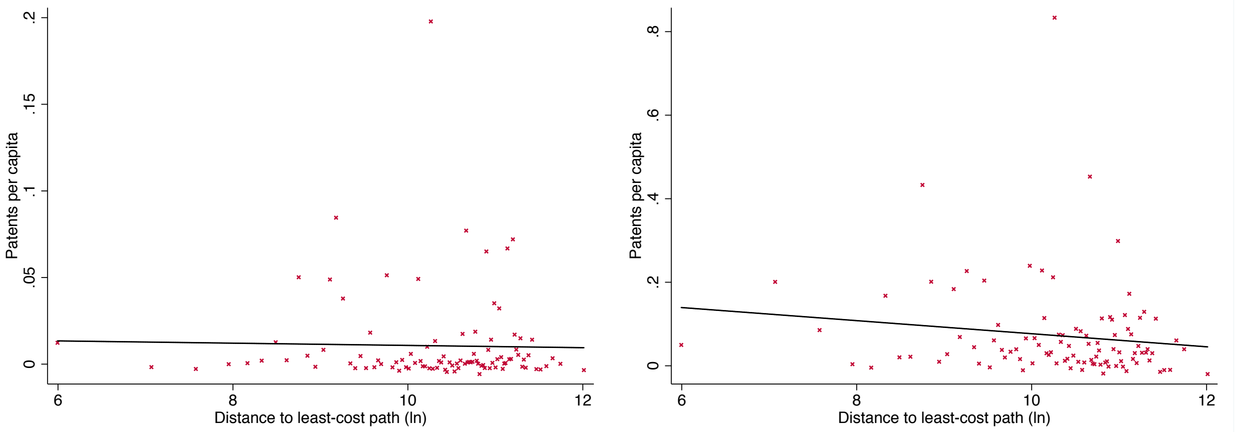
Notes: This figure displays the share of inventors, patents, and population in urban locations.



(a) OLS (b) 2SLS

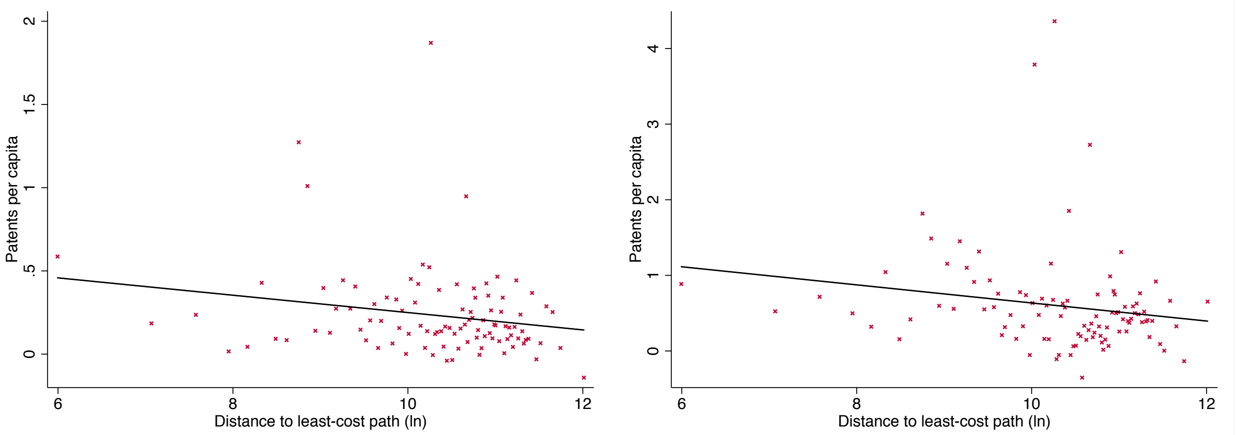
Figure B.1:
Effect of network connection on innovative activity across industries

Notes: OLS and 2SLS regressions. The figures display coefficients for the effect of network access on the number of patents related to different industrial sectors per 1,000 inhabitants. Each coefficient is a separate regression. OLS estimates are displayed in A. 2SLS estimates using the LCP instrument are displayed in B. Standard errors are clustered at the municipality level and bars denote 95% CIs. All regressions include local geography-by-year controls, pre-rail-by-year controls, municipality fixed effects and region-by-year fixed effects. Local geography controls include: the mean slope, the mean elevation as well as the standard deviation of the elevation, the area, and the mean cost of construction based on the land cover and slope data (all in logs). Pre-rail controls include: log population in 1865, the log distance to the nearest town, an indicator for whether a municipality had any granted patent prior to 1860 or not, the number of manufacturing firms per capita and the share of manufacturing workers in 1865, the latitude and longitude of the municipality centroid as well as region fixed effects.



(A) Least-Cost Path 1870

(B) Least-Cost Path 1880



(C) Least-Cost Path 1890

(D) Least-Cost Path 1900

Figure B.1:
Reduced From Relationship - Patents and Instruments

Notes: The figures display the non-parametric relationship between the number of patents per 1,000 inhabitants and our instrument by decade. All variables have been residualized using local geography and pre-rail covariates as well as region fixed effects. Local geography covariates include: the mean slope, the mean elevation as well as the standard deviation of the elevation, the area, and the mean cost of construction based on the land cover and slope data (all in logs). Pre-rail covariates include: log population in 1865, the log distance to the nearest town, an indicator for whether a municipality had any granted patent prior to 1860 or not, the number of manufacturing firms per capita and the share of manufacturing workers in 1865, the latitude and longitude of the municipality centroid. Observations are sorted into 100 groups of equal size and the dots indicate the mean value in each group. A linear regression line based on the underlying (ungrouped) data is also shown.

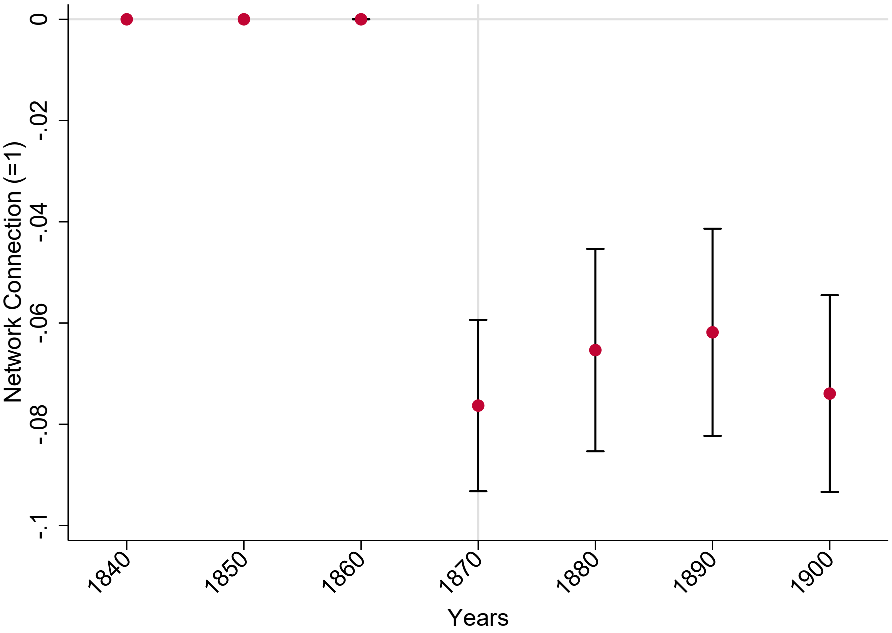
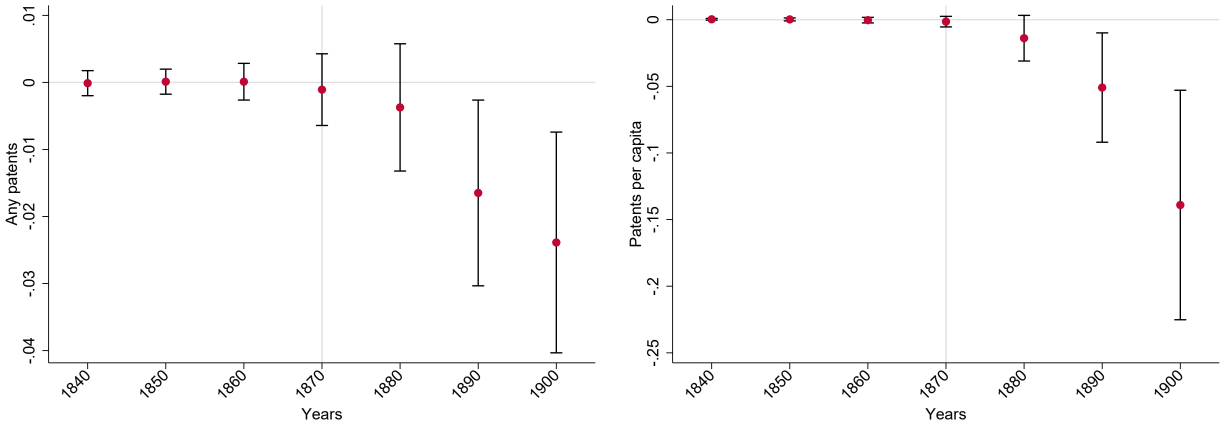


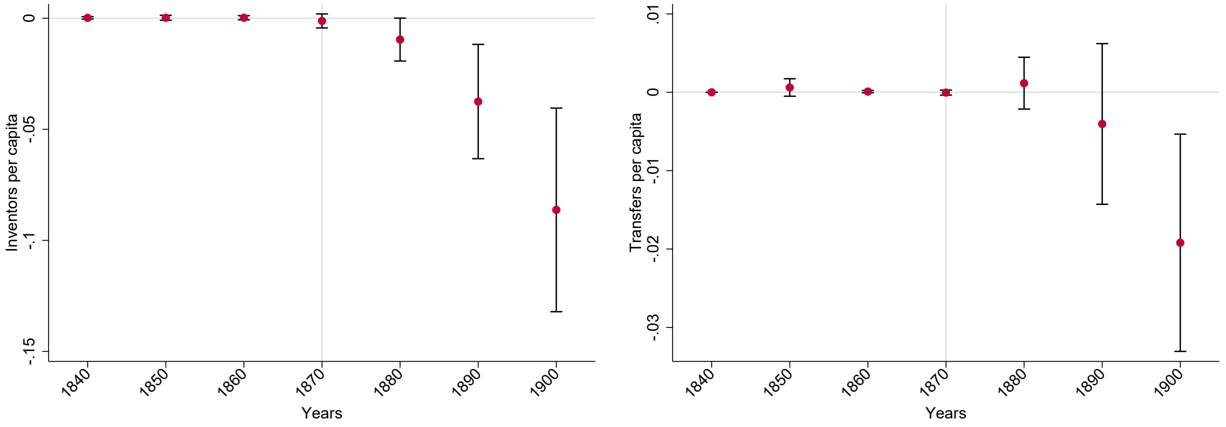
Figure B.1:
First-Stage Relationship by Decade

Notes: OLS regression. The figure displays coefficients for the effect of the log distance to the least-cost path interacted with indicators for each decade on network access. Standard errors are clustered at the municipality level and bars denote 95% CIs. All regressions include local geography-by-year controls, pre-rail-by-year controls, municipality fixed effects and region-by-year fixed effects. Local geography controls include: the mean slope, the mean elevation as well as the standard deviation of the elevation, the area, and the mean cost of construction based on the land cover and slope data (all in logs). Pre-rail controls include: log population in 1865, the log distance to the nearest town, an indicator for whether a municipality had any granted patent prior to 1860 or not, the number of manufacturing firms per capita and the share of manufacturing workers in 1865, the latitude and longitude of the municipality centroid as well as region fixed effects.



(A) Any patent

(B) Patents per capita



(C) Inventors per capita

(D) Transfers per capita

Figure B.1:
Reduced Form Relationships by Decade

Notes: OLS regressions. The figure displays coefficients for the effect of the log distance to the least-cost path interacted with indicators for each decade on a binary variable indicating whether a municipality has at least on patent in a given decade (A), the number of patents per 1,000 inhabitants (B), the number of inventors per 1,000 inhabitants (C), and the number of transfers per 1,000 inhabitants. Numbers of inhabitants are from 1865. Standard errors are clustered at the municipality level and bars denote 95% CIs. All regressions include local geography-by-year controls, pre-rail-by-year controls, municipality fixed effects and region-by-year fixed effects. Local geography controls include: the mean slope, the mean elevation as well as the standard deviation of the elevation, the area, and the mean cost of construction based on the land cover and slope data (all in logs). Pre-rail controls include: log population in 1865, the log distance to the nearest town, an indicator for whether a municipality had any granted patent prior to 1860 or not, the number of manufacturing firms per capita and the share of manufacturing workers in 1865, the latitude and longitude of the municipality centroid as well as region fixed effects.

B.2 Tables

Table B.2: Table presenting OLS estimates depicted in the figures (fixed network 1900)

Dependent variable:	Any patents	Patents per capita	Inventors per capita	Patents per inventor	Technical proximity	Transfers per capita
	(1)	(2)	(3)	(4)	(5)	(6)
Rail (5 km)×1840	0.002	0.000	-0.000	0.003	0.001	-0.000
	(0.001)	(0.001)	(0.001)	(0.002)	(0.001)	(.)
Rail (5 km)×1850	-0.002	0.001	0.001	-0.002	-0.000	0.001
	(0.001)	(0.001)	(0.001)	(0.001)	(0.000)	(0.001)
Rail (5 km)×1860	0.003	0.002	0.002	0.003	0.002	0.000
	(0.004)	(0.003)	(0.002)	(0.006)	(0.001)	(0.000)
Rail (5 km)×1870	0.018***	0.017***	0.010**	0.030***	0.004***	0.002
	(0.006)	(0.006)	(0.004)	(0.010)	(0.001)	(0.002)
Rail (5 km)×1880	0.054***	0.107***	0.060***	0.104***	0.011***	0.015***
	(0.011)	(0.027)	(0.014)	(0.020)	(0.003)	(0.005)
Rail (5 km)×1890	0.099***	0.267***	0.184***	0.158***	0.030***	0.028**
	(0.016)	(0.060)	(0.038)	(0.031)	(0.005)	(0.011)
Rail (5 km)×1900	0.140***	0.748***	0.382***	0.250***	0.042***	0.060***
	(0.018)	(0.156)	(0.068)	(0.043)	(0.006)	(0.022)
Municipality FE	Yes	Yes	Yes	Yes	Yes	Yes
Region FE×Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Local Geography×Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Pre-Rail Controls×Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	18152	18152	18152	18152	18152	18152
Mean dep. var.	0.06	0.12	0.07	0.08	0.01	0.01

Notes: OLS regressions. Local geography controls include: the mean slope, the mean elevation as well as the standard deviation of the elevation, the area, and the mean cost of construction based on the land cover and slope data (all in logs). Pre-rail controls include: log population in 1865, the log distance to the nearest town, an indicator for whether a municipality had any granted patent prior to 1860 or not, the number of manufacturing firms per capita and the share of manufacturing workers in 1865, the latitude and longitude of the municipality centroid as well as region fixed effects. Number of inhabitants is from 1865. Standard errors are given in parentheses and are clustered at the municipality level. *** - $p < 0.01$, ** - $p < 0.05$, * - $p < 0.1$.

Table B.3: Table presenting 2SLS estimates depicted in the figures (fixed network 1900)

Dependent variable:	Any patents	Patents per capita	Inventors per capita	Patents per inventor	Technical proximity	Transfers per capita
	(1)	(2)	(3)	(4)	(5)	(6)
Rail (5 km)×1840	0.002	-0.004	-0.002	-0.007	-0.004	-0.000
	(0.013)	(0.005)	(0.004)	(0.018)	(0.006)	(0.000)
Rail (5 km)×1850	-0.002	-0.003	-0.003	-0.002	-0.000	-0.008
	(0.013)	(0.008)	(0.008)	(0.013)	(0.001)	(0.008)
Rail (5 km)×1860	-0.001	0.005	-0.003	0.018	0.003	-0.001
	(0.019)	(0.014)	(0.007)	(0.041)	(0.006)	(0.001)
Rail (5 km)×1870	0.015	0.020	0.016	0.026	0.007	0.001
	(0.037)	(0.027)	(0.022)	(0.044)	(0.008)	(0.002)
Rail (5 km)×1880	0.050	0.188	0.130*	0.111	0.030	-0.016
	(0.064)	(0.117)	(0.066)	(0.141)	(0.018)	(0.023)
Rail (5 km)×1890	0.223**	0.689**	0.507***	0.284*	0.092***	0.055
	(0.095)	(0.286)	(0.182)	(0.156)	(0.034)	(0.070)
Rail (5 km)×1900	0.323***	1.881***	1.167***	0.465**	0.119***	0.260***
	(0.114)	(0.613)	(0.332)	(0.227)	(0.037)	(0.100)
Municipality FE	Yes	Yes	Yes	Yes	Yes	Yes
Region FE×Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Local Geography×Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Pre-Rail Controls×Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	18152	18152	18152	18152	18152	18152
Mean dep. var.	0.06	0.12	0.07	0.08	0.01	0.01

Notes: 2SLS regressions. Local geography controls include: the mean slope, the mean elevation as well as the standard deviation of the elevation, the area, and the mean cost of construction based on the land cover and slope data (all in logs). Pre-rail controls include: log population in 1865, the log distance to the nearest town, an indicator for whether a municipality had any granted patent prior to 1860 or not, the number of manufacturing firms per capita and the share of manufacturing workers in 1865, the latitude and longitude of the municipality centroid as well as region fixed effects. Number of inhabitants is from 1865. Standard errors are given in parentheses and are clustered at the municipality level. *** - $p < 0.01$, ** - $p < 0.05$, * - $p < 0.1$.

Table B.4: DiD Reduced Form Estimates

Dependent variable:	Any patent	Patents per capita	Inventors per capita	Patents per inventor	Technical proximity (fields)	Any transfer	Transfers per capita		
							All	Indp–Firm	Non-exist. industry
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
ln(Dist. to Least-Cost)×1870	-0.001	-0.002	-0.001	-0.002	-0.001	-0.001	-0.000	0.000	-0.000
	(0.003)	(0.002)	(0.002)	(0.003)	(0.001)	(0.000)	(0.000)	(0.000)	(0.000)
ln(Dist. to Least-Cost)×1880	-0.004	-0.014	-0.010**	-0.008	-0.002	0.001	0.001	0.001	-0.000
	(0.005)	(0.009)	(0.005)	(0.010)	(0.001)	(0.002)	(0.002)	(0.001)	(0.001)
ln(Dist. to Least-Cost)×1890	-0.017**	-0.051**	-0.038***	-0.021*	-0.007***	0.001	-0.004	-0.004	-0.005
	(0.007)	(0.021)	(0.013)	(0.011)	(0.002)	(0.003)	(0.005)	(0.005)	(0.005)
ln(Dist. to Least-Cost)×1900	-0.024***	-0.139***	-0.086***	-0.034**	-0.009***	-0.012***	-0.019***	-0.016***	-0.018***
	(0.008)	(0.044)	(0.023)	(0.017)	(0.003)	(0.004)	(0.007)	(0.006)	(0.007)
Local Geography×Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Pre-Rail Controls×Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Region FE×Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	18152	18152	18152	18152	18152	18152	18152	18152	18152
Mean dep. var.	0.056	0.115	0.073	0.083	0.014	0.008	0.009	0.006	0.007

Notes: OLS regressions. Local geography controls include: the mean slope, the mean elevation as well as the standard deviation of the elevation, the area, and the mean cost of construction based on the land cover and slope data (all in logs). Pre-rail controls include: log population in 1865, the log distance to the nearest town, an indicator for whether a municipality had any granted patent prior to 1860 or not, the number of manufacturing firms per capita and the share of manufacturing workers in 1865, the latitude and longitude of the municipality centroid as well as region fixed effects. Number of inhabitants is from 1865. Standard errors are given in parentheses and are clustered at the municipality level. *** - $p < 0.01$, ** - $p < 0.05$, * - $p < 0.1$.

TABLE B.5: PATENTS WITH AND WITHOUT AGENT INTERMEDIARIES

Dependent variable:	Any patent						Patents per capita					
	Agent			Non-agent			Agent			Non-agent		
	All	Independent	Firm	All	Independent	Firm	All	Independent	Firm	All	Independent	Firm
Panel A: OLS	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Network Connection (=1)	0.086***	0.083***	0.010***	0.004	0.004	-0.000	0.311***	0.292***	0.019***	0.009**	0.009**	-0.000
	(0.010)	(0.009)	(0.003)	(0.003)	(0.003)	(0.000)	(0.064)	(0.062)	(0.006)	(0.004)	(0.004)	(0.000)
Panel B: 2SLS	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Network Connection (=1)	0.150***	0.160***	0.045**	0.030	0.034	-0.004	0.728***	0.696***	0.031	0.024	0.024	-0.001
	(0.050)	(0.050)	(0.021)	(0.021)	(0.021)	(0.004)	(0.228)	(0.216)	(0.025)	(0.016)	(0.017)	(0.002)
Municipality FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Region FE×Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Local Geography×Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Pre-Rail Controls×Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
First-Stage F-stat	26.48	26.48	26.48	26.48	26.48	26.48	26.48	26.48	26.48	26.48	26.48	26.48
Observations	18152	18152	18152	18152	18152	18152	18152	18152	18152	18152	18152	18152
Mean dep. var.	0.052	0.051	0.005	0.006	0.005	0.000	0.111	0.105	0.006	0.004	0.004	0.000

Notes: OLS and 2SLS regressions. The table displays the effect of an indicator for network access (within 5 km) on whether a municipality has any patent (column 1–6) and the number of patents per 1,000 inhabitants (columns 7–12) by legal category. "(Non-)Agent" refers to patents with a (no) registered agent intermediary. Local geography controls include: the mean slope, the mean elevation as well as the standard deviation of the elevation, the area, and the mean cost of construction based on the land cover and slope data (all in logs). Pre-rail controls include: log population in 1865, the log distance to the nearest town, an indicator for whether a municipality had any granted patent prior to 1860 or not, the number of manufacturing firms per capita and the share of manufacturing workers in 1865, the latitude and longitude of the municipality centroid as well as region fixed effects. Numbers of inhabitants are from 1865. Standard errors are given in parentheses and are clustered at the municipality level. *** - $p < 0.01$, ** - $p < 0.05$, * - $p < 0.1$.

Table B.6: Quality of patents

Dependent variable:	Patents per capita			
	PRV		USPTO	
	Fee-weight	Hi-tech		Cite-weight
Panel A: OLS	(1)	(2)	(3)	(4)
Network Connection (=1)	1.495***	0.129***	0.019**	0.017
	(0.308)	(0.035)	(0.008)	(0.012)
Panel B: 2SLS	(1)	(2)	(3)	(4)
Network Connection (=1)	3.575***	0.249**	0.088	0.074
	(1.140)	(0.117)	(0.065)	(0.066)
Municipality FE	Yes	Yes	Yes	Yes
Region FE×Year FE	Yes	Yes	Yes	Yes
Local Geography×Year FE	Yes	Yes	Yes	Yes
Pre-Rail Controls×Year FE	Yes	Yes	Yes	Yes
First-Stage F-stat	26.48	26.48	26.48	26.48
Observations	18152	18152	18152	18152
Mean dep. var.	0.541	0.040	0.010	0.012

Notes: OLS and 2SLS regressions. The table displays the effect of an indicator for network access (within 5 km) on fee-weighted (PRV) patents per 1,000 inhabitants (column 1), high-technology (PRV) patents per 1,000 inhabitants using the definition of (Nuvolari & Vasta, 2015) (column 2), USPTO patents per 1,000 inhabitants (column 3) and citation-weighted USPTO patents per 1,00 inhabitant (column 4). Local geography controls include: the mean slope, the mean elevation as well as the standard deviation of the elevation, the area, and the mean cost of construction based on the land cover and slope data (all in logs). Pre-rail controls include: log population in 1865, the log distance to the nearest town, an indicator for whether a municipality had any granted patent prior to 1860 or not, the number of manufacturing firms per capita and the share of manufacturing workers in 1865, the latitude and longitude of the municipality centroid as well as region fixed effects. Numbers of inhabitants are from 1865. Standard errors are given in parentheses and are clustered at the municipality level. *** - $p < 0.01$, ** - $p < 0.05$, * - $p < 0.1$.

Table B.7: Technical proximity by legal category

Dependent variable:	Technical proximity			Patents weighted by technical proximity		
	All	Independent	Firm	All	Independent	Firm
Panel A: OLS	(1)	(2)	(3)	(4)	(5)	(6)
Network Connection (=1)	0.024***	0.023***	0.002**	0.124***	0.115***	0.005**
	(0.003)	(0.003)	(0.001)	(0.032)	(0.031)	(0.002)
Panel B: 2SLS	(1)	(2)	(3)	(4)	(5)	(6)
Network Connection (=1)	0.064***	0.064***	0.007*	0.305***	0.290***	0.004
	(0.017)	(0.017)	(0.004)	(0.092)	(0.089)	(0.007)
Municipality FE	Yes	Yes	Yes	Yes	Yes	Yes
Region FE×Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Local Geography×Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Pre-Rail Controls×Year FE	Yes	Yes	Yes	Yes	Yes	Yes
First-Stage F-stat	26.48	26.48	26.48	26.48	26.48	26.48
Observations	18152	18152	18152	18152	18152	18152
Mean dep. var.	0.014	0.014	0.001	0.038	0.036	0.001

Notes: OLS and 2SLS regressions. The table displays the effect of an indicator for network access (within 5 km) on technical proximity to the national distribution based on 98 technical (DPK) patent classes by legal category. Local geography controls include: the mean slope, the mean elevation as well as the standard deviation of the elevation, the area, and the mean cost of construction based on the land cover and slope data (all in logs). Pre-rail controls include: log population in 1865, the log distance to the nearest town, an indicator for whether a municipality had any granted patent prior to 1860 or not, the number of manufacturing firms per capita and the share of manufacturing workers in 1865, the latitude and longitude of the municipality centroid as well as region fixed effects. Numbers of inhabitants are from 1865. Standard errors are given in parentheses and are clustered at the municipality level. *** - $p < 0.01$, ** - $p < 0.05$, * - $p < 0.1$.

Table B.8: Any transfers by category

Dependent variable:	Any transfer										
	Independent (I) – Firm (F)	Other combinations				Technology fields		Industrial sector			
		I–I	F–F	F–I	All	Novel	Non-novel	Existing	Non-existing	Leading	Non-leading
Panel A: OLS	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
Network Connection (=1)	0.013***	0.009***	-0.000	0.001*	0.009***	0.032***	0.002*	0.005***	0.016***	0.005***	0.017***
	(0.003)	(0.003)	(0.000)	(0.001)	(0.003)	(0.005)	(0.001)	(0.002)	(0.004)	(0.002)	(0.004)
Panel B: 2SLS	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
Network Connection (=1)	0.033*	0.005	0.006	-0.002	0.010	0.087***	0.006	-0.001	0.055***	0.001	0.051**
	(0.017)	(0.014)	(0.006)	(0.003)	(0.015)	(0.027)	(0.005)	(0.008)	(0.021)	(0.008)	(0.020)
Municipality FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Region FE×Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Local Geography×Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Pre-Rail Controls×Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
First-Stage F-stat	26.48	26.48	26.48	26.48	26.48	26.48	26.48	26.48	26.48	26.48	26.48
Observations	18152	18152	18152	18152	18152	18152	18152	18152	18152	18152	18152
Mean dep. var.	0.005	0.004	0.000	0.000	0.004	0.011	0.000	0.002	0.006	0.002	0.007

Notes: OLS and 2SLS regressions. The table displays the effect of an indicator for network access (within 5 km) on whether a municipality has any patent transfer by category. Local geography controls include: the mean slope, the mean elevation as well as the standard deviation of the elevation, the area, and the mean cost of construction based on the land cover and slope data (all in logs). Pre-rail controls include: log population in 1865, the log distance to the nearest town, an indicator for whether a municipality had any granted patent prior to 1860 or not, the number of manufacturing firms per capita and the share of manufacturing workers in 1865, the latitude and longitude of the municipality centroid as well as region fixed effects. Numbers of inhabitants are from 1865. Standard errors are given in parentheses and are clustered at the municipality level. *** - $p < 0.01$, ** - $p < 0.05$, * - $p < 0.1$.

Table B.9: Patent transfers by duration between grant and transfer

Dependent variable:	Any transfer		Transfers per capita	
	within 3 years	after 3 years	within 3 years	after 3 years
Panel A: OLS				
	(1)	(2)	(3)	(4)
Network Connection (=1)	0.018***	0.006***	0.022***	0.007***
	(0.004)	(0.002)	(0.006)	(0.003)
Panel B: 2SLS	(1)	(2)	(3)	(4)
Network Connection (=1)	0.035*	0.010	0.068**	0.019
	(0.018)	(0.013)	(0.033)	(0.012)
Municipality FE	Yes	Yes	Yes	Yes
Region FE×Year FE	Yes	Yes	Yes	Yes
Local Geography×Year FE	Yes	Yes	Yes	Yes
Pre-Rail Controls×Year FE	Yes	Yes	Yes	Yes
First-Stage F-stat	26.48	26.48	26.48	26.48
Observations	18152	18152	18152	18152
Mean dep. var.	0.006	0.003	0.006	0.002

Notes: OLS and 2SLS regressions. The table displays the effect of an indicator for network access (within 5 km) on whether a municipality has any patent transfer (column 1–2) and transfers per 1,000 inhabitants (columns 3–4) by category. "within 3 years" refers to if the transfer occurred within 3 years after the grant. Local geography controls include: the mean slope, the mean elevation as well as the standard deviation of the elevation, the area, and the mean cost of construction based on the land cover and slope data (all in logs). Pre-rail controls include: log population in 1865, the log distance to the nearest town, an indicator for whether a municipality had any granted patent prior to 1860 or not, the number of manufacturing firms per capita and the share of manufacturing workers in 1865, the latitude and longitude of the municipality centroid as well as region fixed effects. Numbers of inhabitants are from 1865. Standard errors are given in parentheses and are clustered at the municipality level. *** - $p < 0.01$, ** - $p < 0.05$, * - $p < 0.1$.

Table B.10: Cross-sectional 2SLS Estimates - Long-Differences in Innovation 1900-2014

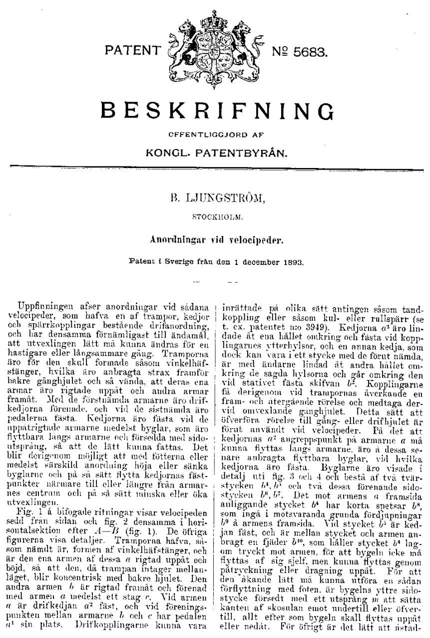
Dependent variable:	Patents 2005–13			
Panel A: OLS	(1)	(2)	(3)	(4)
Network Connection (=1)	0.014***	0.013***	0.019***	0.019***
	(0.004)	(0.004)	(0.005)	(0.004)
Gained network connection (=1)		-0.002		-0.001
		(0.004)		(0.004)
Lost network connection (=1)			-0.016***	-0.016***
			(0.004)	(0.004)
Controls	Yes	Yes	Yes	Yes
Observations	2269	2269	2269	2269
First-Stage F-stat				
Mean dep. var.	0.02	0.02	0.02	0.02
Panel B: 2SLS	(1)	(2)	(3)	(4)
Network Connection (=1)	0.097***	0.099***	0.104***	0.106***
	(0.037)	(0.038)	(0.039)	(0.039)
Gained network connection (=1)		0.036**		0.032**
		(0.016)		(0.015)
Lost network connection (=1)			-0.061***	-0.061***
			(0.021)	(0.021)
Controls	Yes	Yes	Yes	Yes
Observations	2269	2269	2269	2269
First-Stage F-stat	56.17	55.28	56.21	55.50
Mean dep. var.	0.02	0.02	0.02	0.02

Notes: OLS and 2SLS regressions. The table displays the effect of an indicator for network access (within 5 km) on the difference in the number of patents in 2005–2013 and 1900–1910 per 1,000 inhabitants in 1865. All regressions include local geography controls, pre-rail controls, region fixed effects and year fixed effects. Local geography controls include: the mean slope, the mean elevation as well as the standard deviation of the elevation, the area, and the mean cost of construction based on the land cover and slope data (all in logs). Pre-rail controls include: log population in 1865, the log distance to the nearest town, an indicator for whether a municipality had any granted patent prior to 1860 or not, the number of manufacturing firms per capita and the share of manufacturing workers in 1865, the latitude and longitude of the municipality centroid. Observations are sorted into 100 groups of equal size and the dots indicate the mean value in each group. A linear regression line based on the underlying (ungrouped) data is also shown.

C Data appendix

C.1 Patent data

The patent data has been manually scanned and collected from the original handwritten patent registers in the Swedish National Archive (Riksarkivet) for the years 1860-1884 and the archives of the Swedish Patent and Registration Office (PRV) for the years 1885-1910. Below we present some samples of this data. In contrast to the published patent documents (see Figure C.1), these original registers document the complete “history” of the patent, including when patentees paid their renewal fees and if and when a patent was transferred to a new owner. Figure C.1 shows one such example.



PATENT № 5683.

BESKRIFNING

OFFENTLIGGJORD AF

KONGL. PATENTBYRÅN.

B. LJUNGSTRÖM,

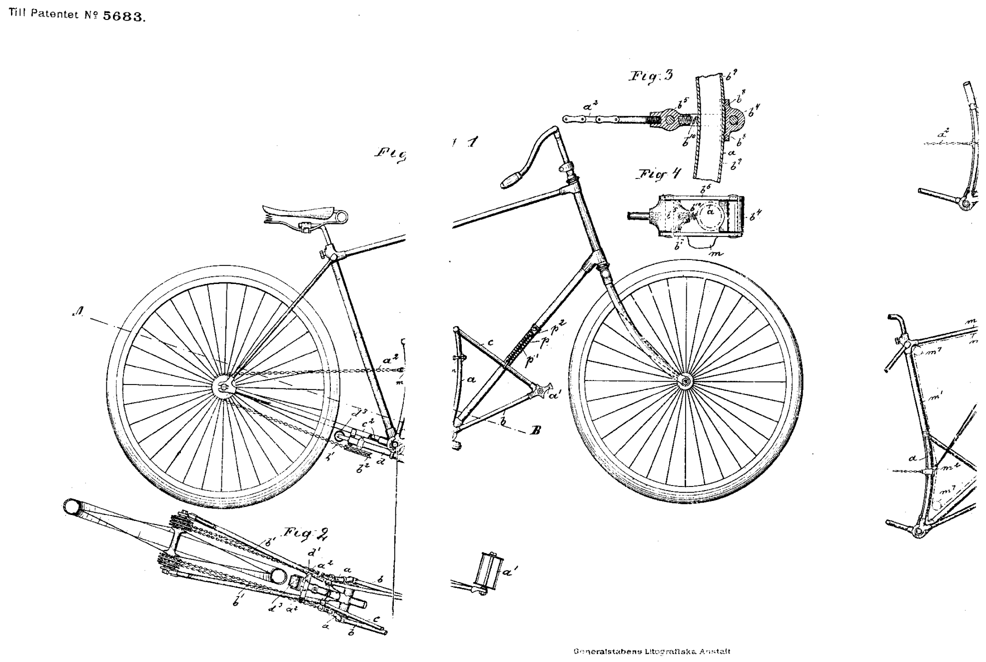
STOCKHOLM.

Anordningar vid velocipeder.

Patent i Sverige från den 1 december 1893.

Uppfinningen afser anordningar vid sådana velocipeder, som hafva en af trampor, kedjor och spärrkopplingar bestående drifanordning, och har densamma förnämligast till ändamål, att utvexlingen lätt må kunna ändras för en hastigare eller långsammare gång. Tramporna äro för den skull formade såsom vinkelhäfstänger, hvilka äro anbragta strax framför bakre gånghjulet och så vända, att deras ena armar äro rigtade uppåt och andra armar framåt. Med de förstnämda armarne äro drifkedjorna förenade, och vid de sistnämda äro pedalerna fästa. Kedjorna äro fästa vid de uppåtrigtade armarne medelst byglar, som äro flyttbara längs armarne och försedda med sidoutsprång, så att de lätt kunna fattas. Det blir derigenom möjligt att med fötterna eller medelst särskild anordning höja eller sänka byglarne och på så sätt flytta kedjornas fästpunkter närmare till eller längre från armarnes centrum och på så sätt minska eller öka utvexlingen.

Fig. 1 å bifogade ritningar visar velocipeden sedd från sidan och fig. 2 densamma i horisontalsektion efter *A*—*B* (fig. 1). De öfriga figurerna visa detaljer. Tramporna hafva, såsom nämdt är, formen af vinkelhäfstänger, och är den ena armen af dessa a rigtad uppåt och böjd, så att den, då trampan intager mellanläget, blir koncentrisk med bakre hjulet. Den andra armen b är rigtad framåt och förenad med armen a medelst ett stag c. Vid armen a är drifkedjan a^2 fäst, och vid föreningspunkten mellan armarne b och c har pedalen a^1 sin plats. Drifkopplingarne kunna vara inrättade på olika sätt antingen såsom tandkoppling eller såsom kul- eller rullspärr (se t. ex. patentet n:o 3949). Kedjorna a^2 äro lindade åt ena hållet omkring och fästa vid kopplingarnes ytterhylsor, och en annan kedja, som dock kan vara i ett stycke med de förut nämda, är med ändarne lindad åt andra hållet omkring de sagda hylsorna och går omkring den vid stativet fästa skifvan b^2. Kopplingarne få derigenom vid trampornas åverkande en fram- och återgående rörelse och medtaga dervid omvexlande gånghjulet. Detta sätt att öfverföra rörelse till gång- eller drifhjulet är förut användt vid velocipeder. På det att kedjornas a^2 angreppspunkt på armarne a må kunna flyttas längs armarne, äro å dessa senare anbragta flyttbara byglar, vid hvilka kedjorna äro fästa. Byglarne äro visade i detalj uti fig. 3 och 4 och bestå af två tvärstycken b^4, b^5 och två dessa förenande sidostycken b^6, b^7. Det mot armens a framsida anliggande stycket b^4 har korta spetsar b^8, som ingå i motsvaranda grunda fördjupningar b^9 å armens framsida. Vid stycket b^5 är kedjan fäst, och är mellan stycket och armen anbragt en fjäder b^{10}, som håller stycket b^4 lagom tryckt mot armen, för att bygeln icke må flyttas af sig sjelf, men kunna flyttas genom påtryckning eller dragning uppåt. För att den åkande lätt må kunna utföra en sådan förflyttning med foten, är bygelns yttre sidostycke försedt med ett utsprång m att sätta kanten af skosulan emot undertill eller öfvertill, allt efter som bygeln skall flyttas uppåt eller nedåt. För öfrigt är det lätt att åstad-

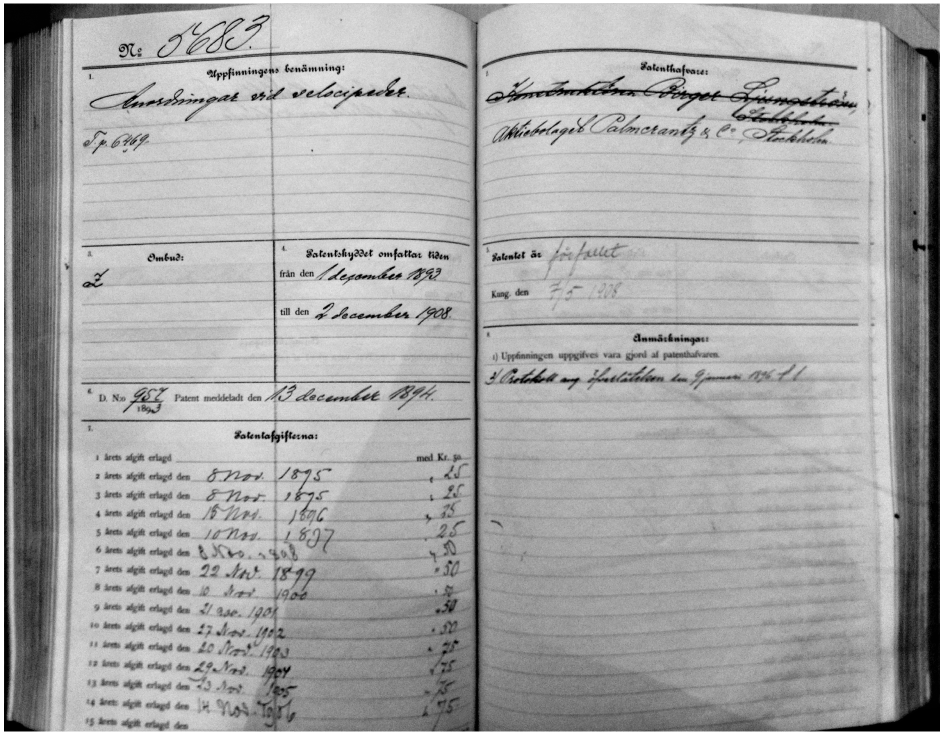


Till Patentet № 5683.

Generalstabens Litografiska Anstalt

FIGURE C.1:
PUBLISHED PATENT

Notes: The images show Birger Ljungström's published patent for "bicycle devices" which became known as part the "Svea Velocipede". Figure C.1 shows the transfer of the patent rights.



N:o 5683.

1. Uppfinningens benämning:

Anordningar vid velocipeder.

T.p. 6469.

3. Ombud:

Z

4. Patentskyddet omfattar tiden

från den 1 december 1893

till den 2 december 1908.

6. D. N:o 957/1893 Patent meddeladt den 13 december 1894.

7. Patentafgifterna:

1 årets afgift erlagd		med Kr. 50.
2 årets afgift erlagd den	8 Nov. 1895	25
3 årets afgift erlagd den	8 Nov. 1895	25
4 årets afgift erlagd den	15 Nov. 1896	25
5 årets afgift erlagd den	10 Nov. 1897	25
6 årets afgift erlagd den	8 Nov. 1898	50
7 årets afgift erlagd den	22 Nov. 1899	50
8 årets afgift erlagd den	10 Nov. 1900	50
9 årets afgift erlagd den	21 Nov. 1901	50
10 årets afgift erlagd den	27 Nov. 1902	50
11 årets afgift erlagd den	20 Nov. 1903	75
12 årets afgift erlagd den	29 Nov. 1904	75
13 årets afgift erlagd den	23 Nov. 1905	75
14 årets afgift erlagd den	14 Nov. 1906	75
15 årets afgift erlagd den		

2. Patenthafvare:

~~Konstruktören Birger Ljungström, Stockholm~~

Aktiebolaget Palmcrantz & C:o, Stockholm

5. Patentet är förfallet

Kung. den 7/5 1908

8. Anmärkningar:

1) Uppfinningen uppgifves vara gjord af patenthafvaren.

3) Protokoll ang. öfverlåtelsen den 9 januari 1896 [illegible]

Figure C.1:
Patent register entry

Notes: The image shows the patent register entry of Figure C.1 in the official register of the PRV. Ljungström's name has been crossed out and replaced by the firm AB Palmcrantz. The transfer was registered on January 9, 1896. The image also shows that 14 renewal fees were paid. Thus, the transfer gave AB Palmcrantz ten years of patent protection.

C.2 Linkage between patent data and censuses

We here describe how we link individuals between data sets. We make use of two algorithms. First, we link inventors in the patent data to individuals in the nearest census in time. Second, we link matched individuals from step one to individuals in each one of the other censuses. To clarify the procedure, we exemplify with the inventor *de Laval, Carl Gustaf Patrik*.

1. Cleaning names We start, however, by cleaning all names in both data sources by going through the following steps:

1. Trim and capitalize names.
2. Clean special characters.
3. Remove suffixes, nobiliary particles etc (JR, SR, VON, DE, AF etc).
4. Minimal phonetic cleaning of names.
5. Remove paternal names.

In the example of Carl Gustaf Patrik de Laval, we obtain one surname, "LAVAL", and three candidates for first name, "KARL", "GUSTAV" and "PATRIK". Since the placement of the first name may differ between individuals, and since individuals may use more than one of them as first name, we do not make any attempts to single out one (1) first name.

2. Matching algorithm for linkages between patent data and nearest census Next, we attempt to link all inventors from the patent data set to individuals in the census data set by using the following algorithm:

1. The inventor (X) and a census individual (Y) live in the same county AND have a Jaro-Winkler distance score above 0.9 for the surname AND an *average* Jaro-Winkler distance score above 0.9 for the first names.[46] For the latter, we calculate all the combinations of the first names between X and Y and take the average over the least common number of first names (where we drop the lowest ranked pairs in terms of JW score). For example, if we attempt to match "KARL GUSTAV PATRIK" (X) to someone named "GUSTAV" (Y), we will obtain an average Jaro-Winkler score of 1, since "GUSTAV" and "GUSTAV" is the highest ranked combination of first names (there are three combinations in this example) and has a Jaro-Winkler score of 1, and

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[46] See e.g. Winkler (1994, 2006) for more information on the Jaro-Winkler distance string metric.

the least common number of first names between X and Y is 1 (since Y only have 1 first name).

– If there is a single match above, we stop. If no match, we stop. If multiple matches, we proceed to step 2.

2. X and Y live in the same municipality.

   – If single match above: stop. If no single match: proceed.

3. X and Y have identical non-phonetically corrected last name and full first name ("LAVAL" and "CARL GUSTAF PATRIK").

   – If single match above: stop. If no single match: proceed.

4. X and Y have a Jaro-Winkler distance score above 0.85 for the full first name ("KARL GUSTAV PATRIK").

   – If single match above: stop. If no single match: proceed.

5. X and Y work within the same occupational sector (HISCO coded).

   – If single match above: stop. If no single match: proceed.

6. X and Y have the same occupation (HISCO coded).

   – If single match above: stop. If no single match: proceed.

7. The average Jaro-Winkler score of the average first name score and the surname is sufficiently higher than the next highest match. We choose the cut-off ratio between the highest ranked and the second highest to be 1.15.

   – If single match above: stop. If no single match: proceed.

8. The age of Y is between 18 and 75.

   – If single match above: stop. If no single match: stop.

Each single match is recorded as a link.

3. Matching algorithm for linkages between census data sets Next, we attempt to link all recorded linkages from step 1 above to individuals in the other three remaining census years. Since we now know the birth year and the birth municipality of individuals from the census data (in contrast to the patent data), we may use these. On the other hand, since we now attempt to link individuals across time, we do not use information in variables that may change over time, such as residential location or occupation.

1. X and Y have the same birth year AND birth municipality AND have a Jaro-Winkler distance score above 0.9 for the surname AND an *average* Jaro-Winkler distance score above 0.9 for the first names.

   – If single match above: stop. If no single match: proceed.

2. X and Y have identical non-phonetically corrected last name and full first name (“LAVAL” and “CARL GUSTAF PATRIK”).

   – If single match above: stop. If no single match: proceed.

3. X and Y have a Jaro-Winkler distance score above 0.85 for the full first name (“KARL GUSTAV PATRIK”).

   – If single match above: stop. If no single match: proceed.

4. The average Jaro-Winkler score of the average first name score and the surname is sufficiently higher than the next highest match. We choose the cut-off ratio between the highest ranked and the second highest to be 1.15.

   – If single match above: stop. If no single match: stop.

Each single match is recorded as a link.