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

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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 improved transport infrastructure on innovative activity. A network connection led to a local surge in patenting due to an increased entry and productivity of inventors. As the railroad network expanded, 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 reductions in communication and transportation costs were an important driver of the historical emergence of a market for ideas.

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1 Introduction

Markets for ideas are central to promote innovation. They may increase the strategy space of firms (Arora et al., 2001), enable small firms or individuals to specialize in innovation (Lamoreaux & Sokoloff, 2001), and ultimately reduce the misallocation of ideas (Akcigit et al., 2016). Trade in technology, however, involves significant frictions. To develop useful ideas, inventors must 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. Despite beliefs that such frictions are a key barrier in the patent market, there is little empirical evidence on how reductions in transaction costs between firms, intermediaries, and inventors affect 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.

Crucially, the expansion of the Swedish railroad network also provides a unique setting to identify the causal impacts of transport infrastructure on innovation outcomes. 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 allow us to circumvent the empirical challenge that investments in infrastructure may be 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 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

Review of Economics and Statistics Just Accepted MS.
https://doi.org/10.1162/rest_a_01067

with the 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 least-cost paths 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 least-cost paths 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.

To establish the causal impact of a network connection on the rate of local innovation, we use new data on the universe of patents granted by the Swedish Patent and Registration Office (PRV) between 1830–1910.[1] 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 output is mainly driven by an increased entry and productivity of independent inventors, which accounted for the vast majority of patents in the period studied, suggesting that the evolving network enabled a growing number of individuals to specialize in innovative activity.

We then proceed to study how the evolving railroad network contributed to the emergence of a national market for ideas. While a connection to the network leads to innovation in industrial sectors and technological fields that previously existed locally, it also leads to patenting in sectors

[1] It is well-known that patents are not a perfect proxy for innovation since all innovations are not patented and since a patent does not necessarily reflect the value of the underlying technological innovation (Griliches, 1990; Moser, 2005). Below we address these concerns by adjusting for the quality of patented innovations to isolate useful technological advances and provide suggestive evidence that the availability of other forms of intellectual property protection (e.g., secrecy) is unlikely to influence our results.

[2] We find no evidence that the increase in output is offset by a reduction in average patent quality, nor that it simply reflects a reallocation across localities, suggesting that the arrival of the railroad led to the development of a large number of new useful innovations.

Review of Economics and Statistics Just Accepted MS.
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and fields that were not present in the local economy. Over time, the distribution of local innovation across sectors and fields in connected municipalities converges with the national distribution. While this could be intertwined with broader local changes in industrial structure, it constitutes suggestive evidence that inventors began to develop ideas for an increasingly national market.

To provide direct evidence that the rail network contributed to the rise of a market for ideas, we collect handwritten data on the buyer and seller of each granted patent. We document a significant causal impact of the establishment of a network connection on the extensive and intensive margin of patent transfers. In particular, the increase in patent transfers is driven by independent inventors selling patents to firms in other connected municipalities. Moreover, while network connections promote innovation in virtually all fields and sectors, the increase in transfers is mainly due to patents in fields and sectors that were not previously present in the inventor's municipality.

Our findings of a surge in innovative activity in locations traversed by the rail network may be driven by a wide range of mechanisms. On the one hand, the arrival of the railroad may induce innovation through local economic growth (Duranton & Turner, 2012). A local economic expansion may increase both the demand for innovation, thus raising the return to develop new ideas (Schmookler, 1954; Acemoglu & Linn, 2004), and the supply of innovation through knowledge spillovers or exposure to innovation (Agrawal et al., 2017; Bell et al., 2018; Akcigit et al., 2018). On the other hand, the spread of the railroad network may integrate local economies with external markets (Donaldson & Hornbeck, 2016; Donaldson, 2018). Access to larger external markets could increase the demand for new ideas, incentivize innovations with applications beyond the local economy, and decrease the cost of inputs into the inventive process by facilitating the exchange of ideas between places.

In fact, local economies expanded as the network spread, as evident in population increases in connected municipalities. Yet two findings suggest that the increase in local innovation cannot fully be attributed to local economic expansion. First, the rate of patenting and transfers increases also when controlling for the subsequent growth in population. Second, we find no increases in patent transfers *within* municipalities. Additional evidence instead highlights the role of reduced

Review of Economics and Statistics Just Accepted MS.
https://doi.org/10.1162/rest_a_01067

transaction costs between firms and inventors in other locations. Using data on the rollout of the postal and telegraph networks, we show that municipalities that also gained access to the postal or the telegraph network saw a differential increase in patenting output and transfers. Lowering the cost of communication was presumably particularly important when it came to patent agents, a key intermediary that aided inventors in the review process and connected buyers and sellers in the patent market (Lamoreaux & Sokoloff, 2003). Consistent with this idea, we show that the increase in patents and transfers is driven by patents filed with agents. Together, these results suggest that the spread of the rail network facilitated interactions with firms and intermediaries in other locations along the network, which enabled individuals to specialize in developing inventions for a national market for ideas.

Our paper relates to an influential body of work 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 (Lamoreaux & Sokoloff, 1999, 2001, 2003; Arora et al., 2001; Spulber, 2015; Akcigit et al., 2016). 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 lowering transaction costs between inventors and firms led to an increased trade in patents, which is primarily driven by patents that are more distant to the technology space of the inventor's municipality. We further document that railroads enabled 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 (Atack et al., 2010; Duranton & Turner, 2012; Faber, 2014; Donaldson & Hornbeck, 2016; Campante & Yanagizawa-Drott, 2018; Pascali, 2017;

Review of Economics and Statistics Just Accepted MS.
https://doi.org/10.1162/rest_a_01067

Donaldson, 2018; Hornbeck & Rotemberg, 2019; Banerjee et al., 2020).[3] In particular, Perlman (2016) documents a positive link between rail access and patenting output across U.S. counties in the 19th century. Relatedly, Agrawal et al. (2017) show that interstate highways increased regional patenting in the late-20th century and led inventors to increasingly draw upon "distant" local knowledge within U.S. metropolitan areas. In contrast, we leverage a different setting and identification strategy to analyze how the spread of the railroad facilitated integration between previously isolated locations and contributed to the emergence of a national market for ideas.

2 Historical background

2.1 Sweden's "technological revolution"

Sweden's economic modernization prior to World War I was fueled 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 patent (or *privilegia exclusiva*) law in 1819, 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.[4]

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

[3]In particular, our paper is related to Berger (2019) 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 his methodology, draws upon 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.

[4]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.

Review of Economics and Statistics Just Accepted MS.
https://doi.org/10.1162/rest_a_01067

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.[5] Another potentially important incentive was the opportunity to patent technological discoveries demanded by firms, which could later be sold. Indeed, a central role for the opportunity of such transfers of technology has been invoked to explain the continued importance of independent inventors in Europe, Japan, and the United States well into the 20th century (Nicholas, 2010, 2011; Nuvolari & Vasta, 2015).

2.2 An Emerging Market for Ideas

Swedish patent legislation played a large part in facilitating trade in technology. Already the 1819 law 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.[6]

[5]In 1885, the applicant had to pay SEK 50 (approximately $378 in 2015 USD) to file a patent application. In 1893, this cost was lowered by 60% to SEK 20 ($153). As a comparison, the same cost was around $524 in the UK and $953 in the US.

[6]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).

Review of Economics and Statistics Just Accepted MS.
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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. These patent agents, that emerged along side the patent system, provided administrative services, such as the drafting and filing of patents at the patent office, and often developed close business relations with clients as well as the Swedish patent office. They also acted as intellectual property consultants, and advertised patented inventions for sale in their own patent journals (Andersson & Tell, 2016; Andersson & La Mela, 2020). Yet, there existed significant barriers to interact with agents and potential buyers and sellers in other locations due to the high communication and travel costs that characterized the pre-rail era (Heckscher, 1954). In fact, before the railroads, innovative activity was fairly concentrated to a few locations as seen in Figure 1C.[7] In the following decades, inventors became increasingly geographically dispersed as seen also in Figure 2.

[7]To estimate the spatial dispersion of inventive activity in Figure 1C, 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 **??** in the Online Appendix showing that inventors became increasingly located in non-urban areas over the same period.

Review of Economics and Statistics Just Accepted MS.
https://doi.org/10.1162/rest_a_01067

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. 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).[8]

Construction of the network began in the 1850s and in the 1860s the first parts of the network were opened for traffic. Figure 2 shows the subsequent rollout of the railroad network 1870–1900. 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.[9] By the early 20th century the major parts of the network had been finished, which meant that about half of all municipalities had gained a network connection (see Figure 1D).

As the railroad network spread throughout the country, it radically lowered travel costs.[10] After

[8] 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). The emerging network therefore closely resembled Ericsson's original proposal (Heckscher, 1954, p.241), as depicted in Online Appendix Figure **??**.

[9] 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.

[10] Transportation costs were often prohibitively high prior to the railroad. Notably, although waterways offered

Review of Economics and Statistics Just Accepted MS.
https://doi.org/10.1162/rest_a_01067

a network connection was established, costs decreased by at least half and speed increased manifold (Sjöberg, 1956). The lowering of travel costs is reflected in an increased mobility of the population displayed in Figure 1D, which may have facilitated interactions between firms, intermediaries, and inventors.

3 Data

Patents, inventors and transfers. Our main data set is built up by the full universe of all granted Swedish patents for the years 1830–1910. The patent data was compiled and digitized from the 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 89 technology classes into the 14 broad industrial groups used by Nuvolari & Vasta (2015).[11] Moreover, the registers include name, address and occupation of the patent holder(s) and inventor(s) behind each patent. Using the information on the legal nature of the patent holder(s), we are able to define independent inventors as those inventors that did not grant a firm the property right of the patent.[12] About 90 percent of the patents in our data were granted to individuals and in 95 percent of these cases the patent holder(s) is also the inventor(s). For brevity, we refer to these patent holder(s) and/or inventor(s) simply as "inventors" throughout the paper.

A little more than 15,000 patents were granted by the PRV to individuals or firms residing in Sweden over the period. About 80 percent of granted patents contain non-missing information on the place of residence for the inventor(s) that enables us to geolocate each individual/patent

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".

[11] The full crosswalk between patent classes and industries is available in Online Appendix Table **??**.

[12] 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.

Review of Economics and Statistics Just Accepted MS.
https://doi.org/10.1162/rest_a_01067

by using the longitude and latitude of the place denoted on the patent. After cross-validating geolocations manually, we obtain 11,949 geolocated patents and 12,601 unique patent-municpality links (since some patents have multiple inventors from different muncipalities). From the PRV patent register, we also collect data on patent transfers.[13] 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.[14] We use Google Patents to collect the citations for all USPTO patents.

Railroads. Using GIS software, we digitize the rollout of the railroad network for each decade during the period 1860–1900 based on historical maps of the railroad network from Statistics Sweden. We restrict our analysis to railroad lines that connects to the main central network, which we refer to as "network connections" throughout the paper.[15]

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.[16] Population data from the 1860s are from Palm (2000) and the Swedish National Archives. Census data for 1880, 1890, 1900 and 1910, which we use to link inventors to individuals in the censuses, are from the Swedish National Archives

[13]In Online Appendix Figure **??** and **??**, we provide an example of the hand-written ledgers that stored information on granted patents and information on eventual transfers.

[14]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.

[15]Thus, we exclude minor rail lines (e.g., short lines built to connect a mine to a factory) that were never connected to the central railroad network.

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

Review of Economics and Statistics Just Accepted MS.
https://doi.org/10.1162/rest_a_01067

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 10-year periods and organize them at the municipal level using historical administrative boundaries based on maps obtained from the Swedish National Archives. 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 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 (i.e., in 1900) 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.[17]

Our first specification takes the following form:

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

[17] In Online Appendix Section **??**, we complement the analysis using an event-study approach, as well as the approach developed in de Chaisemartin & D'Haultfœuille (2020).

Review of Economics and Statistics Just Accepted MS.
https://doi.org/10.1162/rest_a_01067

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.[18] The key variable of interest on the right-hand-side of equation (1) is $Railroad_i^{1900}$, an indicator taking the value one if a municipality is within 5 km of the completed railroad network in 1900.[19] 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 differential changes across municipalities due to geography. In our main specification, we also include several baseline economic conditions, which may further 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:

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

where $Railroad_{it}$ is an indicator variable taking the value one if a municipality is within 5 km of the network at the beginning of each decade.[20] Thus, for decade $t = 1870$, for example, we measure patenting output between 1870–1879 and connections to the rail network existing in 1870. In both equation (1) and (2), the identifying variation stems entirely from the variation within municipalities over time, after controlling for municipality fixed effects, γ_i, region-by-period fixed effects, ϕ_{rt}, and a set of time-invariant control variables, $\mathbf{G}_i$, interacted with time period fixed effects, δ_t. 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

[18] Since population is an endogenous outcome in itself, we measure patents per capita using the baseline population in 1865. While we do not have population data for all decades, we show that results are qualitatively similar when using time-varying population data for a subset of decades in Online Appendix Section **??**.

[19] In Online Appendix Figure **??** we study a flexible specification based on equation (2) below where the cut-off around 5 km is found to be driving the variation behind our results.

[20] Below 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 Online Appendix Table **??**). Again, refer to Online Appendix Figure **??** for a flexible specification using different distance cut-offs.

Review of Economics and Statistics Just Accepted MS.
https://doi.org/10.1162/rest_a_01067

also present alternative standard errors that more flexibly account for spatial correlation in Online Appendix Section **??**.

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 least-cost paths (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 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 monotonically 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.

Figure 2 depicts the LCPs. As seen in the figure, our predicted network mirrors the early phase

Review of Economics and Statistics Just Accepted MS.
https://doi.org/10.1162/rest_a_01067

of railroad expansion in the period 1870–1880 as shown in Figure 2A and 2B. The LCPs capture a static network, thus providing us with cross-sectional variation. However, we are ultimately interested in studying a dynamic relationship as given by equations (1) and (2). We therefore proceed by interacting the distance to the LCPs with time period indicators. While the relationship between the LCPs and actual railroads is zero prior to railroad construction, we allow the relationship to vary flexibly for each decade after construction, which results in four instruments: one for each of the decades starting with 1870, 1880, 1890 and 1900. Thus, each coefficient estimates the effect relative the decades before 1870.

Importantly, local geographic features may be correlated both with the placement of the LCPs and economic conditions. We therefore directly control for a set of municipality-level geographic features: 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.[21] 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 municipalities with town privileges in all our main regressions.[22]

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

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

where λ_t^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

[21]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.

[22]In Online Appendix Section **??**, we show that our results are similar when including town municipalities.

Review of Economics and Statistics Just Accepted MS.
https://doi.org/10.1162/rest_a_01067

after the introduction of the railroad.[23]

4.2.1 Identifying Assumptions

The λ_t^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 when conditioning on local geographic features, distance to the nearest targeted endpoint of the network, as well as municipality and region-by-year fixed effects. To support this, we document in our main panel regressions below that there are no pre-trends in innovative activity using decade-to-decade variation. Moreover, to explicitly test for quasi-randomness, we perform a balance test by regressing potentially related variables on the cross-sectional variation in the log distance to the LCP, conditional on the local geographic conditions. The results, presented in Online Appendix Table **??**, suggests that there are no observed differential levels or trends in economic conditions before the construction of railroads in municipalities that are located closer to the LCPs. 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) and (2): the population size before the railroad era (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.[24]

4.2.2 First Stage Results

Table 1 documents that the distance to our LCPs is negatively related to railroad access.[25] For transparency, the first column displays the effect without controls, except municipality and year

[23]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.

[24]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.

[25]Online Appendix Figure **??** displays the decadal relationship in a figure.

Review of Economics and Statistics Just Accepted MS.
https://doi.org/10.1162/rest_a_01067

fixed effects. The second column introduces our set of local geography controls interacted with time period fixed effects. The third column adds our set of local pre-railroad economic controls interacted with time period fixed effects, while the fourth column additionally adds region-by-year fixed effects. As seen from the table, the negative coefficients increase somewhat after including local geography controls in column 2, which suggests that the local geography influenced the decision to construct a railroad. Conditional on the local geography, however, additional controls added in column 3 and 4 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 targeted destination, do a good job in ensuring the quasi-randomness of the instrument.

The negative relationship is evident in all four post-railroad construction decades, but differences across these decades are small. This is also seen in Online Appendix Figure **??**, where we visualize the first stage by plotting the non-parametric relationship between network access and the distance to the LCPs. While differences in the probability of access for different distances to the least-cost network are similar over time, as reflected by a similar slope coefficient, the probability increases over time for a given distance, as reflected by a higher intercept. Thus, after the main trunk lines are built, the probability of being connected increases at a roughly similar rate across the country. Our identifying variation is therefore likely to capture nearby access to the main trunk lines, rather than to the minor branches of the network constructed in the latter decades of our period of study.

5 Analysis and Results

In this section, we first show that the establishment of a network connection leads to increases in local innovative activity due both to a higher rate of inventor entry and an increased number of patents produced per inventor. Second, we document that innovation increases within a wide range of both new and existing technological fields leading to a convergence between local and

Review of Economics and Statistics Just Accepted MS.
https://doi.org/10.1162/rest_a_01067

national innovation patterns. Third, we provide evidence of the emergence of a market for ideas by documenting an increase in the buying and selling of patents between inventors and firms residing in municipalities along the network. Lastly, we provide a battery of robustness checks and discuss potential mechanisms that may account for our results.

5.1 Local Innovative Activity

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 granted patents. Figure 3A and 3B 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 a given decade (A), or the number of patents per per capita (B).[26] 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.

Figure 3A 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 where we use, as excluded instruments, the natural logarithm of the distance to the LCPs interacted 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 similar when turning to the intensity of patent activity at the local level in Figure 3B: OLS estimates show that the number of patents per capita in connected municipalities increased by an additional 0.75 patents relative to baseline, while the 2SLS estimates indicate a relative increase of about 1.88 patents (or about 1.5 SDs) by the early 20th century.

Importantly, there is no evidence in Figure 3 of any differential pre-trends prior to the major

[26]We scale per capita measures to 1,000 inhabitants in 1865.

Review of Economics and Statistics Just Accepted MS.
https://doi.org/10.1162/rest_a_01067

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.[27]

We next present more standard difference-in-differences estimates focusing on the same two outcomes. Table 2 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 15.9 percentage points according to the 2SLS estimates (panel B). Similarly, the 2SLS estimates in column 2 reveal an average increase of 0.75 patents per capita in the decades following access. In terms of standard deviations, our 2SLS estimates correspond to a 0.7 and 0.6 of a standard deviation, respectively. Taken together, they thus suggest that the establishment of a network connection affected both the extensive margin, making innovative activity increasingly spatially dispersed, and the intensive margin, increasing the local pace of patenting in connected localities.

5.2 Entry and Productivity of Inventors

We proceed to document an increase in the number of inventors per capita after a network connection is established. Figure 3C 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 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 2 similarly documents a relative increase in the number of inventors per capita of 0.49 after a

[27] 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 LCPs in Online Appendix Figure **??**. 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.

Review of Economics and Statistics Just Accepted MS.
https://doi.org/10.1162/rest_a_01067

network connection is established (panel B, column 3).

How did different types of inventors respond to 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. The 2SLS estimates in column 4 of Table 2 suggest a statistically significant increase of 0.47 in the number of independent inventors per capita. The results regarding firm inventors are more mixed. While our OLS estimates in column 5 documents a statistically significant increase in firm inventors per capita, our 2SLS depicts a less robust relationship with a non-significant estimate. In general, the magnitudes for firms are, however, small and less economically meaningful.[28]

We next document that the evolving network increased the productivity of inventors, as proxied by the number of patents produced per inventor.[29] Figure 3D documents that the number of patents per inventor increased in connected municipalities as the network was rolled out. We present 2SLS difference-in-differences estimates in Table 2, panel B, documenting that independent inventors on average produced 0.25 additional patents per inventor after a connection was established (column 7). While also patents per inventors at firms increase, the point estimate is smaller and less precisely estimated (column 8).

Although 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 examine this, 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 the average number of years inventors paid renewal fees on patents in each field.[30] Second, we isolate technologically more

[28]Recall that the vast majority of patents (about 90%) during the period of study were granted to independent inventors. Therefore, it is not surprising 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.

[29]We measure inventor productivity 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.

[30]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). Because we lack information on renewals prior to 1884, we first calculate the mean number of years that renewal fees were paid for patents across the 89 DPK 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.

Review of Economics and Statistics Just Accepted MS.
https://doi.org/10.1162/rest_a_01067

advanced—that is, presumably more valuable—patents by using the classification scheme of Nuvolari & Vasta (2015) to identify "high-tech" patents.[31] 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.[32] In Online Appendix Table **??**, we document that network connections increased inventive output also when proxied by these different quality measures. Thus, the increase in patenting output is seemingly not coupled with a decline in quality.

5.3 Innovation Across Technological Fields and Industrial Sectors

To examine whether inventors developed ideas in a broad or narrow range of fields and sectors, we first estimate our baseline difference-in-differences specification in equation (2) separately for each of the 14 industrial sectors.[33] OLS and 2SLS estimates for each individual sector are reported in Online Appendix Figure **??**. OLS estimates are positive and statistically significant in nearly all sectors; the 2SLS estimates reveal sharp significant increases in patenting across a range of sectors including agriculture, food and beverages, and textiles. Thus, inventors seemingly pursued ideas in a wide range of technological areas after a connection to the network was established.

We then more directly study the development of new ideas with respect to the patenting history and the local economic structure of the inventor's municipality of residence. First, we define "novel" patents as belonging to a technology field or industrial sector in which no inventor in a municipality has previously been granted a patent in. Second, we make use of establishment-level data at the municipality-industry level in 1865 to establish the local economic structure of each municipality. We define a patent as a patent from a "(non-)existing" industry if the patent is (not) related to an industry that existed locally.[34] 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.

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

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

[33] As described above in section 3, we define technological fields based on the 89 DPK technology classes, which are then aggregated into 14 broader industrial sectors (see Online Appendix Table **??**).

[34] As agriculture is not documented in the industrial statistics, we assume that it is an existing industry in all non-urban municipalities (i.e., our main sample).

Review of Economics and Statistics Just Accepted MS.
https://doi.org/10.1162/rest_a_01067

Table 3 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 in technology fields and industrial sectors that were represented locally (columns 2, 4, 5, and 7). At the same time, there is an increase in patent output also in novel patent classes and in non-leading/non-existing industrial sectors (columns 1, 3, 6, and 8). Together, this suggests that a connection to the network spurred broad-based innovation in both previously existing as well as new fields and sectors.

An increase in innovation across fields and sectors suggests that the local distribution of innovation may have become increasingly similar to the national distribution. To study this, we use Jaffe's technological proximity measure (Jaffe, 1986) and construct the uncentered correlation between a municipality's share of patents in each of the 89 technology classes and the corresponding national shares. Letting $\rho_{i,N}$ denote the technological proximity between municipality i and the national distribution, it is defined as:

$$\rho_{i,N} = P_i P_N' / \left[(P_i P_i')(P_N P_N')\right]^{1/2}, \tag{4}$$

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 higher value implies that the technological profile in a municipality is more similar to the national distribution.[35]

Figure 3E presents estimates from equation (1) showing that patents granted to inventors in connected municipalities became increasingly similar to the national distribution of patented inventions. Similarly, Table 3, panel B, column 9, reports estimates from equation (2) showing that a network connection increased the technological proximity with 0.06 (0.9 SDs) on the scale between 0 and 1. The increase in similarity may partly be driven by an extensive increase in patenting activity across fields. However, column 10 shows that the finding remains similar when defining technological proximity based on the 14 industrial sectors, which contain fewer zeros.[36] Thus, the

[35]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.

[36]In Online Appendix **??**, we also document that our results are robust to using the min-complement distance, which

Review of Economics and Statistics Just Accepted MS.
https://doi.org/10.1162/rest_a_01067

broadening and deepening of local innovation over time led to a convergence towards the national distribution of patents, which suggests that inventors may have responded to increasingly national demands for technology.

5.4 Patent Transfers and the Emerging Market for Ideas

To directly establish that the rail network contributed to the rise of a market for ideas, we next examine changes in the buying and selling of patents after a network connection was established. Figure 3F displays estimates of equation (1) documenting a relative increase in such patent transfers in connected municipalities as the network was rolled out. Table 4 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, 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 points, respectively. When moving from the extensive to the intensive margin in column 5, we find an increase of 0.09 transfers per capita, which corresponds to about 0.5 SDs.[37]

To establish that this increased trade in patents 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 and 6–8, 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 little evidence that transfers increase to non-connected locations, nor any increase in transfers within the municipality itself.[38] Thus, the increase in patent transfers is likely due to improved connectivity of

only depends on patent classes with non-zero patents (see Bar & Leiponen, 2012).

[37]Not only the number 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 Online Appendix Table **??**). 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.

[38]Moreover, in Online Appendix Table **??** we document that our results are not solely driven by an increase in transfers to towns. In fact, we find an increase in transfers going to both urban and rural connected locations, and no

Review of Economics and Statistics Just Accepted MS.
https://doi.org/10.1162/rest_a_01067

buyers and sellers in different locations along the network, rather than local increases in patenting activity.

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, we would expect the positive effect on transfers to be more pronounced for patents not related to the local economy of a municipality. As above, we separate between patents that belong to (non-)novel technology fields and industrial sectors 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. 2SLS estimates in Table 5 show that the increase in patent transfers is only evident for novel fields and sectors, 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 little evidence that patents that are more likely to have been useful in the local industry are increasingly sold.[39] These patterns provide an interesting contrast to the results presented in Table 3 above, showing that patenting output increased in *both* novel and non-novel technology fields and industrial sectors, as well as existing/leading and non-existing/non-leading industries, after a network connection was established.

An active market for innovation may enable inventors that have useful ideas to develop those even if they lack the competence or capital to exploit and commercialize their inventions. To shed light on this issue, we categorize all transfers by the legal status of the buyer/seller in Table 6. 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 two independent patentees.[40] In the 2SLS estimates, the effect is no longer statistically significant for transfers between independents, nor to any other combination, but becomes stronger for independent to firm transfers. Thus, the increase in transfers is mainly driven by independent inventors developing ideas that are subsequently sold

increase in transfers to non-connected urban or rural locations.

[39] Online Appendix Table **??** documents a similar pattern for the extensive margin.

[40] 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.

Review of Economics and Statistics Just Accepted MS.
https://doi.org/10.1162/rest_a_01067

to firms located in other areas along the network.

5.5 Robustness

In Online Appendix **??**, we evaluate the robustness of our main results. First, we use several alternative approaches to show that a spatial reallocation of inventors or innovative activity is unlikely to drive our results. Second, we document that innovation in sectors related to the railroad itself does not account for the rise in innovation. Third, patents may have become necessary to protect (pre-existing) inventions after a municipality was connected to the network. However, an increased propensity to patent is unlikely to account for our results since we find similar patenting increases in sectors where alternative forms of protection (i.e., secrecy) is more effective. Fourth, we show that our results are robust to using alternative functional forms and ways to account for potential spatial dependence in estimating standard errors. Fifth, we discuss potential explanations for differences in magnitude between the OLS and 2SLS estimates. In our view, the most plausible explanation for the larger 2SLS estimates involves network connections being allocated to areas with lower unobserved propensities for innovation. Sixth, we examine spatial heterogeneities and extend the sample to include town municipalities. Results are similar though slightly larger in our main sample, consistent with the argument that rural localities may have had comparatively less scope for using patents in production within the municipality. Lastly, we perform a set of placebo exercises showing that there is no increase in innovation in places that were allocated network connections, but where no such connection was established.

5.6 Discussion

Our results document that the spread of the Swedish railroad network led to an increase in patenting as well as an increased trade of patents. Given the potentially diverse impacts of railroads on a location, our results may be driven by a wide range of mechanisms. Although our data does not allow us to disentangle all underlying mechanisms, we here discuss and explore some potential explanations for the rise of innovative activity that we observe.

Review of Economics and Statistics Just Accepted MS.
https://doi.org/10.1162/rest_a_01067

Although our focus is on innovative activity, the arrival of the railroad is likely to have contributed to broader local economic development (e.g., Duranton & Turner, 2012). A local economic expansion may increase the demand for innovation by enlarging the market for new technologies, or increase the supply by lowering the costs of inputs into the inventive process. Indeed, areas traversed by the network saw an increase in population, a proxy for general economic activity (see Online Appendix Figure **??**A).[41] However, both patenting output and the number of patent transfers increase when accounting for this subsequent increase in population (Online Appendix Figure **??**B and **??**C).[42] Moreover, we documented above that there is no similar increase in patents transfers *within* a municipality, which suggests that the increase in patent trade is not driven by a local growth spurt. In other words, while the arrival of the railroad contributed to a local economic expansion that likely contributed to innovation, it does seemingly not fully account for the increase in innovative activity and trade in patents.

A related explanation is that an agglomeration of inventors in locations along the rail network may have spurred innovation by facilitating learning from other inventors or local spillovers (Agrawal et al., 2017; Akcigit et al., 2018), or by encouraging new individuals to become inventors due to exposure to innovation (Bell et al., 2018). Indeed, we document above that the number of inventors in a municipality increase after a network connection is established, which suggests that such mechanisms may be relevant. Yet, the fact that most municipalities had few active inventors suggest that local agglomeration is unlikely to have contributed significantly to innovative output.[43] More broadly, the fact that inventors became increasingly spatially dispersed and located in rural

[41] We use data on municipal populations for the years 1810, 1865, 1880, 1890, and 1900; population data for 1810 and 1865 are drawn from Palm (2000) and the Swedish National Archives, and the 1880–1900 data is drawn from the population censuses. Note that historical population data is not available for all municipalities, which slightly reduces the sample size in these regressions.

[42] Recall that we normalise patenting output by population at baseline (i.e., 1865) in our main regressions. Here we instead normalise by the municipal population in each respective decade. Furthermore, we present similar evidence from estimating equation (2) in Online Appendix Table **??**. After the establishment of a network connection, there is an increase in local population, though these results are somewhat weaker when instrumenting for network access using the LCP instrument. However, we again find substantial increases in both patenting output and patent transfers after accounting for the local increase in population.

[43] The number of inventors in the median municipality with at least one active inventor is 1.0 in our main sample, which indicates that agglomeration economies due to local concentrations of inventors were not empirically relevant in most of the locations along the network.

Review of Economics and Statistics Just Accepted MS.
https://doi.org/10.1162/rest_a_01067

areas over the period further suggests that agglomeration forces were overall relatively weak (see Figure 1C and Online Appendix Figure **??**).

A complementary explanation instead emphasizes the importance of integrating localities with larger external markets thus facilitating trade both in goods and ideas (Donaldson, 2018; Donaldson & Hornbeck, 2016). In particular, access to a larger market may increase the demand for new technologies by raising the return to investments in innovation (Schmookler, 1954; Acemoglu & Linn, 2004). Indeed, the broad-based rise in innovation across industries and technological fields, the gradual convergence between local and national innovation patterns, and the increased sale of patents that presumably lacked local use, are all findings consistent with such explanations. Moreover, the fact that the increase in patent trade is mainly driven by inventors selling patents to firms located in other connected locations—both urban and rural—constitutes more direct evidence of how the railroad created a larger market for innovation.

However, responding to market signals requires inventors to be able to identify the technology demands of firms in other locations, which may have been facilitated by low-cost communications and travel provided by the railroad. We can shed some further light on such mechanisms by exploring the role of the two major communication networks, which were rolled out in parallel with the railroad: a nation-wide postal service and telegraph network.[44] Online Appendix Table **??** presents OLS estimates of equation (2), where we include an additional treatment indicator for the establishment of a postal office or a telegraph station and its interaction with the rail treatment indicator. Access to a telegraph station or a postal office in a municipality is associated with an increase in the probability that a municipality is involved in innovative activity. Moreover, there is a positive and statistically significant interaction between the presence of a telegraph station or postal office and a connection to the rail network both when looking at patents and subsequent patent transfers.[45] Together, this suggests that the combined presence of communication and transport

[44]We digitize the location of all postal offices between 1830–1900 and all telegraph stations from the annual reports published by Statistics Sweden. We focus on telegraph stations designated as "class 1–3", which were the central communication nodes in the network, since detailed data on all telegraph connections is not readily available. Thus, the estimated associations should be interpreted as the link between being close to central nodes of the telegraph network, rather than a telegraph line itself.

[45]In Online Appendix Table **??**, we show that these interaction effects also are present when looking at patents and

Review of Economics and Statistics Just Accepted MS.
https://doi.org/10.1162/rest_a_01067

infrastructure may have facilitated communication and interactions over longer distances, though the fact that the establishment of telegraph stations and postal offices is likely endogenous implies that these results need to be interpreted carefully.[46]

Patent agents were one actor where such interactions were likely of great importance (Andersson & Tell, 2016; Andersson & La Mela, 2020). By lowering the cost of interacting with agents, the evolving transport and communication networks may have encouraged individuals to develop ideas into patentable inventions, or matched inventors with buyers in the market for ideas. Indeed, in Online Appendix Table **??**, we document that the increase in innovative activity, in particular by independent inventors, is driven by patents registered through a patent agent. Moreover, in the tables of Online Appendix Section **??**, we show that the simultaneous establishment of a rail connection and a postal/telegraph station is associated with an increase in both patents and transfers with an agent, but not with those filed directly by the inventor. While somewhat speculative, this further shows how lowered costs of interactions may have facilitated inventors' response to the opportunities offered by larger external markets.

In sum, this discussion highlights that the coming of the railroad may have had substantial impacts on local economies, many of which may have contributed to the rise of innovation that we document above. Yet, taken together, the evidence suggests that such local changes are unlikely to account for all of our findings. Instead, the integration of local economies with larger external markets likely contributed to innovation by raising the return to investing in innovative activity. Moreover, the evidence summarized in this section highlights how responding to such market demands may have been facilitated by the lowering of communication and travel costs that promoted interactions with other inventors, firms, and intermediaries in other locations along the network.

transfers per capita.

[46]Moreover, the spread of the postal and rail networks may also further have contributed to the diffusion of knowledge by lowering 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).

Review of Economics and Statistics Just Accepted MS.
https://doi.org/10.1162/rest_a_01067

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 both the spatial spread of innovative activity and the pace of local innovation. Second, the unfolding railroad network affected patenting in a broad range of economic sectors and technological fields, leading to an increased technological proximity between local and national innovation. Third, it enabled inventors to sell their patented ideas to firms in other locations along the network, most often those patents with applications beyond the local economy. Together, these results suggest that the historical decline in communication and transportation costs was an important causal driver behind the accelerated pace of technological progress in the latter half of the 19th century and the emergence of a national market for ideas.

Review of Economics and Statistics Just Accepted MS.
https://doi.org/10.1162/rest_a_01067

References

Acemoglu, D. & Linn, J. (2004). Market size in innovation: Theory and evidence from the pharmaceutical industry. *The Quarterly Journal of Economics*, *119*(3), 1049–1090.

Agrawal, A., Galasso, A., & Oettl, A. (2017). Roads and innovation. *The Review of Economics and Statistics*, *99*(3), 417–434.

Akcigit, U., Caicedo, S., Miguelez, E., Stantcheva, S., & Sterzi, V. (2018). Dancing with the stars: Innovation through interactions. Working Paper 24466, National Bureau of Economic Research.

Akcigit, U., Celik, M. A., & Greenwood, J. (2016). Buy, keep, or sell: Economic growth and the market for ideas. *Econometrica*, *84*(3), 943–984.

Andersson, D. E. & La Mela, M. (2020). Nordic networks: patent agents and the business of technology intermediation in sweden and finland, 1860–1910. *Scandinavian Economic History Review*, *68*(1), 45–65.

Andersson, D. E. & Tell, F. (2016). Patent agencies and the emerging market for patenting services in Sweden, 1885-1914. *Entreprises et histoire*, *1*(82), 11–31.

Arora, A., Fosfuri, A., & Gambardella, A. (2001). *Markets for technology: The economics of innovation and corporate strategy*. MIT Press.

Atack, J., Bateman, F., Haines, M., & Margo, R. A. (2010). Did railroads induce or follow economic growth? Urbanization and population growth in the American Midwest, 1850-1860. *Social Science History*, *34*(2), 171–197.

Banerjee, A., Duflo, E., & Qian, N. (2020). On the road: Access to transportation infrastructure and economic growth in China. *Journal of Development Economics*, *145*, 102442.

Bar, T. & Leiponen, A. (2012). A measure of technological distance. *Economics Letters*, *116*(3), 457–459.

Review of Economics and Statistics Just Accepted MS.
https://doi.org/10.1162/rest_a_01067

Bell, A., Chetty, R., Jaravel, X., Petkova, N., & Van Reenen, J. (2018). Who becomes an inventor in America? The importance of exposure to innovation. *The Quarterly Journal of Economics*, *134*(2), 647–713.

Berger, T. (2019). Railroads and rural industrialization: Evidence from a historical policy experiment. *Explorations in Economic History*, *74*, 101277.

Berger, T. & Enflo, K. (2017). Locomotives of local growth: The short- and long-term impact of railroads in Sweden. *Journal of Urban Economics*, *98*, 124 – 138. Urbanization in Developing Countries: Past and Present.

Bertrand, M., Duflo, E., & Mullainathan, S. (2004). How Much Should We Trust Differences-In-Differences Estimates?*. *The Quarterly Journal of Economics*, *119*(1), 249–275.

Burhop, C. (2010). The transfer of patents in imperial Germany. *The Journal of Economic History*, *70*(4), 921–939.

Campante, F. & Yanagizawa-Drott, D. (2018). Long-range growth: economic development in the global network of air links. *The Quarterly Journal of Economics*, *133*(3), 1395–1458.

Comin, D. & Hobijn, B. (2010). An exploration of technology diffusion. *American Economic Review*, *100*(5), 2031–59.

Conley, T. G. & Udry, C. R. (2010). Learning about a new technology: Pineapple in Ghana. *American Economic Review*, *100*(1), 35–69.

de Chaisemartin, C. & D'Haultfœuille, X. (2020). Two-way fixed effects estimators with heterogeneous treatment effects. *American Economic Review*, *110*(9), 2964–96.

Dijkstra, E. W. (1959). A note on two problems in connexion with graphs. *Numerische Mathematik*, *1*(1), 269.

Donaldson, D. (2018). Railroads of the Raj: Estimating the impact of transportation infrastructure. *American Economic Review*, *108*(4-5), 899–934.

Review of Economics and Statistics Just Accepted MS.
https://doi.org/10.1162/rest_a_01067

Donaldson, D. & Hornbeck, R. (2016). Railroads and American economic growth: A "market access" approach. *The Quarterly Journal of Economics*, *131*(2), 799.

Duranton, G. & Turner, M. A. (2012). Urban growth and transportation. *The Review of Economic Studies*, *79*(4), 1407.

Faber, B. (2014). Trade integration, market size, and industrialization: Evidence from China's national trunk highway system. *The Review of Economic Studies*, *81*(3), 1046.

Figueroa, N. & Serrano, C. J. (2019). Patent trading flows of small and large firms. *Research Policy*, *48*(7), 1601–1616.

Gårdlund, T. (1973). *Atlas Copco 1873-1973: historien om ett världsföretag i tryckluft*. Atlas Copco AB.

Griliches, Z. (1990). Patent statistics as economic indicators: A survey. *Journal of Economic Literature*, *28*(4), 1661–1707.

Hanlon, W. (2015). Necessity is the mother of invention: Input supplies and directed technical change. *Econometrica*, *83*(1), 68–100.

Heckscher, E. (1954). *An Economic History of Sweden*. Cambridge: Harvard University Press.

Heckscher, E. F. (1941). *Svenskt arbete och liv : från medeltiden till nutiden*. Stockholm: Bonnier.

Hornbeck, R. & Rotemberg, M. (2019). Railroads, reallocation, and the rise of american manufacturing. Working Paper 26594, National Bureau of Economic Research.

Hughes, T. P. (1988). *The Era of Independent Inventors*, (pp. 151–168). Dordrecht: Springer Netherlands.

Jaffe, A. B. (1986). Technological Opportunity and Spillovers of R&D: Evidence from Firms' Patents, Profits, and Market Value. *American Economic Review*, *76*(5), 984–1001.

Review of Economics and Statistics Just Accepted MS.
https://doi.org/10.1162/rest_a_01067

Jaffe, A. B., Trajtenberg, M., & Henderson, R. (1993). Geographic localization of knowledge spillovers as evidenced by patent citations. *the Quarterly journal of Economics*, *108*(3), 577–598.

Jörberg, L. (1988). *Svenska företagare under industrialismens genombrott 1870-1885*. Lund University Press Lund.

Lamoreaux, N. R. & Sokoloff, K. L. (1999). Inventors, firms, and the market for technology in the late nineteenth and early twentieth centuries. In N. R. Lamoreaux, D. M. G. Raff, & P. Temin (Eds.), *Learning by doing in markets, firms, and countries* (pp. 19–60). University of Chicago Press.

Lamoreaux, N. R. & Sokoloff, K. L. (2001). Market trade in patents and the rise of a class of specialized inventors in the 19th-century United States. *The American Economic Review*, *91*(2), 39–44.

Lamoreaux, N. R. & Sokoloff, K. L. (2003). *Finance, Intermediaries, and Economic Development*, chapter Intermediaries in the U.S. Market for Technology, 1870-1920. Cambridge University Press.

Moser, P. (2005). How do patent laws influence innovation? Evidence from nineteenth-century world's fairs. *American Economic Review*, *95*(4), 1214–1236.

Nicander, E. (1980). *Järnvägsinvesteringar i Sverige 1849–1914*. Lund: Ekonomisk-Historiska Föreningen.

Nicholas, T. (2010). The role of independent invention in US technological development, 1880–1930. *The Journal of Economic History*, *70*(1), 57–82.

Nicholas, T. (2011). Independent invention during the rise of the corporate economy in Britain and Japan. *The Economic History Review*, *64*(3), 995–1023.

Review of Economics and Statistics Just Accepted MS.
https://doi.org/10.1162/rest_a_01067

Nuvolari, A. & Vasta, M. (2015). Independent invention in Italy during the liberal age, 1861–1913. *The Economic History Review*, *68*(3), 858–886.

Palm, L. A. (2000). *Folkmängden i Sveriges socknar och kommuner 1571-1997 : med särskild hänsyn till perioden 1571-1751*. Göteborg: Nomen förlag.

Pascali, L. (2017). The wind of change: Maritime technology, trade, and economic development. *American Economic Review*, *107*(9), 2821–54.

Perlman, E. R. (2016). *Connecting the Periphery, Three Papers in the Development Caused by Spreading Transportation and Information Networks in the Nineteenth Century United States*. PhD thesis, Boston University, Graduate School of Arts and Sciences.

Rydfors, A. (1906). Politisk historik. In G. Welin (Ed.), *Statens järnvägar 1856-1906: historisk-teknisk-ekonomisk beskrifning i anledning af statens järnvägars femtioåriga tillvaro, utgifven på Kungl. Maj:ts nådiga befallning af Järnvägsstyrelsen* (pp. 22–213). Centraltryckeriet, Stockholm.

Schankerman, M. & Pakes, A. (1986). Estimates of the value of patent rights in European countries during the post-1950 period. *The Economic Journal*, *96*, 1052–1076.

Schmookler, J. (1954). The level of inventive activity. *The Review of Economics and Statistics*, *36*(2), 183–190.

Serrano, C. J. (2010). The dynamics of the transfer and renewal of patents. *The RAND Journal of Economics*, *41*(4), 686–708.

Sjöberg, A. (1956). Järnvägarna i svenskt samhällsliv, några huvuddrag i deras utveckling. In *Sveriges järnvägar hundra år* (pp. 1–159). Kungl. Järnvägsstyrelsen, Stockholm.

Spulber, D. F. (2015). How patents provide the foundation of the market for inventions. *Journal of Competition Law & Economics*, *11*(2), 271–316.

Review of Economics and Statistics Just Accepted MS.
https://doi.org/10.1162/rest_a_01067

Statistics Sweden (1960). *Historical Statistics of Sweden: Statistical Survey (tables not published in volumes I and II)*. Kungl. Boktryckeriet P.A. Norstedt & Söner.

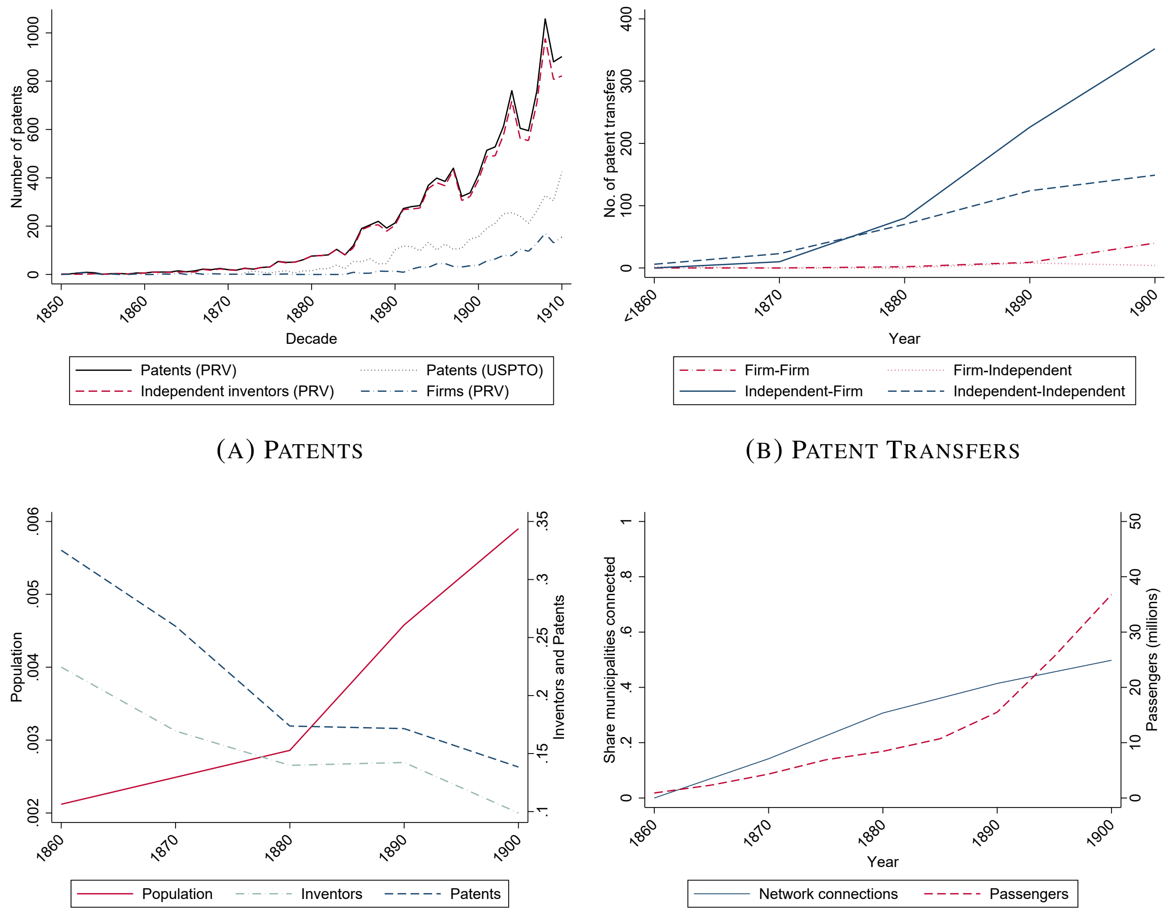
Streb, J., Baten, J., & Yin, S. (2006). Technological and geographical knowledge spillover in the German empire 1877–1918. *The Economic History Review*, *59*(2), 347–373.

Westlund, H. (1998). State and market forces in Swedish infrastructure history. *Scandinavian journal of history*, *23*(1-2), 65–88.

Wohlert, K. (1981). *Framväxten av svenska multinationella företag: en fallstudie mot bakgrund av direktinvesteringsteorier: Alfa-Laval och separatorindustrin 1876-1914*. Almqvist & Wiksell international.

Review of Economics and Statistics Just Accepted MS.
https://doi.org/10.1162/rest_a_01067

7 Figures



(A) PATENTS

(B) PATENT TRANSFERS

(C) HERFINDAHL–HIRSCHMAN INDEX

(D) SPREAD OF RAILROAD NETWORK

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 share of municipalities that are connected to the railroad network (i.e., located within 5 km of a railroad) and the number of passengers traveling on the railroad network from Statistics Sweden (1960, Table 47).

Review of Economics and Statistics Just Accepted MS.
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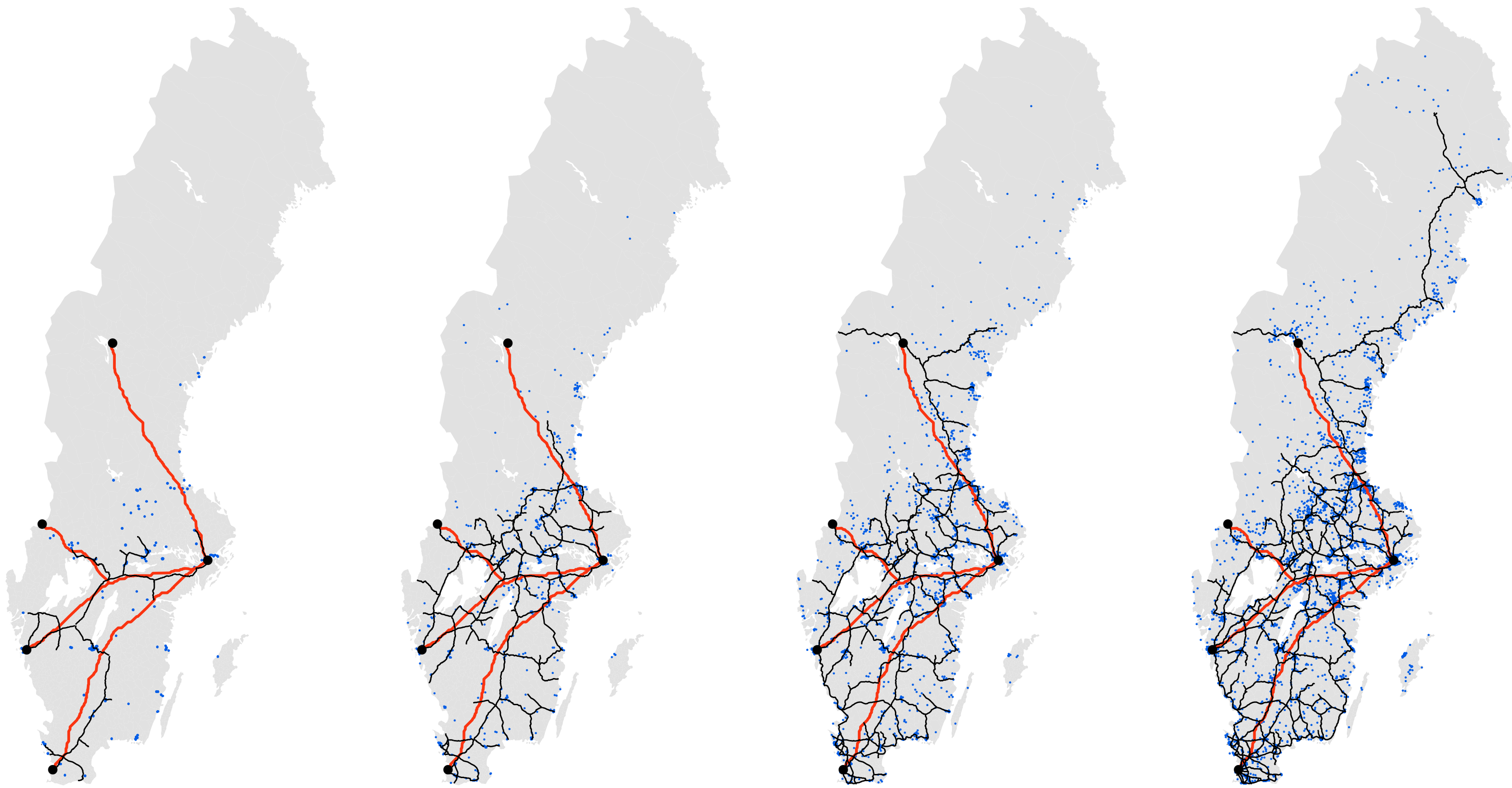

(A) 1870 (B) 1880 (C) 1890 (D) 1900

FIGURE 2:
ROLLOUT OF THE RAILROAD NETWORK AND PATENTS

Notes: Figures A–D display the railroad network for the years 1870, 1880, 1890 and 1900 depicted as thin lines, the LCPs depicted as thick lines between the targeted destinations used to identify the LCPs denoted by circles, and the location of patents in the subsequent decade depicted by small dots.

Review of Economics and Statistics Just Accepted MS.
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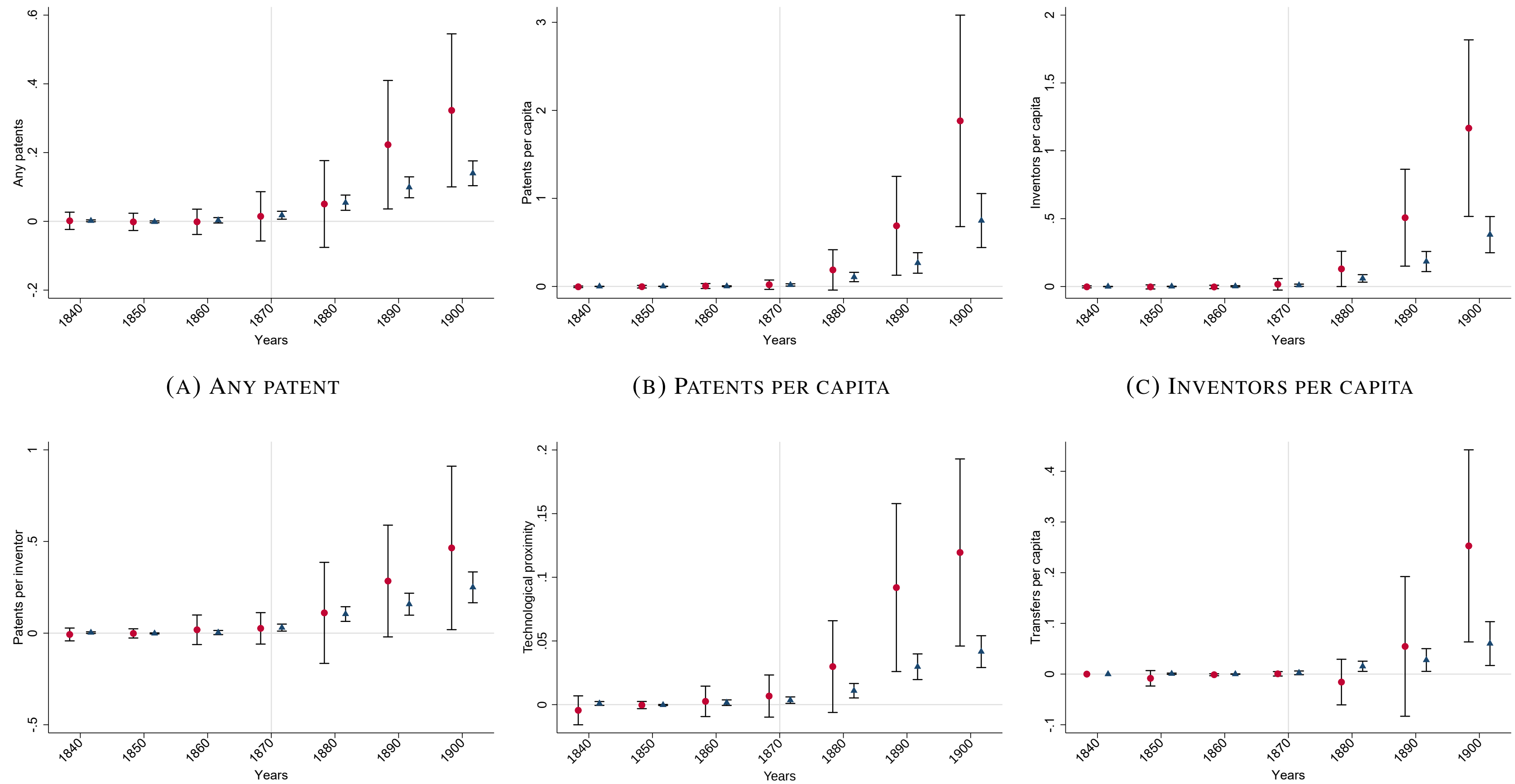

(A) ANY PATENT

(B) PATENTS PER CAPITA

(C) INVENTORS PER CAPITA

(D) PATENTS PER INVENTOR

(E) TECHNOLOGICAL PROXIMITY

(F) PATENT TRANSFERS PER CAPITA

FIGURE 3:
ROLLOUT OF THE RAILROAD NETWORK AND INNOVATIVE ACTIVITY

Notes: The figure displays OLS estimates (triangles) and 2SLS estimates (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), the number of patents per inventor (D), the technological proximity to the national distribution (E), and the number of patent transfers per 1,000 inhabitants (F). 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. Population data to scale patents, inventors, and transfers per 1,000 inhabitants are from 1865. Standard errors are clustered at the municipality level.

Review of Economics and Statistics Just Accepted MS.
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8 Tables

TABLE 1: FIRST-STAGE ESTIMATES

Dependent variable:	Network Connection (=1)			
	(1)	(2)	(3)	(4)
ln(Distance to Least-Cost Path)×Year 1870	-0.085***	-0.069***	-0.067***	-0.076***
	(0.007)	(0.008)	(0.008)	(0.009)
ln(Distance to Least-Cost Path)×Year 1880	-0.097***	-0.078***	-0.066***	-0.065***
	(0.008)	(0.009)	(0.009)	(0.010)
ln(Distance to Least-Cost Path)×Year 1890	-0.097***	-0.062***	-0.052***	-0.062***
	(0.008)	(0.009)	(0.010)	(0.010)
ln(Distance to Least-Cost Path)×Year 1900	-0.106***	-0.071***	-0.063***	-0.074***
	(0.008)	(0.009)	(0.009)	(0.010)
Local Geography×Year FE	No	Yes	Yes	Yes
Pre-Rail Controls×Year FE	No	No	Yes	Yes
Region FE×Year FE	No	No	No	Yes
Observations	18152	18152	18152	18152
Mean dep. var.	0.163	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. *** - $p < 0.01$, ** - $p < 0.05$, * - $p < 0.1$.

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TABLE 2: 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). 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. Population data to scale patents/inventors per 1,000 inhabitants are from 1865. Standard errors are given in parentheses and are clustered at the municipality level. *** - $p < 0.01$, ** - $p < 0.05$, * - $p < 0.1$.

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TABLE 3: THE EFFECT OF NETWORK CONNECTIONS ON THE LOCAL TECHNOLOGICAL PROFILE

Dependent variable:	Patents per capita								Tech. proximity	
	Technology class				Local economic structure				Fields	Sectors
	Novel field	Non-novel field	Novel sector	Non-novel sector	Existing sector	Non-existing sector	Leading sector	Non-leading sector		
Panel A: OLS	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Network Connection (=1)	0.235***	0.084***	0.194***	0.125***	0.046***	0.273***	0.043***	0.276***	0.024***	0.039***
	(0.040)	(0.030)	(0.030)	(0.044)	(0.010)	(0.062)	(0.010)	(0.062)	(0.003)	(0.005)
Panel B: 2SLS	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Network Connection (=1)	0.579***	0.170**	0.376***	0.373***	0.167***	0.584***	0.167***	0.585***	0.064***	0.076***
	(0.178)	(0.080)	(0.126)	(0.136)	(0.056)	(0.206)	(0.055)	(0.206)	(0.017)	(0.029)
Municipality FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Region FE×Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Local Geography×Year FE	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
First-Stage F-stat	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
Mean dep. var.	0.095	0.021	0.081	0.034	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 1–8) and technological proximity to the national distribution based on either 89 technical (DPK) fields or 14 industrial sectors (columns 9–10). A non-novel (novel) field or sector refers to patents in classes with a (no) prior patent in the municipality. A (non-)existing sector refers to if the patent is (not) related to an industrial sector that existed in 1865. A (non-)leading sector refers to if the patent is (non-)related to the industrial sector with the largest share of output. 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. Population data to scale patents per 1,000 inhabitants are from 1865. Standard errors are given in parentheses and are clustered at the municipality level. *** - $p < 0.01$, ** - $p < 0.05$, * - $p < 0.1$.

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TABLE 4: THE EFFECT OF NETWORK CONNECTIONS ON PATENT TRANSFERS

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	0.085**	0.059*	0.004	0.018
	(0.021)	(0.017)	(0.008)	(0.012)	(0.040)	(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. 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. Population data to scale transfers per 1,000 inhabitants are from 1865. Standard errors are given in parentheses and are clustered at the municipality level. *** - $p < 0.01$, ** - $p < 0.05$, * - $p < 0.1$.

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TABLE 5: THE EFFECT OF NETWORK CONNECTIONS ON TRANSFERS BY DISTANCE TO THE LOCAL ECONOMIC STRUCTURE

Dependent variable:	Transfers per capita							
	Technology class				Local economic structure			
	Novel field	Non-novel field	Novel sector	Non-novel sector	Existing sector	Non-existing sector	Leading sector	Non-leading sector
Panel A: OLS	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Network Connection (=1)	0.026***	0.004*	0.024***	0.005**	0.007***	0.022***	0.006***	0.023***
	(0.006)	(0.002)	(0.006)	(0.003)	(0.002)	(0.007)	(0.002)	(0.007)
Panel B: 2SLS	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Network Connection (=1)	0.072**	0.013	0.071**	0.015	0.002	0.084**	0.004	0.082**
	(0.032)	(0.011)	(0.030)	(0.013)	(0.008)	(0.037)	(0.008)	(0.037)
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	0.001	0.007	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) field or sector refers to patents in classes with a (no) prior patent in the municipality. A (non-)existing sector refers to if the patent is (not) related to an industrial sector that existed in 1865. A (non-)leading sector refers to if the patent is (non-)related to the industrial sector with the largest share of output. 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. Population data to scale transfers per 1,000 inhabitants are from 1865. Standard errors are given in parentheses and are clustered at the municipality level. *** - $p < 0.01$, ** - $p < 0.05$, * - $p < 0.1$.

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TABLE 6: 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)	(0.002)	(0.000)	(0.001)	(0.003)
Panel B: 2SLS	(1)	(2)	(3)	(4)	(5)
Network Connection (=1)	0.072**	0.009	0.002	0.001	0.012
	(0.032)	(0.012)	(0.002)	(0.002)	(0.012)
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. 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. Population data to scale transfers per 1,000 inhabitants are from 1865. Standard errors are given in parentheses and are clustered at the municipality level. *** - $p < 0.01$, ** - $p < 0.05$, * - $p < 0.1$.