Journal of Urban Economics 139 (2024) 103629

Contents lists available at ScienceDirect

Journal of Urban Economics

journal homepage: www.elsevier.com/locate/jue

Collaboration and connectivity: Historical evidence from patent records ☆

Thor Berger [a,b,c,d,*,1], Erik Prawitz [e,d,1]

[a] Swedish Collegium for Advanced Study (SCAS), Uppsala University, Sweden
[b] Department of Economic History, School of Economics and Management, Lund University, Sweden
[c] CEPR, United Kingdom
[d] Research Institute of Industrial Economics, Sweden
[e] Linnaeus University, Sweden

ARTICLE INFO

Keywords:
Innovation
Collaboration
Transport infrastructure
Railroads

ABSTRACT

Why has collaboration become increasingly central to technological progress? We document the role of lowered travel costs by combining patent data with the rollout of the Swedish railroad network in the 19th and early-20th century. Inventors that gain access to the network are more likely to produce collaborative patents, which is partly driven by long-distance collaborations with other inventors residing along the emerging railroad network. These results suggest that the declining costs of interacting with others is fundamental to account for the long-term increase in inventive collaboration.

1. Introduction

Innovation is often believed to be an outcome of individual ingenuity. Yet collaboration has become increasingly central to innovation and technological progress over the past century. In recent decades, a growing share of patented inventions originate from collaborations, while the impact of teams has grown across nearly all scientific fields (Wuchty et al., 2007; Jones, 2009; Kerr and Kerr, 2018; Wu et al., 2019).[2]

Why has collaboration increased? One explanation emphasizes the rising complexity of innovation over time (Bloom et al., 2020). In the face of a growing "burden of knowledge" (Jones, 2009), collaboration between inventors may be required to produce technological breakthroughs (Agrawal et al., 2016; Akcigit et al., 2018; Iaria et al., 2018). Another explanation instead emphasizes the secular decline in the cost of collaboration, due to improvements in communication and transport technology. Because collaboration involves significant search frictions as well as complex communication and coordination (Boudreau et al., 2017), lowering the costs of interacting with others may lead inventors to initiate and sustain existing collaborations.

Our paper provides evidence on the role of such interaction costs in shaping inventive collaboration. More specifically, we leverage the historical rollout of the Swedish railroad network across nearly 2,400 municipalities combined with the universe of patents granted by the Swedish Intellectual Property Office (PRV) and the USPTO between 1840 and 1910. We define collaborations as patents that involve more than one individual inventor or patentee and show that the reduction in communication and travel costs after the arrival of the railroad led to a substantial increase in collaboration between Swedish inventors.

To motivate our analysis, we first document that the origins of the long-term increase in collaboration can be traced to the latter half of the 19th century, when collaboration became increasingly prevalent among Swedish inventors. The geography of collaboration also underwent significant changes in this period. Collaboration was initially confined to large cities where search frictions and interaction costs arguably were lower. Yet over the next decades collaboration increasingly involved inventors residing in different urban and rural locations, separated by increasingly larger distances. Notably, the rise of long-distance collaboration coincides both in time and space with the expansion of the railroad network.

To establish a causal link between lowered travel costs and the rise of collaborations, we leverage the staggered rollout of the Swedish rail network. Unlike in many European countries, the railroad network was mainly constructed and funded by the state (Heckscher, 1954, pp. 241–42). The aim was to connect the capital Stockholm with other important

☆ We are grateful for comments by the editor, Stephan Heblich, and two anonymous referees. We are also indebted to David Andersson for his contribution to this project at an early stage, as well as Linh Pham and Krystal Zhao Jansson who provided excellent research assistance. Funding from Jan Wallanders och Tom Hedelius stiftelse, The Lars Erik Lundberg Foundation for Research and Education, and Riksbankens Jubileumsfond is gratefully acknowledged.

* Corresponding author at: Department of Economic History, School of Economics and Management, Lund University, Sweden.
E-mail address: thor.berger@ekh.lu.se (T. Berger).

[1] The authors contributed equally to the paper.

[2] A similar trend is evident when focusing on academic papers. Jones (2021) documents that sole-authored work is becoming increasingly rare among academic economists, while the impact advantage of co-authored papers is rising.

https://doi.org/10.1016/j.jue.2023.103629
Received 19 July 2022; Received in revised form 14 November 2023
Available online 13 December 2023

cities in the east, west, and north. Consequently, the placement of the main rail lines meant that locations along these routes gained access more or less by chance. Indeed, we show that there are no pre-existing differences in collaboration prior to a municipality obtaining a network connection.

Our main analysis takes a difference-in-differences approach examining whether inventors increasingly collaborate after their municipality becomes connected to the national rail network.[3] We find increases in collaboration both along the extensive and intensive margin in the decades after a network connection is established. First, we show that the probability that at least one inventor in a municipality is involved in a collaborative patent granted by the PRV or the USPTO increases. Second, we find that the number of collaborations increase. The increase in collaboration is driven by the establishment of new teams involving independent inventors, rather than firms, as well as an increasing patent output within existing teams. One concern is that the increase in collaboration mechanically results from a higher entry or reallocation of inventors to areas connected to the rail network as documented by Andersson et al. (2023). However, we find sizable increases in collaboration also when normalizing the number of collaborations by the number of inventors or patents in each municipality.

We then proceed to examine how the spread of the railroad network affected the geography of collaboration. First, we document that the increase in collaboration partly reflects an increase in collaboration between inventors residing in different localities along the network, which is further evident from the fact that collaborations took place over increasingly longer distances. Second, we show that the increase is solely driven by collaborations between inventors that are located in places connected to the network, while there is no evidence that collaborations increased with inventors residing in areas that remained unconnected. Third, we examine the differential impacts on rural and urban areas, respectively. While rural areas saw large increases in collaboration with inventors located in other rural and urban locations, a network connection in an urban area led to increases in local collaboration but seemingly not with inventors in other locations.

Our paper contributes to a growing literature studying the role of travel costs in shaping spatial patterns of innovation. We provide new evidence that the lowering of travel costs due to the coming of the railroad led to the rise of collaboration between inventors residing in places separated by increasingly greater distances. Most directly, these results relate to recent work analyzing the role of travel costs in shaping collaboration due to the introduction of U.S. low-cost airlines (Catalini et al., 2020), the expansion of the Beijing subway (Koh et al., forthcoming), and the Chinese high speed rail network (Dong et al., 2020). While these modern empirical contexts provide large relative reductions in travel costs along the intensive margin (e.g., travel speed), the individuals and locations under study have access to a variety of alternative pre-existing communication and transport modes. A useful feature of our historical setting is that the prohibitively high communication and transport costs in the pre-rail era meant that most inventors were virtually isolated from other parts of the country prior to the coming of the railroad. Moreover, while most existing work has focused on scientists and academic collaboration, we study the role of transport costs in shaping collaboration between inventors where search and matching costs may be higher given the less standardized forms of collaboration.

Our findings are also more broadly related to the literature that studies the role of communication and transportation costs in shaping the diffusion of new ideas and knowledge. In particular, Agrawal et al. (2017) shows that the spread of highways increased innovative activity partly by facilitating the local diffusion of knowledge *within* U.S. metropolitan areas. While their empirical strategy does not allow them to identify knowledge flows between areas, we contribute evidence of how a lowering of travel costs facilitates collaboration and the spread of knowledge between places. These results are also related to recent work by Hanlon et al. (2022) showing that the lowering of communication costs due to the introduction of the Uniform Penny Post in 19th-century Britain led to increases in citations between scientists that experienced greater reductions in communication costs, as well as an increase in patenting activity. While this work isolates the role of communication costs, we in contrast examine a technology that primarily lowered travel costs and thus facilitated face-to-face interactions between inventors.

Lastly, our paper is related to the literature studying trends in scientific and academic collaboration (e.g., Wuchty et al., 2007; Jones, 2009, 2021). While most of this literature focuses on the recent past, we show that the rise of collaboration is a long-run phenomenon. At least in the Swedish case, the rise of collaboration between inventors began more than 150 years ago thus contributing to recent work that examines long-run trends in inventive collaboration (van der Wouden, 2020).

2. Data and descriptive evidence

2.1. Data: patents and railroads

Our dataset is built up by the full universe of all granted Swedish patents between 1840 and 1910. It was manually compiled and digitized from the patent registers at the Swedish National Archives (*Riksarkivet*) and the archives of the PRV and include information on the name and occupation of the patentees and inventors for each patent. The registers also contain detailed information on patent duration, application and grant date, and patent class according to the German patent classification, *Deutsche Patentklassifikation* (DPK).[4]

A total of 16,674 patents were granted by the PRV to 11,000 unique individuals or firms residing in Sweden over the period.[5] Crucially, each patent lists all patentees and inventors credited with invention. As our main definition, we define a collaborative patent as a patent with more than one individual registered as a patentee or an inventor on the patent.[6] We view this as the broadest form of collaboration since it includes all types of collaboration in innovation taking place between individuals. Using our main definition, we identify 2,504 collaborative patents in our dataset. Additionally, in our analysis below, we also employ more narrow definitions of inventive collaboration where we define a patent as collaborative: (1) if there is more than one inventor registered on a patent (i.e., excluding all patentees); or (2) if a patent has more than one inventor registered on the patent or in the case that it has no listed inventors, but more than one patentee (i.e., cases where we cannot identify the true inventor). The latter definition is motivated by the fact that if no inventor was specified on a Swedish patent, the patentee was the inventor.

In addition to our Swedish patent data, we also collect data on all patents granted in the United States by the USPTO to Swedish residents from the Annual Reports of the Commissioner of Patents for the same time period. Since all US patents had to provide a list of the inventors, we simply define a collaborative USPTO patent as a patent with two or more inventors. According to this definition, we observe 113 collaborative patents among the 1,350 total USPTO patents.

[3] Recent literature highlights the empirical challenges in estimating treatment effects in settings with many groups and time periods. To alleviate such concerns, we also use the approach developed by de Chaisemartin and D'Haultfoeuille (2020) that is consistent and robust to treatment heterogeneity.

[4] We code these 89 DPK patent classes into 14 industrial sectors defined by Nuvolari and Vasta (2015).

[5] In the Swedish patent system, which was partly inspired by its German counterpart, a patent could be granted to a firm or a non-inventor individual as long as they stated who the inventor was.

[6] For example, Online Appendix Figure A.1 shows patent no. 25666, with three patentees who are also the inventors.

To measure the spread of the railroad network, we digitize maps of the rail network available from Statistics Sweden for each decade until the early 1900s. For each of the consistently defined 2,387 municipalities, we calculate the distance from the municipality centroid to the nearest railroad at the start of each decade 1860–1900.[7] To pair the railroad data with the patent records, we leverage the fact that the latter include information about inventors address and place of residence. Approximately 80 percent of granted patents contain non-missing information on the place of residence for the inventor(s) or the patentee(s) which enables us to geolocate each individual/patent by using the longitude and latitude of the place denoted on the patent. Since our railroad data provides us with information of the railroad network at the start of each decade, we aggregate the patent data to 10-year periods. For each municipality, we thus observe rail access at the beginning of each decade starting in 1840 to 1900 and patenting output during the next 10 years.

To aggregate collaborations at the municipality level in our main analysis, we want to handle within- and across-municipality collaborations in a consistent fashion. In our main definition, we therefore let each individual involved in a collaborative patent correspond to one collaboration at the municipality level. To exemplify, Online Appendix Figure A.1 shows Swedish patent no. 25666 that involved two engineers from the capital of *Stockholm* and one engineer from the municipality of *Trollhättan*. In this case, Stockholm obtains two collaborations and Trollhättan obtains one collaboration. In other words, each node of the patent-level collaboration is distributed to the municipality it belongs to. We document in Online Appendix A.1 that our results are robust to instead counting each link connected to the nodes in a municipality (i.e., in the example above, Stockholm and Trollhättan would obtain four and two collaborations, respectively).

At the municipality level, we add other data from a variety of sources. We collect population data from Palm (2000) and the Swedish National Archives. Additional data on manufacturing activity originating from Statistics Sweden, as well as geographical data (e.g., the elevation and slope) for each municipality, is drawn from Andersson et al. (2023).

2.2. Descriptive evidence: railroads and the rise of patent collaborations

2.2.1. Expansion of the Swedish railroad network

The plans for Sweden's railroad network were drawn up in the mid-1850s, when the *Riksdag* decided that the main parts of the network were to be funded and operated by the state. The network proposal by the designated state planner — Nils Ericson — involved connecting the capital Stockholm with key cities in the north, west, and south. Ericson's proposal was to route lines along the shortest routes, avoiding pre-existing transport modes (i.e., canals) and the coastline for strategic military reasons. As a result, many historically important cities remained unconnected (Berger and Enflo, 2017), as the backbone of the network traversed previously isolated areas in the interior (Heckscher, 1954; Berger, 2019).

In the mid-1850s, the state started building the main trunk lines of the network connecting the capital of Stockholm with the main cities in the West (Gothenburg) and the South (Malmö). Fig. 1A shows that the main backbone of the network was finished by the early 1870s. A key building block of Ericson's network proposal was that privately funded lines would connect those areas that had been neglected by the early state railroads. Indeed, starting in the 1870s, there was a proliferation of privately funded railroads. By the turn of the century most parts of the network were completed (see Fig. 1D).

2.2.2. Railroads and the rise of patent collaboration

Sweden experienced rapid growth in patenting output as the rail network expanded over the latter half of the 19th century (Andersson et al., 2023). Fig. 2A shows that the rise of innovative activity was also coupled with a growing number of patent collaborations.[8] In the 1860s, about 60 collaborative patents were granted, which had increased to more than 1,000 during the first decade of the 20th century. While the growth of collaborations partly reflect a higher patent volume, the *share* of patents that were collaborative nearly doubled over the same period (Online Appendix Figure A.2). Fig. 2A shows that the increase in collaborations coincides with a growing intensity of rail travel, which arguably reflects the reduced travel costs due to the expanding network.

Independent inventors in Sweden produced about 90% of patented inventions in the pre-World War I era. Consequently, most collaborations involved independent inventors rather than firms. Inventors involved in collaborations most commonly were highly-skilled engineers, managers, or factory owners (Online Appendix Figure A.4A).[9] At the same time, lower-skilled workers such as mechanics and instrument makers are also represented.[10] Most collaborations consisted of inventors working in small teams of two to three individuals (Online Appendix Figure A.5), which is indicative of high coordination and communication costs. Notably, the increase in collaboration is evident across most industrial sectors, ranging from industries such as agriculture to more complex industries such as chemicals. Thus, collaboration was not confined to particularly complex technological areas.

2.2.3. Railroads and the geography of patent collaboration

Fig. 1 shows that the geography of collaboration underwent considerable changes as the rail network expanded in the late-19th century. Initially, patent collaborations are concentrated in a few urban locations such as the capital Stockholm (Online Appendix Figure A.7), where interaction costs arguably were lower. Indeed, Fig. 2B shows that collaborations in the 1860s typically only involved inventors residing in the same municipality, which is suggestive of prohibitively high communication and transport costs. Yet over the latter half of the 19th century, collaborative patents increasingly involved inventors located in different and more distant municipalities.

Collaboration was initially confined to urban areas, yet Fig. 2C shows that inventors in both urban and rural municipalities were increasingly more likely to collaborate in the latter half of the 19th

[7] Our historical administrative boundaries are based on maps obtained from the Swedish National Archives (*Riksarkivet*). To adjust for urban expansion over the period we study, we merge urban municipalities with their adjacent rural areas.

[8] Alternative measures of collaboration yields a similar picture. For example, Online Appendix Figure A.3 documents that also the average number of patentees and/or inventors per patent increased. Between 1860 and 1910, the average number of inventors and patentees per patent increased from one to 1.17. For comparison, Wuchty et al. (2007, p.1037) report that average team size on US patents rose from 1.7 to 2.3 inventors between 1975 and 2000.

[9] While engineer is by far the most common occupation among collaborating inventors, the probability that a patent is collaborative is broadly similar across different occupational groups (Online Appendix Figure A.4B). That is, higher- and lower-skilled inventors do not seem to collaborate to a different extent once one adjusts for differences in patenting output (Online Appendix Figure A.4C). See (Berger and Prawitz, forthcoming) for more information about the economic and social origins of independent inventors in Sweden during the period under study.

[10] A potential explanation for collaboration among inventors belonging to the lower economic and social strata is that collaboration could alleviate financial constraints. However, the low application fees of the Swedish patent system likely enabled also individuals belonging to middle- or lower-skill groups to patent alone if they had valuable ideas. The Swedish patent system had a low application fee and an increasing fee structure. In 1885, the application fee was SEK 50 (approximately $13.2 USD and £2.7 GBP in contemporary currencies, respectively) and it was lowered further in 1893 to SEK 20. This was lower compared to both the US and the UK. For example, in the same year the application fee was about £4 in the UK (£25 before the reform in 1884).

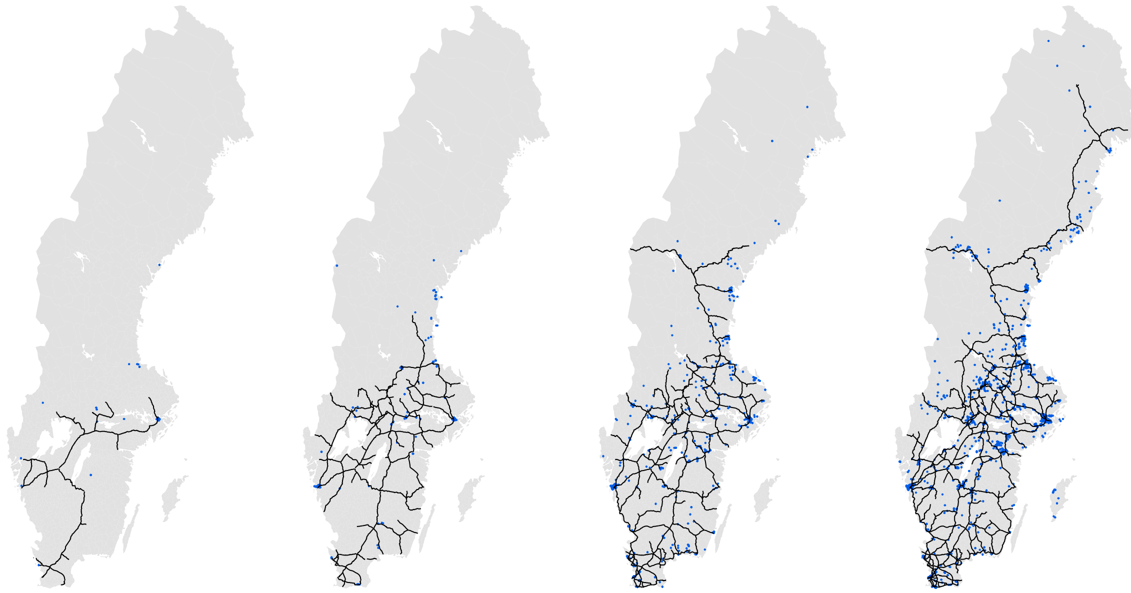


Fig. 1. Spatial diffusion of patent collaborations.
Notes: This figure displays the extent of the rail network at the start of each decade and the number of collaborative PRV patents granted to Swedish inventors in each municipality over the subsequent decade. Each blue dot denotes a collaborative patent.

century.[11] While inventors in urban municipalities become relatively more likely to collaborate with others in the same city, those located in rural areas become relatively more likely to collaborate with inventors in other municipalities (Fig. 2D). The railroad may have helped rural inventors to learn about other inventor's work and identify potential collaborators in several ways. First, it facilitated participation at industrial exhibitions and trade fairs, which provided ample opportunity to interact with other inventors.[12] Second, the railroad also presumably helped inventors to interact with patent agents in Stockholm. Agents had geographically dispersed networks, which they may have leveraged to connect inventors with complementary skills or ideas in different parts of the country. Third, the railroad led to a substantial increase in the circulation of ideas in the form of journals and magazines that enabled inventors also in peripheral areas to stay informed about inventors and innovative activities beyond their locality.[13]

Together, these descriptive results and the fact that the spread of collaboration displayed in Fig. 1 closely tracks the expansion of the rail network provide suggestive evidence that the rise of collaboration was deeply intertwined with the diffusion of the railroad. We next proceed to document a plausibly causal link between the expansion of the rail network and patent collaborations.

3. Analysis and results

3.1. Empirical strategy

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

$$Y_{irt} = \gamma_i + \beta Network_{it} + \phi_{rt} + \mathbf{X}_i' \delta_t + \varepsilon_{irt}, \quad (1)$$

where Y_{irt} is a measure of collaboration (e.g., the number of collaborations) in a municipality i, in region r, and in decade t. $Network_{it}$ is an indicator variable taking the value one if a municipality is connected to the rail network at the start of the decade t. In our main specifications, we define this indicator to take the value one if a municipality centroid is within 5 km of the rail network. In alternative specifications, we instead include additional distance cutoffs or the log distance to the network in each decade to measure connectivity.[14]

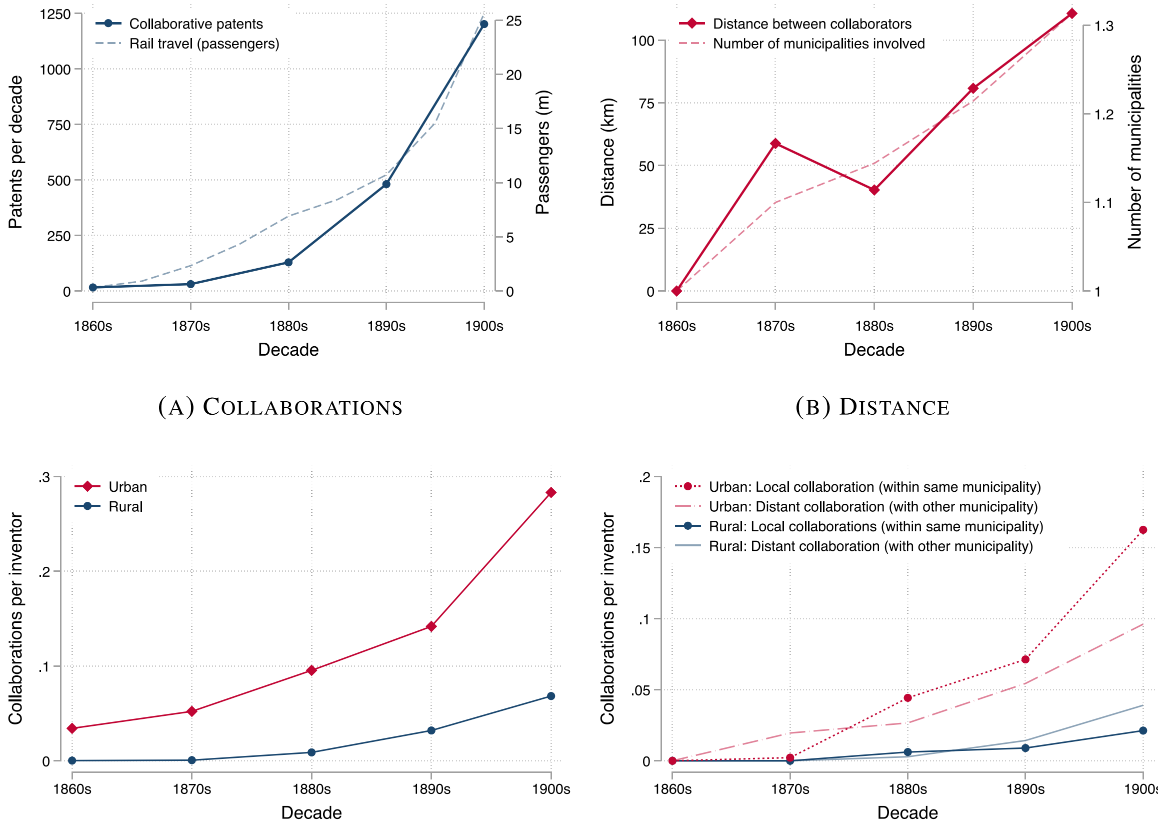
We include municipality (γ_i) fixed effects to control for time-invariant differences across municipalities, as well as region-by-decade fixed effects (ϕ_{rt}) to flexibly allow for shocks that may vary across

[11] We more directly examine differences in collaboration among inventors residing in smaller and larger municipalities in the Online Appendix. Online Appendix Figure A.8A displays the number of patent collaborations per inventor and the population in their municipality of residence, which shows that collaboration was more prevalent in more populous places in the late-19th and early-20th century. However, Online Appendix Figure A.8B shows that while collaboration was initially confined to the largest municipalities, collaboration increased substantially also in less populous places particularly in the 1890s and 1900s.

[12] As in most European countries, craft and industrial exhibitions proliferated in late-19th century Sweden. Exhibitions took place in many larger and smaller cities throughout the country, but perhaps the most well-known is the Stockholm Exhibition of 1897 where thousands of industrialists and inventors exhibited their products to about 1.5 million visitors drawn from across the country.

[13] Although the railroad facilitated the distribution of a large and growing number of newspapers, journals, and magazines, perhaps the most important for inventors was the leading industry journal *Norden*, a Swedish equivalent to *Scientific American*. In 1886, The Association of Swedish Inventors created an "Inventor Exchange" in the journal that became a key outlet for inventors to spread information about their new (patented) inventions available for sale. As evidence of its popularity, the Inventor Exchange received more than a thousand advertisements during its first twenty years in existence (see Andersson and Tell, 2018).

[14] In particular, we choose the 5 km cutoff based on the estimates reported in Online Appendix Figure A.11 where we report estimates of Eq. (1) where we allow the impact of a network connection on collaboration to vary flexibly across different distances to the network. As evident from Online Appendix Figure A.11, the effect is evident only for the 0–5 km cutoff, while it is small in magnitude and not statistically significant at further distances.



(A) Collaborations (B) Distance

(C) Urban vs. rural (D) Local vs. distant

Fig. 2. The rise of patent collaborations before World War I.
Notes: A: the number of patents granted by the PRV that listed more than one inventor or patentee and the number of passengers traveling along the railroad network from Sweden (1960). B: the average distance between all georeferenced inventors listed on collaborative patents and the average number of municipalities per collaborative patent. C: the number of collaborations per active inventor in urban and rural municipalities. D: the number of collaborations per active inventor with inventors in the same and other municipalities, separately reported for urban and rural municipalities. Note that the unit of observation is a patent in A and B and a municipality in C and D.

regions and time. Throughout, we cluster standard errors at the municipality level to allow for heteroskedasticity and correlation within municipalities.

The railroad network was principally designed to connect the capital Stockholm with a few major other cities, while it traversed many not directly targeted areas (Heckscher, 1954; Berger and Enflo, 2017; Berger, 2019; Andersson et al., 2023). In our main specifications, we exclude these targeted areas (Stockholm, Gothenburg, Malmö, Östersund, and the area where the Swedish network connected to the Norwegian railroads) to alleviate endogeneity concerns. While we control for any time-invariant characteristics at the local level using our municipality fixed effects, the trajectories of municipalities connected to the network may still differ in ways from those that remained unconnected. We address this issue in two ways.

First, we interact a set of time-invariant controls with decadal fixed effects in our regressions. In particular, we control for a set of geographic characteristics aimed to capture the cost of rail construction in each municipality, as well as a set of measures capturing potential pre-existing differences between areas (not) traversed by the rail network. In particular, we control for the log area, the mean and standard deviation of elevation, the longitude and latitude, as well as the mean slope of each municipality. We also control for log population at baseline (1865), an indicator capturing whether a municipality had been granted any patent prior to the 1860s, log distance to the nearest town, the number of firms and manufacturing workers per capita in 1865, as well as an indicator for all urban municipalities.

Second, we also use the difference-in-differences approach developed by de Chaisemartin and D'Haultfoeuille (2020, 2022) that circumvents common challenges in estimating treatment effects in settings with many groups and time periods. Similar to an event-study setup, we estimate dynamic treatment effects of a rail connection on patent collaborations. Under the assumption that switchers and non-switchers (i.e., municipalities that change their treatment status and gain access to the rail network or not) follow a common trend prior to treatment, the resulting treatment effect for switchers is consistent and robust to the presence of heterogeneous treatment effects, in contrast to standard two-way fixed effects models.

3.2. Main results

3.2.1. Railroads and the rise of patent collaborations

We first examine whether the establishment of a connection to the railroad network increased the probability that any inventor in a municipality became involved in a collaborative patent granted by the PRV. Fig. 3 displays estimates using the approach developed by de Chaisemartin and D'Haultfoeuille (2020, 2022). Importantly, there are no pre-existing differences in the probability that a municipality is involved in a collaborative patent during the decades prior to a connection is established, which suggests that the common trends assumption holds. However, in the decades after a municipality becomes connected to the network we observe a gradual increase in the probability that at least one inventor in that municipality becomes involved in a patent collaboration.

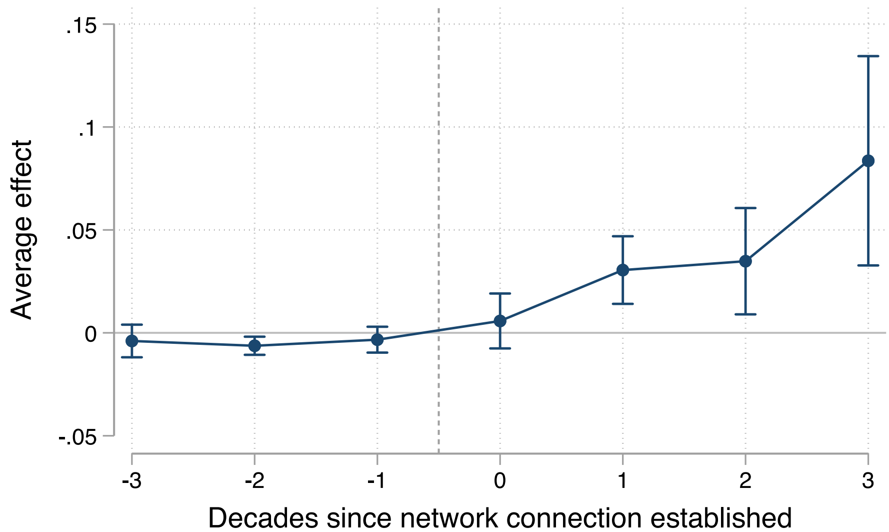


Fig. 3. The effect of network connections on any patent collaboration.
Notes: This figure displays estimates of dynamic treatment effects of a network connection using the method developed in de Chaisemartin and D'Haultfoeuille (2020, 2022) on whether a municipality is involved in at least one patent collaboration. The unit of observation is a municipality-decade, where we observe connections to the network at the beginning of each decade and patenting activity during the next 10 years. All regressions include the mean slope, the mean elevation as well as the standard deviation of the elevation, and the area (all in logs), the log population in 1865, an indicator for urban municipality, the log distance to the nearest urban municipality, 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-by-year fixed effects. Bars indicate 95 percent confidence intervals. Standard errors are clustered at the municipality level.

Table 1
The Effect of Network Connections on Collaborations.

Dependent variable:	Number of collaborations				
	Any	Total	per capita	per inventor	per patent
Panel A. PRV patents	(1)	(2)	(3)	(4)	(5)
Network Connection (=1)	0.025***	0.103***	0.068***	0.025***	0.009**
	(0.006)	(0.034)	(0.018)	(0.007)	(0.004)
Mean dep. var.	0.024	0.087	0.036	0.019	0.014
Panel B. USPTO patents	(1)	(2)	(3)	(4)	(5)
Network Connection (=1)	0.003**	0.009**	0.008**	0.002*	0.005**
	(0.001)	(0.004)	(0.003)	(0.001)	(0.002)
Local Geography×Decadal FE	Yes	Yes	Yes	Yes	Yes
Pre-Rail Controls×Decadal FE	Yes	Yes	Yes	Yes	Yes
Region FE×Decadal FE	Yes	Yes	Yes	Yes	Yes
Observations	16674	16674	16674	16674	16674
Mean dep. var.	0.002	0.003	0.002	0.001	0.002

Notes: OLS regressions. The unit of observation is a municipality-decade, where we observe connections to the network at the beginning of each decade and patenting activity during the next 10 years. The dependent variable is an indicator variable equal to 1 if there is at least one collaboration (and zero otherwise) in column 1, the number of collaborations (in total numbers) in column 2 as well as per 1,000 inhabitants, per inventor, and per patent in columns 3, 4, and 5. Panel A uses patent data from PRV, while panel B uses patent data from USPTO. Network Connection (=1) is an indicator variable equal to one if the municipality has a railroad within 5 km of the municipality centroid. Local geography controls include: the mean slope, the mean elevation as well as the standard deviation of the elevation, and the area (all in logs). Pre-rail controls include: log population in 1865, an indicator for urban municipality, the log distance to the nearest urban municipality, 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. Region FE denotes fixed effects at the NUTS-II level. Decadal FE denotes fixed effects at the decadal level. Standard errors are given in parentheses and are clustered at the municipality level. *** — $p < 0.01$, ** — $p < 0.05$, * — $p < 0.1$.

Table 1 documents similar results from the standard difference-in-differences specification in Eq. (1). Column 1 of panel A shows that the probability that at least one inventor in a municipality was involved in a collaborative patent granted by the PRV increased by about 2.5 percentage points, which can be compared to a sample mean of 2.4 for the entire period. In panel B, column 1, we present similar results based on collaborations on USPTO patents suggesting an increased probability of a collaboration of 0.3 percentage points, which can be compared to a sample mean of 0.2.

We next document that collaboration increased also along the intensive margin. Columns 2 and 3 of Panels A and B document that the number of patent collaborations increased after a connection was established, both in totals and per capita terms (based on population in 1865). In terms of magnitudes, the estimate in column 2 (panel A) implies an increase of 0.1 collaborative patents, which amounts to an increase of 118 percent compared to the mean over the entire period. However, Andersson et al. (2023) document that the arrival of the railroad led to an increased entry of new inventors and rising patenting activity, which may partly explain the increase in collaborations. To get at such explanations, we adjust the number of collaborations by the number of unique inventors in a municipality as well as patents granted in a municipality. Columns 4 and 5 show that after a network connection was established, the number of collaborations per inventor or per patent increased respectively by 0.025 and 0.009 per decade,

Table 2
Network Connections and Inventor Teams.

Dependent variable:	Number of collaborations					
	Any		per inventor		per patent	
	Indep.	Firm	Indep.	Firm	Indep.	Firm
Panel A. Inventor type	(1)	(2)	(3)	(4)	(5)	(6)
Network Connection (=1)	0.026***	0.000	0.026***	0.004	0.009**	−0.000
	(0.006)	(0.002)	(0.007)	(0.004)	(0.004)	(0.000)
Mean dep. var.	0.023	0.002	0.018	0.003	0.013	0.000
	New	Old	New	Old	New	Old
Panel B. Team type	(1)	(2)	(3)	(4)	(5)	(6)
Network Connection (=1)	0.021***	0.009***	0.014***	0.012***	0.005	0.003***
	(0.005)	(0.003)	(0.004)	(0.004)	(0.004)	(0.001)
Local Geography×Decadal FE	Yes	Yes	Yes	Yes	Yes	Yes
Pre-Rail Controls×Decadal FE	Yes	Yes	Yes	Yes	Yes	Yes
Region FE×Decadal FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	16674	16674	16674	16674	16674	16674
Mean dep. var.	0.022	0.007	0.014	0.005	0.011	0.002

Notes: OLS regressions. The unit of observation is a municipality-decade, where we observe connections to the network at the beginning of each decade and patenting activity during the next 10 years. The dependent variable is an indicator variable equal to 1 if there is at least one collaboration (and zero otherwise) in columns 1–2 and the number of collaborations per inventor and per patent in columns 3–4 and 5–6 respectively. In panel A, we separate between patent collaborations that only involved independent inventors and those where at least one patentee was a firm. In panel B, we separate between patent collaborations involving existing (old) or new team formations. Network Connection (=1) is an indicator variable equal to one if the municipality has a railroad within 5 km of the municipality centroid. Local geography controls include: the mean slope, the mean elevation as well as the standard deviation of the elevation, and the area (all in logs). Pre-rail controls include: log population in 1865, an indicator for urban municipality, the log distance to the nearest urban municipality, 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. Region FE denotes fixed effects at the NUTS-II level. Decadal FE denotes fixed effects at the decadal level. Standard errors are given in parentheses and are clustered at the municipality level. *** — $p < 0.01$, ** — $p < 0.05$, * — $p < 0.1$.

which are large effects compared to the sample means.[15] Again, we find similar results in panel B when using information about collaborations drawn from USPTO patents. Thus, while the railroad led to an increased level of innovative activity, it also led to a disproportionate increase in collaborations.

Are these large or small effects in the aggregate? Considering the staggered roll-out of the railroad across our sample, we can calculate the number of connected municipality-decades and make a simple back-of-the-envelope calculation. Taking the estimate in column 2 at face value, this exercise suggests an aggregate increase of 333 patent collaborations in the decades following railroad access.[16] This amounts to about 32 percent of all collaborations in connected municipalities in the post-decades of railroad connection. A related question is how large an increase in total patent activity this constitutes for these municipalities. Under the assumption that collaborative patents did not crowd out non-collaborative patents, the suggested total increase in patent activity due to railroad-induced collaborations would amount to about 7 percent of all post-rail patent activity in connected municipalities. While these calculations are admittedly suggestive, they point towards railroads having an economically substantial impact on collaborative innovative activity.

We next examine whether the increase in collaboration is driven by firms or independent inventors, existing teams or the formation of new teams, and whether the increases in collaboration is driven by any particular industrial sector.

First, we document that the increase in collaboration is primarily driven by an increased collaboration among independent inventors. Panel A of Table 2 presents estimates of our baseline specification using firm and independent collaborations as outcomes; the former corresponds to patents involving at least one firm and the latter to those where all collaborators are independent inventors. Throughout, we find positive effects on collaborations involving independent inventors, while collaborations involving firms are seemingly not affected by railroad access. While the latter results should be interpreted carefully given the relatively few firm patents in this period, the fact that magnitudes for independent collaborations are similar to Table 1 suggests that our main results are largely driven by collaborations between independent inventors.

Second, a lowering of search costs and frictions may facilitate the formation of new inventor teams and/or increases in patent output within existing teams. Panel B of Table 2 presents estimates from Eq. (1) where we split up collaborations by new and old teams.[17] The establishment of a network connection increased collaboration both along the extensive margin (in terms of building new teams) and intensive margin (in terms of intensifying collaboration within already existing teams). For example, we find an increase of 2.1 and 0.9 percentage points in the probability of collaborating in new and old teams, respectively. The increase in collaboration is primarily driven by smaller teams of two independent inventors (see Online Appendix Table A.1), which dominated collaboration throughout our period (see Online Appendix Figure A.5). While increases are of similar relative size compared to the sample means, the fact that new teams were more prevalent suggests an important role for the evolving railroad network in enabling inventors to initiate new collaborations.

Third, we document that the increase in collaboration is evident across a wide range of industrial sectors. To do this, Online Appendix Figure A.10 presents separate estimates from Eq. (1) for each of 14 broad industrial sectors. After a network connection is established, collaboration increases in most sectors both along the extensive and intensive margin. Increases in collaboration are evident in sectors spanning relatively complex industries (e.g., machinery and metals) to those that are less technologically demanding (e.g., food and beverages).[18]

3.2.2. *Robustness*

We present a battery of robustness checks of our main results in the Online Appendix. First, we show that results are similar when using

[15] Online Appendix Figure A.9 shows that results are similar using the method developed in de Chaisemartin and D'Haultfoeuille (2020, 2022).

[16] There are 336, 395, 253, and 201 municipalities with four, three, two, and one decade(s) of railroad connection, respectively. This gives $336 \times 4 + 395 \times 3 + 253 \times 2 + 201 = 3236$ municipality decades with railroad access, and a total increase of $3236 \times 0.103 = 333$ collaborations.

[17] A patent by a new team is defined as a patent with a combination of team members that have never previously patented together. In contrast, a patent

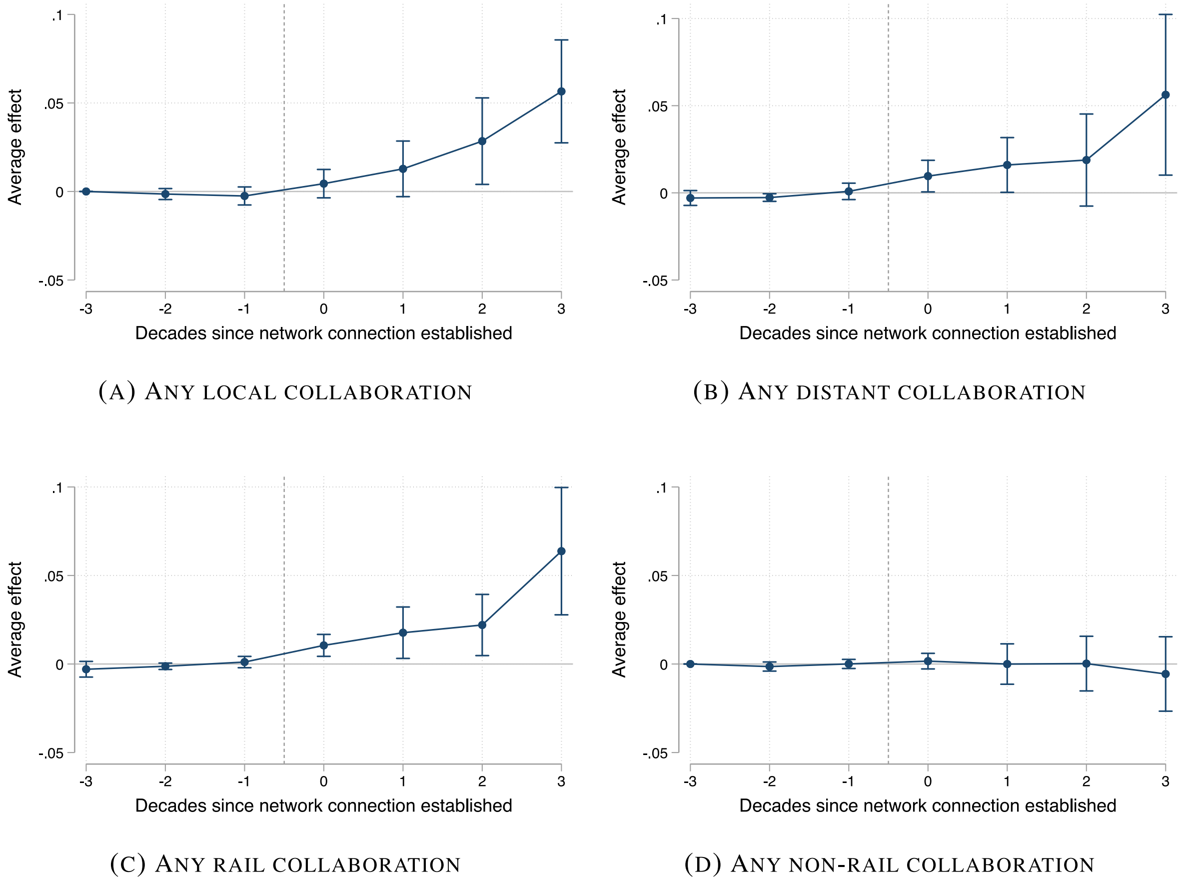


Fig. 4. The effect of network connections on the geography of patent collaborations.
Notes: This figure displays estimates of dynamic treatment effects of a network connection using the method developed in de Chaisemartin and D'Haultfoeuille (2020, 2022) on whether a municipality is involved in A: at least one collaboration with inventors in the same municipality; B: at least one collaboration with inventors in another municipality; C: at least one collaboration with inventors in another municipality along the rail network; and D: at least one collaboration with inventors in another municipality that is not connected to the rail network. The unit of observation is a municipality-decade, where we observe connections to the network at the beginning of each decade and patenting activity during the next 10 years. All regressions include the mean slope, the mean elevation as well as the standard deviation of the elevation, and the area (all in logs), the log population in 1865, an indicator for urban municipality, the log distance to the nearest urban municipality, 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-by-year fixed effects. Bars indicate 95 percent confidence intervals. Standard errors are clustered at the municipality level.

alternative definitions of collaborative patents and functional form (Online Appendix A.1), as well as alternative specifications including different measures of connectivity to the rail network (Online Appendix A.2). Second, we show that results are similar in more demanding dyad specifications at the municipality-pair level that allows us to include both municipality-pair and municipality-by-decade fixed effects (Online Appendix A.3). Third, we validate the robustness of our main results to using the instrumental variable design developed in Andersson et al. (2023) based on least-cost paths between the targeted endpoints of the network (Online Appendix A.4). Fourth, we show that there are no systematic increases in collaboration in areas where rail lines had been planned but ultimately not constructed (Online Appendix A.5). Fifth, we document that our main estimates are stable in magnitude and statistical precision when controlling for the spread of communication technologies (i.e., the telegraph) that often followed the railroad (Online Appendix A.6). Lastly, we provide suggestive evidence that the quality of collaborative patents were broadly similar among inventors residing in (non-)connected municipalities (Online Appendix A.7).

3.3. Railroads and the geography of collaboration

3.3.1. Collaboration within and beyond the municipality

We next document that the spread of the rail network increased collaboration both within and across municipalities. Figs. 4A and 4B show that collaborations involving inventors located in the same municipality ("local") and those involving inventors in other municipalities ("distant") both increase. Table 3 presents similar results using Eq. (1). Columns 1 and 2 show that access to the network is associated with an increased probability of both types of collaborations. Compared to their respective means, distant collaborations increase somewhat more than local collaborations. Turning to the intensive margin in columns 3–6, where we use the number of collaborations per inventors or patents, both types of collaborations increase, although the magnitudes are somewhat smaller and not statistically significant regarding local collaboration. Distant collaborations increase with about 0.013 collaborations per inventor and 0.005 collaborations per patent, which is substantial relative to the mean.

by an old team is a patent with team members who have previously worked together on a patent.

[18] A particular concern is that a connection to the rail network may mechanically increase collaborations in rail-related technologies. While we observe an increase in collaboration in patents relating to transport in Online Appendix Figure A.10A, we note that there are significant increases in industries arguably unrelated to the rail sector (e.g., paper and printing) that largely mitigates concerns that our results are mainly driven by rail patents.

Table 3
Network Connections and Local and Distant Collaboration.

Dependent variable:	Number of collaborations						ln Distance btw collaborators		
	Any		per inventor		per patent		Total	per inventor	per patent
	Local	Distant	Local	Distant	Local	Distant	All	All	All
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Network Connection (=1)	0.008**	0.016***	0.006*	0.013**	0.002	0.005**	0.077***	0.058***	0.048***
	(0.003)	(0.004)	(0.003)	(0.006)	(0.003)	(0.002)	(0.023)	(0.018)	(0.016)
Local Geography×Decadal FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Pre-Rail Controls×Decadal FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Region FE×Decadal FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	16674	16674	16674	16674	16674	16674	16674	16674	16674
Mean dep. var.	0.011	0.014	0.007	0.009	0.007	0.005	0.072	0.052	0.045

Notes: OLS regressions. The unit of observation is a municipality-decade, where we observe connections to the network at the beginning of each decade and patenting activity during the next 10 years. The dependent variable is an indicator variable equal to 1 if there is at least one collaboration (and zero otherwise) in columns 1–2, the number of collaborations per inventor and per patent in columns 3–4 and 5–6, respectively. "Local" denotes collaboration within the municipality and "distant" denotes collaboration with other municipalities. Network Connection (=1) is an indicator variable equal to one if the municipality has a railroad within 5 km of the municipality centroid. Local geography controls include: the mean slope, the mean elevation as well as the standard deviation of the elevation, and the area (all in logs). Pre-rail controls include: log population in 1865, an indicator for urban municipality, the log distance to the nearest urban municipality, 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. Region FE denotes fixed effects at the NUTS-II level. Decadal FE denotes fixed effects at the decadal level. Standard errors are given in parentheses and are clustered at the municipality level. *** — $p < 0.01$, ** — $p < 0.05$, * — $p < 0.1$.

An overall stronger effect on distant collaborations suggests that the rail network facilitated collaboration over longer distances. To more directly address this question, we turn to studying the distance between team members. The last three columns of Table 3 reports estimates where the outcomes capture the distance between collaborating inventors.[19] Column 7 shows that the total distance between individuals on collaborative patents increased by about 8 percent after a network connection was established. Normalizing for the number of inventors or patents decreases this estimate somewhat to about 5–6 percent (columns 8 and 9). Thus, after a connection to the network is established, the distance between collaborating team members increased, consistent with the finding that the railroad facilitated distant collaborations.

3.3.2. Collaboration on and off the rail network

A natural question is whether the collaborations involving inventors residing in other locations arose along the evolving rail network, which would be consistent with a direct role of travel along the network in facilitating patent collaborations. Indeed, as shown in Fig. 4C, we find that the effect is driven by collaboration with individuals located in municipalities connected to the network. In contrast, Fig. 4D shows that there is no significant increase in the probability that inventors begin to collaborate more with inventors located in areas that remain unconnected to the railroad network.

We find similar results when using our standard difference-in-differences specification in Table 4. Column 1 shows that the probability of having at least one collaboration with an inventor in another rail-connected municipality increases with 1.4 percentage points after gaining railroad access. The effect on the number of such collaborations, per inventor or patent, also increases by 0.012 and 0.003, respectively, as given by columns 3 and 5. In contrast, the effect on collaborations with individuals located in non-connected municipalities is small and non-significant as seen from the estimates in columns 2, 4, and 6. Thus, the rise in collaboration is seemingly driven by improved connectivity between inventors along the emerging rail network.

3.3.3. Collaboration in rural vs. urban areas

We lastly examine the differential impact of the rail network on urban and rural municipalities. As described above, collaboration was around the mid-19th century confined to large cities where search and interaction costs were arguably lower. While inventors residing in big cities collaborated to a larger extent also by the early 20th century, the late-19th century saw the rise of collaboration in rural and more remote areas (see Fig. 2C and 2D). To examine whether the railroad affected rural and urban places in different ways, we interact our indicator for network connection with an indicator for being an urban municipality.[20] As before, we absorb urban and rural trends by including an indicator for urban among our set of controls interacted with year fixed effects.

Table 5 presents results for all our main outcomes. Columns 1 and 2 show once more that after a network connection is established, collaboration increases both along the extensive and intensive margin. However, there is no statistically significant differential effect for urban municipalities.

We next show that the effect on total collaborations masks spatial differences between rural and urban locations. In fact, our results suggest that the rail network facilitated distant collaborations among inventors residing in rural areas, while it led to an increase in local collaboration among those residing in urban areas. Rural areas saw no increase in local collaborations (column 3–4), but a significant increase in distant collaborations with inventors residing in other municipalities (column 5–6). In contrast, urban areas saw an increased rate of local collaboration between inventors residing in the same city, but a decline (although statistically insignificant) in distant collaborations with inventors in other areas.

The higher probability of distant collaborations appear not to be driven by any particular type of destination as seen in columns 7–9. At the same time they took place over greater distances, as captured in columns 10 and 11 showing that the distance between inventors and their collaborators increased after a network connection was established. The coefficient belonging to the interaction between urban and network connection remains statistically insignificant throughout these specifications. Splitting the sample into a rural and an urban sample (see Online Appendix Table A.10), however suggests that rural municipalities are key in driving these relationships.

4. Conclusions

Our findings show that lowering the cost of interacting with others can spur long-distance collaboration between inventors. We first document that the origins of the long-run increase in inventive collaboration

[19] Note here that collaborations within a municipality are given the value of 0 kilometers, such that increases reflect collaborations with individuals located outside the municipality.

[20] In the Online Appendix Table A.10, we also display results when we instead split our sample in an urban and rural sample, respectively.

Table 4
Network Connections and Collaboration On and Off the Rail Network.

Dependent variable:	Number of collaborations					
	Any		per inventor		per patent	
	Rail	Non-rail	Rail	Non-rail	Rail	Non-rail
	(1)	(2)	(3)	(4)	(5)	(6)
Network Connection (=1)	0.014***	0.003	0.012**	0.002	0.003*	0.002
	(0.004)	(0.002)	(0.005)	(0.002)	(0.002)	(0.002)
Local Geography×Decadal FE	Yes	Yes	Yes	Yes	Yes	Yes
Pre-Rail Controls×Decadal FE	Yes	Yes	Yes	Yes	Yes	Yes
Region FE×Decadal FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	16674	16674	16674	16674	16674	16674
Mean dep. var.	0.012	0.003	0.007	0.002	0.004	0.001

Notes: OLS regressions. The unit of observation is a municipality-decade, where we observe connections to the network at the beginning of each decade and patenting activity during the next 10 years. The dependent variable is an indicator variable equal to 1 if there is at least one collaboration (and zero otherwise) in columns 1–2, the number of collaborations per inventor and per patent in columns 3–4 and 5–6, respectively. "Rail" and "non-rail" denote collaboration with other municipalities with and without network connection, respectively. Network Connection (=1) is an indicator variable equal to one if the municipality has a railroad within 5 km of the municipality centroid. Local geography controls include: the mean slope, the mean elevation as well as the standard deviation of the elevation, and the area (all in logs). Pre-rail controls include: log population in 1865, an indicator for urban municipality, the log distance to the nearest urban municipality, 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. Region FE denotes fixed effects at the NUTS-II level. Decadal FE denotes fixed effects at the decadal level. Standard errors are given in parentheses and are clustered at the municipality level. *** — $p < 0.01$, ** — $p < 0.05$, * — $p < 0.1$.

Table 5
Network Connections and Collaboration in Rural and Urban Municipalities.

Dependent variable:	Collaborations		Collab. (local)		Collab. (distant)		Any collaboration with			ln Distance	
	Any	per patent	Any	per patent	Any	per patent	Rural	Urban	Stockholm	Total	per patent
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
Network Connection (=1)	0.024***	0.009**	0.005	0.000	0.016***	0.006**	0.007**	0.012***	0.004*	0.075***	0.050***
	(0.005)	(0.004)	(0.003)	(0.003)	(0.004)	(0.002)	(0.003)	(0.004)	(0.003)	(0.022)	(0.015)
Network Con.×Urban (=1)	0.015	−0.004	0.065**	0.030**	−0.002	−0.019	−0.005	0.011	0.008	0.034	−0.045
	(0.037)	(0.021)	(0.031)	(0.013)	(0.034)	(0.017)	(0.023)	(0.034)	(0.031)	(0.191)	(0.127)
Local Geography×Decadal FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Pre-Rail Controls×Decadal FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Region FE×Decadal FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	16674	16674	16674	16674	16674	16674	16674	16674	16674	16674	16674
Mean dep. var.	0.024	0.014	0.011	0.007	0.014	0.005	0.006	0.011	0.007	0.072	0.045

Notes: OLS regressions. The unit of observation is a municipality-decade, where we observe connections to the network at the beginning of each decade and patenting activity during the next 10 years. The dependent variable is an indicator variable equal to 1 if there is at least one collaboration (and zero otherwise) in columns 1, 3, 5, and 7–9; and the number of collaborations per patent in columns 2, 4, and 6. We report estimates separately for all, local, and distant collaborations in columns 1–6, and for collaborations with another rural or urban municipality and Stockholm in columns 7–9. The dependent variable in columns 10 and 11 is the ln distance between collaborators (per patent). Network Connection (=1) is an indicator variable equal to one if the municipality has a railroad within 5 km of the municipality centroid. Local geography controls include: the mean slope, the mean elevation as well as the standard deviation of the elevation, and the area (all in logs). Pre-rail controls include: log population in 1865, an indicator for urban municipality, the log distance to the nearest urban municipality, 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, and the latitude and longitude of the municipality centroid. Region FE denotes fixed effects at the NUTS-II level. Decadal FE denotes fixed effects at the decadal level. Standard errors are given in parentheses and are clustered at the municipality level. *** — $p < 0.01$, ** — $p < 0.05$, * — $p < 0.1$.

can be traced to the latter half of the 19th century. In this period, collaboration became increasingly prevalent among Swedish inventors. While initially concentrated to a few urban areas where search and interactions costs were arguably lower, the rise of collaboration in the late-19th century was partly driven by inventors residing in different locations that collaborated over increasingly longer distances. A potential explanation for the rise of long-distance collaborations is the sustained declines in the cost of interactions across space due to the coming of the railroad.

The main empirical analysis leverages patent data from the PRV and USPTO combined with the staggered rollout of the Swedish railroad network across municipalities. After a municipality becomes connected to the national rail network, inventors in that municipality increasingly enter into new collaborations. Inventors entered into collaborations with other inventors located in different municipalities along the emerging network, which suggests that the railroad directly facilitated long-distance collaborations. The rise of such long-distance collaboration is mainly driven by inventors residing in rural areas, where high search frictions and a limited local supply of potential collaborators may have restricted collaboration in the pre-rail era. Together, these results underline that lowering communication and travel costs may be a key lever to facilitate collaboration and that the sustained decline in such costs are central in accounting for the long-term increase in collaboration.

Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.jue.2023.103629.

References

Agrawal, Ajay, Galasso, Alberto, Oettl, Alexander, 2017. Roads and innovation. Rev. Econ. Stat. 99 (3), 417–434.

Agrawal, Ajay, Goldfarb, Avi, Teodoridis, Florenta, 2016. Understanding the changing structure of scientific inquiry. Am. Econ. J.: Appl. Econ. 8 (1), 100–128.

Akcigit, Ufuk, Caicedo, Santiago, Miguelez, Ernest, Stantcheva, Stefanie, Sterzi, Valerio, 2018. Dancing with the Stars: Innovation Through Interactions. Working Paper Series 24466, National Bureau of Economic Research.

Andersson, David, Berger, Thor, Prawitz, Erik, 2023. Making a market: Infrastructure, integration, and the rise of innovation. Rev. Econ. Stat. 105 (2), 258–274.

Andersson, David, Tell, Fredrik, 2018. The market for patents in Sweden: Past and present. Stock. Intellect. Prop. Law Rev. 1 (2), 6–17.

Berger, Thor, 2019. Railroads and rural industrialization: Evidence from a historical policy experiment. Explor. Econ. History 74, 101–277.
Berger, Thor, Enflo, Kerstin, 2017. Locomotives of local growth: The short- and long-term impact of railroads in Sweden. J. Urban Econ. 98, 124–138, Urbanization in Developing Countries: Past and Present.
Berger, Thor, Prawitz, Erik, Inventors among the ''Impoverished Sophisticate''. J. Econ. History, forthcoming.
Bloom, Nicholas, Jones, Charles I., Van Reenen, John, Webb, Michael, 2020. Are ideas getting harder to find? Amer. Econ. Rev. 110 (4), 1104–1144.
Boudreau, Kevin J., Brady, Tom, Ganguli, Ina, Gaule, Patrick, Guinan, Eva, Hollenberg, Anthony, Lakhani, Karim R., 2017. A field experiment on search costs and the formation of scientific collaborations. Rev. Econ. Stat. 99 (4), 565–576.
Catalini, Christian, Fons-Rosen, Christian, Gaulé, Patrick, 2020. How do travel costs shape collaboration? Manage. Sci. 66 (8), 3340–3360.
de Chaisemartin, Clément, D'Haultfoeuille, Xavier, 2020. Two-way fixed effects estimators with heterogeneous treatment effects. Amer. Econ. Rev. 110 (9), 2964–2996.
de Chaisemartin, Clément, D'Haultfoeuille, Xavier, 2022. Difference-in-Differences Estimators of Intertemporal Treatment Effects. Working Paper Series 29873, National Bureau of Economic Research.
Dong, Xiaofang, Zheng, Siqi, Kahn, Matthew E., 2020. The role of transportation speed in facilitating high skilled teamwork across cities. J. Urban Econ. 115, 103212.
Hanlon, W. Walker, Heblich, Stephan, Monte, Ferdinando, Schmitz, Martin B., 2022. A Penny for Your Thoughts. Working Paper Series 30076, National Bureau of Economic Research.
Heckscher, E.F., 1954. An Economic History of Sweden. Harvard University Press, Cambridge.
Iaria, Alessandro, Schwarz, Carlo, Waldinger, Fabian, 2018. Frontier knowledge and scientific production: Evidence from the collapse of international science. Q. J. Econ. 133 (2), 927–991.
Jones, Benjamin F., 2009. The burden of knowledge and the ''death of the renaissance man'': Is innovation getting harder? Rev. Econom. Stud. 76 (1), 283–317.
Jones, Benjamin F., 2021. The rise of research teams: Benefits and costs in economics. J. Econ. Perspect. 35 (2), 191–216.
Kerr, Sari Pekkala, Kerr, William R., 2018. Global collaborative patents. Econ. J. 128 (612), F235–F272.
Koh, Yumi, Li, Jing, Xu, Jianhuan, Subway, Collaborative Matching, and Innovation. Rev. Econ. Stat. forthcoming.
Nuvolari, Alessandro, Vasta, Michelangelo, 2015. Independent invention in Italy during the liberal age, 1861–1913. Econ. History Rev. 68 (3), 858–886.
Palm, Lennart Andersson, 2000. Folkmängden I Sveriges Socknar Och Kommuner 1571-1997: Med Särskild Hänsyn Till Perioden 1571-1751. Nomen förlag, Göteborg.
Sweden, Statistics, 1960. Historical Statistics of Sweden: Statistical Survey (Tables Not Published in Volumes I and II). Kungl. Boktryckeriet P.A. Norstedt & Söner.
van der Wouden, Frank, 2020. A history of collaboration in US invention: Changing patterns of co-invention, complexity and geography. Ind. Corp. Change 29 (3), 599–619.
Wu, Lingfei, Wang, Dashun, Evans, James A., 2019. Large teams develop and small teams disrupt science and technology. Nature 566 (7744), 378–382.
Wuchty, Stefan, Jones, Benjamin F., Uzzi, Brian, 2007. The increasing dominance of teams in production of knowledge. Science 316 (5827), 1036–1039.