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Abstract

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Keywords: Innovation, Collaboration, Transport infrastructure, Railroads

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Collaboration and Connectivity: Historical Evidence from Patent Records*

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March 28, 2023

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 19^{th} and early-20^{th} 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.

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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).[1]

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 new 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 19^{th} 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 cities in the east, west, and

[1] 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.

north. Consequently, the placement of the main rail lines meant that locations along these routes gained access more or less by chance. Indeed, using the approach developed in De Chaisemartin and d'Haultfoeuille (2020), 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.[2] 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 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. (2021). 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 communication and travel costs in shaping spatial patterns of innovation. By reducing the cost of interacting over longer distances, improvements in communication and transport infrastructure may reduce spatial frictions leading to an increase in innovative activity. Indeed, recent work documents the central role of communication and transport technologies for innovation both in historical and modern contexts (Perlman, 2016; Agrawal et al., 2017; Andersson et al., 2021; Hanlon et al., 2022). Recent evidence further shows that lowering interaction costs may directly facilitate scientific collaboration

[2] 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.

either through ICT technologies that lower communication costs (Agrawal and Goldfarb, 2008; Aneja and Xu, 2022), or transport infrastructure that facilitate face-to-face interactions (Catalini et al., 2020; Dong et al., 2020; Koh et al., 2022). We contribute novel evidence on how lowering the cost of interacting with others can spur collaboration between inventors.

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).[3]

A total of 16,674 patents were granted by the PRV to 11,000 unique individuals or firms residing in Sweden over the period.[4] 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.[5] 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 inventor(s), we simply define a collaborative USPTO pateent as a patent with two or more inventors. According to this definition, we observe 113 collaborative patents among the 1,350 total USPTO patents.

To measure the spread of the railroad network, we digitize maps of the rail network available

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

[4] 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.

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

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.[6] 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).

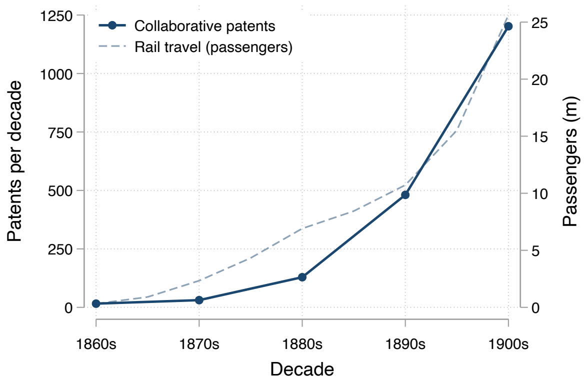
At the municipality level, we add other data from a variety of sources. We collect population data from Palm (2000) and the the Swedish National Archives. Additional data on manufacturing activity originating from Statistics Sweden, as well as geographical data (e.g., the elevation and slope) for each municipality, is drawn from Andersson et al. (2021).

2.2 Descriptive evidence: railroads and the rise of patent collaborations

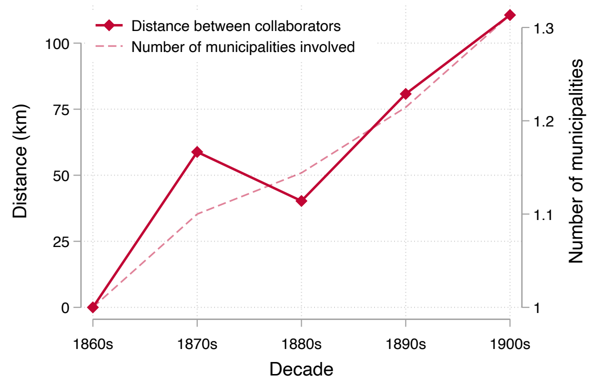
2.2.1 Expansion of the Swedish railroad network

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 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

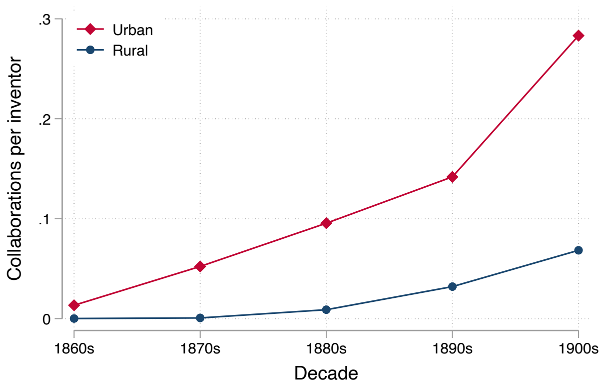
[6] Our historical administrative boundaries are based on maps obtained from the Swedish National Archives (*Riksarkivet*). To adjust for urban expansion over the period we study, we merge urban municipalities with their adjacent rural areas.



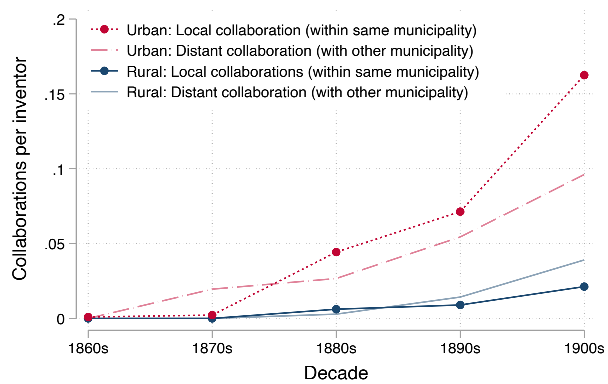
(A) COLLABORATIONS



(B) DISTANCE



(C) URBAN VS. RURAL



(D) LOCAL VS. DISTANT

FIGURE 1:
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 Statistics 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.

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). Figure 2A 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.

2.2.2 Railroads and the rise of patent collaboration

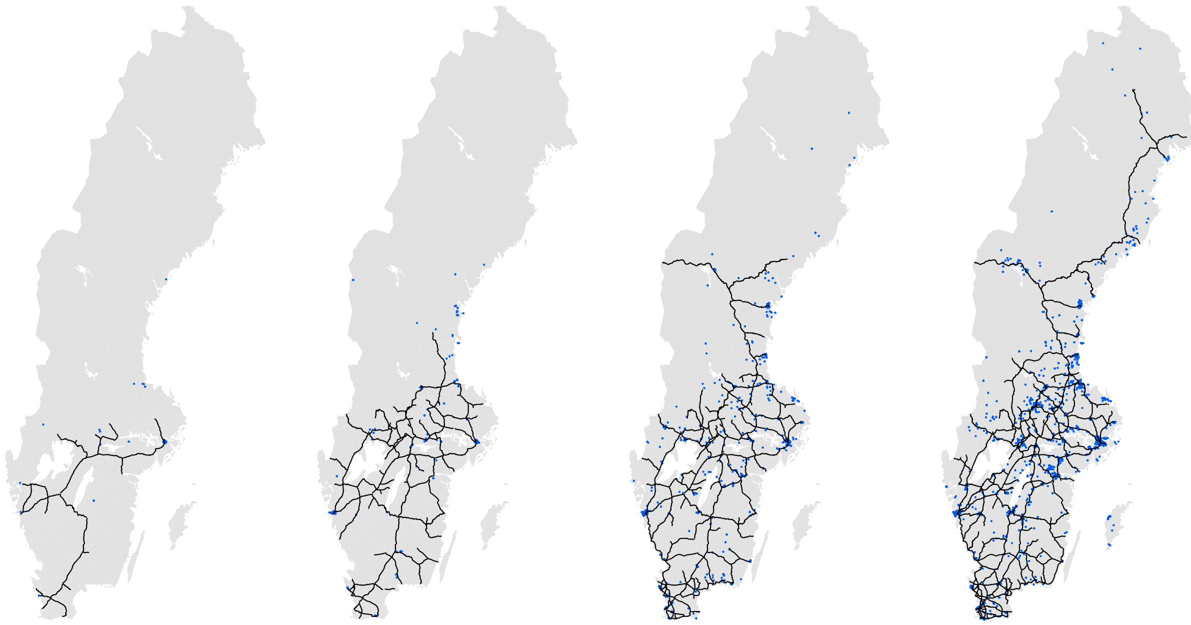
Sweden experienced rapid growth in patenting output as the rail network expanded over the latter half of the 19th century (Andersson et al., 2021). Figure 1A shows that the rise of innovative activity was also coupled with a growing number of patent collaborations.[7] In the 1860s, about 60 collaborative patents were granted, which had increased to more than 1,000 during the first decade of the 20^{th} 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). Figure 1A 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).[8] At the same time, lower-skilled workers such as mechanics and instrument makers are also represented.[9] 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.

[7] 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 1.05 to 1.16. 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.

[8] 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).

[9] 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).



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

FIGURE 2: 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 one inventor or patentee that was involved in a collaboration.

2.2.3 Railroads and the geography of patent collaboration

Figure 2 shows that the geography of collaboration underwent considerable changes as the rail network expanded in the late-19^{th} century. Each dot corresponds to a collaborative patent involving (at least) one inventor in a municipality during a given decade. 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, Figure 1B 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 19^{th} century, collaborative patents increasingly involved inventors located in different and more distant municipalities.

Collaboration was initially confined to urban areas, yet Figure 1C shows that inventors in both urban and rural municipalities were increasingly more likely to collaborate in the latter half of the 19^{th} century.[10] The increase in collaboration is driven both by collaborations between inventors

[10]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

residing in the same municipality, as well with inventors in in other places (Figure 1D). Notably, over time inventors in urban municipalities become relatively more likely to collaborate with others in the same city, while inventors located in rural areas became more likely to collaborate with inventors in other municipalities.

Together, these descriptive results and the fact that the spread of collaboration displayed in Figure 2 closely tracks the expansion of the rail network provide suggestive evidence that the rise of collaboration was deeply intertwined with the spread of the railroad network. We next proceed to document a plausibly causal link between the expansion of the rail network and 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.[11]

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 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., 2021). In our main specifications, we exclude

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.

[11] In particular, we choose the 5 km cutoff based on the estimates reported in Appendix Figure A.11 where we report estimates of equation (1) where we allow the impact of a network connection on collaboration to vary flexibly across different distances to the network. As evident from 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.

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, 2021) that circumvents common challenges in estimating treatment effects in settings with many groups and time periods.[12] 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. Figure 4 displays estimates using the approach developed by De Chaisemartin and d'Haultfoeuille (2020, 2021). 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.

Table 1 documents similar results from the standard difference-in-differences specification in

[12]To produce these estimates, we use the *did_multiplegt* Stata command, available from the SSC repository.

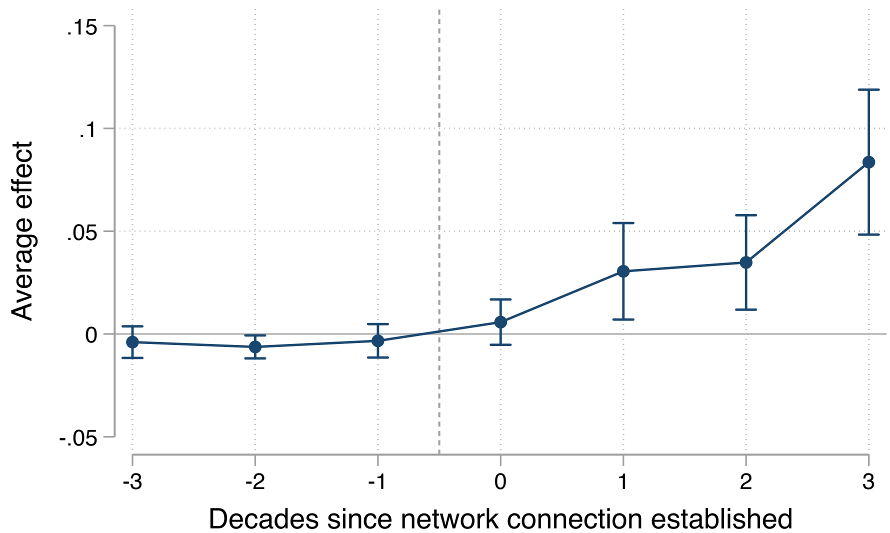


FIGURE 3: THE EFFECT OF NETWORK CONNECTIONS ON ANY PATENT COLLABORATION

Notes: This figure displays estimates of dynamic treatment effects of a network connection using the method developed in De Chaisemartin and d'Haultfoeuille (2020, 2021) 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, 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-by-year fixed effects. Bars indicate 95 percent confidence intervals. Standard errors are clustered at the municipality level.

equation (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. (2021) 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

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**	0.005**	0.008**	0.002*	0.005**
	(0.001)	(0.002)	(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	0.002	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, 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. 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. *** - $p < 0.01$, ** - $p < 0.05$, * - $p < 0.1$.

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, which are large effects compared to the sample means. Online Appendix Figure A.9 shows that results are similar using the method developed in De Chaisemartin and d'Haultfoeuille (2020, 2021). 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

TABLE 2: NETWORK CONNECTIONS AND INVENTOR TEAMS

Dependent variable:	Number of collaborations					
	Any		per inventor		per patent	
Panel A. Inventor type	Indep. (1)	Firm (2)	Indep. (3)	Firm (4)	Indep. (5)	Firm (6)
Network Connection (=1)	0.025***	0.000	0.039**	0.004	0.009**	-0.000
	(0.006)	(0.002)	(0.019)	(0.004)	(0.004)	(0.000)
Mean dep. var.	0.024	0.002	0.023	0.003	0.013	0.000
Panel B. Team type	New (1)	Old (2)	New (3)	Old (4)	New (5)	Old (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, 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. 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. *** - $p < 0.01$, ** - $p < 0.05$, * - $p < 0.1$.

access.[13] 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 collaborative teams, and whether the increases in

[13]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.

collaboration is driven by any particular industrial sector.

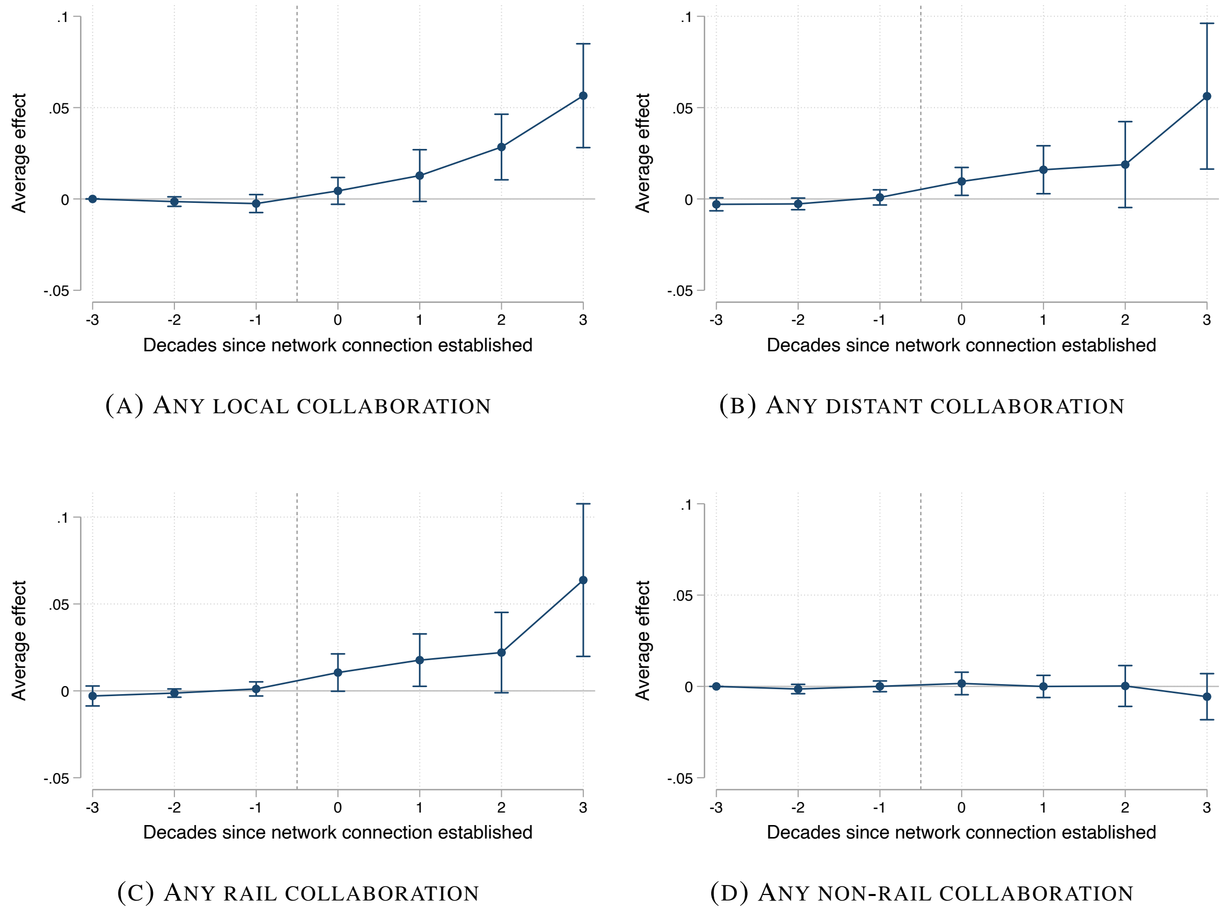
First, we document that the increase in collaboration is primarily driven by an increased collaboration among independent inventors. Panel A of Table 2 presents estimates of our baseline specification using firm and independent collaborations as outcomes; the former corresponds to patents involving at least one firm and the latter 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 equation (1) where we split up collaborations by new and old teams.[14] 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 equation (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).[15]

[14]A patent by a new team is defined as a patent with a combination of team members that has never previously patented together. In contrast, a patent by an old team is a patent with team members who have previously worked together on a patent.

[15]A particular concern is that a 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 Figure A.10A, we again 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.



(A) Any local collaboration

(B) Any distant collaboration

(C) Any rail collaboration

(D) Any non-rail collaboration

Figure 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, 2021) 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, 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-by-year fixed effects. Bars indicate 95 percent confidence intervals. Standard errors are clustered at the municipality level.

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 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. (2021) based on least-cost paths between the targeted endpoints of the network (Online Appendix A.4). Fourth, we show that there are no significant increases in collaboration in areas where rail lines had been planned but ultimately not constructed (Online Appendix A.5). Fifth, we document in Online Appendix A.6 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. 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. Separating patent collaboration into those involving inventors located in the same municipality ("local") and those involving inventors in other municipalities ("distant"), Figures 4A and 4B documents positive effects for both. Table 3, presents similar results using equation (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.

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.[16] 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

[16]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.

network is established, the distance between collaborating team members increased, consistent with the finding that the railroad facilitated distant collaborations.

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
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, 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. 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. *** - $p < 0.01$, ** - $p < 0.05$, * - $p < 0.1$.

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 Figure 4C, we find that the effect is driven by collaboration with individuals located in municipalities connected to the network. In contrast, Figure 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 3, panel B. Column 1 displays that the probability of having at least one collaboration with an individual 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.

TABLE 4: NETWORK CONNECTIONS AND COLLABORATION ON AND OFF THE RAIL NETWORK

Dependent variable:	Number of collaborations					
	Any		per inventor		per patent	
	Rail (1)	Non-rail (2)	Rail (3)	Non-rail (4)	Rail (5)	Non-rail (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, 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. 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. *** - $p < 0.01$, ** - $p < 0.05$, * - $p < 0.1$.

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. To examine whether the railroad affected rural and urban places in different ways, we split our sample and estimate the baseline specification in equation (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
Panel A. Rural municipalities	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
Network Connection (=1)	0.024***	0.008*	0.006**	0.000	0.016***	0.006**	0.007**	0.012***	0.005*	0.081***	0.051***
	(0.005)	(0.004)	(0.003)	(0.003)	(0.004)	(0.002)	(0.003)	(0.004)	(0.002)	(0.021)	(0.015)
Observations	15883	15883	15883	15883	15883	15883	15883	15883	15883	15883	15883
Mean dep. var.	0.016	0.011	0.006	0.006	0.009	0.004	0.004	0.006	0.004	0.045	0.031
Panel B. Urban municipalities	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
Network Connection (=1)	0.012	0.005	0.048	0.031**	-0.019	-0.023*	-0.018	0.004	-0.026	-0.111	-0.131
	(0.040)	(0.021)	(0.034)	(0.014)	(0.034)	(0.014)	(0.029)	(0.035)	(0.032)	(0.197)	(0.120)
Local Geography$\times$Decadal FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Pre-Rail Controls$\times$Decadal FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Region FE$\times$Decadal FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	791	791	791	791	791	791	791	791	791	791	791
Mean dep. var.	0.176	0.057	0.097	0.028	0.110	0.019	0.040	0.096	0.072	0.605	0.319

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. Panels A and B restricts the sample to rural and urban municipalities respectively. 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, 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, 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. *** - $p < 0.01$, ** - $p < 0.05$, * - $p < 0.1$.

Table 5 presents results for all our main outcomes separately for rural (panel A) and urban (panel B) municipalities. Columns 1 and 2 show that after a network connection is established in a rural area, collaboration increases both along the extensive and intensive margin. While the estimated effects are positive for urban areas in panel B, they are of a smaller magnitude and are not statistically significant.

We next show 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. At the intensive margin, rural areas saw no increase in local collaborations (column 4), but a significant increase in distant collaborations with inventors residing in other municipalities (column 6). In contrast, the same columns in panel B shows that urban areas saw an increased rate of local collaboration between inventors residing in the same city, but a decline in distant collaborations with inventors in other areas.

A higher probability of distant collaborations involving inventors in rural areas is driven by an increased probability of collaboration with inventors in other rural areas, cities, as well as in Stockholm (columns 7–9). These collaborations also took place over greater distances, as captured in columns 10 and 11 showing that the distance between inventors in rural areas and their collaborators increased after a network connection was established. Thus, the overall increase in collaboration due to the coming of the railroad is seemingly driven mainly by inventors residing in rural areas.

4 Conclusions

Our findings show that lowering the cost of interacting with others can spur collaboration between inventors. We first document the descriptive fact that the origins of the secular increase in inventive collaboration can be traced to the latter half of the 19^{th} 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-19^{th} 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.

Our 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, independent 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.

References

Agrawal, Ajay, Alberto Galasso, and Alexander Oettl, "Roads and Innovation," *The Review of Economics and Statistics*, 2017, *99* (3), 417–434.

_ **and Avi Goldfarb**, "Restructuring research: Communication costs and the democratization of university innovation," *American Economic Review*, 2008, *98* (4), 1578–90.

_ **,** _ **, and Florenta Teodoridis**, "Understanding the changing structure of scientific inquiry," *American Economic Journal: Applied Economics*, 2016, *8* (1), 100–128.

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

Andersson, David, Thor Berger, and Erik Prawitz, "Making a Market: Infrastructure, Integration, and the Rise of Innovation," *Review of Economics and Statistics*, 2021, *Forthcoming*.

Aneja, Abhay and Guo Xu, "Strengthening State Capacity: Postal Reform and Innovation during the Gilded Age," Working Paper 29852, National Bureau of Economic Research March 2022.

Berger, Thor, "Railroads and rural industrialization: Evidence from a historical policy experiment," *Explorations in Economic History*, 2019, *74*, 101–277.

_ **and Kerstin Enflo**, "Locomotives of local growth: The short- and long-term impact of railroads in Sweden," *Journal of Urban Economics*, 2017, *98*, 124 – 138. Urbanization in Developing Countries: Past and Present.

Bloom, Nicholas, Charles I Jones, John Van Reenen, and Michael Webb, "Are ideas getting harder to find?," *American Economic Review*, 2020, *110* (4), 1104–44.

Boudreau, Kevin J, Tom Brady, Ina Ganguli, Patrick Gaule, Eva Guinan, Anthony Hollenberg, and Karim R Lakhani, "A field experiment on search costs and the formation of scientific collaborations," *Review of Economics and Statistics*, 2017, *99* (4), 565–576.

Catalini, Christian, Christian Fons-Rosen, and Patrick Gaulé, "How Do Travel Costs Shape Collaboration?," *Management Science*, 2020.

Chaisemartin, Clément De and Xavier d'Haultfoeuille, "Two-way fixed effects estimators with heterogeneous treatment effects," *American Economic Review*, 2020, *110* (9), 2964–96.

_ **and** _ , "Difference-in-Differences Estimators of Intertemporal Treatment Effects," 2021.

Dong, Xiaofang, Siqi Zheng, and Matthew E Kahn, "The role of transportation speed in facilitating high skilled teamwork across cities," *Journal of Urban Economics*, 2020, *115*, 103212.

Hanlon, W. Walker, Stephan Heblich, Ferdinando Monte, and Martin B Schmitz, "A Penny for Your Thoughts," Working Paper 30076, National Bureau of Economic Research May 2022.

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

Iaria, Alessandro, Carlo Schwarz, and Fabian Waldinger, "Frontier Knowledge and Scientific Production: Evidence from the Collapse of International Science," *The Quarterly Journal of Economics*, 01 2018, *133* (2), 927–991.

Jones, Benjamin F, "The burden of knowledge and the "death of the renaissance man": Is innovation getting harder?," *The Review of Economic Studies*, 2009, *76* (1), 283–317.

Jones, Benjamin F., "The Rise of Research Teams: Benefits and Costs in Economics," *Journal of Economic Perspectives*, May 2021, *35* (2), 191–216.

Kerr, Sari Pekkala and William R Kerr, "Global collaborative patents," *The Economic Journal*, 2018, *128* (612), F235–F272.

Koh, Yumi, Jing Li, and Jianhuan Xu, "Subway, Collaborative Matching, and Innovation," *Review of Economics and Statistics*, 2022, pp. 1–45.

Nuvolari, Alessandro and Michelangelo Vasta, "Independent invention in Italy during the Liberal Age, 1861–1913," *The Economic History Review*, 2015, *68* (3), 858–886.

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

Perlman, Elisabeth Ruth, "Connecting the Periphery, Three Papers in the Development Caused by Spreading Transportation and Information Networks in the Nineteenth Century United States." PhD dissertation, Boston University, Graduate School of Arts and Sciences 2016.

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

Wu, Lingfei, Dashun Wang, and James A Evans, "Large teams develop and small teams disrupt science and technology," *Nature*, 2019, *566* (7744), 378–382.

Wuchty, Stefan, Benjamin F Jones, and Brian Uzzi, "The increasing dominance of teams in production of knowledge," *Science*, 2007, *316* (5827), 1036–1039.

Online Appendix

Collaboration and Connectivity: Historical Evidence from Patent Records

A.1 Alternative definitions of collaborations and functional form

We first document that our results are robust to using alternative definitions of collaborative patents and different functional forms. First, recall that in our main definition of a collaboration, we include patents that include more than one patentee and/or inventor. Here, we examine two alternative definitions:

1. Patents that include more than one listed inventor (i.e., disregarding the number of patentees).

2. Including patents with more than one listed inventor and patents that have no listed inventor but more than one patentee.

As shown in Online Appendix Table A.2, we find similar increases in collaborative activity when using these alternative definitions. Second, Online Appendix Table A.3 documents that our results are robust to an alternative method of counting collaborative activity between municipalities.[17] Third, we show that collaborations also increased in logarithms (ln) in Online Appendix Table A.4, where we add 1 to the number of collaborations in each municipality before taking the natural

A.2 Alternative specifications

We next document the robustness of our main results using alternative specifications. First, Online Appendix Figure A.11 reports estimates of our main equation (1) that includes additional treatment indicators for distance bins to the network. Clearly, the impact is only evident within the 0–5 km bin, which motivates our cutoff used in the main analysis. Second, an alternative approach is to instead measure connectivity by a municipality's (ln) distance to the network, rather than defining a distance cutoff. In Appendix Table A.5 we show that our main results are similar when measuring access this way. Third, we find similar results when using a standard event study approach in Online Appendix Figure A.12.

[17] In contrast to our main definition, where we count the nodes in the collaboration, we here allow each link to be counted separately. Taking the example of Swedish patent no. 25666 (see Appendix Figure A.1), where there are two engineers from the capital of *Stockholm* and one engineer from the municipality of *Trollhättan*, Stockholm and Trollhättan would obtain four and two collaborations, respectively.

A.3 Dyads

To explore the robustness of our results to a gravity-type specification, we construct a dataset with all municipality pairs for each decade 1850–1910. This allows us to run the following type of specification:

$$Y_{ijt} = \beta Network_{ijt} + \gamma_{ij} + \phi_t + \varepsilon_{ijt}, \tag{2}$$

for a municipality pair i and j, and a decade t. The outcome Y_{ijt} is either an indicator variable capturing if there is any collaborative activity or a continuous measure of the number of collaborations within the pair in decade t. The key regressor of interest is $Network_{ijt}$, which captures if both municipalities are connected to the railroad network at the start of the decade. Moreover, we include dyad and decadal fixed effects, captured by γ_{ij} and ϕ_t in all regressions. In an additional more demanding specification, we additionally introduce decadal fixed effects for each separate municipality in the pair. Table A.3 displays the results.

A.4 Instrumental variables design

We validate the robustness of our results to the instrumental variable design used in Andersson et al. (2021). First, we follow Dijkstra's optimal route algorithm to construct bilateral least-cost paths between all targeted destinations using data on land cover and slope gradients. Second, we then calculate the distance to the nearest least-cost path for each municipality. Third, we interact this cross-sectional variation with period fixed effects for each decade after the introduction of railroads, starting in the 1870s, to obtain four instruments.[18] Online Appendix Table A.7 presents our 2SLS estimates. In general, point estimates are qualitatively the same, but less precise. Interestingly, the most robust findings is the increases in collaboration with inventors residing in other locations connected to the network. In contrast, both within-municipality and non-rail collaboration are in general statistically insignificant. Thus, our 2SLS estimates are consistent with the notion that the positive effect of railroads on collaboration is mainly driven by distant collaborations along the railroad network.

A.5 Placebo lines

If network connections were opened in a way that correlates with time-varying unobserved factors that in turn shape collaboration, we could erroneously attribute the rise of patent collaborations to the establishment of a network connection. To examine whether such empirical threats are plausible in out setting, we estimate the "effects" for a battery of rail lines that were planned but

[18] We refer to Andersson et al. (2021) for additional details.

ultimately not constructed (see Andersson et al. (2021)). In Appendix Figure A.8 we document that there are no statistically significant increases in collaboration at conventional levels along lines that were put forth in the original network proposal from the 1850s, nor along any lines that were later proposed in the 1870s.

A.6 Communication technologies

At the same time as the railroad spread, other communication networks were rolled out. In particular, the latter half of the 19^{th} century saw the emergence of a telegraph network, which often expanded along the rail. Thus, our baseline estimates may partly reflect that a network connection often also came with improved communication through access to the telegraph network. To explore this issue, we use data on telegraph stations from reports published by Statistics Sweden (Andersson et al., 2021). Because data on all stations is not readily available, we focus on the central nodes in the network (i.e., stations belonging to "class 1–3") and code an indicator taking the value one if one of these stations are located in a municipality at the start of a decade. The estimates thus capture the effect of being close to central nodes of the telegraph network, rather than the average effect of a telegraph line.

Online Appendix Table A.9 presents presents estimates of equation (1) where we additionally include an indicator capturing whether a municipality had access to a telegraph station. Reassuringly, the estimated impact of a rail connection on collaboration, both at the extensive (columns 1–2) and intensive (columns 3–10) margin, remains stable in magnitude when controlling for access to the telegraph network. At the same time, access to a telegraph station has a large positive association with collaboration. Together, these estimates show that the estimated impact of the railroad is robust to controlling for access to the telegraph, but also provide suggestive evidence that technologies that facilitate long-distance communication may further have contributed to the rise of collaboration.

A.7 Quality of collaborative patents

We here provide suggestive evidence on the quality of collaborative patents using information on the number of years that patents were renewed, a commonly used proxy for patent quality in historical settings. Patents could be renewed up to a maximum of 15 years and the assumption is that inventors and patentees would only renew their patents if they remained valuable. We only observe renewals for patents granted between 1885 and 1910, so the analysis is here limited to this subset of patents.

We first compare renewals among collaborative and non-collaborative patents. Figure A.13A plots kernel densities of the number of years patents were renewed separately for non-collaborative patents and collaborative patents. Collaborative patents do not differ much in terms of renewal years compared to non-collaborative patents. If anything, collaborative patents seem to be associated with lower quality as reflected in a higher density in the left tail.

We then compare differences in renewal among collaborative (Figure A.13B) and non-collaborative (Figure A.13C) patents where we separate between patents that are granted to inventors residing in a municipality connected to the rail network and those that remained unconnected. Figure A.13B shows that collaborations between inventors along the rail network were more likely to be renewed for just a few years and were less likely to be renewed for the full 15 years. Figure A.13C shows that renewals were more similar for non-collaborative patents, which suggests that the rail network may have facilitated collaboration partly among more marginal inventors. However, these comparisons must be interpreted carefully given that many other factors may differ between areas connected to the rail network.

A.8 Additional figures and tables

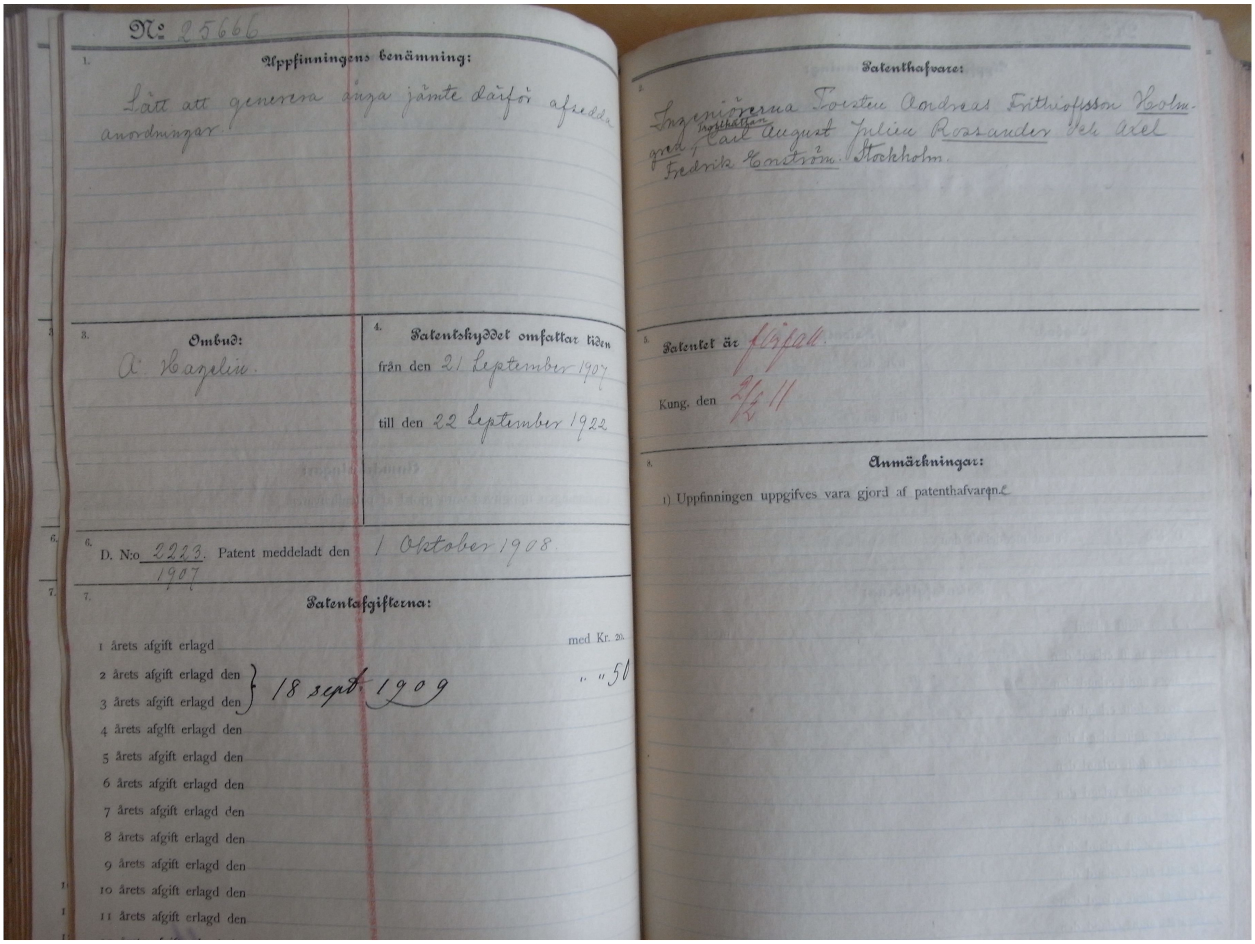


FIGURE A.1:
COLLABORATIVE PATENT

Notes: This figure displays Swedish patent no. 25666 for ”devices to generate steam” granted to engineers Carl Rossander and Fredrik Enström residing in Stockholm and engineer Torsten Holmgren residing in Trollhättan.

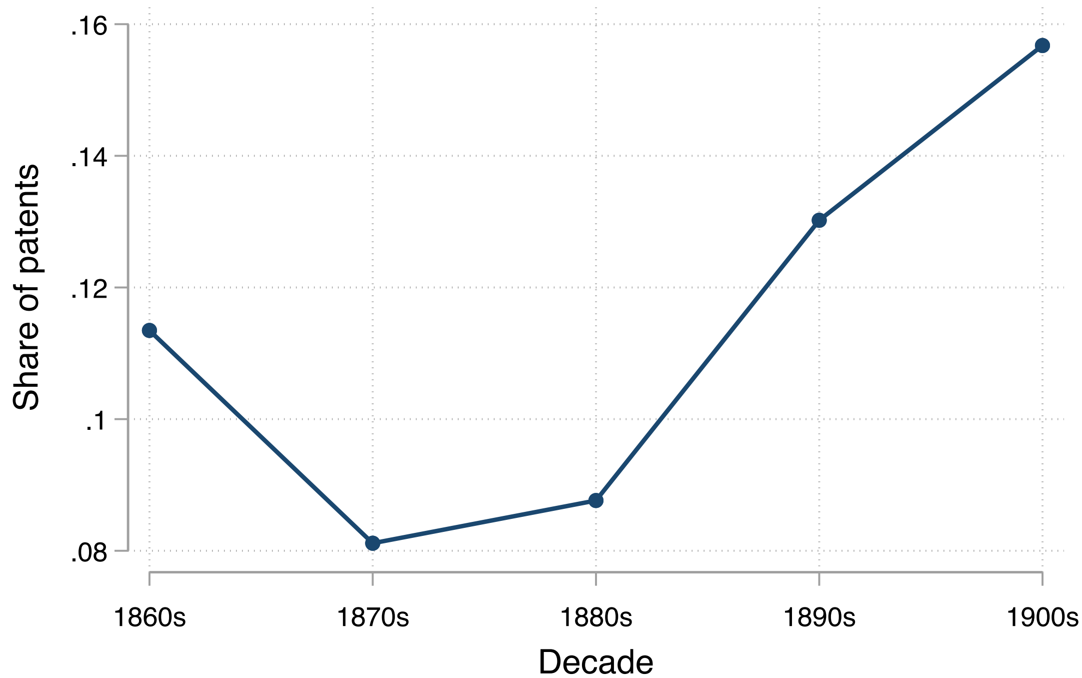


FIGURE A.2: SHARE OF PATENTS THAT ARE COLLABORATIVE

Notes: This figure displays the share of patents granted by the PRV that listed more than one inventor or patentee.

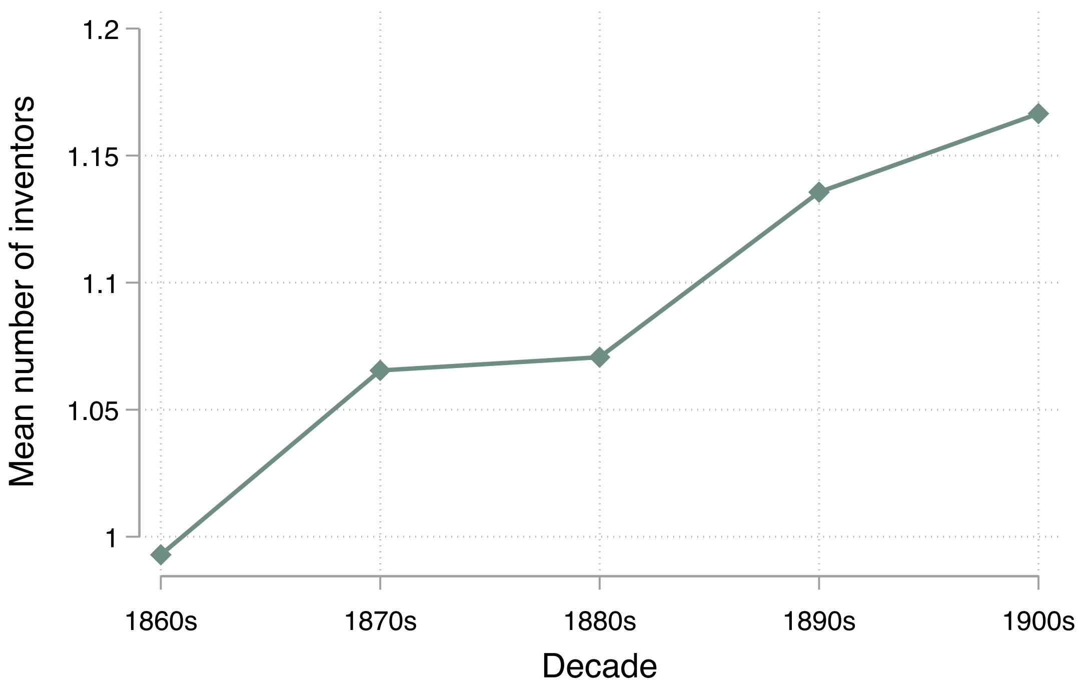
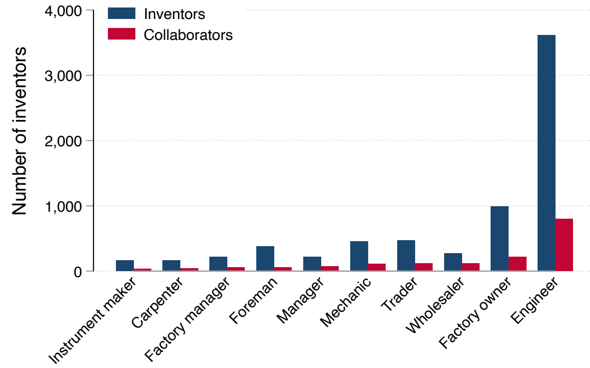
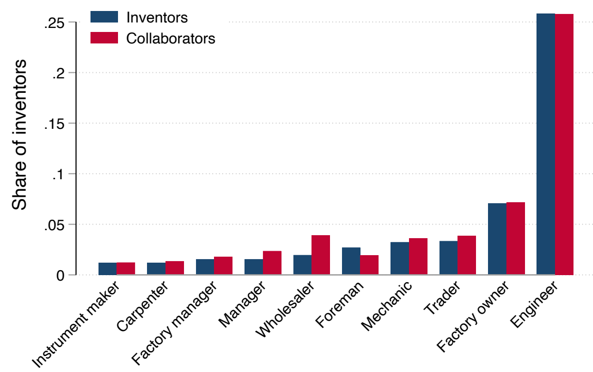


FIGURE A.3: INVENTORS PER PATENT.

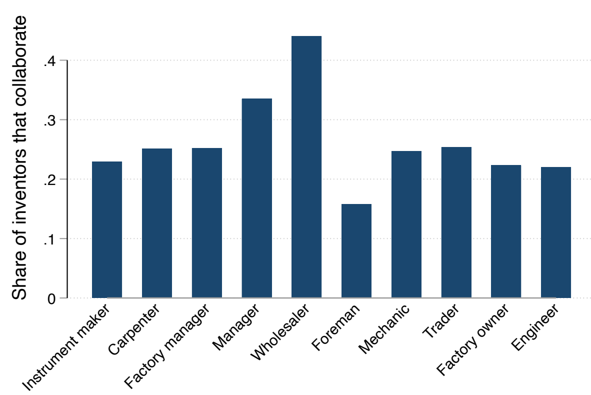
Notes: This figure displays the mean number of inventors and patentees listed on patents granted by the PRV.



(A) NUMBER OF (COLLABORATING) INVENTORS



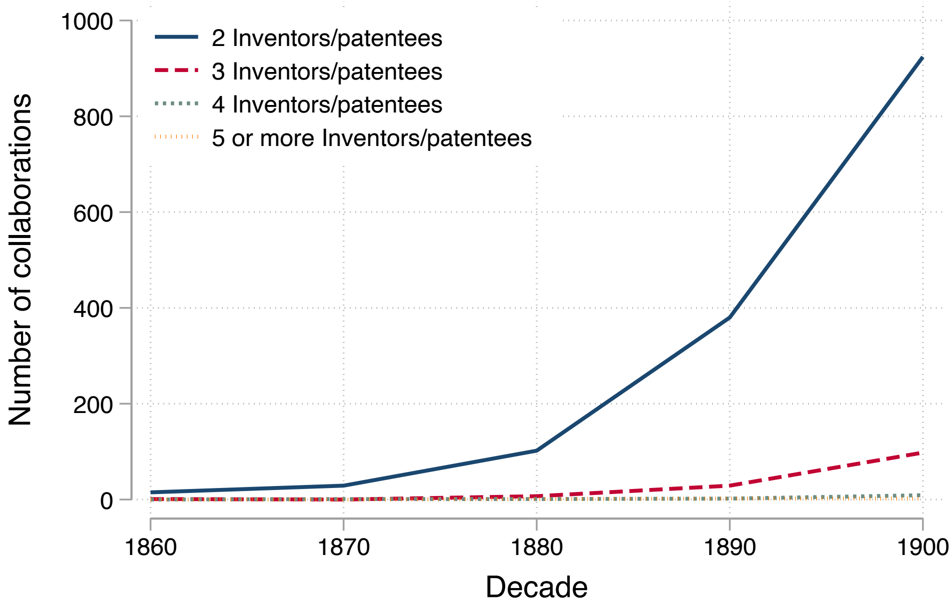
(B) SHARE OF (COLLABORATING) INVENTORS



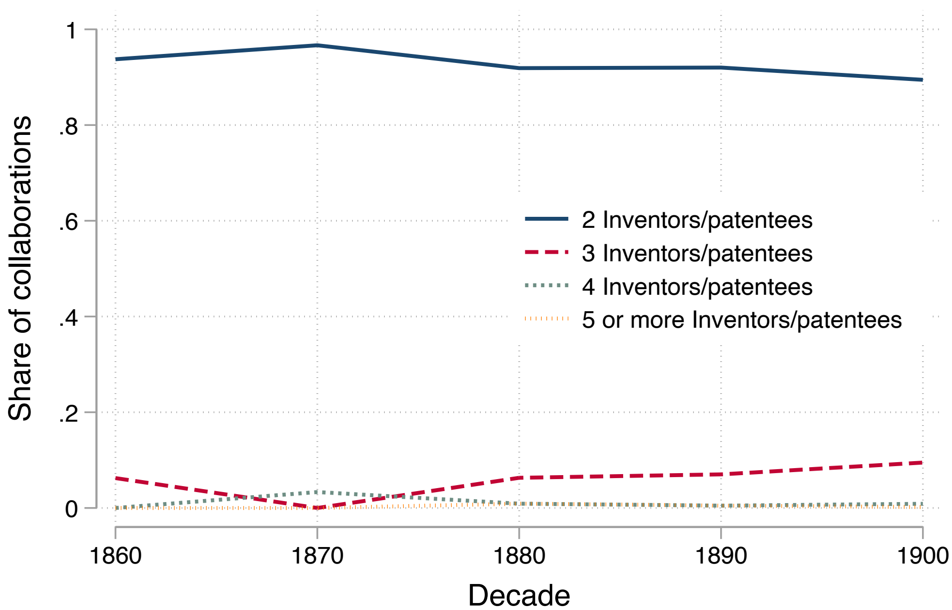
(C) SHARE OF INVENTORS THAT COLLABORATE

FIGURE A.4:
MOST COMMON OCCUPATIONS AMONG (COLLABORATING) INVENTORS, 1840–1910.

Notes: A: The 10 most common occupations among all inventors and the subset of inventors that were involved in a patent collaboration between 1840 and 1910. B: The share of inventors and collaborating inventors that held each occupation respectively. C: The share of inventors that were involved in at least on collaboration by occupation.



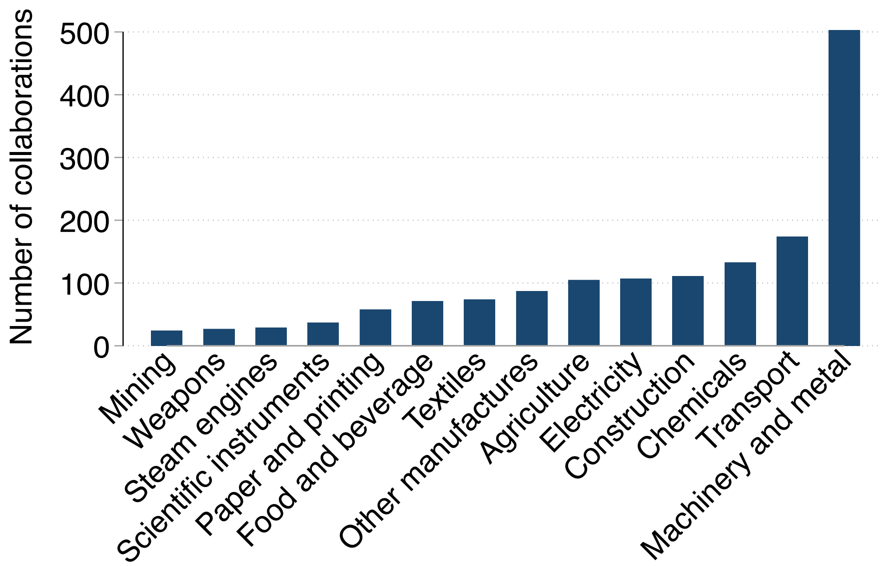
(A) NUMBER



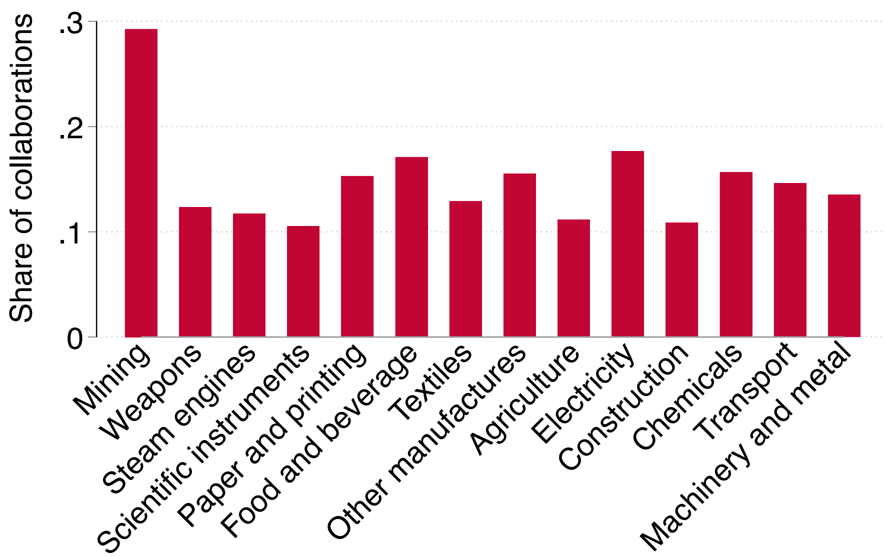
(B) SHARE

FIGURE A.5: TEAM SIZE

Notes: This figure displays the number (A) and share (B) of collaborative patents granted by the PRV that involved two, three, four, and five or more inventors and patentees respectively.



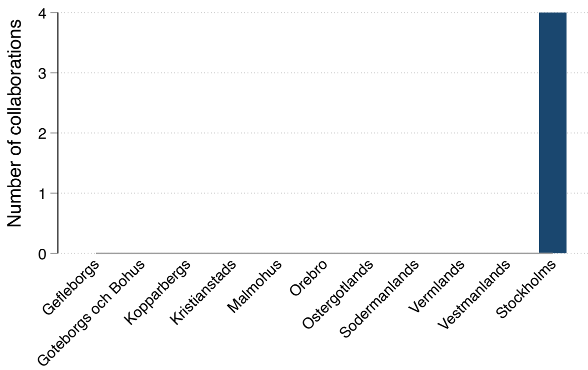
(A) NUMBER



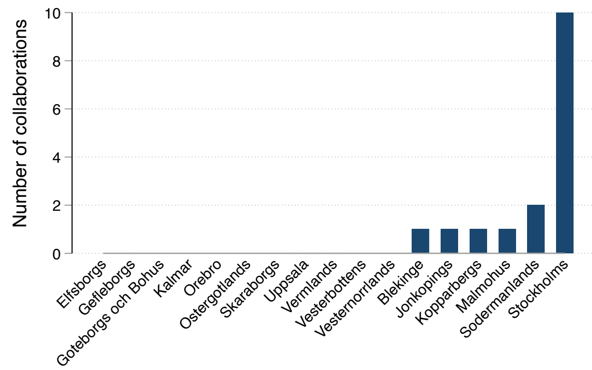
(B) SHARE

FIGURE A.6: PATENT COLLABORATIONS BY INDUSTRY

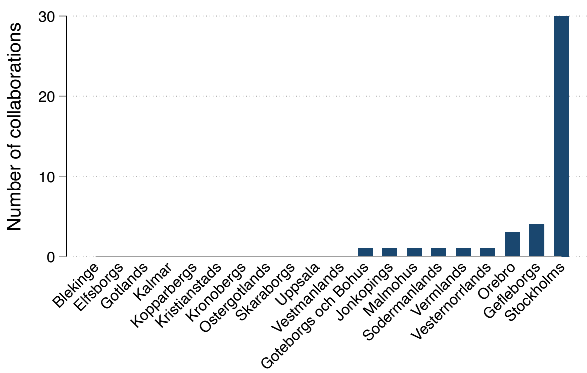
Notes: This figure displays the distribution of collaboration across industries based on all patents granted to Swedish inventors by the PRV between 1840–1910. The figure reports the number of collaborations (A) and the share of patents in an industry that are collaborative (B) across 14 industrial sectors based on the classification in Nuvolari and Vasta (2015).



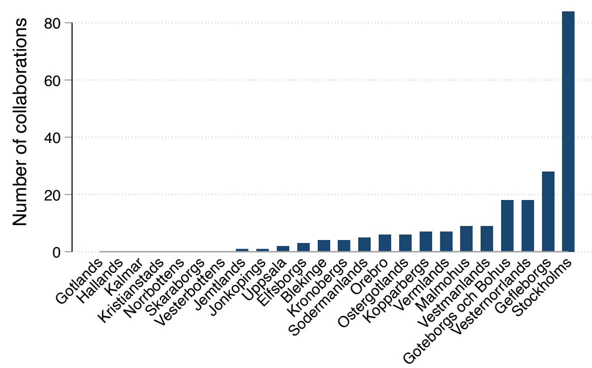
(A) 1840S AND 1850S



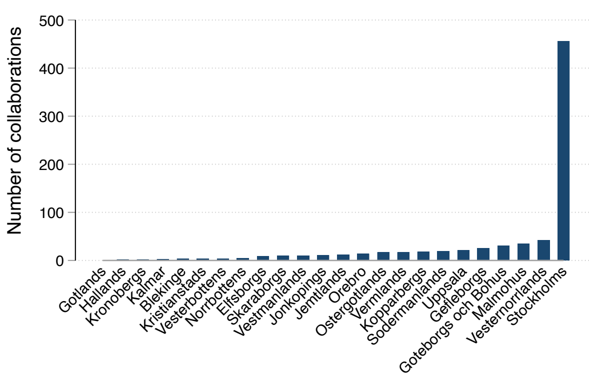
(B) 1860S



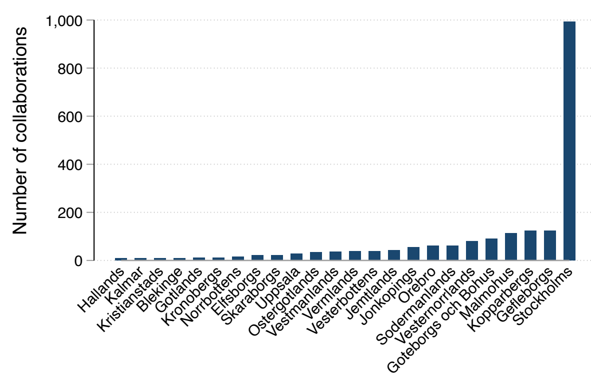
(C) 1870S



(D) 1880S



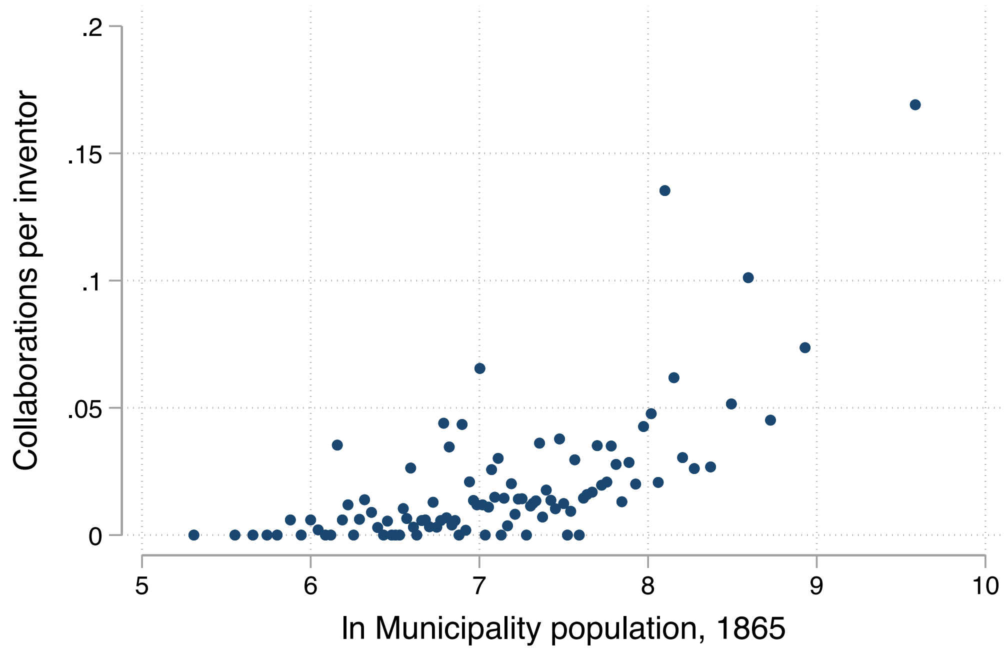
(E) 1890S



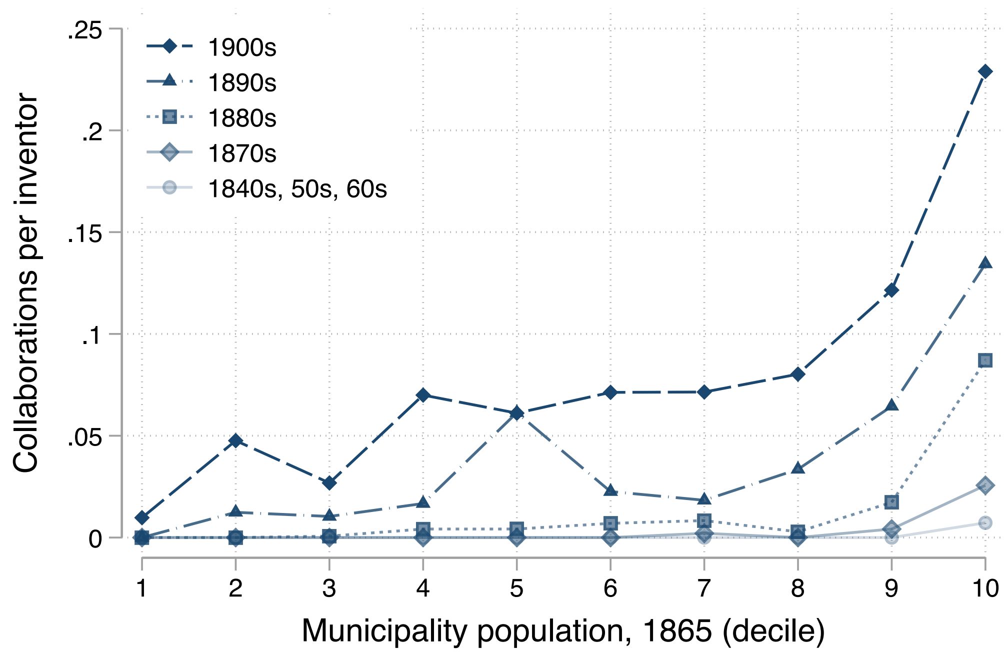
(F) 1900S

FIGURE A.7: NUMBER OF PATENT COLLABORATIONS BY COUNTY, 1840–1910.

Notes: This figure displays the number of patent collaborations across the 24 Swedish counties among all patents granted to Swedish inventors by the PRV between 1840–1910. Each panel displays all counties with at least one granted patent in each respective decade.



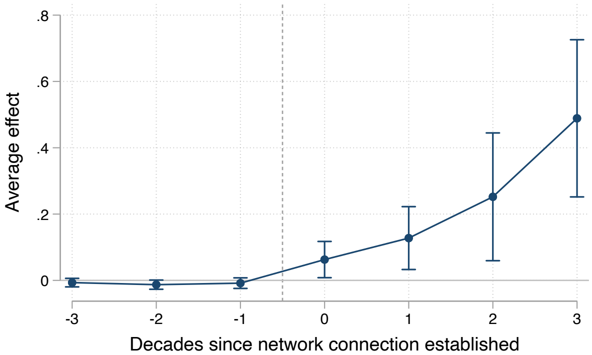
(A) ALL YEARS



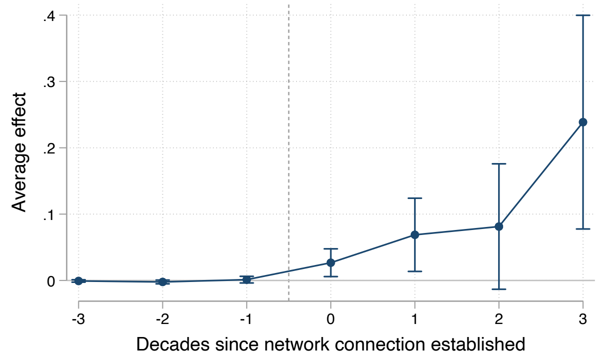
(B) BY DECADE

FIGURE A.8: MUNICIPALITY SIZE AND PATENT COLLABORATIONS, 1840–1910.

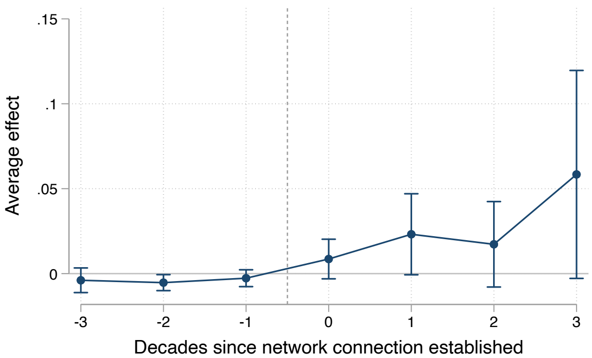
Notes: This figure displays municipality-level binned scatterplots of the number of collaborations per inventor between 1840–1910 and the ln population of each municipality in 1865 (A) and the number of collaborations per inventor for each respective decade and the population of each municipality in 1865 divided into deciles (B).



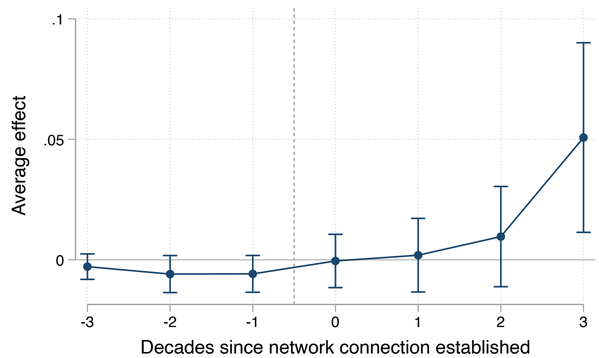
(A) TOTAL COLLABORATIONS



(B) COLLABORATIONS PER CAPITA



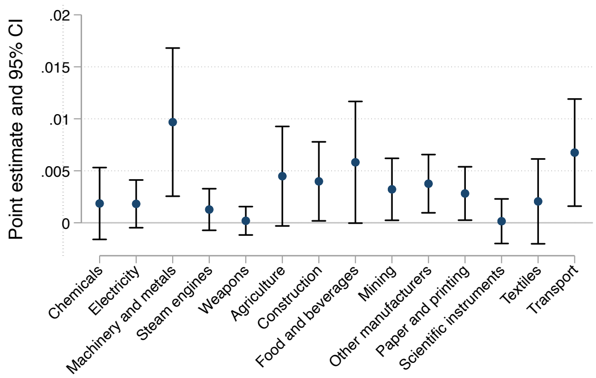
(C) COLLABORATIONS PER INVENTOR



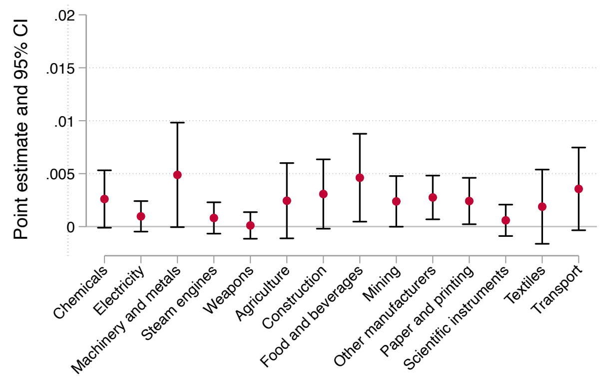
(D) COLLABORATIONS PER PATENT

FIGURE A.9: THE EFFECT OF NETWORK CONNECTIONS ON 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, 2021) on A: the total number of collaborations; B: the number of collaborations per 1,000 inhabitants; C: the number of collaborations per inventor; and D: the number of collaborations per patent. 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, 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-by-year fixed effects. Bars indicate 95 percent confidence intervals. Standard errors are clustered at the municipality level.



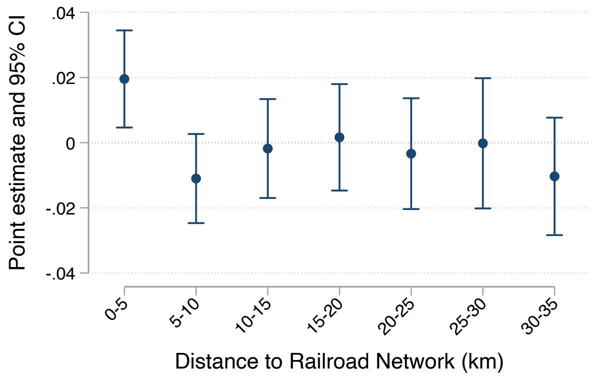
(A) ANY COLLABORATION



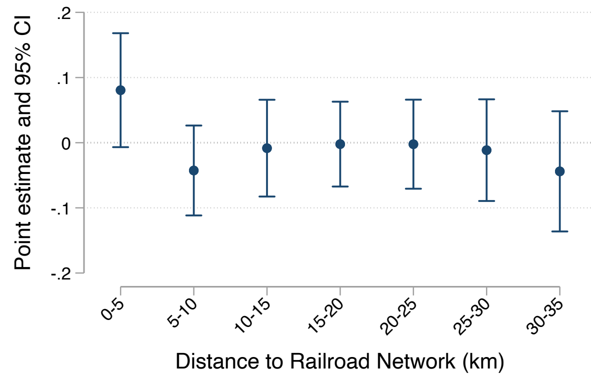
(B) COLLABORATIONS PER PATENT

FIGURE A.10: PATENT COLLABORATIONS BY INDUSTRIAL SECTOR

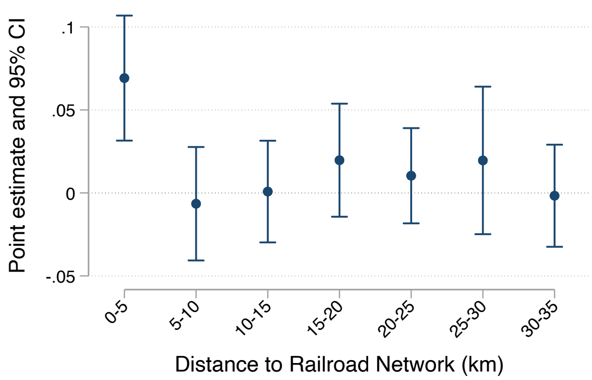
Notes: OLS regressions. The figure displays the relationship between collaborations in different sectors and railroad access, defined as an indicator variable equal to one if the municipality has a railroad within 5 km of the municipality centroid. The dependent variable is defined as an indicator variable equal to 1 if there is at least one collaboration (and zero otherwise) in panel A, and as the number of collaborations per patent in panel B. 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, 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-by-year fixed effects. Bars indicate 95 percent confidence intervals. Standard errors are clustered at the municipality level.



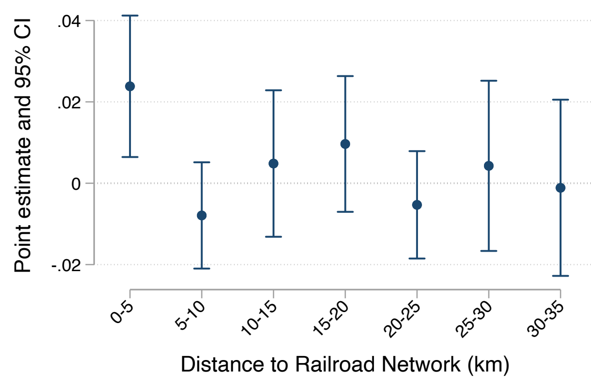
(A) ANY COLLABORATION



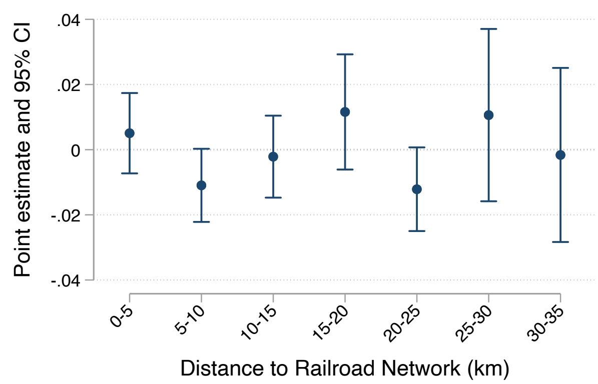
(B) TOTAL



(C) PER CAPITA



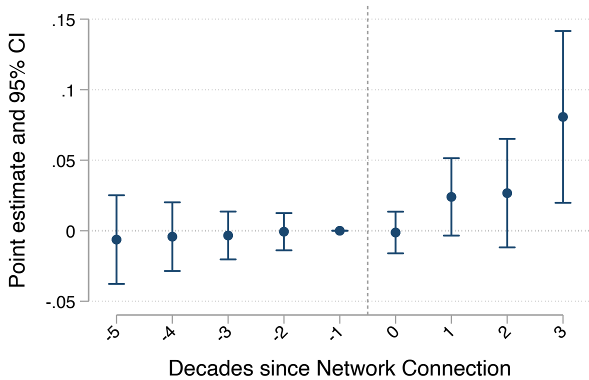
(D) PER INVENTOR



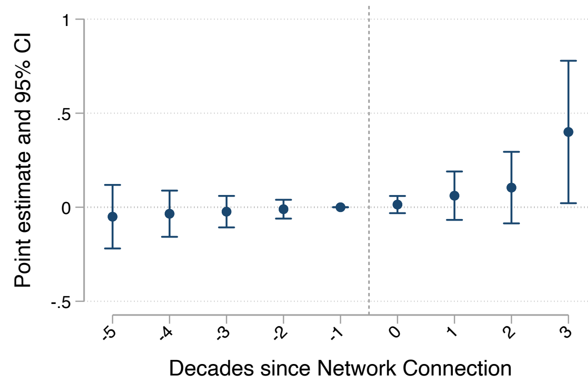
(E) PER PATENT

FIGURE A.11: NETWORK CONNECTIONS AND COLLABORATION: FLEXIBLE SPECIFICATIONS

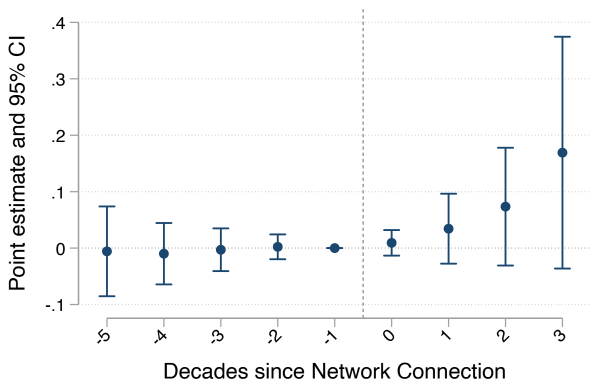
Notes: This figure display point estimates (denoted by circles) and 95% CIs (denoted by bars) from a set of OLS regressions where the dependent variable is A: an indicator variable equal to 1 if there is at least one collaboration (and zero otherwise); B: the number of collaborations (in total numbers); C: the number of collaborations per 1,000 inhabitants; D: the number of collaborations per inventor; and E: the number of collaborations per patent. We here include additional treatment indicators taking the value one if the municipality centroid is within 0–5, 5–10, ..., 30-35 km from the rail network at the start of each decade. We also include the full set of controls reported in Table 1.



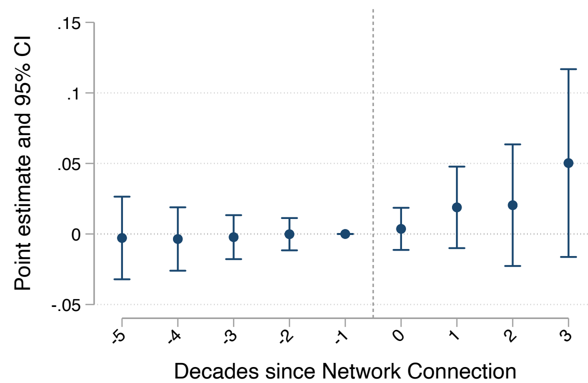
(A) ANY COLLABORATION



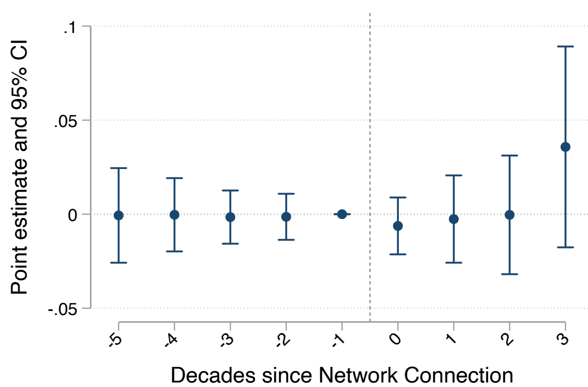
(B) TOTAL COLLABORATIONS



(C) COLLABORATIONS PER CAPITA



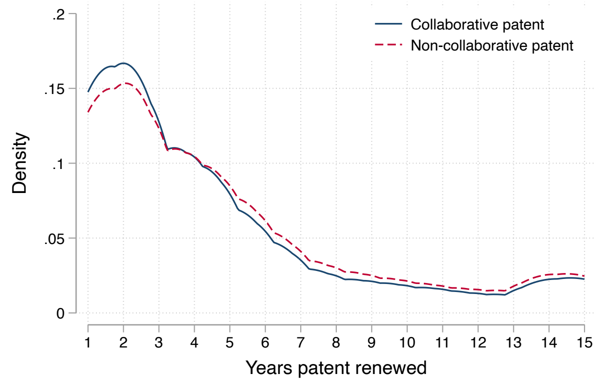
(D) COLLABORATIONS PER INVENTOR



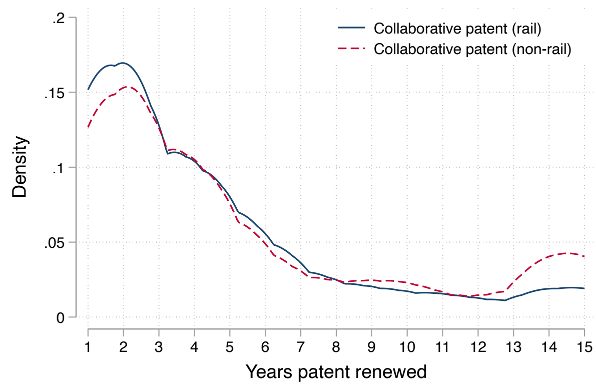
(E) COLLABORATIONS PER PATENT

FIGURE A.12: EVENT-STUDY ESTIMATES

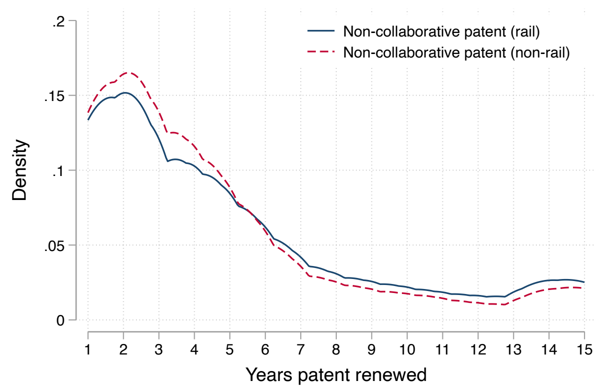
Notes: This figure display point estimates (denoted by circles) and 95% CIs (denoted by bars) from a set of standard event-study regressions where the dependent variable is A: an indicator variable equal to 1 if there is at least one collaboration (and zero otherwise); B: the number of collaborations (in total numbers); C: the number of collaborations per 1,000 inhabitants; D: the number of collaborations per inventor; and E: the number of collaborations per patent. We also include the full set of controls reported in Table 1.



(A) COLLABORATION VS. SINGLE INVENTOR



(B) COLLABORATION: RAIL VS. NO RAIL



(C) NON-COLLABORATION: RAIL VS. NO RAIL

FIGURE A.13: QUALITY OF (NON-)COLLABORATIVE PATENTS

Notes: This figure displays patent-level kernel densities (A) and shares (B) for the number of years PRV patents granted to Swedish inventors between 1885–1910 were renewed separately for A: collaborative and non-collaborative patents; B: collaborative and non-collaborative patents involving inventors in municipalities connected to the rail network; and C: collaborative and non-collaborative patents involving inventors in municipalities not connected to the rail network. We use an Epanechnikov kernel with a half width of 1.

TABLE A.1: RAILROADS AND THE SIZE OF TEAMS

Dependent variable:	Any collaboration	
	2 inv	3 or more inv
	(1)	(2)
Network Connection (=1)	0.024***	0.003
	(0.005)	(0.002)
Local Geography×Decadal FE	Yes	Yes
Pre-Rail Controls×Decadal FE	Yes	Yes
Region FE×Decadal FE	Yes	Yes
Observations	16674	16674
Mean dep. var.	0.022	0.005

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) for teams of either two individuals or above two individuals. 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, 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. 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 A.2: ALTERNATIVE DEFINITIONS OF COLLABORATIONS

Dependent variable:	Number of collaborations				
	Any	Total	per capita	per inventor	per patent
Panel A. Inventors or patent holders (main)					
	(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. Inventors or patent holders if no inventors					
	(1)	(2)	(3)	(4)	(5)
Network Connection (=1)	0.020***	0.090***	0.052***	0.016***	0.006
	(0.005)	(0.030)	(0.015)	(0.006)	(0.004)
Mean dep. var.	0.020	0.068	0.028	0.015	0.011
Panel C. Only inventors					
	(1)	(2)	(3)	(4)	(5)
Network Connection (=1)	0.003	0.007	0.005	0.001	0.001
	(0.002)	(0.005)	(0.003)	(0.002)	(0.001)
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.	0.003	0.006	0.003	0.001	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 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. Panels A–C use different definitions of collaborations as described further in the main text. 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, 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. 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 A.3: ALTERNATIVE DEFINITION OF COLLABORATIONS USING LINKS BETWEEN INDIVIDUALS

Dependent variable:	Number of collaborations				
	Any	Total	per capita	per inventor	per patent
	(1)	(2)	(3)	(4)	(5)
Network Connection (=1)	0.082***	0.552***	0.373***	0.179***	0.093***
	(0.009)	(0.146)	(0.086)	(0.026)	(0.013)
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.	0.078	0.535	0.224	0.144	0.097

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. The number of collaborations correspond to the number of links between individuals. 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, 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. 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 A.4: THE EFFECT OF NETWORK CONNECTIONS ON COLLABORATIONS IN LOGARITHMS

Dependent variable:	Number of collaborations (ln)			
	Total	per capita	per inventor	per patent
Panel A. PRV patents				
	(1)	(2)	(3)	(4)
Network Connection (=1)	0.032***	0.025***	0.015***	0.008***
	(0.008)	(0.005)	(0.004)	(0.003)
Observations	16674	16674	16674	16674
Mean dep. var.	0.030	0.017	0.013	0.010
Panel B. USPTO patents				
	(1)	(2)	(3)	(4)
Network Connection (=1)	0.003**	0.004***	0.002**	0.003**
	(0.001)	(0.001)	(0.001)	(0.001)
Local Geography×Decadal FE	Yes	Yes	Yes	Yes
Pre-Rail Controls×Decadal FE	Yes	Yes	Yes	Yes
Region FE×Decadal FE	Yes	Yes	Yes	Yes
Observations	16674	16674	16674	16674
Mean dep. var.	0.001	0.001	0.000	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 the natural logarithm of 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, 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. 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 A.5: THE EFFECT OF DISTANCE TO NETWORK ON PATENT COLLABORATIONS

Dependent variable:	Number of collaborations				
	Any	Total	per capita	per inventor	per patent
Panel A. PRV patents					
	(1)	(2)	(3)	(4)	(5)
ln(Dist. rail)	-0.008***	-0.035***	-0.019***	-0.009***	-0.003**
	(0.002)	(0.011)	(0.005)	(0.002)	(0.001)
Observations	16674	16674	16674	16674	16674
Mean dep. var.	0.024	0.087	0.036	0.019	0.014
Panel B. USPTO patents					
	(1)	(2)	(3)	(4)	(5)
ln(Dist. rail)	-0.001	-0.001	-0.002**	-0.001**	-0.002**
	(0.001)	(0.001)	(0.001)	(0.000)	(0.001)
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	0.002	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. ln(Dist. rail) corresponds to the distance from the municipality centroid to the nearest railroad at the start of each decade. 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, 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. 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 A.6: COLLABORATIONS WITHIN MUNCIPALITY PAIRS

Dependent variable:	Any collaboration		Number of collaborations	
	(1)	(2)	(3)	(4)
Both connected (=1)	0.00008***	0.00002***	0.00019***	0.00006**
	(0.00001)	(0.00001)	(0.00004)	(0.00003)
Dyad FE	Yes	Yes	Yes	Yes
Decadal FE	Yes	No	Yes	No
Decadal-municipalities FE	No	Yes	No	Yes
Observations	17100432	17086098	17100432	17086098
Mean dep. var.	0.00002	0.00002	0.00004	0.00004

Notes: OLS regressions using a decadal sample of all pairs of municipalities 1850–1900. The dependent variable is an indicator variable equal to 1 if there is at least one collaboration within the pair (and zero otherwise). Both connected (=1) is an indicator variable equal to one if both municipalities have a railroad within 5 km of their municipality centroids. Only one connected (=1) is an indicator variable equal to one if one of the municipalities has a railroad within 5 km of the municipality centroid and the other does not. Dyad FE denotes fixed effects at the municipality-pair level. Decadal FE denotes fixed effects for each decade. Decadal-municipalities FE denotes fixed effects at each decadel-municipality combination. Standard errors are given in parentheses and are clustered at the municipality-pair level. *** - $p < 0.01$, ** - $p < 0.05$, * - $p < 0.1$.

TABLE A.7: 2SLS ESTIMATES

Dependent variable:	Number of patent collaborations				
	Any	Total	per capita	per inventor	per patent
	(1)	(2)	(3)	(4)	(5)
Network Connection (=1)	0.082***	0.467**	0.212**	0.035	0.028
	(0.030)	(0.202)	(0.089)	(0.033)	(0.019)
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
First-Stage F-stat	31.36	31.36	31.36	31.36	31.36
Observations	16674	16674	16674	16674	16674
Mean dep. var.	0.024	0.087	0.036	0.019	0.014

Notes: 2SLS 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 capita, per inventor, and per patent in columns 3, 4, and 5. 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, 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. Region FE denotes fixed effects at the NUTS-II level. Decadal FE denotes fixed effects at the decadal level. The excluded instruments are a set of period fixed effects interacted with the log distance to the nearest least-cost path. Standard errors are given in parentheses and are clustered at the municipality level. *** - $p < 0.01$, ** - $p < 0.05$, * - $p < 0.1$.

TABLE A.8: PLACEBO LINES

Dependent variable:	Number of collaborations														
	Any			Total			per capita			per inventor			per patent		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)
Network Connection (=1)	0.025***	0.025***	0.025***	0.103***	0.105***	0.103***	0.068***	0.069***	0.068***	0.025***	0.026***	0.025***	0.009**	0.010**	0.009**
	(0.006)	(0.005)	(0.006)	(0.034)	(0.034)	(0.034)	(0.018)	(0.018)	(0.018)	(0.007)	(0.007)	(0.007)	(0.004)	(0.004)	(0.004)
Placebo line (Ericson's proposal)	-0.006			0.010			-0.013			-0.003			-0.000		
	(0.017)			(0.051)			(0.021)			(0.018)			(0.017)		
Placebo line (1870 committee proposal)		0.042*			0.238***			0.079			0.031			0.060	
		(0.024)			(0.080)			(0.048)			(0.021)			(0.039)	
Placebo line (1870 municipality proposal)			-0.003			0.030			0.002			-0.003			-0.008
			(0.016)			(0.074)			(0.013)			(0.012)			(0.008)
Local Geography×Decadal FE	Yes	Yes	Yes	Yes	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	Yes	Yes	Yes	Yes
Region FE×Decadal FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	16674	16674	16674	16674	16674	16674	16674	16674	16674	16674	16674	16674	16674	16674	16674
Mean dep. var.	0.024	0.024	0.024	0.087	0.087	0.087	0.036	0.036	0.036	0.019	0.019	0.019	0.014	0.014	0.014

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, the number of collaborations (in total numbers) in columns 4–6, as well as per 1,000 inhabitants, per inventor, and per patent in columns 7–9, 10–12, and 13–15 respectively. Network Connection (=1) is an indicator variable equal to one if the municipality has a railroad within 5 km of the municipality centroid. Placebo lines are indicators taking the value one if a railroad that was not ultimately built was planned to traverse a municipality. 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, 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. 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 A.9: TELEGRAPH STATIONS.

Dependent variable:	Number of collaborations									
	Any		Total		per capita		per inventor		per patent	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Network Connection (=1)	0.025***	0.026***	0.103***	0.107***	0.068***	0.071***	0.025***	0.026***	0.009**	0.010**
	(0.006)	(0.005)	(0.034)	(0.033)	(0.018)	(0.018)	(0.007)	(0.007)	(0.004)	(0.004)
Telegraph Station (=1)		0.094***		0.326**		0.196**		0.055**		0.030**
		(0.019)		(0.146)		(0.099)		(0.023)		(0.013)
Local Geography×Decadal FE	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
Region FE×Decadal FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	16674	16674	16674	16674	16674	16674	16674	16674	16674	16674
Mean dep. var.	0.024	0.024	0.087	0.087	0.036	0.036	0.019	0.019	0.014	0.014

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 and 2, the number of collaborations (in total numbers) in columns 3 and 4 as well as per 1,000 inhabitans, per inventor, and per patent in columns 5–6, 7–8, and 9–10. Network Connection (=1) is an indicator variable equal to one if the municipality has a railroad within 5 km of the municipality centroid. Telegraph Station (=1) is an indicator variable equal to one if the municipality has a (class 1–3) telegraph station 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, 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. 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. *** - $p < 0.01$, ** - $p < 0.05$, * - $p < 0.1$.