UNIVERSITAT DE BARCELONA

Three Essays on the Geography of Innovation: The Role of Transportation Networks and Institutions

Georgios Tsiachtsiras

PhD in Economics

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1 Introduction

The long-term growth of economies depends crucially on their capacity to introduce technological progress (Weitzman, 1998; Kuznets, 1960). Innovation and technological change are at the heart of economic growth (Schumpeter, 1942; Romer, 1986). Yet, there is remarkable variation in the growth rates across sub-national regions (Rodriguez-Pose, 2018; Iammarino et al., 2019; Akcigit and Nicholas, 2019; Kemeny and Storper, 2020). This variation exists because important determinants of innovation are neither randomly nor evenly distributed. Several different forces promote and reinforce the concentration of economic and innovation activities across the space, such as agglomeration economies (Glaeser and Kerr, 2009; Glaeser, 2010; Carlino and Kerr, 2014), the localized nature of knowledge diffusion (Jaffe et al., 1993; Audretsch and Feldman, 2004; Lucas, 2009; Buera and Oberfield, 2020), as well as the concentration of human capital and talent, especially in urban areas (Lucas, 1988).

The diffusion of knowledge and ideas is a key element for innovation performance of firms, regions and countries. An invention by a firm has a positive external effect on the production possibilities of other firms because knowledge cannot be kept secret as if it was a public good (Arrow, 1962; Romer, 1986). At the heart of this diffusion process are the inventors and their interactions. Inventors build their knowledge over time by interacting with others and learning from them (Akcigit et al., 2018). They are mobile across firms and space (Akcigit et al., 2016), and form networks (Breschi and Lissoni, 2009) that facilitate the diffusion of knowledge. They develop strong bonds with each other within these networks. Their bonds endure over time as co-located inventors in the past are more likely to conduct teamwork again in the future even if they are located far apart (Miguelez, 2019). Inventors build their own knowledge but at the same time they enrich the learning environment for the people around them (Lucas and Moll, 2014). Yet, knowledge diffusion is bounded in space, as innovators behaviours are geographically limited and occur mostly in urban environments (Jaffe et al., 1993; Storper and Venables, 2004).

Human capital is an important determinant of economic growth (Lucas, 1988). It includes assets such as education, training, intelligence and skills. Education, and more specific research-type education, is associated with innovation performance (Aghion et al., 2009). Studies looking at the likelihood to become an inventor find that the family background has an effect on the formation of human capital only through education, either the education of the child (Akcigit et al., 2017) or the education of the parents (Aghion et al., 2017). Recent findings suggest that exposure to innovation during childhood has a significant effect on the probability of the child to become an inventor (Bell et al., 2019). High exposure is more likely to happen in urban areas, too. Lastly, universities and research institutions are important generators of new ideas too, (Hausman, 2021), which in turn affect local innovation (Andrews, 2020).

Agglomeration has a direct and an indirect effect on innovation and technological progress. The direct effect appears when highly dense areas affect the incentives to inventive activity. A larger pool of both potential customers and competing suppliers push the individuals and firms to commit additional resources to search for useful discoveries. This is happening because larger markets increase the expected return to such investments (Sokoloff, 1988). Cities are exactly that. Highly populated areas that offer firms and innovators more opportunities to sell their products and commercialize their inventions. An increase in connectivity thanks to transportation networks further increases market access (Perlman, 2015) leading to more people being willing to pay a fixed cost for innovation (Bustos, 2011; Lileeva and Trefler, 2010).

Agglomeration effects are also evident indirectly through other channels, such as knowledge diffusion and the accumulation of human capital. People possessing similar skills tend to co-locate. Cities significantly promote face to face interactions by lowering the cost of exchanging ideas (Duranton and Puga, 2004; Marshall, 1890). They create better idea-exchange environments for the higher-ability partners who are even willing to pay higher local prices in order to co-locate (Davis and Dingel, 2019). Empirical evidence suggest that there is a significant improvement in the number and quality of patents produced by an inventor who moves to a city with a large cluster of inventors in the same field (Moretti, 2021). Dense urban agglomerations provide a faster rate of contact between individuals and each new contact provides an opportunity for learning (Glaeser, 1999).

Geographical proximity can facilitate face to face interactions. Face to face interactions are important especially in environments with imperfect information as they promote trust and incentives in a relationship (Storper and Venables, 2004). But it is not the only type of proximity that matters for innovation performance and knowledge diffusion. Local firms can be rivals and refuse any collaboration (Torre and Rallet, 2005). Other forms of proximity, apart from geographical, that are important determinants of knowledge creation and learning are cognitive proximity, organizational proximity, social proximity and institutional proximity (Boschma, 2005). Empirical evidence suggests that, for inventors as a whole, organisational proximity is a key feature for the creation of co-patenting teams, together with institutional proximity. On the other hand, geographical proximity is associated to co-patenting only through other proximities (Crescenzi et al., 2016). Using citation data Agrawal et al. (2008) report that institutional proximity and geographical proximity have on impact on the knowledge flows. Meanwhile, geographical proximity matters more for inventors who are not socially close. In line with the findings of Agrawal et al. (2008), Lychagin et al. (2016) provide evidence that geography matters and that intraregional spillovers are significant, sizable and economically important.

Another well-established approach in the literature is that innovation is "path dependent". This issue is based on the history and microeconomics of technology. The historical pattern of technological progress has a crucial role in determining the pace of future technological change (Dosi, 1988). Historical events can cause the lock-in of an economy to the production of an inferior technology (Arthur, 1989). The intuition is that a technology which by chance gains an early lead in adoption may eventually cause the exclusion of other similar inventions from the market. The introduction of uncertainty over the impact of secondary knowledge spillovers can create a distinction between a temporary technological lock-in and a permanent technological lock-in (Redding, 2002).[1] The difference between the temporary and permanent lock-in is being determined by the secondary knowledge spillovers. In the first case, it is not profitable to employ a new fundamental technology, once discovered, for small realizations of knowledge spillovers, while in the second case lock-in is no longer profitable to search for new fundamental technologies given the expected magnitude of secondary knowledge spillovers.

The branching literature and the idea of technological relatedness precisely build on the framework of innovation being path dependent. The concept of relatedness suggests that technological change may follow a path dependent process, in which production of new knowledge is bound to the existing knowledge (Patel and Pavitt, 1994; Petralia et al., 2017). Empirical studies find that technological related-

[1]Secondary spillovers is knowledge that has been acquired from one fundamental technology after this invention becomes public.

ness at the city level was a crucial driving force behind technological change in US (Boschma et al., 2014; Rigby, 2015).

Next, in parallel to the mentioned studies, there is a large body of literature reporting evidence that there is a growth slowdown in the generation of new ideas because the flow of these new ideas becomes more costly (Kortum, 1993; Griliches, 1994; Kogan et al., 2017; Bloom et al., 2020). In contrast to physical capital, that can be produced one for one from forgone output, new knowledge is the outcome of a research (Romer, 1986). Technological change provides the incentive for continued capital accumulation, and together, capital accumulation and technological change account for much of the increase in output per hour worked (Romer, 1990). As knowledge is the main input to produce more knowledge, this process can lead to a sustained growth path. However, according to Jones (2009), there are two empirical facts about innovation that are responsible for this slowdown: knowledge which becomes specialized and the growing need for always bigger research teams, as they are the source of the most creative ideas.

Against all this backdrop, the first purpose of this dissertation is to shed light, empirically, on the determinants of innovation performance from both a recent and a historical perspective. In all the chapters, innovation is proxied by patent data, a commonly used measure of innovation in the empirical literature on technological change (Akcigit et al., 2017), despite its well-known drawbacks (Griliches, 1990). Regarding the factors that can have an impact on innovation performance, this Ph.D. dissertation studies transportation infrastructure networks (Perlman, 2015; Agrawal et al., 2017; Andersson et al., 2021) and religious institutions (Benabou et al., 2021).

Investment in transport infrastructures is a cornerstone of growth-promoting strategies (Crescenzi et al., 2016; Crescenzi and Rodríguez-Pose, 2012). Over the last few decades, the World Bank has spent a large proportion of money on funding infrastructure investments (World Bank, 2007, 2013, 2017) with the goal of promoting long run economic growth.Transport infrastructures can foster economic efficiency and territorial equity (Crescenzi and Rodríguez-Pose, 2008). It provides higher accessibility and market integration of peripheral and lagging regions allowing them to catch up with more advanced territories (Crescenzi and Rodríguez-Pose, 2008). This thesis digs deeper on the relationship between transport connectivity and knowledge diffusion, as physical infrastructures may provide a broader reach to otherwise localized knowledge spillovers (Jaffe et al., 1993; Murata et al., 2014). Diffusion, in turn, affects the rate and direction of innovation in regions, as well as their growth path.

The role of institutions on economic growth has been widely explored by the literature (North, 1990). Institutions are capable to determine the development of any territory (Acemoglu and Robinson, 2012). Institutions have been linked to all sort of outcomes in the literature. Weak institutions, like poor quality government, can directly hamper regional economic development (Rodriguez-Pose, 2013) or indirectly through its negative effect on entrepreneurship (Nistotskaya et al., 2015). Furthermore, the quality of government affects infrastructure investments. Investing in transport infrastructure in poor or inadequate local government institutional conditions can seriously undermine the returns of the investment (Crescenzi et al., 2016). According to Arrow (1962), the role of institutions is to facilitate the learning process, specially institutions related to education and research. Recent empirical evidence connects the level of corruption and low policy-making capacity with knowledge generation proxied by patents (Rodriguez-Pose and Cataldo, 2015). Corrupted government can cause distortions in the motives of the firms. Akcigit et al. (2020) reports empirical evidence that firms which are market leaders are much more likely to be politically connected, but much less likely to innovate. Political connections are important for firms when it comes to their survival, but they do not affect their productivity. Institutional quality affects regions' labour productivity growth both directly —as improvements in institutional quality drive productivity growth— and indirectly —as the short- and long run returns of human capital and innovation on labour productivity growth are affected by regional variations in institutional quality (Rodriguez-Pose and Ganau, 2022). In the case of Europe, many regions and cities which are either lagging behind or declining have weaker 'good' institutions (Iammarino et al., 2019).

The focus of this thesis is on religious institutions. Max Weber, in his book "The Sociology of Religion", documents that for every type of priesthood, it is important to meet the needs of the laity in order to preserve its power. One of the three forces that the priesthood must confront in order to maintain its power is intellectualism (Weber, 1993). Even in recent days, religious institutions promote on several occasions an anti-scientific agenda which may affect the society. During the recent Covid-19 pandemic, religious leaders tried to convince their congregation not to receive the vaccine (Galang, 2021). Religious conservatives often manage to hamper science through politics and this effect gets more intense at the local level (Benabou et al., 2021). For instance, in 2011, Kentucky allocated over \$40 million in tax incentives for an expansion of the Creation Museum, with a theme park designed to demonstrate the literal truth of the story of Noah's ark (Benabou et al., 2021). Clashes between science and religion have been common throughout history (Lecce et al., 2021).

With the literature background surveyed in the paragraphs above, this Ph.D. thesis consists of 3 main chapters. Chapters 2 and 3 deal with the study of transportation networks and their relationship with innovation whereas Chapter 4 studies the impact of religiosity, again on the rate of innovation across areas.

The second chapter of this dissertation, with the title *"Transportation Networks and the Rise of the Knowledge Economy in 19th Century France"*, exploits an episode of French history to study the impact of the largest-scale construction of railroads on innovation performance. Over the second half of the 19th century, the roll-out of railroads transformed the French economy. Railways triggered economic relations and cultural environments, stimulated commerce and created new economic opportunities.

This chapter uses rich historical data to construct a panel dataset at the canton level for France (2,925 cantons) over the period 1850-1890. The analysis is based on a recent dataset of communes with access to a rail station over the second half of 19th century (Mimeur et al., 2018) and complements these data with the historical patent applications database of the National Institute of Industrial Property (INPI) office to construct a unique dataset.

Equipped with this dataset, the chapter relies on the expansion of the French railroad network, as it provides a unique setting to identify the causal impact of transport infrastructure on innovation outcomes. The three different French railway plans over the 19th century are used for the construction of a time variant straight-line instrument. We find that access to a rail station increases a canton's innovation activity. Additional findings are provided to support the benchmark analysis by applying an inconsequential units approach, a cross section analysis by decade, a difference-in-differences model and a falsification test.

Thus, in this chapter we contribute to the literature by exploring access to knowledge as an underlying mechanism behind the results. The focus is therefore on the supply side (Akcigit et al., 2018), which has been less investigated. Prior literature explores how market access affects innovation performance (Perlman, 2015). We compute accessibility measures, based on the rail and canal networks, for the largest cities of the 2,925 French cantons. Findings suggest that the innovation performance of a given canton depends crucially on how well connected is, based on rail and canal networks, to other cantons inhabited by inventors. This effect is mainly driven by potential interactions among inventors residing in different cantons.

In the last part of the chapter, we use text analysis techniques to determine the technological class of each patent application in the historical database of INPI. Equipped with this additional feature, the chapter documents that less costly access to the global city of Paris, compared to other large urban centers, is associated with a higher probability for the inventors of a given canton to innovate in a new technology. The intuition behind these findings is that for the inventors residing outside of Paris, it matters more a less costly connection to the capital because they can travel and learn how to innovate in a new technology. To further motivate this theoretical channel about the importance of Paris for the diffusion of new ideas, we provide anecdotal evidence about events that took place in Paris and served as connections to the outside world. An example of such events were the World Fairs. During the second half of 19th century, five World Fairs (1855, 1867, 1878, 1889 and 1900) took place in Paris and many foreign inventors from all around the world attended them as they could display their inventions and possibly win the award for the best invention of the event.

Next, moving to a more recent time period, we also explore the role of transport infrastructure on knowledge diffusion and innovation. Empirical evidence suggests that knowledge diffusion has not been strong enough to provide better opportunities for people remaining in lagging behind regions (Martin and Sunley, 1998; Dunford and Smith, 2000; Iammarino et al., 2019; Rodriguez-Pose, 2018). Knowledge concentration in space is therefore the rule, with influence on income per capita and spatial inequality (Kemeny and Storper, 2020). Face-to-face interactions are crucial in finding new collaborators, establishing trust, and advancing joint work (Kemeny et al., 2016). Even with online communication being extremely efficient, internet may have enhanced the role that travel technology plays in the economy (Catalini et al., 2020). Improvements in accessibility and declines in transportation costs facilitate the creation of teams by scientists and inventors and the generation of more ideas (Wuchty et al., 2007; Dong et al., 2020). In the third chapter of the thesis, *"Rails and innovation: Evidence from China"*, we explore the impact of the enormous expansion of high speed rail (HSR) lines in China, over the period 2008-2016, on knowledge diffusion and innovation performance.

In this chapter, we report evidence that the opening of a HSR station is associated with an increase in the number of patents per capita of a city. We base our analysis on a recent and unique dataset of disambiguated Chinese inventors (Yin et al., 2020) which covers the entire universe of patent applications of the China National Intellectual Property Administration database. We introduce a novel identification strategy, which relies on historical couriers' stations during the Ming dynasty (1403–1644), to create exogenous variation for our main independent variable. We complement our benchmark analysis with additional robustness checks based on a difference-in-differences regression with staggered treatment, a falsification test between our instrument and innovation performance before the creation of the HSR network, as well as controlling for variables related to the historical framework of our instrument.

As a mechanism behind the increase in the patenting activity, we investigate knowledge diffusion, using the framework of the branching literature on technological diversification (Hidalgo et al., 2007; Hausmann et al., 2007; Essletzbichler, 2015; Rigby, 2015; Petralia et al., 2017; Boschma, 2017; Balland et al., 2019; Bahar et al., 2020; Gao et al., 2021). We report findings showing that the probability of a city to specialize in a new technology depends on the specialization patterns of the cities to which the city connects through HSR, other things being equal. Additionally, we use gravity equations and report evidence that the reduction in transportation costs among cities fosters cross-city patent co-applications and citations.

In the fourth chapter of the dissertation, entitled *"Religiosity and Innovation in 19th Century France"*, we study, from a historical perspective, the effect of religiosity on innovation. We take advantage of a new legislation which re-established divorce in 1884 and we propose, as a novel proxy for religiosity, the number of divorces per capita. We extract and clean data on the number of divorces at the department level from the census of France over the period 1885 to 1897 (Censuses, 2011). Based on this measure, we can exploit time and geographical variation and construct a panel dataset at the department level. We complement these data with two unique historical patent databases. First, we make use again of the historical database of INPI, and second, we construct the historical United States Patent and Trademark Office (USPTO) database for France, which contains all the patents registered at USPTO with inventors residing in France, for the period 1838-1960.

While results in this chapter are still preliminary and the exercise is exploratory in nature, the findings seem to suggest a negative effect of religiosity on innovation, but only when it is proxied by USPTO patents. We believe that USPTO patents were able to capture inventions that were highly significant for technological progress, and therefore were the only ones affected by the influence of the Church.

In sum, this dissertation contributes to the recent literature studying the impact of transportation projects on economic outcomes (Büchel and Kyburz, 2020; Heblich et al., 2020; Pontarollo and Ricciuti, 2020; Andersson et al., 2021; Bogart et al., 2022) with a particular focus on innovation performance and how these projects may help to smooth the persistent inequalities among urban and rural areas (Rodriguez-Pose, 2018; Balland et al., 2020). It also adds on the impact of religiosity on knowledge activities, which has gained momentum recently (Benabou et al., 2015; Squicciarini and Voigtländer, 2015; Squicciarini, 2020; Benabou et al., 2021; Lecce et al., 2021).

2 Transportation Networks and the Rise of the Knowledge Economy in 19th Century France

"There is no country in the world where so small a proportion of the capital invested within the last forty years in canals and railroads, has been wasted or where traveling is safer, or in which travel and trade are accommodated at more reasonable rates than in France" (Moncure Robinson, American Philosophical Society, 1880)

2.1 Introduction

Productivity growth depends on two elements: new ideas bringing new technologies, and the diffusion of these ideas among people and places. Connecting places via transportation networks is essential in order to promote knowledge diffusion across the space, and hence long-term economic growth. Over the last few decades, the World Bank has spent a large proportion of money on funding infrastructure investments (World Bank, 2007, 2013, 2017).[2]Despite an emphasis on reducing transportation costs, we lack empirical evidence on understanding how transportation infrastructure projects can actually create meaningful connections to places that matter in terms of boosting innovation performance and strengthening channels related to the diffusion of knowledge.

In this chapter, I exploit an episode of French history to study the impact of the largest-scale construction of French railroads on innovation performance. Over the second half of the 19th century, railroad construction transformed the French economy. Railways generated economic relations and cultural environments, stimulated commerce and created new economic opportunities. The creation of the rail network changed the perception of time (Schwartz et al., 2011). According to Thévenin et al. (2013) a striking example of this transformation is the travel time between Paris and Marseille. In 1814, the duration of this trip was four to five days while in 1857, this trip needed about 13 hours.

Remarkably, the roll-out of the network coincided with a rise of innovation activity. Up to 1850, the number of patent applications owned by inventors in the historical French patent database was 22,978. From 1850 to 1902, this figure increases to 285,597. Some of the greatest inventions in history took place in France during the second half of the 19th Century, such as Louis Pasteur's inventions for

[2]Based on reports of 2007, 2013 and 2017, the World Bank spent approximately $105 billion on transport-related projects.

wine and beer pasteurization in 1865 and 1871, respectively. Another example is the invention of the French chemist, Charles Frederic Gerhardt who, in 1853, was the first person to prepare acetylsalicylic acid (aspirin). Lastly, the very first patented film camera was invented by Louis Le Prince in 1888.

I use rich historical data to construct a panel dataset at the canton level for France (2,925 cantons) over the period 1850-1890.[3] I combine a very recent dataset of communes with access to rail station in the 19th century (Mimeur et al., 2018) with the historical patent applications database of the National Institute of Industrial Property office (hereinafter, the INPI) (INPI, 2019) for the period 1850-1890 to construct a unique dataset.[4] The historical patent database of INPI is still fairly unexplored. Previous papers have used the INPI database during the first half of 19th century to study the effect of technology transfer from Britain to France (Nuvolari et al., 2020), the influence of the patent system on economic performance (Galvez-Behar, 2019) and the role of women in enterprise and invention in France (Khan, 2016).

Equipped with this dataset, this chapter focuses on the expansion of the French railroad network which provides a unique setting to identify the causal impact of transport infrastructure on innovation outcomes. I use the three different French railway plans over the course of the 19th century to construct a time variant straight line instrument. I document that access to a rail station increases a canton's innovation activity. For robustness analysis, and to complement the instrumental variance approach, I apply an inconsequential units approach based on the randomly chosen subset of municipalities that received railway access because they lie on the most direct route between the nodal destinations used to create the straight line instrument. In addition, I exploit the richness of the patent data to create a falsification exercise in which I regress the distance to rail stations on invention rate of the cantons over the period 1800-1840 one decade prior to the actual arrival of railroads. I do not report a significant effect meaning that future railroads are not associated with past innovation activity, at least the decades immediately prior to the sample period. I interpret this as evidence that my results are not driven by pre-trends related to the railroads and innovation performance. Moreover, I provide a conventional difference-in-differences regression model with staggered treatment using a binary indicator as an independent variable, switching to 1 if the canton has access to a rail station. This design covers the period 1800-1890 allowing me to control for a

[3] I include only the cantons from the mainland of France.

[4] The patent database is available on request.

long period of time, 1800-1840, before the arrival of railroads, when none of the cantons have access to a rail station. Finally, I explore cross section variation for every decade over the period 1850-1890 to identify the year that railroads started to have an impact on the patenting rate and to test the validity of the instrument by decade.

In a second step, I explore the mechanism behind the main results. This chapter adds to the literature by using the rationality of the "market access" framework, developed by Donaldson and Hornbeck (2016), to provide a supply side mechanism related to potential interactions (Akcigit et al., 2018) and knowledge spillovers (Jaffe et al., 1993) among the inventors residing in different cantons. Rather than using the population in the market access index, the chapter uses the number of inventors. The potential interactions and spillovers among inventors residing in different cantons could occur by establishing less costly routes, due to infrastructure improvements, within mainland France. I call this mechanism access to knowledge. A previous attempt in the literature uses a market access framework (Perlman, 2015) to identify the mechanism that boosts innovation performance. Other papers in the literature (Agrawal et al., 2017; Andersson et al., 2021; Inoue and Nakajima, 2017; Wong, 2019; Gao and Zheng, 2020; Dong et al., 2020; Sun et al., 2021; Hanley et al., 2021; Komikado et al., 2021; Cui et al., 2020; Huang and Wang, 2020) provide evidence on how transportation networks facilitate the diffusion of knowledge but without directly connecting the knowledge diffusion mechanism to innovation performance. Prior literature explores also supply side mechanisms on innovation performance like past co-inventors, inventors in the same firm, inventors in the same geographical region (Akcigit et al., 2018), degree and closeness centrality of a city (Yao et al., 2020), collaborations (Inoue and Liu, 2015; MingJi and Ping, 2014; Guan et al., 2005) and mobility of the inventors (Rahko, 2017). To the best of my knowledge, this is the first attempt to establish a supply side mechanism which connects via a transportation network a region's innovation performance to the outside world.

Finally, this chapter uses the unique setting of France to introduce as a special case the importance for the inventors of a given canton i to have a less costly connection to a global city such as Paris. Prior literature argues that Paris can work as a gatekeeper of knowledge that connects the national innovation system to global innovation networks (Miguelez et al., 2019). This is confirmed by the fact that inventions in Paris are more diverse and spread across the different technologies

(Kogler et al., 2018). However, for only a small sample of patent applications, INPI database contains information about their technological class. In order to explore this special case, I assign technological classes to the remaining patent applications in the historical database of INPI. I assemble a vocabulary which is based on key words from the titles of the patent applications for which I have their technological class. Using this vocabulary, I can assign technological classes to all the patent applications in the INPI database.

This chapter directly speaks to the literature about transportation networks and innovation activity. Studies that are close to my research include the papers by Perlman (2015), Agrawal et al. (2017) and Andersson et al. (2021). Perlman (2015) establishes a relationship between network access and innovative activity in the USA over the 19th century. Agrawal et al. (2017) find that the stock of highways has a positive effect on patenting in metropolitan statistical areas of the USA. Finally, Andersson et al. (2021) explore the effect of the Swedish railroad on patent activity over the period 1830-1910. They assert that network access fosters innovation activity. They find solid evidence that independent inventors start to specialize in specific technologies when they enter the market. General railroad access helps the inventors to develop ideas beyond the local economy and invent in new technological classes.

There is a growing body of literature exploring the interplay between infrastructure and economic outcomes from a historical perspective. Railroads in the USA, Sweden, England, Wales and Switzerland transformed all towns into new places. They managed to lure banks and to increase urbanization (Atack et al., 2008, 2009; Atack and Margo, 2009; Berger and Enflo, 2017; Büchel and Kyburz, 2020; Bogart et al., 2022) and are responsible for the growth and the economic development of US and Nigeria cities (Nagy, 2016; Okoye et al., 2019). Railroads also have a significant impact on the development of the agricultural sector (Donaldson and Hornbeck, 2016; Donaldson, 2018) and on fertility and human capital (Katz, 2018). Transportation linkages have an adverse effect on health in the rural US (Zimran, 2019). Railroads manage to boost manufacturing productivity in US (Hornbeck and Rotemberg, 2019; Pontarollo and Ricciuti, 2020). Finally, the steam railway led to the first large-scale separation of workplace and residence (Heblich et al., 2020).

In general, infrastructure networks can affect the economy through different channels. The reallocation of road investments after the division of Germany created regional income inequalities in terms of GDP per capita (Santamaria, 2020). Highways affect population and employment (Baum-Snow, 2007; Duranton and Turner, 2012). Lastly, the adoption of the steamship between 1850 and 1900 boosted the globalization of trade (Pascali, 2017).

In addition, this chapter proposes that targeted investments to infrastructure projects can facilitate access to big cities. This direct policy may level out the persistent inequalities between urban and rural areas. It may increase the probability of smaller cities to innovate in new patent classes. Recent papers rise concerns about the correct allocation of infrastructure funds (Flyvbjerg, 2009) and the proper circumstances for such projects to be efficient (Crescenzi et al., 2016). At the same time, complex economic activities concentrate disproportionately in a few large cities, compared to less complex activities (Balland et al., 2020). Large cities are also the places with more interactions between higher-ability participants (Davis and Dingel, 2019).

Lastly, given the setting of the analysis, this chapter adds to the literature on the economic progress and economic history of France around the turn of the 19th and 20th century by studying the impact of railroads on technological progress. Other papers in the literature explore as determinants of economic growth religiosity (Squicciarini, 2020; Lecce et al., 2021), knowledge elites (Squicciarini and Voigtländer, 2015), trade (Juhász, 2018), adoption of technological breakthroughs (Juhász et al., 2020), large income shock of the phylloxera (Banerjee et al., 2010), emigration intensity (Franck and Michalopoulos, 2017), population shifts (Talandier et al., 2016), early industrialization through the adoption and persistence of unskilled-labor-intensive technologies (Franck and Galor, 2019) and fertility rates Daudin et al. (2019). One previous attempt related to railroads focuses on the effect of railroads on population distribution in France, Spain, and Portugal from 1870 to 2000 (Mojica and Martí-Henneberg, 2011).

The rest of the chapter is organized as follows: Section 2.2 contains the historical background, Section 2.3 presents the data, Section 2.4 shows the empirical strategy, Section 2.5 presents the main results, Section 2.7 explores the mechanisms and Section 2.8 concludes.

2.2 Historical Background

2.2.1 Railroads

The first railway line in France was built in 1828 by mining companies to connect St. Etienne to the Loire River. They used this line to transfer coal. The first line for passengers was opened in 1837. It was a short line from Paris to Le Pecq (Dunham, 1941). At the time, France was already lagging behind Britain and Belgium. In 1842 Britain had 1,900 miles of railways in operation while France had only 300 (Lefranc, 1930).

After the success of the first line, the French government saw the importance of a national railway network. However, the next attempt for constructing a rail line between Paris and Versailles was unsuccessful. Two different companies each built a line to connect Paris with Versailles but they failed financially. The government recognized the problem of rivalry between local interests (Dunham, 1941). Although the government was aware of the importance of a national railroad, it did not provide funding until 1842 (Ratcliffe, 1976).

According to Dunham (1941) the planning of rail network was given to *Corps des ponts et chaussees*, an organization of highly trained engineers which was in charge for major infrastructure projects in France. The expansion of railroads during the period 1840-1860 was based on Legrand Star, a design by the *Corps des ponts et chaussees*. According to Legrand plan, the purpose of the government was to connect major communes, borders, and coastlines with Paris. In 1865, based on the Migneret law, the government established direct lines connecting all the prefectures. The final expansion of the rail network was constructed according to the Freycinet plan which was introduced in 1878 (Thévenin et al., 2013).

The most important railroad expansion occurred between 1860 and 1900 when 45,000 km of rail lines were built. The final phase ran until the 1930s and by the end of this phase 56,000 km of railroad were in operation (Thévenin et al., 2013). The introduction of motor vehicles at the end of the 1930s limited the expansion of the railroad network.

2.2.2 Patent System

Great Britain, France and the United States were the first countries to adopt legislation on patents in 1791 (Macleod, 1991; Galvez-Behar, 2019). In France, prior to the establishment of a patent legislation, and more specifically during the 18th century, patent applications were known as "les privileges" and were granted by the king and registered by the parliament in Paris (Macleod, 1991). In addition, inventors received remarkable awards for their inventions, such as national or local production, a lifelong pension or tax exemption. Lastly, a major difference between the English and French system was that the application procedure was far more severe in the latter case (Macleod, 1991).

In 1791, Boufflers' bill became the first Patent Act in France establishing three different categories for patenting: 1) Patents for invention, 2) Patents for improvement and 3) Patents for importation. The patents were granted from five until fifteen years. The name of the inventions changed to "brevets de invention". However, their cost was prohibitive. Apart from the initial cost, several taxes were added over the course of the examination process. The patent system did not facilitate the spread of patenting, because a lot of inventors could not afford the high cost (Galvez-Behar, 2019).

The rise of patenting activity was underpinned by the introduction of a patent law in 1844. This legislation allowed the inventors to export their patents to foreign countries and also changed the method of payment for inventors enabling patentees to spread the payment of the tax over the entire duration of their patent (Galvez-Behar, 2019).

2.3 Data

2.3.1 Setting

I start collecting data by first extracting shapefiles of 19th century France making use of the recent constructed shapefiles of Gay (2020), for the period 1870-1940. Over the sample period, France did not experience any large changes in the national administrative system except for the departments that became part of Germany. I base my analysis on the shapefile of 1870 which contains 2,925 cantons for mainland France.

Next, I can determine the majority of the city areas in order to use the centroids of the cities. The first data source is Perret et al. (2015), which contains the polygons of the cities, towns, domains and forts during the 18th century. For a given canton i, I first use the cities within the polygon followed by the towns, domains and forts.

If a canton has more than one city, I keep the centroid of the largest city (by area) as a reference point. The same rule applies in the case of a town, domain or fort. I determine the location of 1,961 cities, 69 towns, 112 domains and 3 forts which corresponds to 2145 cantons, or 73.33% of the sample. I complement my analysis using the population raster file of 1840 from HYDE (2020). I use the year 1840 because it is the closest available year before the arrival of railroads. Based on the second source of data, I use QGIS to convert the raster file into pixels and for the remaining cantons, without a reference point, I choose the pixel with the highest population value. Furthermore, I assign a reference point in 738 cantons, which corresponds to 25.23% of the sample. For the remaining 42 cantons without a reference point (1.44% of the sample), I use the centroid of the polygon. Figure 2.1 illustrates an example of the empirical setting. The brown areas are the cantons and the pink areas are the city polygons. The black dots, within the pink areas, are the city centroids. The white dots are the rail stations, while the blue lines are the navigable waterways. Finally, the black dots without a pink area are the points with the highest population value within the cantons. I believe that the use of these points, instead of the centroids of the polygons, makes the analysis more realistic as they represent with a higher precision the location of the cities.

2.3.2 Railroad Data

The data on communes with a rail station over the period 1860-1920 come from Mimeur et al. (2018). It is a very detailed database that contains five variables of interest for all the communes.[5]

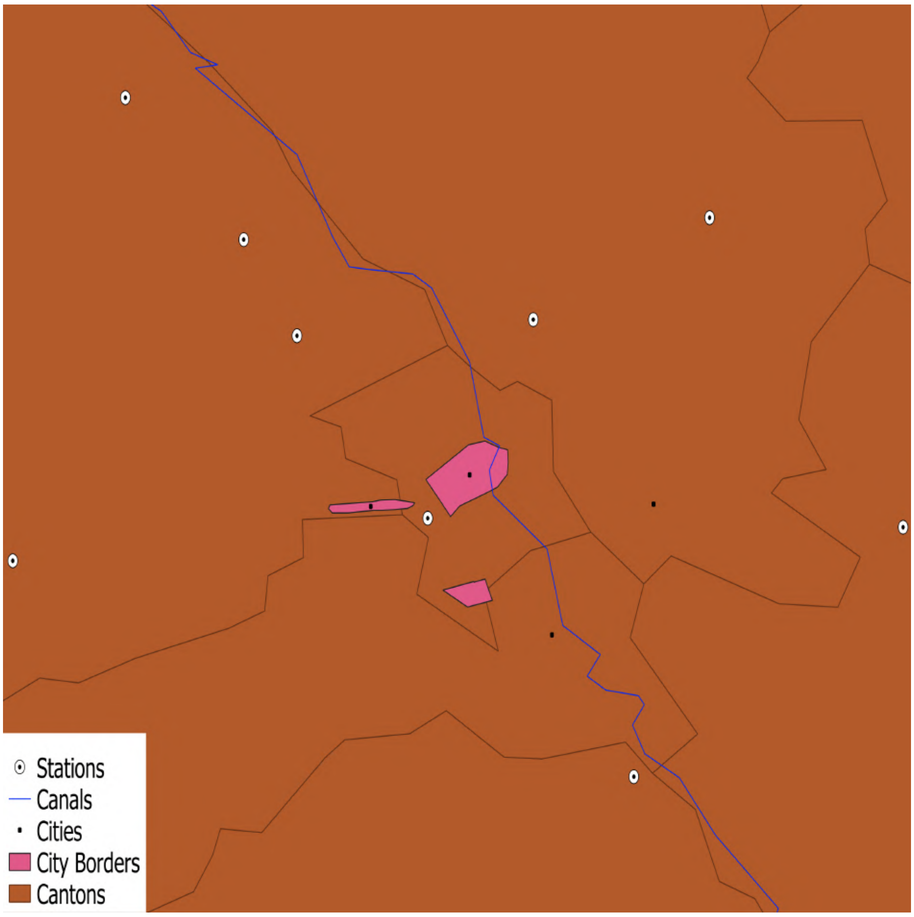
I make use of an historical image with rail lines until 1860 to add one additional decade to my sample.[6] I extract the lines from the image that were already established until 1850 to identify the communes that had a rail station in 1850. In order to do that, I rely on the historical rail station data of 1860 from Mimeur et al. (2018) and I preserve only the communes which are crossed by a rail line of 1850. This exercise allows me to identify the communes with a rail station in 1850.

Distance to Rail Station: It is the distance in km from any canton city point to the closest commune centroid with access to a rail station.

[5]It contains a dummy variable of access (=1 if the commune has a rail station), a variable of the type of line, and three variables with travel time to reach from any commune to Paris, regional centers and departmental centers.

[6]For more details see Figure C2.1 in the Appendix 2C.

Figure 2.1: Setting



Notes: This figure illustrates the research setting of the chapter.

Furthermore, I attempt to create the historical rail line network of France. In the absence of high resolution historical maps, I use the communes with rail stations in the period 1850-1890 and modern French rail lines.[7] Baum-Snow et al. (2017, 2018) argue that historical infrastructure networks are good predictors and facilitate the construction of a lower cost and more modern infrastructure network. In this chapter, I use a modern infrastructure network to re-create an old one. I use a shapefile with the rail lines in the period 2000-2020 (Jeansoulin, 2019) and a shapefile with the lines until 1992 (DIVA-GIS, 2020). Figure 2.2 shows the results of this exercise. According to the findings a significant development of rail network occurred in France over the 19th century.

[7] For more details see Figure C2.2 and Figure C2.3 in the Appendix 2C.

2.3.3 Canal Data and Ports

Aside from the railroads, France also developed a canal network. I make use of two sources of data to identify the canal network of France.

The first source of data on navigable waterways comes from Ryavec and Henderson (2017). It is a shapefile developed by Jordi Marti Henneberg. [8] This shapefile includes the canal network of France in 1850. The second source of data is the collection of historical maps of Chicago (2020) which contains very detailed maps of the navigable waterways of France over the second half of 19th century.[9] I digitized these historical maps in QGIS. Figure 2.2 shows the expansion of canals. Next, I construct the indicator of access to the canal network.

Access to Navigable Waterways: It is a binary indicator which switches to 1 for a canton if there is a canal within 3 km distance from the city centroid. In the Appendix 2A, I apply robustness check with different thresholds.

In addition, I make use of a historical map from Rumsey (2020) collection, in order to identify the ports of France in 1877.[10] I complement this data with active ports over the period 1662-1855 from García-Herrera et al. (2006). Their database focuses on the reconstruction of oceanic wind field patterns for this period that precedes the time in which anthropogenic influences on climate became evident. They include the variables "voyagefrom" and "voyageto" which contain the names of the places where the ship departed from or sailed to. I apply geocoding on Stata (Zeigermann, 2018) and I identify 13 active ports for France.[11] I use the ports to construct the instrument for the IV approach.

2.3.4 Patent Data

The historical database of the INPI contains all the patent applications (409,324 applications with their additions) covering the period 1791-1902. The database includes the application number of the patents, the filing year, the name of the applicant(s), the commune, the street and number of the applicant(s), the title of the patents and the expiry date of the patent applications. Additional details are included in the database such as whether an application is a patent that was imported

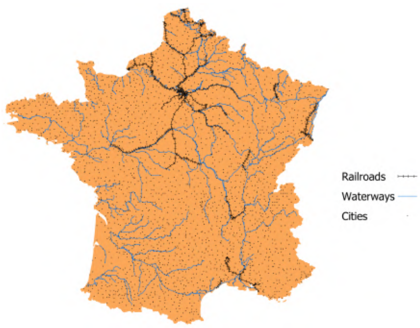
[8] Source: http://europa.udl.cat/projects/inland-waterways/

[9] For an example of the maps see Figure C2.4 in the Appendix 2C.

[10] For more details see Figure C2.4, Appendix 2C.

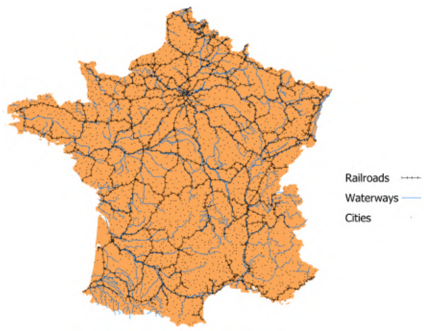
[11] At least one ship departed or sailed to these ports.

Figure 2.2: Expansion of Railroads and Navigable Waterways

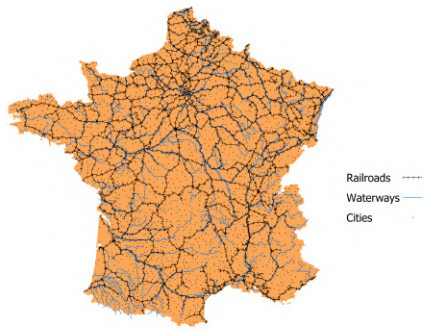


(a) 1850

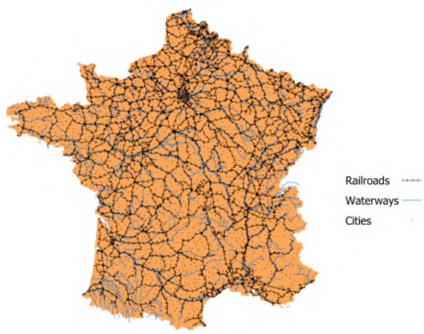
(b) 1860



(c) 1870



(d) 1880



(e) 1890

Notes: This figure shows the expansion of navigable waterways in France over the period 1850-1890. Source: the shapefile of canal network for 1850 comes from Ryavec and Henderson (2017) and for the period 1860-1890, it is based on author's digitization of the historical maps from the Chicago (2020). The railroads lines are constructed by the author based on historical rail stations by Mimeur et al. (2018) and recent shapefiles of rail lines from DIVA-GIS (2020) and Jeansoulin (2019).

from abroad, the number of additions of every patent application and the profession of the applicant.

I restrict my sample only to applications with at least one inventor residing in France. I remove applications that belong only to firms using key words.[12] Next, I exclude 116 applications without a filing date. When one application has several improvements (additions), I do not consider the improvements, but only the initial design. Finally, I exclude from the sample the patent applications that are importations since it is more likely that the inventor was resident of another country and only the patent agent was in France. I end up with 308,926 patent applications over the entire period. Figure 2.3 presents the evolution of patent applications per capita over the sample period of the chapter as well as the time trend for the average distance to rail stations.

With this information, I construct the following variables.

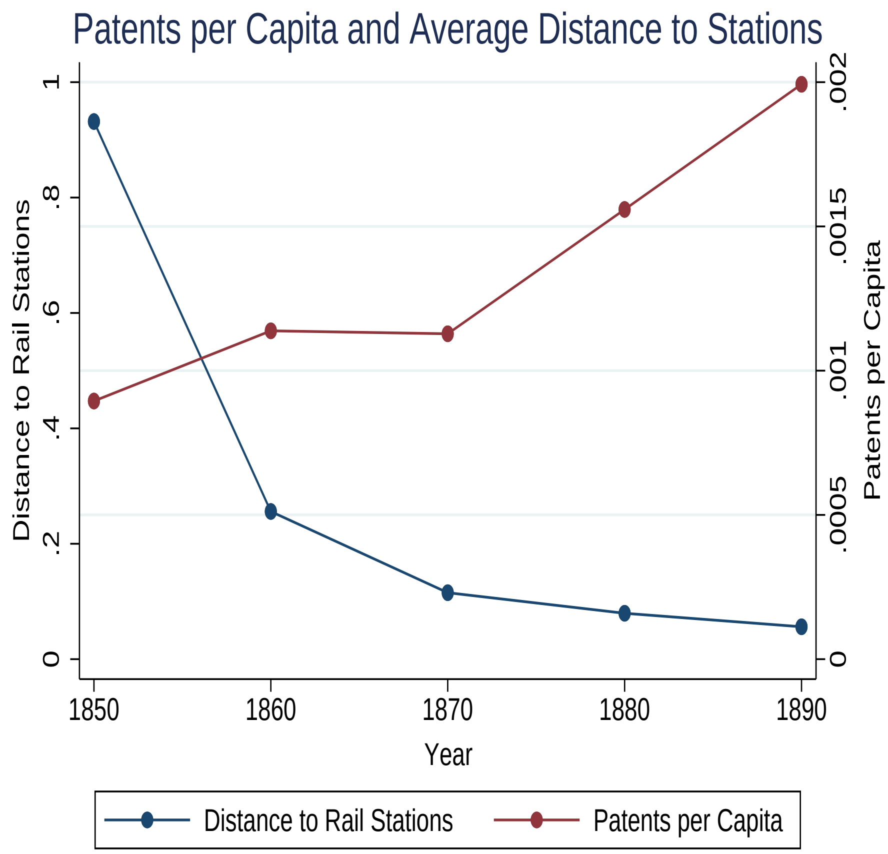
Number of patent applications: I calculate the total sum of patents for each decade from 1850 to 1890 like in Andersson et al. (2021).
Number of patent applications that received an addition: INPI database contains the number of additions of each patent application. The patent law of 1844 gave the applicants the option to apply for certificates of addition (Galvez-Behar, 2019) which allowed applicants to protect a minor improvement to the initial patent throughout its term. An addition to the initial design costs an extra of 24 francs (Nuvolari et al., 2020). As a quality measure of innovation, I restrict the sample of patents to the ones that received an addition.

Apart from the main database, INPI includes a sample of 38,527 patent applications with their technological field. These patents are divided in 20 main classes.[13] For only this sample of patents, I have information on their main class and their title. I use the "lsemantica" command in Stata (Schwarz, 2019) to extract key words from the titles of the patent applications and then complement these key words with additional words from the names of the main and sub classes of patent applications. Afterwards, I keep the unique words among classes to create a vocabulary. Based

[12]I exclude all the applications that have the words “COMPAN” or “COMPAGNI” or “SOCIETA” or “SOCIET” or "GESELLSCHAFT" or "SYNDICAT" or "GESELLSCHAF" or "MANUFACTUR" in the applicant’s name.

[13]The 20 classes are: Agriculture, Alimentation Railways and Trams, Arts textile, Fibers and Yarns, Machines, Marine and Navigation Construction, Public and Private, Mines and Metallurgy, Domestic Economy, Weapons, Road Transport, Instruments of Precision and Electricity, Ceramics, Chemics, Lighting Heating Refrigeration and Ventilation, Clothes, Arts, Office Supplies and Education, Medicine and Health, Articles and Various Industries.

Figure 2.3: Innovation per Capita and Average Distance to Rail Stations



Notes: Summary graph showing the time trend of patent applications per capita and average distance to rail station. Source: author's computations based on the patent applications from INPI (2019) database, population from HYDE (2020) and rail stations from Mimeur et al. (2018).

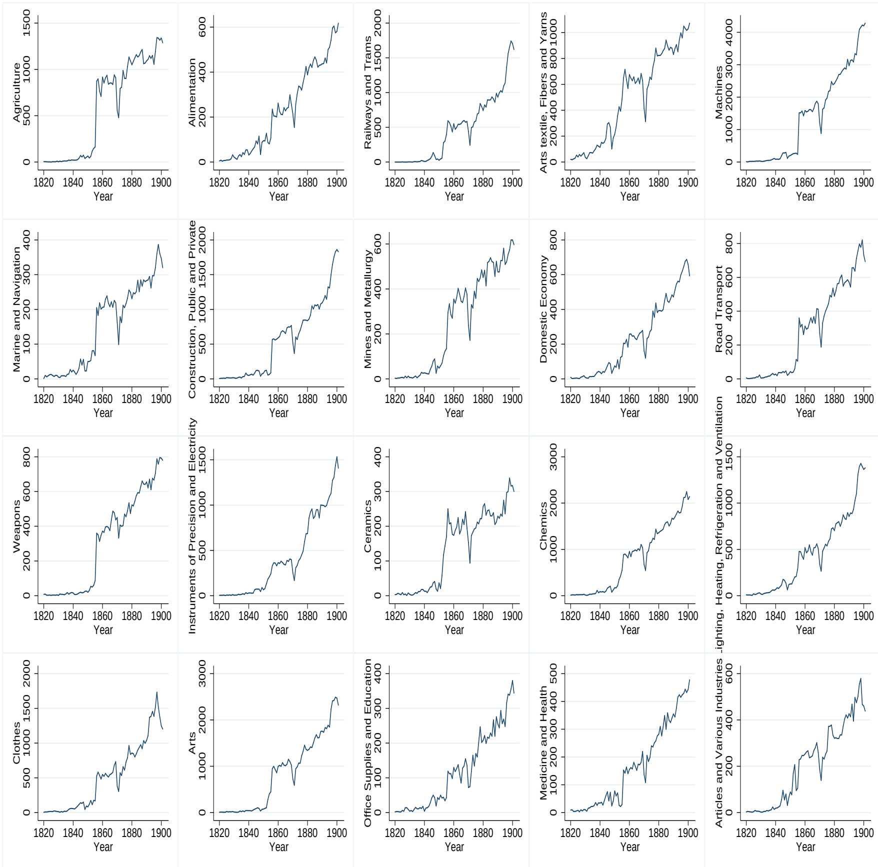
on this vocabulary, I manage to assign classes to the rest of the patent applications in the INPI database. More technical details regarding this method and the vocabulary can be found in the Appendix 2B. Figure 2.4 illustrates the time trend for every class. As a result of this analysis, I construct two more indicators of innovation.

Number of Novel Classes: It is the number of new technology fields in which a canton has at least one invention in a given year

Stock of Classes: It is for every time period the number of technological classes that a canton already has at least one invention.

Next, in order to be sure that I do not double count inventors residing in the same canton, I apply a simple applicant disambiguation based on their name, surname and address. This exercise allows me to assign a unique identifier to the inventors. I apply fuzzy matching (Raffo, 2020) on the name and surname of applicants residing

Figure 2.4: Applications by classes



Notes: Summary graph presenting the evolution of patent applications by classes. If an application has several classes, I allocate one application to all of them. The classes are: Agriculture, Alimentation Railways and Trams, Arts textile, Fibers and Yarns, Machines, Marine and Navigation Construction, Public and Private, Mines and Metallurgy, Domestic Economy, Weapons, Road Transport, Instruments of Precision and Electricity, Ceramics, Chemics, Lighting Heating Refrigeration and Ventilation, Clothes, Arts, Office Supplies and Education, Medicine and Health, Articles and Various Industries. Source: author's computations based on patent applications from INPI (2019).

in the same street. I then consider the applicants with a matching score over 73% to be the same person. I identify 334,504 unique applicants from 353,017 patent applications. Even though the disambiguation is simple and "kills" the mobility of the inventors, since one of the criteria is the applicant's address, it serves its purpose. In the sample every period is a decade and this simple disambiguation allows me to build an indicator of the stock of inventors. One additional advantage of this method is that the stock of inventors is not driven by outliers in the data (Bahar et al., 2020).[14]

[14] As already explained in Bahar et al. (2020) there could be fluctuations in the stock of inventors if one inventor residing in a commune has a patent in year $t-1$ and $t+1$ but not in year t. Taking the average of ten years these fluctuations are no longer an issue.

2.3.5 Other Data

I use the HYDE (2020) database to export (gridded) time series of population and land use. I rely on raster files to form the indicators in QGIS at the canton level. All the indicators have time variation. I extract data on population (defined as the population counts, in inhabitants/gridcell), cropland (defined as the total cropland area, in km2 per grid cell) and grazing area (defined as the total land used for grazing, in km2 per grid cell). I use the baseline estimates of the database.[15]

In addition, I construct a binary indicator that switches to one if the canton has a university or a grande ecole, as in Lecce et al. (2021). I manually collect the locations of the universities from Ruegg (2004) and check whether the universities were abolished during the French Revolution in 1793. Next, I manually extract the addresses of the grand ecole from the Conference des Grandes Ecoles.[16] Using STATA, I geolocalize the addresses of the universities and grand ecole using the command developed by Zeigermann (2018). Finally, I control for the number of post offices a canton has, using the database of Verdier and Chalonge (2018), to be in line with the literature about state capacity and innovation (Acemoglu et al., 2016).

2.4 Empirical Strategy

2.4.1 Baseline approach

I start the analysis by estimating the main model using OLS regressions (Correia, 2015). The estimation equation is:

$$Pat_{it} = \alpha_0 + \beta DistStat_{it-1} + \gamma_i + \delta_t + \zeta X_{it} + \epsilon_{it} \tag{1}$$

where Pat_{it} is the number of patents in the canton i, in time period t. The main variable of interest is $DistStat_{it-1}$, which contains the distance in km from any city centroid of a canton to the closest commune centroid with a rail station as computed in the previous period.[17] I include canton fixed effects, γ_i and year fixed effects,

[15] I use the version 3.2 which was released in 04-08-2020.

[16] Source: www.cge.asso.fr, accessed on November of 2021

[17] A one-lag structure of the effect of the railway variable on innovation outcomes is intuitive in this framework because the railway stations constructed near the end of the calendar year are likely to affect innovation outcomes only in the following year (Melander, 2020).

Table 2.1: Summary Statistics

Variable	Mean	Std. Dev.	Min.	Max.	N
Innovation Variables					
INPI Applications	17.5745	776.0184	0	68635	14625
Probability to Innovate	0.4755	0.4994	0	1	14625
Additions	2.8867	107.7245	0	7232	14625
Number of Novel Classes	1.1625	1.9716	0	20	14625
Stock of Classes	3.9177	5.1607	0	20	14625
INPI Applications by technological class	1.9523	107.4823	0	25804	292500
Transportation Variables					
Distance to Rail Station	41.1569	75.6703	0.0608	594.5292	14625
Access to Waterways	0.0003	0.0185	0	1	14625
Travel Cost to Paris	7790.6959	7213.0369	0	92328.3125	14625
Travel Cost to Lyon	7498.2269	6672.2881	0	87256.3359	14625
Travel Cost to Marseille	9951.6185	6981.023	0	84630.1094	14625
Distance to Straight Line (Instrument)	28.6276	39.1383	0	339.3349	14625
Access to Knowledge	0.0002	0.0002	5.64e-06	0.0032	14625
Access to Knowledge by technological class	0.0001	0.0000453	1.00e-06	0.0013	292500
Control Variables					
Population	13244.6819	35836.6914	0	2524117	14625
Average Cropland Area	29.4377	16.1494	0	61.8082	14625
Average Grazing Area	18.3853	11.993	0	55.9528	14625
University	0.0116	0.1072	0	1	14625
Post Offices	2.1933	1.8605	0	40	14625
Robustness Analysis - Variables					
Travel Time to Paris	931.1978	625.1727	0	7817.8740	11700
Distance to a Discrete Station	183.4004	183.5866	0.1922	759.4374	14625
Distance to International Collaboration	100.2293	69.7108	0	409.8712	14625
Access to Knowledge based on Elevation	0.0002	0.0002	8.80e-07	0.0029	14625
Differences in Differences Model - Variables					
INPI Applications	9.3656	550.2264	0	68635	29250
Access to rail within 3km distance	0.1115	0.3148	0	1	29250
Access to rail within 5km distance	0.1532	0.3602	0	1	29250
Access to rail within 7km distance	0.1817	0.3856	0	1	29250
Population	12090.7981	27842.4077	0	2524117	29250
Average Grazing Area	18.302	11.9084	0	55.9528	29250
Average Cropland Area	28.6418	16.2708	0	61.9237	29250

Notes: Summary statistics for all the main variables (2,925 cantons, every 10 years is one period in the sample, five time periods in total.). Innovation variables: INPI Applications is the total number of patent applications, Probability to innovate is a binary indicator that switches to one if the canton has a patent application, Additions is the total number of patent applications that received an addition, Number of Novel Classes contains the number of novel technological classes that a canton has in a given year and Stock of classes the number of technological classes that a canton already has. Transportation variables: Distance to Rail Station is the distance (in kilometers) from any city centroid to the closest commune centroid with access to a rail station, Access to Waterways is defined as a dummy variable that takes the value 1 if the centroid of a canton is within 3 kilometers distance from the closest canal, travel cost to Paris, Lyon and Marseille is the computed travel cost based on rail lines and canals of every city centroid to Paris, Lyon and Marseille and distance to straight line is the instrument (in kilometers). Access to knowledge variables: Access to knowledge is the computed access of every canton based on the share of inventors over population and accessibility in rail lines and canals and market access is the computed market access of every canton based on the number of citizens and accessibility in rail lines and canals. Control variables: population is the total number of inhabitants, cropland is the average cropland area, grazing is the average land used for grazing, university is a binary variable which switches to 1 if the canton has a university and post offices is the number of post offices in a canton. The dimension of the variables INPI Applications by technological class and Access to Knowledge by technological class is 2,925 cantons, 20 technological classes every 10 years, 5 time periods in total. The time period for the differences in differences model is from 1800 to 1890.

δ_t. X_{it} contains all the controls at the canton level, such as population, the average cropland area, the average grazing area, the number of post offices and the existence of a university.

The variable Pat_{it} and population have been transformed using the log transformation to reduce the effect of the extreme values in the sample (Squicciarini and Voigtländer, 2015).[18] As a robustness test, I also apply the Poisson pseudo-maximum likelihood regressions model in the Appendix 2A with no transformation in the data.

I have to take into consideration the potential endogeneity problem due to omitted variable bias. The placement of the actual network may be endogenous and affected by unobservable local economic conditions (Andersson et al., 2021). To mitigate any concerns that could naturally arise, I complement the analysis with an instrumental variable approach and several robustness tests.

2.4.2 Endogeneity and Instrumental Variables

Following a similar strategy as Katz (2018), I propose the use of a time variant instrument for the French rail network. The identification strategy builds on straight lines (Perlman, 2015; Katz, 2018; Banerjee et al., 2020) as they represent the Euclidean (least cost) distance between two places. In addition, (Dunham, 1941, page 19) mentions about French rail network that "*Corps des ponts et chaussees* believed in making railroads as straight as possible, no matter what important centres of trade or industry they might by pass on the way". This team of highly trained engineers was not interested in trade or industry, nor in the problems of economics. The above theoretical framework justifies the use of straight lines as an instrument in the case of France.

In order to create time variation for the instrument, I rely on the 3 different French rail plans.

Legrand plan (1840-1860): The purpose of the government was to connect the major cities, borders, and coastlines to the capital of Paris (Thévenin et al., 2013). For the year 1850, I connect with straight lines Paris as well as the rest of regional centers (major cities) as they are closer than the ports, see Figure 2.5 (a). Next, for the year 1860, I make use of the data about French ports and I draw straight lines from Paris to the communes with access to a port (coastlines), see Figure 2.5 (b).

Migneret law (1865): According to Thévenin et al. (2013), the second phase of railroad expansion involved connections among all departmental seats (prefectures).

[18] I add 1 in the variables "number of patent applications" and "population" before I apply the log transformation.

Based on this plan, I use a spanning tree to connect all the departmental centers with regional centers and ports, see Figure 2.5 (c).

Freycinet plan (1878): The Freycinet plan had no effect on travel time to reach Paris. Its purpose was to facilitate access to departmental centers (Mimeur et al., 2018) and to eliminate the regional disparities among rural and urban areas (Schwartz et al., 2011). According to Bris (2012), all the sub-prefectures were connected to the railway network. For the year 1880, I connect all the sub-prefectures to the closest straight line. Finally, for the year 1890, I create an updated spanning tree among all nodal destinations. Then, I estimate the following equations:

$$DistStat_{it-1} = (Distance\,to\,Straight\,Line)_{it-1} + \alpha_0 + \gamma_i + \delta_t + \zeta X_{it} + \epsilon_{it} \qquad (2)$$

and

$$Pat_{it} = \alpha_0 + \beta Dist\hat{S}tat_{it-1} + \gamma_i + \delta_t + \zeta X_{it} + \epsilon_{it} \qquad (3)$$

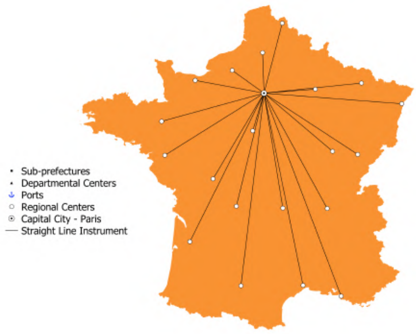
$Distance\,to\,Straight\,Line_{it-1}$ in equation 2 is the railway instrument. For every time period, it includes the distance from any canton city centroid to the closest straight line. I use the "ivreghdfe" command of Correia (2018) in Stata. In all the regressions, I cluster the standard errors at the canton level.

2.5 Results

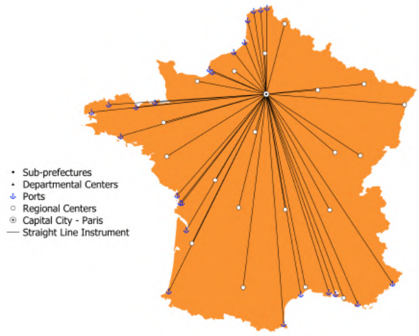
Table 2.2 provides the first-stage results. Distance to straight line is positively associated to the distance to a rail station. This positive relationship for a city centroid of a canton means that if it is far away from the straight line instrument is also more likely to be far away from an actual rail station. The straight line distance and distance to station are both expressed in kilometers. In terms of interpretation of the results, a one standard deviation increase in the distance to the straight line corresponds to a 0.41 standard deviations increase in the distance to the actual rail stations. Finally, the instrument is highly significant.

Moving now to the main results, Table 2.3 presents the OLS and the IV results. The dependent variable in the first three columns is the number of patent applications. Both OLS and IV estimates are highly significant and negative, as shown

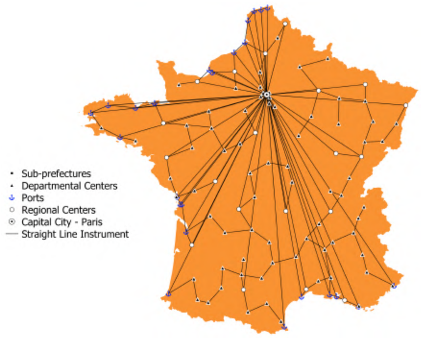
Figure 2.5: Evolution of the Straight Line Instrument



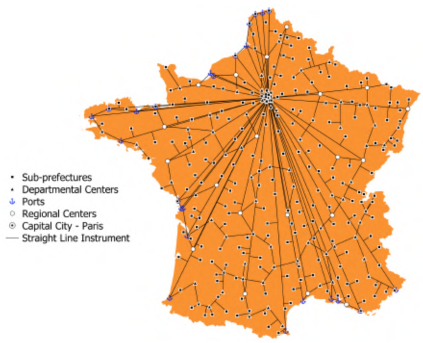
(a) 1850



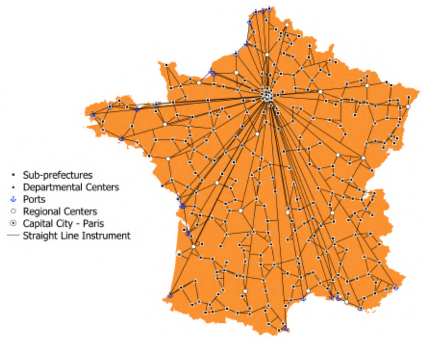
(b) 1860



(c) 1870



(d) 1880



(e) 1890

Notes: This figure illustrates the expansion of straight line instrument based on the regional centers in 1850, regional centers and ports in 1860, a spanning tree between regional centers, departmental centers and ports in 1870, subprefecture centers in 1880 and a spanning tree between all the nodal destinations in 1890. Source: author's computations.

Table 2.2: First stage: distance to straight line instrument and railway stations

Dep. var. =	Distance to Station
	(1)
Distance to Straight Line	0.413***
	[0.016]
Sample Size	14625
Canton FE	Yes
Year FE	Yes
Canton Controls	Yes

Notes: First stage regressions. The dependent variable is the distance to the nearest constructed railway station. Distance to straight line is the distance of any centroid to the closest straight line. Canton controls contain the population, the accessibility to waterways, the average cropland area, the average land used for grazing, the existence of a university and the number of post offices. The population is transformed using a log transformation. The results are based on the equation 2. Clustered standard errors at the canton level are reported in the parenthesis.

in columns 1 and 2, for OLS, and column 3, for the IV. I rely on the IV estimates (column 3) to interpret the results. Since all the variables are standardized the interpretation is that for a given canton a one standard deviation decrease in the distance to a rail station is associated with a 0.049 standard deviations increase in the number of patent applications. A one standard deviation increase in the population is associated with approximately 0.22 standard deviations increase in the number of patent applications. In addition, in line with the literature, the number of post offices has a positive and significant effect, meaning that a one standard deviation increase in the number of post offices in a canton corresponds to a 0.025 standard deviations increase in the number of patent applications. Average cropland and grazing land have no significant effect on the patenting rate. Finally, access to waterways does not affect innovation activity. In the Appendix 2A, I use alternative indexes of accessibility to canals based on different thresholds. The Kleibergen-Paap Wald rk F statistic is high, indicating that the instrument performs well. In column 4 and 5, I use a binary indicator as dependent variable that switches to 1 if the canton has at least one patent application. Based on the findings of the IV regressions, column 6, a one standard deviation decrease in the distance to a rail station is associated with a 0.07 standard deviations increase in the probability of a canton to innovate.

Given that the literature considers number of patents as a crude measure of innovation, at least in the recent years (Aghion et al., 2019), I complement my analysis by introducing as a quality index of innovation the patents that received an addition. I present the results in the Appendix 2A. In addition, in the Appendix 2A, I include Poisson pseudo-maximum likelihood regressions models where I do not log-transform the dependent variable.

Table 2.3: Baseline results: distance to rail stations and innovation

Dep. var. =	Log (Applications+1)			Patent =1	
	(1)	(2)	(3)	(4)	(5)
	OLS	**OLS**	**IV**	**OLS**	**IV**
Distance to Rail Station	-0.069***	-0.074***	-0.049***	-0.075***	-0.071***
	[0.007]	[0.007]	[0.018]	[0.010]	[0.024]
Log (Population+1)		0.241***	0.223***	0.084	0.081
		[0.068]	[0.071]	[0.075]	[0.077]
Post Offices		0.026***	0.025**	0.041***	0.041***
		[0.010]	[0.010]	[0.013]	[0.013]
Average Cropland Area		-0.063	-0.065	-0.020	-0.020
		[0.095]	[0.096]	[0.127]	[0.128]
Average Grazing Area		0.025	0.028	0.024	0.024
		[0.051]	[0.051]	[0.072]	[0.072]
Access to Waterways		0.007	0.011	0.010	0.011
		[0.015]	[0.015]	[0.024]	[0.025]
University		-0.036	-0.038	-0.003	-0.003
		[0.040]	[0.040]	[0.006]	[0.006]
R-squared	0.80	0.80	-	0.50	-
Sample Size	14625	14625	14625	14625	14625
Canton FE	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes
Kleibergen-Paap Wald rk F statistic	-	-	689.38	-	689.38
Kleibergen-Paap rk LM statistic Chi-sq(1)	-	-	273.595	-	273.595

Notes: Baseline results. Innovation is measured by the number of INPI patent applications in the first three columns and the probability for a given canton to innovate in the last two columns. Distance to rail station is the distance to the nearest constructed railway station. Population is the total number of inhabitants. Post offices is the number of post offices that a canton has. Average cropland area and average land used for grazing is the average cropland and grazing area in km2 per grid cell. Accessibility to waterways is a binary indicator which switches to 1 if there is a canal within 3 km distance from the city centroid. University is a binary indicator which switches to 1 if a canton has a university. The dependent variable INPI patent applications and the population are transformed using a log transformation. Column 1, 2 and 4 contain the OLS results based on the equation 1 and column 3 and 4 the IV results based on the equation 3. Clustered standard errors at the canton level are reported in the parenthesis.

2.6 Robustness Analysis

2.6.1 Inconsequential Units Approach

To further mitigate any concerns, in this section, I adopt an inconsequential units approach as a robustness test. This method is widely used in the literature (Büchel and Kyburz, 2020; Möller and Zierer, 2018; Faber, 2014). The intuition is that in the early stages of transport infrastructure developments, major destinations are typically connected first. This IV approach relies on the randomly chosen subset of municipalities that received railway access because they lie on the most direct route between these nodal destinations. Even though I follow the actual rail plans when I draw the straight lines, the selection of the nodal destinations could be endogenous.

To this end, I re-estimate equation 1 and equation 3, using the inconsequential units approach, in order to eliminate any concerns.

Based on this approach, I remove from the sample all the focal destinations that were used in the construction of the instrument. By doing that, I also exclude the capital city of Paris. This is crucial since it takes into account another type of endogeneity. The only office of INPI was in Paris and as a result, it may have been easier for an inventor to use in the application file an address of a patent agent in Paris. This may introduce bias in the benchmark analysis which is possibly not addressed by the instrument.

Moving to the results in Table 2.4, I re-estimate the equations 1 and 3 after removing the nodal destinations. Again, I rely on the IV estimates to interpret the results. The magnitude is now lower than the benchmark estimates in Table 2.3 but still significant at 5%. A possible explanation for the lower magnitude is the exclusion of the big urban centers from the sample.

Table 2.4: Distance to rail stations and innovation - inconsequential units approach

Dep. var. =	Log (Applications+1)	
	(1)	(2)
	OLS	**IV**
Distance to Rail Station	-0.062***	-0.040**
	[0.007]	[0.016]
R-squared	0.64	-
Sample Size	13010	13010
Canton FE	Yes	Yes
Year FE	Yes	Yes
Canton Controls	Yes	Yes
Kleibergen-Paap Wald rk F statistic	-	620.68

Notes: I exclude from the sample all the destinations which I use to create the instrument. Innovation is measured by the number of INPI patent applications. Distance to rail station is the distance from the most populous point of a canton to the nearest constructed railway station. Canton controls contain the population, the accessibility to waterways, the average cropland area, the average land used for grazing, the existence of a university and the number of post offices. The dependent variables and the population are transformed using a log transformation. Column 1 contains the OLS results based on the equation 1 and column 2 the IV results based on the equation 3. Clustered standard errors at the canton level are reported in the parenthesis.

2.6.2 Falsification Exercise

In this section, I present the results of a falsification exercise. I re-estimate equation 3 but this time I use as dependent variable the number of patents from 1800 until

1840. The intuition behind this empirical exercise is that it allows me to explore if the model captures some long-run common causal factor behind both the rail network and patent activity (Dix-Carneiro et al., 2018; Autor et al., 2013). I regress past changes in the number of patents on future changes in the distance to railroads.

Table 2.5 presents the IV results. According to the findings, distance to rail station has no significant effect on innovation performance and also the coefficient is positive. This result confirms that the distance to railroads variable is not associated with pre-trends regarding the patent activity in the decades immediately prior to the sample period.

Table 2.5: Distance to rail stations and innovation - Falsification Exercise 1800-1840

Dep. var. =	Log (Applications+1)
	(1)
	IV
Distance to Rail Station	0.003
	[0.010]
Kleibergen-Paap Wald rk F statistic	689.38
Sample Size	14625
Canton FE	Yes
Year FE	Yes
Canton Controls	Yes

Notes: I repeat the same IV regression but this time the depedent variable is the number of patents from 1800 until 1840 one decade prior to the arrival of railroads. Innovation is measured by the number of INPI patent applications. Distance to rail station is the distance from the most populous point of a canton to the nearest constructed railway station. Canton controls contain the population, the accessibility to waterways, the average cropland area, the average land used for grazing, the existence of a university and the number of post offices. The dependent variable and the population are transformed using a log transformation. IV results based on the equation 3. Clustered standard errors at the canton level are reported in the parenthesis.

2.6.3 Difference-in-Differences Model

Next, as a robustness test, I apply a conventional difference-in-differences regression model with staggered treatment. I collect data on population, cropland and grazing area over the period 1800-1840 to complement the panel dataset of the benchmark analysis. I create three different variables of access to a rail station based on the distance to the closest commune with a rail station. The advantage of this method is that it allows me to control for pre-trends since the arrival of railroads. I am able to do that by using the period 1800 to 1840 in which there is not any canton with access to a rail station. I estimate the following equation:

$$Pat_{it} = \alpha_0 + \beta Acc_{it-1} + \gamma_i + \delta_t + \zeta X_{it} + \epsilon_{it} \tag{4}$$

where Acc_{it-1} is the access variable switching to one if a canton has access to a rail station. I consider three different variables of access depending on the distance from the city point to the closest rail station. I use as thresholds 3, 5, or 7 km away. I include canton and year fixed effects and time variant controls such as log of population, grazing area and cropland area. Table 2.6 summarizes the results. The sample period now is from 1800-1890. I find that access to a rail station has a positive and significant effect which confirms the results of the benchmark analysis.

Table 2.6: Distance to rail stations and innovation - Difference in Differences

Dep. var. =	Log (Applications+1)		
	(1)	(2)	(3)
Access to rail 3km distance	0.102***		
	[0.008]		
Access to rail 5km distance		0.103***	
		[0.008]	
Access to rail 7km distance			0.088***
			[0.008]
R-squared	0.67	0.67	0.67
Sample Size	29250	29250	29250
Canton FE	Yes	Yes	Yes
Year FE	Yes	Yes	Yes
Canton Controls	Yes	Yes	Yes

Notes: Access to rail is a binary indicator switching to 1 if a canton has access to railroads within a given distance threshold. Innovation is measured by the number of INPI patent applications. Canton controls contain the population, the average cropland area and the average land used for grazing. The dependent variable and the population are transformed using a log transformation. Differences in differences model based on equation 4. Clustered standard errors at the canton level are reported in the parenthesis.

2.6.4 Cross Sectional Analysis by decade

Finally, I apply a cross sectional analysis to further explore the interplay between the distance to railroads and innovation performance. Since, it is a cross section analysis, I cannot include canton fixed effects in the model. The next higher level of aggregation is the arrondissements. The number of arrondissements for France was 367. Given that, I use arrondissement fixed effects and cluster the standard errors at the department level.[19] I estimate the following equation for each decade:

$$Pat_i = \alpha_0 + \beta Dist\hat{S}tat_i + \gamma_i + \zeta X_i + \epsilon_i \tag{5}$$

where γ_i is the arrondissement fixed effects. The rest of the variables are the same as in equation 3. Table 2.7 presents the results. According to Panel A, the IV estimates, the significant effect of the distance to railroads on innovation activity starts in 1870. In 1865 the expansion of railroads based on the second plan, the Migneret law, started. It is the phase that the departmental centers joined also to the network through direct connections. In addition, the effect gets stronger in column 4 and 5. This means that the increase in innovation performance is not driven only by the large urban centers which got connected during the first decades. Finally, the instrument predicts quite well the expansion of railroads for every decade.

Table 2.7: Distance to rail stations and innovation by decade

Dep. var. =	Log (Applications+1)				
	(1)	(2)	(3)	(4)	(5)
Decade	**1850**	**1860**	**1870**	**1880**	**1890**
Panel A - Second Stage	**IV**	**IV**	**IV**	**IV**	**IV**
Distance to Rail Station	-0.304	-0.539	-2.475***	-6.417***	-7.014***
	[0.187]	[0.687]	[0.547]	[1.350]	[1.776]
Kleibergen-Paap Wald rk F statistic	38.55	14.91	38.05	26.25	22.82
Panel B - First Stage	**OLS**	**OLS**	**OLS**	**OLS**	**OLS**
Distance to Straight Line	0.207***	0.078***	0.115***	0.087***	0.069***
	[0.033]	[0.020]	[0.019]	[0.017]	[0.015]
Sample Size	2924	2924	2924	2924	2924
Canton FE	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes
Canton Controls	Yes	Yes	Yes	Yes	Yes

Notes: Distance to rail station is the distance from the most populous point of a canton to the nearest constructed railway station. Innovation is measured by the number of INPI patent applications. Canton controls contain the population, the accessibility to waterways, the average cropland area, the average land used for grazing, the existence of a university and the number of post offices. The dependent variable and the population are transformed using a log transformation. Panel A contains the IV results based on the equation 5 and panel B the first stage results. Clustered standard errors at the department level are reported in the parenthesis.

2.6.5 OLS vs IV estimates

This section attempts to shed more light on the gap between OLS and IV estimates in Table 2.3, with the IV estimates being lower than the corresponding OLS in every column. According to the literature, transportation improvements are not randomly

[19] An arrondissement is a level of administrative division in France. Arrondissements are further divided into cantons and communes.

assigned and this causes the difference between the OLS and IV coefficients (Redding and Turner, 2015). The OLS estimates capture the impact of transportation investments assigned through the existing political process while on the contrary the corresponding IV estimates the impact of transportation investments assigned through quasi-experimental variation. Baum-Snow (2007) explains in his paper that if the only source of endogeneity of actual lines to changes in the focal variables is through the effect of state and local governments, then a valid instrument should produce IV estimates smaller in magnitude than the corresponding OLS estimates.

In the case of France, indeed, the rail lines planned along the borders with Germany were an act of political interference due to the Franco-Prussian War in 1870. According to Jonathan (2005) the French government constructed the railways in eastern France along the German border because they served strategically crucial ends. The endogenous selection of these places as recipients of rail lines violates the assumption that transportation improvements are randomly assigned and introduces bias to the OLS estimates. Table 2.8 explores the effect of distance to a rail station on innovation activity after removing from the sample areas that may have gained access to a rail station for defensive reasons because they are close to the borders with Germany. The OLS coefficient is reduced while the IV increases as we move from column 1 to 3. In column 3, after excluding from the sample the cantons which are less than 35 km from the border, the two coefficients are approximately the same magnitude.

The war ended with the Treaty of Frankfurt in May 1871, which declared that the departments Bas-Rhin, Haut-Rhin, Moselle, one-third of the department of Meurthe, including the cities of Château-Salins and Sarrebourg, and the cantons Saales and Schirmeck in the department of Vosges became part of the German Empire. In the Appendix 2A, I re-estimate the equations 1 and 3 after excluding the cantons that were affected by the war.

2.7 Mechanisms

2.7.1 Access to Knowledge

Dittmar (2011) studies the adoption of printing in cities in the 16th century. Printing was the major technological innovation of 16th century. The author finds that places with access to ports and cheap water transportation benefited more from this invention. Network connections could reduce the obstacles involved in knowledge

Table 2.8: Distance to rail stations and cantons on the borders

Dep. var. =	Log (Applications+1)		
	(1)	(2)	(3)
Panel A	**OLS**	**OLS**	**OLS**
Distance to Rail Station	-0.069***	-0.068***	-0.067***
	[0.007]	[0.007]	[0.007]
R-squared	0.80	0.80	0.80
Panel B	**IV**	**IV**	**IV**
Distance to Rail Station	-0.059***	-0.061***	-0.065***
	[0.017]	[0.017]	[0.017]
Kleibergen-Paap Wald rk F statistic	708.68	712.28	716.22
Sample Size	14440	14420	14370
Canton FE	Yes	Yes	Yes
Year FE	Yes	Yes	Yes
Canton Controls	Yes	Yes	Yes
Distance from the German Borders	25 km	30 km	35 km

Notes: Column 1 does not contain the cantons that are within 25 kilometers from the borders, column 2 30 kilometers and column 3 35 kilometers. Innovation is measured by the number of INPI patent applications. Distance to rail station is the distance from the most populous point of a canton to the nearest constructed railway station. Canton controls contain the population, the accessibility to waterways, the average cropland area, the average land used for grazing, the existence of a university and the number of post offices. The dependent variables and the population are transformed using a log transformation. Panel A contains the OLS results based on the equation 1 and panel B the IV results based on the equation 3. Clustered standard errors at the canton level are reported in the parenthesis.

diffusion (Breschi and Lissoni, 2009). Recent literature has shown that in contrast to the stock of physical capital, human capital is not transferred easily and inventors interact with each other to combine their skills (Jones, 2009). In the absence of one of the collaborators, the remaining inventors lose in terms of patent production and earnings (Jaravel et al., 2018). An inventor acquires knowledge through interactions with others (Akcigit et al., 2018) and this fosters innovation activity.

The intuition of the mechanism is based on the theory that there are specific interactions which are central to individual productivity (Lucas, 1988). Akcigit et al. (2018) show that inventors built their knowledge and improve their skills by interacting with others and learning from them. The inventors' knowledge could act as an input in the production function (like R&D) and not just as an output (like a patent).

I employ the share of inventors over population instead of population as a numerator in the traditional market access index of Donaldson and Hornbeck (2016). I call it access to knowledge index. This index takes into account how well connected is a given canton i with other canton inhabited by inventors. This supply side mechanism depends on how important the interactions and potential knowledge spillovers among inventors are during the innovation process.

More details about the construction of costs for the access to knowledge indicator can be found in Appendix 2C. Figure 2.6 shows the accessibility of every canton based on railroads and canals over the period 1850-1890. Less accessible areas are darker. As the network expands, the areas become brighter.

In order to disentangle the effect of knowledge spillovers from the market size, I divide the number of inventors in every canton with the population. I rely on the inventor disambiguation to avoid double counting inventors who live in the same canton. Next, I formulate the access to knowledge index as:

$$AccesstoKnowledge_{it} = \sum_{h \neq i} \frac{Inventors_{ht}/Pop_{ht}}{Cost_{iht}} \tag{6}$$

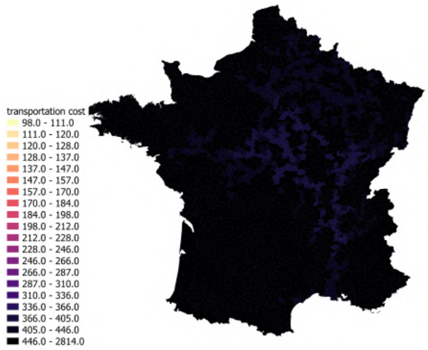
where, for a canton i, access to knowledge is defined as the sum of the share of inventors over population living in all the other cantons except i, divided by the cost to travel to these cantons. To be in line with the rest of the analysis, the knowledge indicator has been log-transformed. I estimate the following equation:

$$Pat_{it} = \alpha_0 + \beta AK_{it-1} + \gamma_i + \delta_t + \zeta X_{it} \epsilon_{it} \tag{7}$$

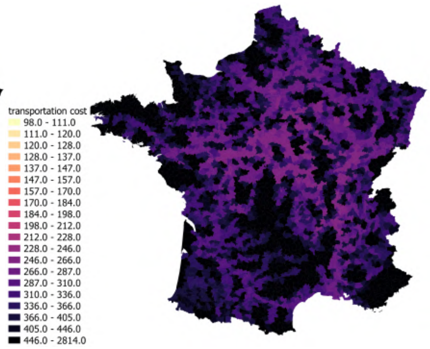
The independent variable, AK_{it}, is the index of access to knowledge. I do not control for access to waterways in the 19th century because I use the canals to compute the travel costs. The rest of the control variables are population, the average cropland area, the average grazing area, the number of post offices and the existence of a university.

Table 2.9 summarizes the results. Column 1 shows the reduced form equation where I control only for canton and year fixed effects. One standard deviation increase in the share of access to knowledge mechanism corresponds to a 0.06 standard deviations increase in the number of patent applications. I include all the controls in column 2. The coefficient is now slightly higher. In the third column, I introduce an IV estimation model where I use as an instrument the distance to straight line as in the benchmark analysis. The effect is again positive and much higher than the OLS estimate in column 2. As in the benchmark analysis, the coefficient of OLS regression may suffer from endogeneity issues. There are other mechanisms that could affect innovation, like market access, which the OLS model

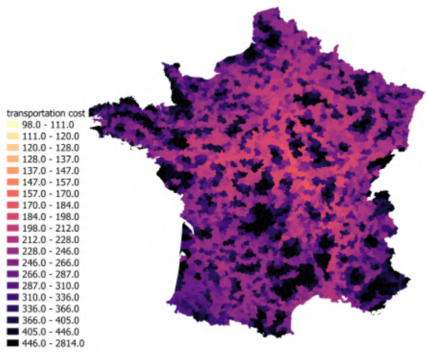
Figure 2.6: Transportation Cost and Accessibility of every Canton



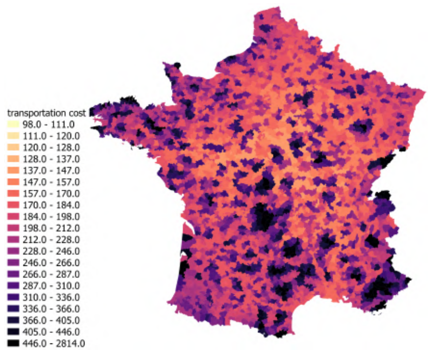
(a) 1850



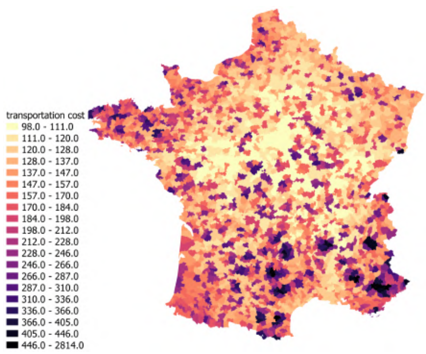
(b) 1860



(c) 1870



(d) 1880



(e) 1890

Notes: This figure shows the reduction in the transportation cost and the accessibility of every canton due to the expansion of railroads and canals over the time period 1850-1890. Source: author's computations based on the shapefiles of canal network and railroads.

in column 2 cannot take into consideration and this introduces a problem of omitted variable bias. To provide more evidence, in column 4, I re-estimate equation 7 but this time I add a third dimension in the model which is the technological class of the patent data. The updated equation is:

$$Pat_{ict} = \alpha_0 + \beta AK_{ict-1} + \kappa_{it} + \lambda_{ic} + \mu_{tc} + \epsilon_{ict} \tag{8}$$

This allows me to introduce three pairwise fixed effects: canton-year fixed effects, κ_{it}, canton-technological class fixed effects, λ_{ic}, and year-technological class fixed effects, μ_{tc}. These combinations of fixed effects deal with all possible variables that do not vary by canton, year and technology like market access. Given that, I find again in the Table 2.9 that access to knowledge has a positive and significant effect on the number of patent applications (column 4). The coefficient of column 4 is closer to the coefficient of the IV regression (column 3) than the coefficient of the OLS regression in column 2. Again, the model in column 4 could suffer from endogeneity concerns because it does not take into consideration specific technology socks that could vary by canton, year and technological class.

Table 2.9: Mechanism: access to knowledge and innovation

Dep. var. =	Log (Applications+1)			
	(1)	(2)	(3)	(4)
	OLS	**OLS**	**IV**	**OLS**
Log Access to Knowledge	0.060***	0.064***	0.304***	0.174**
	[0.017]	[0.017]	[0.109]	[0.073]
R-squared	0.79	0.79	-	0.82
Sample Size	14625	14625	14625	292500
Canton FE	Yes	Yes	Yes	No
Year FE	Yes	Yes	Yes	No
Canton Controls	No	Yes	Yes	No
Canton x Year FE	No	No	No	Yes
Canton x Technology FE	No	No	No	Yes
Year x Technology FE	No	No	No	Yes
Kleibergen-Paap Wald rk F statistic	-	-	161.95	-

Notes: Access to knowledge is the sum of the share of inventors over population residing in all the other cantons except i divided by the cost to reach in these cantons. Innovation is measured by the number of INPI patent applications. Canton controls contain the population, the average cropland area, the average land used for grazing, the existence of a university and the number of post offices. The dependent variable, the index of access to knowledge, the index of market access and the population are transformed using a log transformation. OLS model based on the equations 7 and 8, columns 1, 2 and 4 and IV model for column 3. Clustered standard errors at the canton level are reported in the parenthesis.

2.7.2 Diffusion of Novel Technologies and Access to a Global City

This section illustrates the special case of connectivity to Paris. This mechanism relates to the arrival of new technologies to a canton. Perlman (2015) argues that local transportation access has no effect on how fast new technologies appear in a new county (the paper focuses on the USA). In this section, I build on her initial idea and combine it with new literature based on the importance of global cities.

Larger cities are places with more idea exchanges between higher-ability participants (Davis and Dingel, 2019). According to Sassen (2001) a global city is a city generally considered to be an important node in the global economic system. Paris acts as a gatekeeper that connects the national innovation system to global innovation networks (Miguelez et al., 2019). This is in line with recent findings that patents in Paris are more diverse and spread across the spectrum of IPC classes while, for instance, in Toulouse they are more concentrated (Kogler et al., 2018). I hypothesize that in the absence of ICT technologies, due to the historical framework, accessibility to a global city is the only crucial factor when it comes to the diffusion of novel technologies.[20] Besides, Paris was the first city in 1826 that had at least one invention in all 20 technological classes according to INPI database.

Instead of using words, such as Perlman (2015), which are more difficult to capture similar inventions, I make use of patent classes. Next, I describe the estimation method:

$$Number\,of\,Novel Technologies_{it} = \alpha_0 + \beta Travel\,Cost_{iut-1} + \gamma_i + \delta_t + \zeta X_{it} + \epsilon_{it} \tag{9}$$

$Number\,of\,Novel Technologies_{it}$ is a variable which counts the number of novel classes in a canton.[21] $Travel\,Cost_{itu}$ is the cost to join any canton centroid with a

[20]Other types of communication could be the telegraphic communication or the telephone. Regarding the telegraphic communication, the French Post Office gradually absorbed the telegraph service (Atten, 1994). Controlling for the number of post offices that a canton has during the empirical analysis should take into consideration this potential concern. Furthermore, the diffusion of telephone in France occurred only in the end of 19th century. Until 1926 the city-to-city connections in France were limited and varied between 170 in Paris to 3 in Nantes, with 25 in Lyons, 19 in Bordeaux, 7 in Marseille, 17 in Rouen, 12 in Le Havre and 22 in Lille (Calvo, 2006). In the beginning the telephone systems tended to be established only to large cities and in particular in cities that were industrial or business centers or to cities with access to a port(Calvo, 2006; Carre, 1993). I believe that the inconsequential units approach, where I remove all the big urban centers, should take into consideration this possible concern.

[21]The minimum value is 0 while the maximum is 20, since 20 are all the possible technological

big urban center, u, which could be Paris, Lyon or Marseille. I do not control for access to waterways in the 19th century, because I use them to compute travel costs. I also use the stock of classes fixed effects, a variable that takes into consideration the number of technological classes that a canton already has.[22] The other control variables are population, average cropland area, average grazing area the number of post offices and the existence of a university.

Given the nature of the dependent variable, I estimate the new equation using the Poisson pseudo-maximum likelihood regressions model of Correia et al. (2019) which allows for a high dimension of fixed effects.[23] I apply the log transformation only to population. I exclude from the sample the cantons that already have all the technological fields before the arrival of railroads, that is, Paris, Lyon, Marseille, Lille, Rouen and Bordeaux since it is not possible to have a patent application in a novel field. Finally, I cluster the standard errors at the canton level.

Table 2.10 explores the effect of access to a global city on the diffusion of novel technologies. The main independent variable in column 1 is the travel cost from the city centroid of each canton to Paris. The coefficient of travel cost to Paris is highly significant and negative indicating that one standard deviation decrease in the cost to reach Paris is associated with a 0.079 standard deviations increase in the number of novel classes. Moving to column 2 and 3, I test the effect of travel cost to Lyon and Marseille on the number of novel classes respectively. According to the results, travel cost to other big urban centers does not have a significant effect on the number of novel classes. Finally, in column 4, I run a regression using the travel costs to all nodal destinations. Again, travel cost to Paris is the only that is significant.

One possible concern may be that connectivity to Paris is associated with a lower cost for registering patent applications and has nothing to do with the diffusion of novel technologies. As the INPI patent office was in Paris a faster connection, because of the railroads, could have facilitated the registration of patent applications by inventors. According to Galvez-Behar (2019) there were patent agents in Paris that could fill in the patent applications on behalf of the inventors. Even after the construction of railroads and the reduction in transportation costs, it may have been

classes.

[22]A canton with a high number of technological classes is less likely to adopt a novel technology.

[23]The 63.25% of the values in the dependent variable are zeros. According to Bellemare and Wichman (2020) as a rule of thumb, they state that if the data has more than one third zero-valued observations, it is perhaps best to explicitly apply Tobit or zero-inflated Poisson or negative binomial model.

Table 2.10: Diffusion of novel technologies and access to a global city

Dep. var. =	Number of Novel Classes			
	(1)	(2)	(3)	(4)
	PPML	**PPML**	**PPML**	**PPML**
Travel Cost to Paris	-0.079***			-0.727***
	[0.028]			[0.145]
Travel Cost to Lyon		-0.035		0.424
		[0.026]		[0.291]
Travel Cost to Marseille			-0.017	0.230
			[0.028]	[0.213]
Sample Size	11484	11484	11484	11484
Canton FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Canton Controls	Yes	Yes	Yes	Yes
Stock of Classes	Yes	Yes	Yes	Yes

Notes: I exclude from the sample the cantons of Paris, Lyon, Marseille, Lille, Rouen and Bordeaux because they already had all the technological classes before the arrival of railroads. The dependent variable is the number of novel technological classes in a canton. Travel cost to Paris, Lyon and Marseille is the computed travel cost to reach in Paris, Lyon and Marseille. Canton controls contain the population, the average cropland area, the average land used for grazing, the existence of a university and the number of post offices. Population transformed using a log transformation. PPML model based on the equation 9 with clustered standard errors at the canton level are reported in the parenthesis.

far easier for inventors simply to send a letter to patent agents via a post office and avoid having to deal with bureaucratic procedures. With this in mind, controlling for the number of post offices should take this potential concern into account. Furthermore, I repeat the same regressions by excluding the Seine department and the region of Île-de-France in the Appendix 2A (Table A2.4) because for inventors living close to Paris the cost of registering a patent may have been the same, either applying through a post office or going to the INPI office. The effect of the cost of travelling to Paris remains strongly significant.

2.7.3 Limitations of the Access to Knowledge Approach

The use of freight rates makes comparable the transportation via canals and railroads. However, according to Donaldson and Hornbeck (2016), there are several important limitations to take into consideration when using a similar methodology to the market access approach based on freight rates. This chapter attempts to address several of these issues.

Firstly, Donaldson and Hornbeck (2016) use Fogel's average national rates, which remain constant over the entire sample period. According to the authors freight rates may have varied with local demand and market power in the transportation sector. In this chapter, I take into consideration the improvements in the transportation sector and I allow the freight rates to vary over time. As I document in the Appendix 2C, there is a significant reduction in the freight rates between years. The initial value for canals is 4.1, in 1850, and at the end of the sample period in 1890, it has dropped to 1.8. The decrease in the cost of railway transportation is even more dramatic, failing from 14.5 in 1850 to 6.8 in 1890.

Secondly, the authors report that there are no congestion effects or economies of scale with respect to transporting goods. They do not control for locations where trains can turn or switch tracks, so actual railroad transportation routes may be less direct. Thirdly, they do not take the speed of the lines into consideration. In order to deal with these issues, at least partially, I make use of an additional variable computed in Mimeur et al. (2018). According to the authors, this variable is a discrete measure that combines two pieces of information: the number of axes converging in a station and the quality of the infrastructure. Next, for every canton most populous point, I compute the straight line distance to the rail stations that combine the above two characteristics. Then I re-estimate equation 6 including this variable.

Table 2.11: Access to Knowledge index and innovation - distance to discrete stations

Dep. var. =	Log (Applications+1)	
	(1)	(2)
	OLS	**OLS**
Log Access to Knowledge	0.056***	0.058***
	[0.017]	[0.017]
Distance to a Discrete Station	-0.079***	-0.085***
	[0.012]	[0.012]
R-squared	0.79	0.80
Sample Size	14625	14625
Canton FE	Yes	Yes
Year FE	Yes	Yes
Canton Controls	No	Yes

Notes: Innovation is measured by the number of INPI patent applications. Access to knowledge is the sum of the share of inventors over population residing in all the other cantons except i divided by the cost to reach in these cantons. Distance to a discrete station controls for the straight line distance in meters from the most populous point of a canton to a station that combines information based on the fastest lines and the number of axes converging in. Canton controls contain the population, the average cropland area, the average land used for grazing, the existence of a university and the number of post offices. The dependent variables, the index of access to knowledge and the population are transformed using a log transformation. OLS model based on the equation 7. Clustered standard errors at the canton level are reported in the parenthesis.

Table 2.11 presents the results. The distance to a discrete station is significant and negative indicating that cantons which are close to a discrete station experience an increase in the number of INPI applications. However, the magnitude of access to knowledge is very close to the baseline estimates reported in Table 2.9.

Next, I make use of the additional variable in Mimeur et al. (2018) to confirm the effect of Paris being a global city on the diffusion of novel technologies. This variable reflects the duration of the fastest route from all the communes in France to reach Paris in the period 1860-1890. It is based on the graph theory definition of the shortest route using time rather than length as the edge weight. It combines information based on the fastest lines and the number of axes converging in a station. However, the variable does not consider the frequency of train at the time and the transition from the walking network to the train network is considered instantaneous. Since this study uses cantons as the level of analysis, I first associate every commune centroid with the most populous point of the closest canton in order to match the two different level of analysis and then, for every canton i, I compute the average travel time based on the communes in canton i. By definition this measure does not take the canal network into consideration.

Table 2.12: Diffusion of novel technologies and access to a global city based on travel time

Dep. var. =	Number of Novel Classes
	(1)
	PPML
Travel Time to Paris	-0.296***
	[0.063]
Sample Size	8702
Canton FE	Yes
Year FE	Yes
Canton Controls	Yes
Stock of Classes	Yes

Notes: I exclude from the sample the cantons of Paris, Lyon, Marseille, Lille, Rouen and Bordeaux because they already had all the technological classes before the arrival of railroads. The dependent variable is the number of novel technological classes in a canton. Travel time to Paris is the ability to reach in Paris based on the time duration of the fastest route. Canton controls contain the population, the average cropland area, the average land used for grazing, the existence of a university and the number of post offices. Population transformed using a log transformation. PPML model based on the equation 9 with clustered standard errors at the canton level are reported in the parenthesis.

In line with the baseline results in Table 2.10, I find that accessibility to the city of Paris has a strong effect on the number of novel technologies, as shown in Table

2.12. The difference from Table 2.10 is that the magnitude of the coefficient of travel cost to Paris is much larger. One explanation is that this cost is computed only based on rail lines and not canals and it could overestimate the impact of railroads.

Another limitation is that the network is restricted to transportation linkages within France. The computation of transportation cost includes only the cantons of France and does not take into consideration the exposure of the cantons to international patent collaborations. I exploit the richness of the patent database and I exclude from the sample all the patent applications that come as a result of an international collaboration. Then, I compute again the number of patent applications at the canton level. Furthermore, I include as a control the straight line distance in kilometers from any most populous canton point to the closest canton point with a patent application based on international collaboration. I control for the straight line distance because areas that are close to the cantons which benefited from exposure to international patent collaborations could also be benefited. Table 2.13 provides the results. I find that even though straight line distance to a canton with an international collaboration has a negative effect it is not significant. On the other hand, the variables of interest, distance to rail stations and access to knowledge, have a similar effect with the benchmark analysis.

Finally, it may be more costly to cross areas at a high altitude by train or boat. With this in mind, I use QGIS to compute the least costly routes, but this time I weight the cost values of cantons that have an altitude value over than 200 with their elevation rate. Figure C2.5 in the Appendix 2C presents these cantons of France. I extract the elevation raster file from DIVA-GIS (2020). Table 2.14 summarizes the results with the weighted cost. The magnitude of the coefficient of access to knowledge is slightly lower comparing to the baseline estimates in Table 2.9 but still highly significant.

2.7.4 Removal of Railroads - Back of the Envelope Exercise

This section provides additional evidence about the importance of railroads on innovation performance. For this exercise, I assume that railroads have never been constructed and I focus on canal transportation to create this back of the envelope exercise. Next, I use QGIS to compute the least costly paths between cities in the absence of railroads using the same cost values for canals as in the baseline model. I find that the new access to knowledge measure based on canals is on average

Table 2.13: Access to Knowledge and innovation - exposure to international collaborations

Dep. var. =	Log (Applications+1)		
	(1)	(2)	(3)
	OLS	**IV**	**OLS**
Distance to Rail Station	-0.074***	-0.048***	
	[0.007]	[0.018]	
Log Access to Knowledge			0.065***
			[0.017]
Distance to International Collaboration	-0.075	-0.070	-0.064
	[0.054]	[0.054]	[0.054]
R-squared	0.80	-	0.79
Sample Size	14625	14625	14625
Canton FE	Yes	Yes	Yes
Year FE	Yes	Yes	Yes
Kleibergen-Paap Wald rk F statistic	-	698.49	-
Kleibergen-Paap rk LM statistic Chi-sq(1)	-	274.314	-
Canton Controls	Yes	Yes	Yes

Notes: Innovation is measured by the number of INPI patent applications except the ones that are result of an international collaboration. Distance to rail station is the distance from the most populous point of a canton to the nearest constructed railway station. Canton controls contain the population, the average cropland area, average land used for grazing, the existence of a university and the number of post offices. Additional control is the distance to a canton with an international patent application. The dependent variables, the indexes of access to knowledge and the population are transformed using a log transformation. OLS and IV model based on the equation 1 and equation 3 for column 1 and column 2 and on the equation 7 for columns 3 and 4. Clustered standard errors at the canton level are reported in the parenthesis.

Table 2.14: Access to Knowledge index based on elevation and innovation

Dep. var. =	Log (Applications+1)
	(1)
	OLS
Log Access to Knowledge	0.054***
	[0.017]
R-squared	0.79
Sample Size	14625
Canton FE	Yes
Year FE	Yes
Canton Controls	Yes

Notes: Innovation is measured by the number of INPI patent applications. I weight the cost of the access to knowledge indexes by elevation. The dependent variables, the indexes of access to knowledge and the population are transformed using a log transformation. OLS model based on the equation 1. Clustered standard errors at the canton level are reported in the parenthesis.

26.37% lower (with a standard deviation of 24.17) than the access to knowledge measure obtained using equation 7.

Following the same approach as Donaldson and Hornbeck (2016), I take the coefficient of the baseline regression of access to knowledge on innovation, as shown in column 1 of Table 2.9, and I use it together with the updated index of access to knowledge, keeping everything else constant, to predict the number of patents in the absence of railroads. I find that, in the absence of railroads, the invention rate of the French cantons would have been, on average, 21.3% lower (see Table 2.15).

Table 2.15: Back of the Envelope Exercise based on Canals

Time Period	Percent Lower - Invention Rate	Standard Errors	Obs.
1850-1890	21.3	(5.227993)	14,625

Notes: This Table presents the counterfactual impact on invention rate from the removal of railroads. Robust standard errors clustered by canton are reported in parentheses.

The purpose of this exercise is to understand the importance of railroads for innovation during the 19th century in France, but it is not a counterfactual scenario. In a counterfactual scenario, other aspects have to be taken into consideration, such as the re-allocation of population, as reported by Donaldson and Hornbeck (2016).

2.8 Concluding Remarks

In this chapter, I make use of two historical databases to study the effect of access to railroads on patent activity: a recently constructed database of rail stations (Mimeur et al., 2018) and the database of the French INPI. I focus on the enormous expansion of railroads in France over the second half of 19th century to document that access to the rail network fosters patent activity at the canton level. Controlling for navigable waterways and the number of postal offices, I can capture the net effect of rail network. Finally, the results are also confirmed by an IV strategy and several robustness tests regarding the validity of the instrument.

I explore access to knowledge as an underlying mechanism behind the results. I compute accessibility measures for the largest cities of the 2,925 French cantons. Findings suggest that, for a given canton i, a reduction in transportation costs to all the other cantons with a high percentage of inventors has a positive impact on patenting activity of the canton i. I assert that this effect is mainly driven by potential interactions among inventors living in different cantons. A back of the envelope exercise based on canals provides additional evidence that, in the absence of railroads, the invention rate of the French cantons would have been, on average, 21.3% lower.

In the last part of the chapter, I use text analysis techniques to determine for the first time the technological class of each patent application in the historical INPI database. Equipped with this dataset, this chapter documents that less costly access to the global city of Paris, compared to other large urban centers, is associated with a higher probability that a given canton i will innovate in a novel patent class. This effect suggests that Paris acts as a gatekeeper of knowledge (Miguelez et al., 2019) that connects the national innovation system to global innovation networks.

This chapter contributes to a growing body of literature on infrastructure and economic outcomes from a historical perspective and, more specifically, to research on railroads and innovation activity. It also adds to the literature on the industrial age in France. In terms of policy, the chapter shows that the general network contributes to an increase in innovation. However, in the case of the diffusion of novel technologies, what matters more is connections to global cities. This is crucial, especially in our times with the intense concentration of complex activities in big cities (Balland et al., 2020).

Appendix 2A: Additional Findings

This Appendix provides additional findings that confirm the benchmark analysis. Table A2.1 summarizes the results of the patents that have an addition as a quality index of innovation. The results hold for all the three models. Yet, it should be taken into consideration that this is a very crude measure based only on the additional cost for an inventor to have an addition.

Next, as a robustness test, I estimate a PPML model in Table A2.2 to consider the count nature of the dependent variable, as well as its high number of zeros. The dependent variables are now the INPI patent applications without any transformation. The results are again highly significant at 1% column 1 and column 2 and 5% in column 2.

In Table A2.3, I re-estimate equation 1 and equation 3 after excluding from the sample the canton that became part of Germany in the end of the Franco-Prussian War in 1870. I rely on the shapefile of 1880 from Gay (2020) to identify these cantons. Again, the results, both OLS and IV, are highly significant.

Road Network of 18th Century

Historical infrastructure networks may be correlated with the construction of modern infrastructure networks (Baum-Snow et al., 2017, 2018). This is true in the case of France. According to Smith (1990), the same organization was responsible for the construction of the Legrand Star rail plan of 1842 and the royal highways of 1770. They continued from the highway system in the eighteenth century through the waterways and railroads of the 19th century to electric power and economic planning in the 20th. The purpose of the rail network was to imitate the improved highway system of the eighteenth and early 19th centuries (Schwartz et al., 2011). The road network of the 18th century seems a good potential instrument. However, there are two main drawbacks: the absence of time variation, since the road network is static compared to the rail network, and possibly correlated (directly or indirecly) with outcomes of interest (Baum-Snow et al., 2017, 2018). These reasons discourage its use as an instrument. In contrast, I incorporate it into the analysis to control for pre-trends in infrastructure network since the arrival of railroads. I extract data on road network of France during the 18th century from Perret et al. (2015). I use only the main road network. Based on this data, I create an indicator of accessibility in the infrastructure network of the 18th century.

Transportation in 18th century: I compute straight line distance of any canton city centroid to the closest infrastructure network line in the 18th century.

Roman Road Network

Recent literature finds an association between Roman roads and modern urban networks in the case of France. Michaels and Rauch (2018) explore the resetting of the urban network for Britain and France. They find that France's urban network was largely shaped by its Roman origins. In their online Appendix, they argue that bishops had crucial roles in the evolution of the town life in France after the fall of the Western Roman Empire. According to Nicholas (1997) bishops were instrumental in the survival of towns in France after the end of the Roman Empire. I extract data for the main Roman network from McCormick et al. (2013). Next, I define accessibility to Roman road network.

Roman Road Network: I compute straight line distance of any canton city centroid to the closest line of Roman road.

Table A2.4 summarizes the results. In the first three columns, I use different thresholds for the binary indicator access to navigable waterways. Comparing to the results in Table 2.3, they are similar in magnitude even though the results are now significant at 5%. In column 5, I control for the distance to canals, a measure like the main independent variable distance to rail stations. There is a reduction in the magnitude, but the coefficient is still highly significant. Finally, in the last column, I add the additional variables, distance to road network of the 18th century and distance to Roman road network multiplied with time dummies. The coefficient of the IV estimator is similar to the one in Table 2.3.

Table A2.5 presents the results for the diffusion of novel technologies model when I remove from the sample the department of Seine. This is done both in column 1, where I use the transportation cost based on canals and rails, and in column 3 where I use the travel time measure based on railroads. In columns 2 and 4, I remove the entire region of Île-de-France. The results are highly significant. This robustness test confirms that the results are not driven by inventors who are close to Paris and are facilitated by the fact that they can now travel to INPI's office faster for bureaucratic procedures which are not related to the diffusion of novel technologies.

Table A2.1: Distance to rail stations and quality indexes of innovation

Dep. var. =	Log (Additions+1)		Additions
	(1)	(2)	(3)
	OLS	**IV**	**PPML**
Distance to Rail Station	-0.051***	-0.032*	-0.135**
	[0.007]	[0.019]	[0.063]
R-squared	0.76	-	-
Sample Size	14625	14625	7550
Canton FE	Yes	Yes	Yes
Year FE	Yes	Yes	Yes
Canton Controls	Yes	Yes	Yes
Kleibergen-Paap Wald rk F statistic	-	689.38	-

Notes: Innovation is measured by the number of INPI patent applications that have an addition. Distance to rail station is the distance from the most populous point of a canton to the nearest constructed railway station. Canton controls contain the population, the accessibility to waterways, the average cropland area, the average land used for grazing, the existence of a university and the number of post offices. The dependent variables and the population are transformed using a log transformation. Column 1 contains the OLS results based on the equation 1 column 2 the IV results based on the equation 3 and column 3 the PPML results. Clustered standard errors at the canton level are reported in the parenthesis.

Table A2.2: Distance to rail station and innovation - PPML model

Dep. var. =	Applications
	(1)
	OLS
Distance to Rail Station	-0.143**
	[0.063]
Sample Size	11830
Canton FE	Yes
Year FE	Yes
Canton Controls	Yes

Notes: Innovation is measured by the number of INPI patent applications. Distance to rail station is the distance to the nearest constructed railway station. Canton controls contain the population, the accessibility to waterways, the average cropland area, the average land used for grazing, the existence of a university and the number of post offices. The population is transformed using a log transformation. PPML model. Clustered standard errors at the canton level are reported in the parenthesis.

Table A2.3: Distance to rail stations and innovation - German Empire

Dep. var. =	Log (Applications+1)	
	(1)	(2)
	OLS	**IV**
Distance to Rail Station	-0.061***	-0.073***
	[0.007]	[0.016]
R-squared	0.81	-
Sample Size	14145	14145
Canton FE	Yes	Yes
Year FE	Yes	Yes
Canton Controls	Yes	Yes
Kleibergen-Paap Wald rk F statistic	-	732.91

Notes: Innovation is measured by the number of INPI patent applications in the first column. Distance to rail station is the distance to the nearest constructed railway station. Canton controls contain the population, the accessibility to waterways, the average cropland area, the average land used for grazing, the existence of a university and the number of post offices. The dependent variables and the population are transformed using a log transformation. Panel A contains the OLS results based on the equation 1 and panel B the IV results based on the equation 3. Clustered standard errors at the canton level are reported in the parenthesis.

Table A2.4: Distance to rail stations and innovation - Other types of Networks

Dep. var. =	Log (Applications+1)				
	(1)	(2)	(3)	(4)	(5)
Panel A	**OLS**	**OLS**	**OLS**	**OLS**	**OLS**
Distance to Rail Station	-0.073***	-0.073***	-0.073***	-0.073***	-0.075***
	[0.007]	[0.007]	[0.007]	[0.007]	[0.007]
R-squared	0.80	0.80	0.80	0.80	0.80
Panel B	**IV**	**IV**	**IV**	**IV**	**IV**
Distance to Rail Station	-0.048***	-0.047**	-0.047**	-0.038**	-0.048**
	[0.018]	[0.018]	[0.019]	[0.018]	[0.019]
Kleibergen-Paap Wald rk F statistic	690.35	691.14	692.09	723.22	580.36
Sample Size	14625	14625	14625	14625	14625
Canton FE	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes
Canton Controls	Yes	Yes	Yes	Yes	Yes
Access to Waterways	5km	7km	9km	No	No
Distance to Waterways	No	No	No	Yes	Yes
Distance to other Road Networks x Time Dummies	No	No	No	No	Yes

Notes: In the first column, I include a variable which switches to 1 if a city is within 5 km from a canal, in column 2 if it is within 7 km from a canal, in column 3 if it is within 9 km from a canal and in fourth column I control for the distance to navigable waterways. In the last column, I control for the distance to other road networks like the distance to roman road network and to the road network of 18th century. I have multiplied the distances with time dummies. Innovation is measured by the number of INPI patent applications. Distance to rail station is the distance to the nearest constructed railway station. Canton controls contain the population, the accessibility to waterways, the average cropland area, the average land used for grazing, the existence of a university and the number of post offices. The dependent variables and the population are transformed using a log transformation. Panel A contains the OLS results based on the equation 1 and panel B the IV results based on the equation 3. Clustered standard errors at the canton level are reported in the parenthesis.

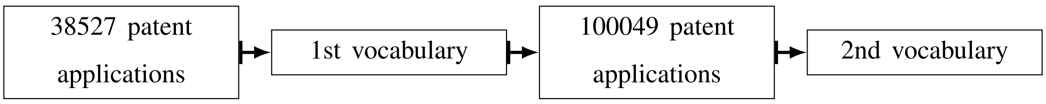
Table A2.5: Diffusion of novel technologies and access to a global city - Robustness

Dep. var. =	Number of Novel Classes			
	(1)	(2)	(3)	(4)
	PPML	**PPML**	**PPML**	**PPML**
Travel Cost to Paris	-0.080***	-0.069**		
	[0.028]	[0.028]		
Travel Time to Paris			-0.296***	-0.290***
			[0.063]	[0.064]
Sample Size	11472	11174	8702	8478
Canton FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Canton Controls	Yes	Yes	Yes	Yes
Stock of Classes	Yes	Yes	Yes	Yes

Notes: I exclude from the sample the cantons of Paris, Lyon, Marseille, Lille, Rouen and Bordeaux because they already had all the technological classes before the arrival of railroads. In addition, I exclude from the sample the department of Seine in columns 1 and 3 and the whole Region of Ile de France in columns 2 and 4. The dependent variable is the number of novel technological classes in a canton. Travel cost to Paris is the computed travel cost to reach in Paris. Travel time to Paris is the ability to reach in Paris based on the time duration of the fastest route. Canton controls contain the population, the average cropland area, the average land used for grazing, the existence of a university and the number of post offices. Population transformed using a log transformation. PPML model based on the equation 9 with clustered standard errors at the canton level are reported in the parenthesis.

Appendix 2B: Assignment of Technological Classes to the Patents

INPI includes in the database a sample of 38,527 (out of 308,513) patent applications that already have a patent class. I use these patents to create a vocabulary which helps me to assign classes to the rest of patent applications. Even though INPI contains a subclass, I only use the main class. I start my analysis by splitting the sample of patents based on their main class. The 35,663 patent applications have a unique class. Using the "lsemantica" command in Stata (Schwarz, 2019), for a given class i, I keep the words from the title of patent applications that appear at least 3 in the sample of patents of the class i.[24] I exclude from the vocabulary the words with length less than 2 letters. Finally, I keep in the vocabulary the words that are unique among classes. Then, I use this vocabulary to assign classes to the rest of patent applications. Based on this methodology, I manage to delegate classes in 138,611 patent applications out of 290,761. From these 138,611 patent applications the 100,049 have a unique class. I repeat the same analysis but this time, I expand my initial vocabulary based on the 100,049 patent applications with a unique class. I complement the vocabulary with key words from the titles of the classes and sub classes of the patents.



I repeat the same procedure manually until there are in the sample 28,645 patent applications with no class. The allocation of patent classes could be bias from the number of words in each individual step. For instance, it could be possible for agriculture sector to have more key words in the 1st vocabulary than weapons, because it has a higher number of patent applications in the initial sample. This bias may generate more patent applications for agriculture in the second step. A second problem regarding this methodology is that for a given class, let say machines, it is possible in the second step to has more applications, which leads to more words, and if the class machines had these words in the first step, it may even have more patent applications in the first round. To this end, after I sum up the words from all the vocabularies and keep those which are unique among classes, I repeat the procedure from the beginning using only the final vocabulary. This again leaves me with the 28,645 patent applications with no class. For these patent applications, given that the previous approach fails to allocate them in a technological class, I

[24] Only for class 11 I keep the words that appear 2 times because it has a very limited number of patents

apply fuzzy matching in Stata (Raffo, 2020) between their titles and the key words from the vocabulary. For every patent application, I store the key word which has the maximum similarity score with the patent title and then I assign a class according to this key word.[25]

Table B2.1: Initial and final statistics by main class

main class	name	initial applications	initial percentage	final applications	final percentage
1	Agriculture	1206	3.13	44168	6.71
2	Alimentation	1751	4.54	17460	2.65
3	Railways and Trams	1693	4.38	36788	5.59
4	Arts textile Fibers and Yarns	5526	14.34	38411	5.84
5	Machines	4017	10.42	107912	16.4
6	Marine and Navigation	947	2.46	11732	1.78
7	Construction Public and Private	1783	4.63	42037	6.38
8	Mines and Metallurgy	1209	3.14	19356	2.94
9	Domestic Economy	1394	3.61	18107	2.75
10	Weapons	1013	2.63	22125	3.35
11	Road Transport	641	1.66	23211	3.53
12	Instrument of Precision and Electricity	1716	4.44	31152	4.73
13	Ceramics	932	2.42	10607	1.61
14	Chemics	3901	10.12	60939	9.26
15	Lighting Heating Refrigeration and Ventilation	2860	7.42	34452	5.23
16	Clothes	2279	5.91	38898	5.91
17	Arts	2492	6.47	62577	9.51
18	Office Supplies and Education	714	1.85	9292	1.41
19	Medicine and Health	1065	2.76	12721	1.93
20	Articles and Various Industries	1388	3.59	16038	2.44

Notes: This table presents the initial number of patent applications by main class, second column, the percentage of the patent applications by class in the initial sample, third column, the final number of patent applications by main class, fourth column and the final percentage of patent application by main class, fifth column. When a patent application has several classes, I allocate one patent application to each class.

[25] If several key words have the same maximum similarity score, I assign two classes in the patent application.

Vocabulary

Agriculture: abri agricole agricoles agricultur animau araire aratoire aratoires arracher arrosoir avoine basée batteuse battoir beche bestiaux bineuse brabant brouette brouettes bétail bêche charancon charançons chariot charrue charrues colza cultiver culture dessèchement décanteur décortication défoncement défoncer défricher dépiquer ecuries engrai ensemencement etrille extirpateur extraire faire faucher faucheuse feve fleau fléau foin foins fourrage fourrages fourragère fourragères fruit fruitier fruitiers fumure fève fèves gelee gelée granuleuse granuleuses greffage greffe greffer greffoir grisou grêle hache haricot haricots harpon herse houe huitre huîtres jardinage l'herbe labour labourage labourer liege liège luzerne magnanerie maladie moissonner moissonneur moissonneuse monder nourriture oidium oïdium peche phosphorée phylloxera phylloxéra phylloxérée phylloxérées piège pièges plantation plante planter planteur plantoir pois prairie prairies printemp printemps pulverulent pulvérulent pyrale rateau ratière rats rural râteau râteaux récoltes secateur semence semences semer semoir siege siège soc socs soufrage soufre soufrer soufreuse souri souricière souris sulfatage sulfate sulfater sécateur taille taupe taupes traire trefle trèfle vegetal versoir viand viande viandes vigne végétal végétale végétative échala échalas écosser écurie écuries égrainer égrener étrille

Alimentation: aliment amandes anille arome arôme avarie avariés baratt baratte barattes baril barils barrique barriques beurr beurre bluter bluterie boulanger bruts brûloir cannelle cannelles claircage clairçage comestible comestibles confire confiture crible cribles cristallisable cristalliser crues depot douves défécation dépôt fecule ferment ferments froid froide fromage fromages fécale fécule fécules gazeificateur gazéificateur gland gruau insufflation levain levur levure limonade lors maceration macérateur macération marrons melasse menthe meuneri meunerie moka mousseuse mousseuses mousseux moutarde mélasses patisserie petrissage petrisseur produi prune pâtissier pétrin pétrir pétrissage pétrisseur raffinerie rafraîchissante sante santé semoule sucreries sucrée terrage tonneau tonnellerie tonnes vannage vermicelle vinasse vineuse vinificateur étuvage évitant

Railways and Trams: accrochage adherence adhérence aiguille aiguilleur amortir attraction automobile automoteu automoteur barrière bourrage chemi chocs circuler collisions conducteur conducteurs connexion convergent convergents convoi couplage croisement d'isolation d'isolement d'éclissage decrochage destination detacher décrochage dégagement déraillement déraillements désincrustation détacher enrayeur etanche ferrée ferrées filtration franchir frein freins funiculaire gare gomme gravir gravite gravité indéraillable installation isolant isolante isolateur isoler isolé l'impression l'isolation l'isolement locomobile locomobiles locomoteur locomoteurs locomotion locomotiv locomotive manoeuvre manoeuvrer mecanicien mécanicien nettoyeur parachoc parcour parcourir parcours passage pentes porte-crayon porte-mine porte-plume preservateur pression pressions protecteur préservateur pétard rail railway ralentir rarefie raréfié rayon refroidissement relier rencontre rencontres retarder reçoit roulement routier routière serre-frein station stations superstructure suppression tender tournant tournante tournantes traction train tramwa tramway travail travailler traverse trolley truck valve voie étanche

Arts textile, Fibers and Yarns: agissant aloès araignée armoire batiste blousse bobin bobine bobiner bobines bobineuse bobinoir bobinoirs broche brocheurs broché brochée brochées brode broder broderie broderies brodeur brodeuse brodé brodés calicot calicots canettes canevas canneler cannetilles cardeuse cardée cardées cardés caret cerf-volant chardons chaussettes chenille cheviller chiffon châle cirer coco cocon cocons coller collet contours cordonnet coupage coupé coupées coupés crapaudine crins d'écheveaux decoupage dentelle devidoir draperie défiler démêler déroulement dérouler détisser dévidage dévide dévider dévideur dévidoir dévidoirs effiler effilochage façonnées fibr fibre fibres fibreuse ficelles filage filament filamenteuse filaments filature filatures filer fileur fileuse filigraner filoir foulard foulards galons gaze grège grèges grége guipure guipures imprimée instar jacquard jaspés jenny jennys lainage laine lainer lainières largeur largeurs laveuse linge lingerie linon lins lisage lisse lisser lisses longueurs loquette loquettes lustrage maille mailles mailleuse maillon maillons malines marchure moirage moire moirer moiré moirés moquette moquettes moulinage mousse mousseline mousselines mâché noué ombrer ombrée ombrées ombrés ondulées papie papier pein peignage peigne peignée peignées peignés peintes perrotine phormium picot piler pinceaux plisser presseur profiler rayer rayure rayures rayé rayée rayés retordre satinage satins satinés soierie soieries sylphide tissag tissage tissant tisse tisserand tisseur tisseurs tissé tissée tissées tissés tondeuse tondeuses tonte tordage tordoir tordre tricot tricoter tricoteur tulle tulles veloutées vergé vernie volant volante volantes volants vélin écheveau écheveaux épinglé épinglés

Machines: actionne actionner actionné actionnée agencement anse articulation articule articulee articulée ascenseur balancier bielle bouche bouchon broyeur bâti casse-fil charnière chaudiere chaudière chéneaux clape clapet cliquet condensateur couverture d'entraînement d'introduction d'ouverture d'élévateur d'émaillage d'étamage entretien equilibre essieu fardeau feux fluide freinage gouttière hydraulique l'ouverture lanière levag machine machines-outil manivelle manivelles manutention manèges molette monte-charge motocycle moufle mouvant multiplicateur multitubulair multitubulaire mâchoire mèche noria obtention obturateur obturateurs opaque opère organe orientant oscillant oscillante ouverture ouvertures ouvrier palan pedale perforateur perforer pesanteur physico pivot pneumato pompe porte porte-outil porter porteur poulie pouvant pressoirs primitif produire produit produites progressif progressive précieux puiser puissance puissances pulverisation pulveriser pulvérisateur pulvérisation pulvériser pédale pédalier quadruple rabot rabots raccords rectification reflux refoulante refouler regulateur relief reparation roche rogner rondelles rotateur rotule roulant roulante rouli râpe réchauffeur réfrigérant régulateur régulatrice réparation scier scierie scieries scies sieur sieurs siphon siphons sortie soufflante soufflantes soufflerie soufflet soufflets soulever tamiser tamiseur tampon tarare tarauder tare tarière teindre tombereau trancher transbordement transportable transports transvaser treuil trieur tubulaire tuyère vanne vannes vapeur varier vasista vendange verticalement viroles visser vitess vitesse vitesses wagon élévateur élévatoire épuisements équilibre équilibré étau

Marine and Navigation Construction: ailette ancre aviation aviron barque barrage boisseau bouée buee buée canalisée canaux canot ciseaux d'hélice dock embarcation fabriquer fleuve flot flottante flotteur gouverner hélic hélice latéraux marin marine maritime navigable navigation navire propulseur propulsive sonore sous-mari sous-marin toile torpille trame

Construction Public and Private: alluvion architecture armé assemblage aérienn aérienne balayeuse boulangerie brosse canalisation caniveau citerne classement constructio construction courbe cuvier d'aronde d'assemblage d'attelage d'echelle d'ecluse d'indicateur d'échelle d'écluse dallage dalle destruction dispositif disposition echelle elastique excavateur façade ferme fermeture fermé fondation fosse frottement frotter hourdi incassable incendie indicateur interieur l'assemblage latte magasi mecanique mortier mécanique ondule ondulé palier passementerie pavage pelle pincette plafond planche plastique plate poutre poutrelle pratique quai scellement solaire substitution suspendu suspendus terrain terrassement terrassements terrasses terrassier toit toits tourbe tranchées treilli triangulaires trottoir trottoirs utilisable viaducs vieux vitrage vitre vitrerie vitrine voiri volcanique voûte voûtes échafaud échafaudage échafaudages échelles écluses élastique

Mines and Metallurgy: acier aciers affinage affinerie alliage alliages argenter artésiens braser camphre cannelure ciselés couche couches coudés coulé creuset cuivrage cuivre cémentation cémenté damasquinage décapage element emboutir emboutissage enclumes fonte fontes forage forge forgeage forger fourche galvanisation guimpier laminage laminoir laminoirs laminé laminés maillechort malléabl malléable martinets metallurgie mine miniere métallurgie métallurgique pilon platinage plombage proportions puddlage puddler raccord recuit revêtir réchauffage salants scories sondage soudage soudés souterrains spéciaux sucre treillage treillages trempe tréfilerie trépan tôles zincage élément étirés

Domestic Economy: affiche affiler affiloir affiloirs alcôves ameublement ameublements baignoire balcon banquette banquettes bassinoire berceau bibliothèque bouillante cache-entrée cadena cadenas cafetiere cafetière cage canapé cane casseroles cisaille coffre coffres coisées commode contrevent contrevents corbeille coucher couchette coutellerie cremon croisee croisée crémon crémone crémones d'affiche d'appel diffusion divan divans dossier dossiers espagnolette espagnolettes fauteuil ferrements ferronnerie feuillure fiches fusion galet gonds gorge gorges hachoir hermétiquement incrochetable incrochetables infusion infusions literie loquets manteau menage meuble mobilier mousqueton mécaniquement patères paumelle pene pentures persienne pincettes pliant poinconneuse poinçonneuse pène pêne pênes quincaillerie rallonges rappel rasoirs repliable rideaux roulette râpes secret serrure serrurerie serrures sonnettes sphériques table tabourets tapisserie tenture théière tournebroche tringle valise verrou verrous vols vrilles

Weapons: arme artillerie baionnette barreau barreaux baïonnette bouclier calibre canon carneaux carreaux cible classeur d'alarm d'armure detendeur detente dynamite défensive détendeur détente embrasure emploi engin explosible faible flexible force fusee fusil fusée gaine hammerles l'art l'artillerie lance masque militaire noyau nuance pistolet piston poignées portatif portativ portative poudrière projectile projectiles rayées recharger revolve revolver revolvers rotative sabre sabres schakos silex tendeur tente tente-abri tir tonnerre troupes épée équipement

Road Transport: appelées bitumineux brancard brancards bridon brisés burette cabriolet cabriolets calcination capote carrosserie d'arçon diligences dételage ferrement ferrer flèche gourmette harnachement inversable inversables landau licou longe lubrifiante luxe marc marchepied marechalerie messageries mors moyen moyeu muselière oxyde oxydé porte-brancard portière publique rais renferment roulage selle selles separateur separation sulfuré séparateur séparation transport velocipedie voiturette écartement éperon étrier

Instrument of Precision and Electricity: abat-jour accumulateur acoustique aimant anéroïde bascul bascule binocle blutoir communication commutateur compensateur compteur consommation curseur d'arpentage d'horloge d'électricit demontage dosage dynamique dynamo dynamo-électrique electricite electrique electro-automatique electro-magnetique electro-moteur electrode electrolyse electrolytique enregistrer enregistreur enregistreuse galvanique horloge instrument l'electrolyse l'électricit l'électrolyse lentille lorgnette lorgnettes lorgnon lunette magnétiques magnétisme magnéto manomètre manomètres mathematique mesurage mesurant mesure mesureur microscope montage mètre mètres médecine méridien métrique métriques niveau niveaux nombres objectif obscure observation pesage peseur peson pesée piles pince-ne pince-nez planimètre polymètre pondérateur precision pyromètre pèse quadrature quantième rapporteur recepteur reconnaître remontage remontoir remontées rouage récepteur secondes sonnerie sonneries spectacle stadia surveillance telegraphie telephon tempes terrestres thermique thermo-électrique thermomètre thermomètres tracer transmetteur transmettre triangulaire télégraphe télégraphes télégraphie télégraphique télégraphiques téléphone téléphoni téléphonie téléphonique voltaïque échappements électricité électrique électro-automatique électro-chimique électro-magnétique électro-moteur électrode électrolyse électrolyte électrolytique

Ceramics: argile argileuse brique briqueterie carrelage creuse céramiqu céramique faience faïence glaise goulots incrustés manchon manchons marqueterie plâtr plâtre porcelain porcelaine poterie poteries potier pouzzolane rebord rebords recuire refractaire réfractaire réfractaires soufflage tain tuile verrerie verreries vitrifiées

Chemics: absorbante acétate acétates acétique alambic albumine alcali alcalines alcalins alcalis alcool alcooliques alcools altération aluminate alumine alumineuses aluminium alun ambulant ammoniac ammoniaque amorphe amylacée antiseptique appret apprêt apprêter aqueuse aromatique asphaltes asphaltiques azote azotique azurer barium baryte baryum bases bichromate bioxyde bisulfate bisulfite borate borax borique bouillon brome brute cachou caoutchouc carbonatation carbonate carbonates carburation carburé caustique caustiques celluloid chaleu chaleur chimique chimiquement chlor chlorate chlore chlorhydrate chlorhydrique chlorure cidre cirage cire colle colorants composition compositions compound conservateur conservateurs copal coque corroyer couleur couperose creme cristallisé crème crèmes cuir cuve cyanogène cyanure cyanures cérus céruse d'aluminium d'ammonium d'appret d'apprêt d'aprè d'eau d'eaux d'encre d'encrier d'epuration d'ether d'hydrate d'oxydation d'oxyde d'épuration d'éther d'évaporatio d'évaporation decantation dentifrice dessécher dissou dissoudre distillation distillatoire distillatoires distille distiller distillée distillés dorer dorure doseur décantation déchet décreusage désagrégation désinfectante désulfuration encre encres encrier epuration essence evaporation evaporer explosive extracteur extrait extraite extraits fermentation fermentescible fermentés feutre filtr filtrante filtrantes filtre filtrer filtres fluorure foie fondants frigorifique galle gallique galvanoplastie garancine gelatine glucose glucoses glycérine gommes gommeuses gommo goudron goudrons graisseur gras hydrate hydraté hydratée hydrochlorique hydrofuge hydrofuges hypochlorite imperméabl imperméable imputrescible inattaquable incolore indicatrice industriel industrielle inflammable injecter injecteur injection inodor inodore instantane instantanée iode l'alcoo l'aluminate l'aluminium l'amiante l'amidon l'ammoniaqu l'anhydride l'apprêt l'eau l'epuration l'evaporation l'hydrate l'industrie l'oxyde l'ozon l'ozone l'évaporation laques lessives levûre lichen liquide lubrifiantes lubrifier luisant magnesium magnésie magnésium manganèse margarique maroquin melange melangeur methyle minérale minéraux mixtion morue mucilagineuse muriate muriatique mélange mélanger mélangeur mélangé mélangée métallisation méthyle nature naturel naturelle naturels neutralisation neutre neutres nitrate nitreux nitrique ocres olive oléine oléique onctueux ourdir oxalique oxydant oxygène parfum parfumerie parfums pendant periodique perméables peroxyde phenique phenol phosphate phosphore phénique phénol plaque potable potasse potassium protoxyde prussiate prussiates précipitation pulpe pulpes purifier pyrites périodique pétrol pétrole queue quinine reducteur resine rouille réactif réducteur réfrigération résine résines résineux saccharatus saccharification saccharine saline salins salpêtre sang saponification saponifier saturation savon savonneuse savonneuses savons schiste siccatif silicate silice siphoïd siphoïde sodium soi sorgho souder soudes soutache steriliser strontiane strontium stéarine stéarique stéariques stériliser sucré suif suifs sulfates sulfite sulfonique sulfures sulfureux sulfuriqu sulfurique surtout tableau taches tanin tanner tannerie tannin tanné tannés taquet tartre tartrique terreux tinctoriales térébenthine vaporisation vernir vernis volatil volatils végéto émailler évaporation évaporatoires évaporer

Lighting Heating Refrigeration and Ventilation: absorber active activer aeration agglomération agglomérer aggloméré allumage allume-fe allume-feu allumer allumette allumeur allumoir amadou appliquee appliquée artificiel artificielle aérage aéro bobèche bougeoir bougeoirs bouilloire brai braise briquet briquets bruler brûlant brûler brûleur bûches calorifèr calorifère caloripède candélabre carboniser carbure carbures carcel centra central chandelier chandeliers chapeliers charbonnières chaud chaude chauffage chauffages chauffant chaufferette chaufferettes cheminée combustible congélateur crémaillère cuisines cuisinière culinaire d’anthracite d’extincteur d’extinction d’hydrocarbure d’éclairage d’écran dirigeable eclairage ecran enflammer etincelle etui extincteur flambeau flambeaux flamm flamme forêts fournaises fumeurs fumi fumifuge fumivores galerie galeries gazo glacière houille hydrocarbure hydrocarbures hydrogene hydrogène hydrostatique ignition illuminations incandescence incandescente inflammables ininflammable intensité intermittente l’incandescence l’éclairage l’étincelle lampe lanterne lanternes lenticulaire lignite longues-vue lumineux phares phosphoriques pignon porte-allumette porte-bougie porte-meche porte-mèche poussier poêle pyro pyrogène pyrogènes pyrogénées pyrotechnique rayonnant refrigeration reverbere réchaud réflecteur réflexion réverbère réverbères salles sechoir supérieur séchoir séchoirs thermosiphon thermostat ustensile veilleuse ventilation volume vues échauffer éclairant éclairer écran écrans éteignoir étincelle étui étuves

Clothes: anneau ardillon ardillons benzidine bijou blanche bleue botte bottine boutonnière boutonnières bretelle brodequin brodequins brun brune brunir buanderie buanderies caleçon caleçons cambre cambrée cambrées canne canne-paraplui caoutchoute caoutchouté casquette chapea chapeau chapellerie chaussette chausson chaussure coiffes coiffure col concentree concentrée corsages corset coulant coulants coupes cousu cousues couture couturiere couturière cravache cravat cravate crinoline culotte d'adaptation d'alizarine d'espadrille d'uniforme doublure drapé dressage embauchoirs empeigne epingle eventail ferrage fixe-cravat flanelle fleur forme fouet fourrure friser frisure ganse gant gibus gilet griffes guêtre guêtres gélatine habillements habit habits hiver invisible jambiere jambière jarretière jarretières jaune jupe jupon lacer lacet latanier lessive lessiver leur ligno manchette manchettes mannequin mannequins manteaux marquises musette ombrelle osier panier pantalon pantoufle paracrotte paraplui parapluie parasol parasols perruque plissage plume porte-canne poser propreté rebras repassage sandale semelle semelles socque socques soulier suspensoir tailleur talon teignant teinte toques toupets tournure tournures tournurière tresses tricoté uniform velocipede verte vetement violet violette visière visières vélocipède vélocipédiste vêtement épingle

Arts: accord accorder accords accordéon accordéons agrafe album amplificateur anime animé animée applique archet archets argentés arrondir artistique autographie autographique bague bagues baleine basses battant bijoux boiseries bonde bourrelet bouto bustes cahiers calorique carcasse carnet chant charge charger chargeur chemise chevalet chevalets cheveux chromatique chromatiques chromo cinematographe cinématographe ciselure clairons clarinette clarinettes clavi clavier claviers coloriées compositeur concertinas confection confectionner cor cornet cornets couronne couronnes coussin crin culot d'agrandissement d'album d'amiante d'image d'imitation d'instrument d'oreille d'ornement d'épreuve daguerréotype dessin dessinateur dessiner diamant dièses décors découpés déterminer déterminée développer ecremeuse emboitement embouti emboîtement emporte-piece emporte-pièce encadrement encrage estampes estampé estampés explosif expressif expressifs expressives faconne feuille feuillets fixateur fleurons flûte flûtes flûtinas fonction format graphique gravure gravures gravées guitare harmonie harmonique harmoniques harmonium harpe harpes hautbois image images imitation imprime imprimé joaillerie jonction l'image l'imitation l'imprimerie l'influence l'ivoire l'ornementation l'outillage lavis lithochromique lithographie lithographier lithographique mate medaille medaillon miniature monnaie monnaies monétaire mouvoir murale musical musicale musicaux musique médaille médailles médaillon médaillons métronome nacre nappe notation note notes négatif négative octaves orchestre orfevrerie orfèvrerie orgue orgues ornement ornementé ouvrage paillette panoramique papeterie passe-partout peint peintre pelliculaire pellicule pendule perce perforation perfore perforé perle perles phonographe photographie photographique photogravure pian pianinos piano pierre piquage pointure poinçons polychrome porte-monnaie portrait portraits pourvu presse-etoupe presse-étoupe production projeter précieuse précisio précision présentant recouvert reproduction rondelle s'appliquant sculpter sculpture sertissure sons stéréoscop stéréoscope stéréoscopiques tabletterie tabouret taille-douce teint ton tons touche toucher touches tourne-feuillet tourne-page transformable transformant transformer transparents travaux trompette types typo typographiques veloutage velouter vignettes violon violons vitraux vitrification zincographie écrémeuse

Office Supplies and Education: affichage albums almanach apprendre biblorhapte brochure calligraphie calligraphique copie copies copiste correspondance d'enveloppe document ecrire enseignement enseigner enveloppe envelopper facture géographie géographique journal journaux lecture lettre leçons manuscrit mettre orthographe paquets porte-journa postale postaux poste prendre public publication quotidien reliure reliures rendre reproduire sciences sphère tendre uranographique écrire écrit écritoire

Medicine and Health: accouchement accouchements affections allaitement analeptique aromatiques aseptique baignoires balayage baume bibero biberon biberons blessé blessés cabinets cachet cadavre canules cautère cercueil cercueils chalumeau chauffe chauffe-bain chauffe-pied chauffer chirurgical chirurgicaux chirurgie clysoir clysopompe clysopompes crachoir cremation cuisses curage dentaire descente descentes difformités domestique douche douches délétères désinfecteur désinfecteurs déviations egout embaumement gymnastique hernie hernies humain hydrotherapie hygiene hygiène immondice jambes latrines lavabo linceul malade malades mamelon matrice mauvaise maux medecine mortuaire médical médicament médicinales médicinaux méphitiques natation nettoyage orthopédique pansement pessaire pessaires pharmaceutique pharmacie plaies plumeau poitrine redressement remède salubrite sangsue sein stereotypie sterilisateur stérilisateur stéréotypie sulfureuses topique traitement urinoir urinoirs utérus varices ventouse ventouses vertébrale vidange égout émanations

Articles and Various Industries: banque bebe bidon bidons billard billards bille blouses bouquet bouquin bourse bourses bruyere bruyère bébé campement canonnière carnets casier cerceau cigare cigarette cigarettes concert coupon course d'échec domino dominos désigné emballage emballer embouchure empaqueter entonnoir estagnon fermoir fermoirs fragiles fumeur gainerie goulot guidon hochet illustre illustré jeux jouer jouet joueurs loto marqueur nicotine oeillet ongles oranger panorama panoramas papier patin patins pipe pipes porte-papier poupée poupées serviette serviettes société tabac tabatières theatre théâtre tourniquet voyage échecs

Appendix 2C: Computation of Least Cost Paths

The key element of the market access framework is the least cost paths among the city points of the cantons, the term $Cost_{iht}$. This cost term is allowed to vary by year, t. The source of variation relies on the expansion of railroads and waterways. Therefore, I compute the least cost paths in QGIS for each year based on the following steps:

1. Division of France into $0.008^o \times 0.008^o$ grid[26].

2. Assignment of a cost to each grid cell using the same properties as in Zobl (2018), Toutain (1967) and Daudin (2010). The values proposed by the authors are:

Table C2.1: French absolute freight rates by transport mode

Period	Road	Canal	Railway
1841-1844	25	4.1	14.5
1845-1854	25	3.8	10.6
1855-1865	25	3.2	8.7
1865-1874	25	2.4	7.5
1885-1894	25	1.8	6.8

Freight absolute rates are measured as centimes per ton and kilometre. The canals have a lower value in terms of cost than the railways. However, the reduction over the years is greater for the railways than the canals. Next, the roads have a fixed cost over the sample period. The effect of roads is then captured by the time fixed effect. I assign a cost of 231[27] for walking like in the paper of Donaldson and Hornbeck (2016).

3. Construction of the cost raster file.

4. For each of the 2,925 cantons in the sample, computation of the travel cost to every other canton. This is a minimisation problem based on the Dijkstra (1959) algorithm over the least cost surface which selects the optimal route.

This methodology produces 8,555,625 pairwise least cost terms for every year. These cost terms can be collected in a cost matrix:

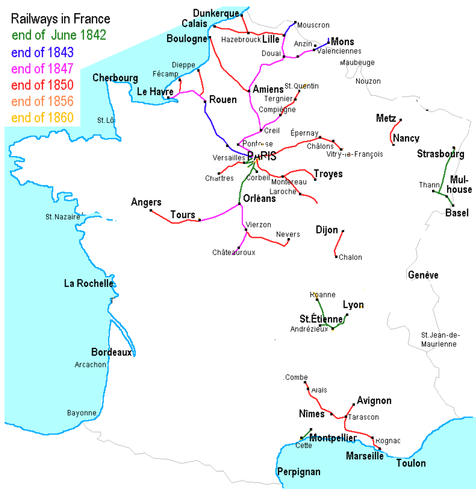
[26]One grid is approximately 1.2 square kilometers.

[27]The value of Donaldson and Hornbeck (2016) is 23.1. I have multiplied it by 10 in order to be in line with the other values.

$$
C_t = \begin{bmatrix} \text{Cost}_{11}^{-\theta} & \text{Cost}_{12}^{-\theta} & \dots & \text{Cost}_{1n}^{-\theta} \\ \text{Cost}_{21}^{-\theta} & \text{Cost}_{22}^{-\theta} & \dots & \text{Cost}_{2n}^{-\theta} \\ \vdots & \vdots & \ddots & \vdots \\ \text{Cost}_{n1}^{-\theta} & \text{Cost}_{n2}^{-\theta} & \dots & \text{Cost}_{nn}^{-\theta} \end{bmatrix}_t
$$

Figure C2.1: Rail lines until 1860

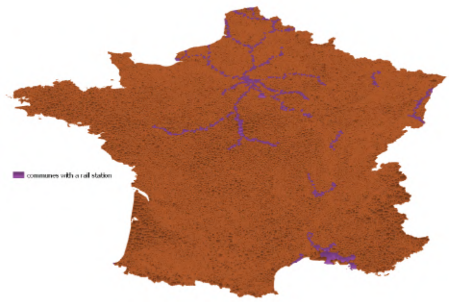
(a) initial image



(b) 1850

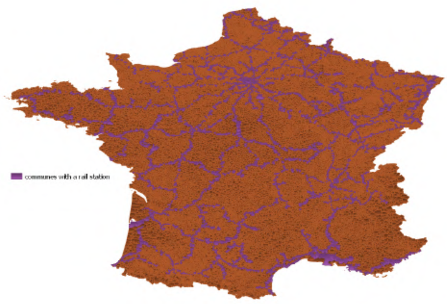
Notes: Railroads until 1860. Source: https://www.wikiwand.com.

Figure C2.2: Communes with rail stations

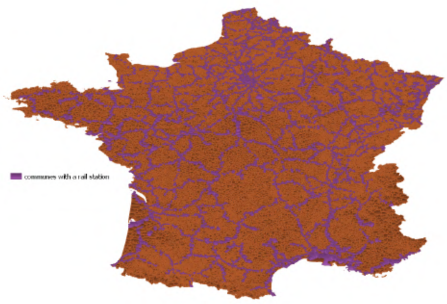


(a) 1850

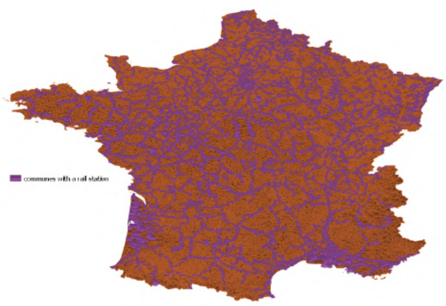
(b) 1860



(c) 1870



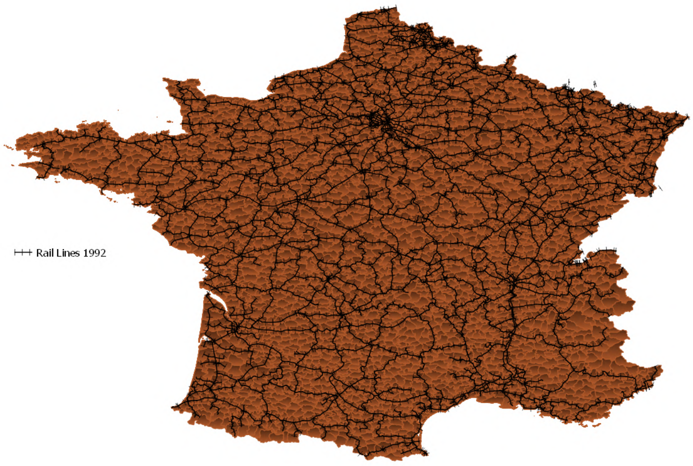
(d) 1880



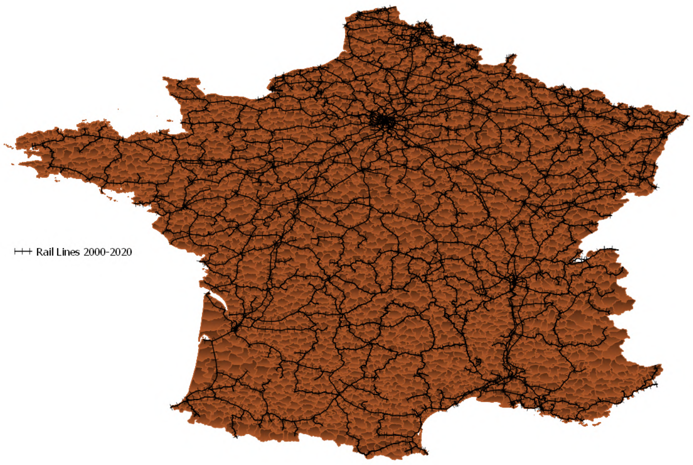
(e) 1890

Notes: This figure shows the expansion of the communes with rail stations. Source: Mimeur et al. (2018).

Figure C2.3: Modern rail network



(a) rail lines until 1992



(b) rail lines 2000-2020

Notes: Modern railroad network. Source: DIVA-GIS (2020) and Jeansoulin (2019).

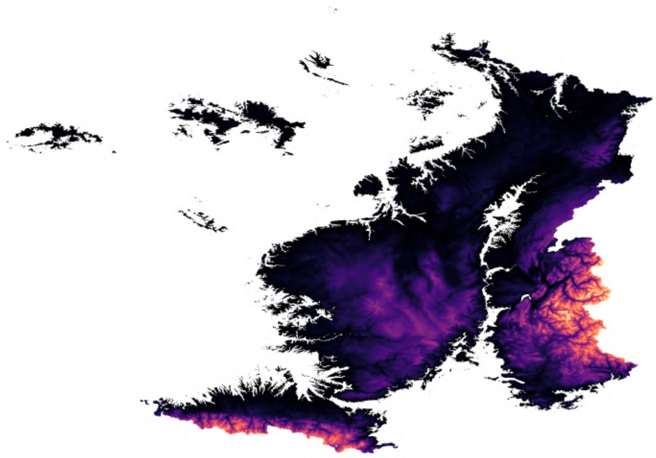
Figure C2.4: Canal network and ports

(a) canal network in 1878

(b) Ports in 1877

Notes: The first graph presents the canal network of France in 1878. The second includes the ports in 1877. Source: Chicago (2020) and Rumsey (2020).

Figure C2.5: Areas with high elevation



Notes: Cantons of France with high elevation. Source: DIVA-GIS (2020).

3 Rails and innovation: Evidence from China

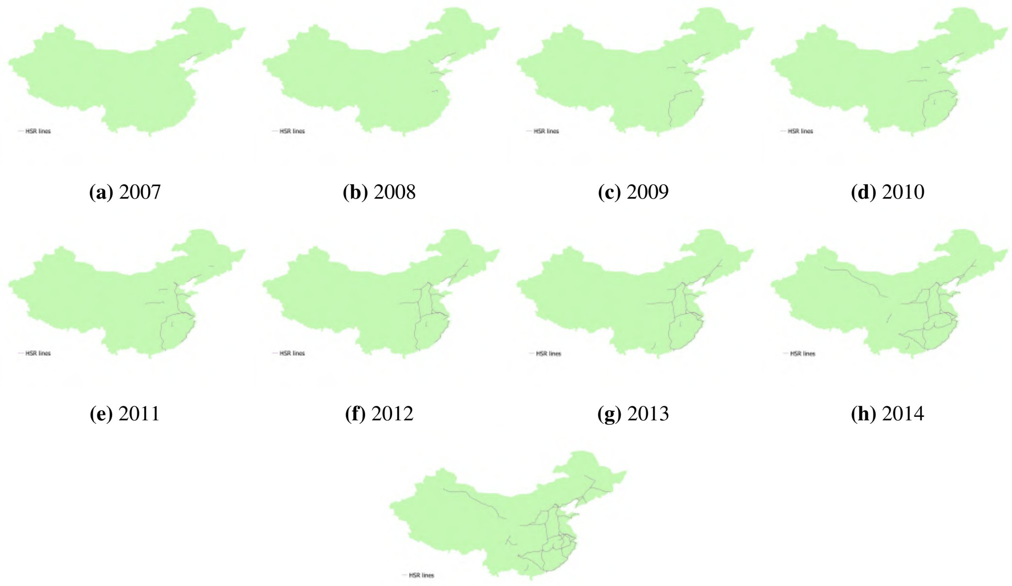
3.1 Introduction

Over the last decades, China has become a science and technology powerhouse, and ambitions to become an innovation global leader by mid of the 21st century (Veugelers, 2017). Since 2011, the China National Intellectual Property Administration (CNIPA) has outnumbered other patent offices, like the JPO or the USPTO, in terms of the applications it receives (WIPO, 2012). If one concentrates on the international innovations actually produced in China's territory (patent families produced by Chinese firms and inventors, and with at least one extension abroad), China has recently overcome the Republic of Korea, reaching 14% of all patent production, not far from other big patent producers (US, 21.1%; Japan, 21%; Europe, 23.9%) (WIPO, 2019). Yet, as in many other countries, the internal spatial distribution of innovation is highly skewed. While Beijing, Shanghai, and Shenzhen-Hong Kong concentrated 36.5% of all internationally-oriented patents produced in China in 1991-1995, these three leading innovation hotspots accounted for 52.2% of all international patents in the period 2011-2015 (WIPO, 2019).

This is not a new phenomenon, as innovation the innovation rate tends to be higher in urban and metropolitan areas (Carlino and Kerr, 2014; Florida et al., 2017). This is due to the existence of agglomeration economies in cities, larger market access, or localized knowledge spillovers, among others things (Lucas, 1993; Moretti, 2021; Jaffe et al., 1993). On the other hand, transportation infrastructure endowments facilitates the flow of labor and human capital, and lowers the cost of accessing knowledge (Agrawal et al., 2017). The roll-out of the High-Speed Rail (HSR) has the potential to affect agglomeration economies, knowledge diffusion and the geography of innovation, and the case of China is the focus of this chapter.

The first HSR line in China introduced in 2007. The rest of the network developed rapidly over the past 15 years with substantial funding from the Chinese government and has become the longest in the world. It is designed for speeds of 250–350 km/h (155–217 mph). Another aspect of China's HSR network is that it complements existing transportation networks (Lin, 2017). The design of the network is based on the economic growth, population and resource distribution, national security, environmental concerns and social stability of each region (Lawrence et al., 2019). Figure 3.1 presents the expansion of HSR network from 2007 to 2015.

Figure 3.1: Expansion of HSR network



(a) 2007 **(b)** 2008 **(c)** 2009 **(d)** 2010

(e) 2011 **(f)** 2012 **(g)** 2013 **(h)** 2014

(i) 2015

Notes: This Figure presents the expansion of HSR network from 2007 until 2015. We include only lines with an average speed of 250 kilometers per hour and more. Source: Li (2016) and World Map (2011).

According to the recent report by Lawrence et al. (2019) at the moment the current level of demand for HSR is 1.7 billion passengers per year. In addition, based on a very recent article published in Global Times, on June of 2021, only the Beijing-Shanghai HSR handled 1.35 billion passengers over the last 10 years (Global Times, 2021). Motivated by this recent evidence and in line with the economic literature (Agrawal et al., 2017), we believe that transport infrastructure investments in cities, and across them, affect how people and firms interact, and may affect the geography of innovation and other economic outcomes. Hence, HSR network allows longer commuting, favoring better quality employer-employee matches and, in general, labor market pooling. It drastically changes market size and market opportunities of local innovators. Scientists and inventors see increased their opportunities to collaborate and build new and larger teams, generating more ideas (Wuchty et al., 2007; Dong et al., 2020). Finally, they allow connecting locations far apart (Cao et al., 2021) and the recombination of knowledge pieces across the space (Owen-Smith and Powell, 2004).

In this chapter, we focus on the effect of HSR intercity connectivity on knowledge creation and diffusion for the period 2008-2016. We find solid evidence that the opening of a HSR station is associated with an increase in the number of patents per capita of a city. We further argue that this relationship exists not only in large urban centers but also among second and third tier cities, more peripheral in the urban system of Chinese cities. Using different approaches, we then investigate to what extent the HSR rollout affects knowledge diffusion. First, we test the effect of the expansion of HSR network on cross-city patent co-applications and citations, and whether it helps overcoming the localized nature of knowledge spillovers (Jaffe et al., 1993). Second, we test whether the reduction in transportation cost, due to infrastructure improvement, affects knowledge diversification towards domains in which the inter-connected cities are specialized in, borrowing from the branching literature the idea of technological diversification (Hidalgo et al., 2007; Hausmann et al., 2007; Essletzbichler, 2015; Rigby, 2015; Boschma, 2017). That is, we study the probability of a city to specialize in a new technological field, as a function of the specialization patterns of the cities to which the city connects through HSR, other things being equal.

The chapter speaks to different strands of literature. First, it contributes to the scholarly work linking transport infrastructure, such as the HSR, and economic outcomes in China by exploring the effect of HSR on technological progress proxied by patent data.[28] Prior literature associates HSR with regional economic growth (Yu, 2021) and economic linkages among cities (Hong and Su, 2019).[29] The underlying mechanism behind the impact of HSR on regional growth is the movement of people from more peripheral counties to the urban core as a result of the reduction of transportation costs (Qin, 2017; Gao et al., 2018; Zou et al., 2019; Lin, 2017). The reallocation of a high-skilled labour force which could work as a mechanism in the reduction of water pollution (Guo et al., 2021). Apart from the movement of people HSR contributes significantly to the venture capital mobility of the cities (Duan et al., 2021). However, a second body of literature argues that the impact of HSR on Chinese cities can be heterogeneous because it depends on the location, route, and region of the cities (Ke et al., 2017). The heterogeneous effect is also present among

[28]Beyond China, Heuermann and Schmieder (2019) explore the expansion of HSR in Germany and find that a reduction in travel time boosts the number of commuters between regions. They argue that this effect is mainly driven by workers changing jobs to smaller cities while keeping their place of residence in larger ones. In addition, Ahlfeldt and Feddersen (2018) analyze the economic impact of the German HSR connecting Cologne and Frankfurt on the GDP of the three counties with intermediate stops.

[29]Economic linkages are measured based on the economics strength index which takes into consideration GDP, the added value of secondary/tertiary industry, GDP per capita, total sales of social consumer goods, total investment in fixed assets, general financial revenue, and permanent resident population.

different industries. Dong (2018) reports empirical findings that HSR network has a controversial effect on employment growth among different industries.

Closer to our research are the papers of Lin et al. (2015), Tamura (2017), Inoue and Nakajima (2017), Dong et al. (2020), Cui et al. (2020), Gao and Zheng (2020), Huang and Wang (2020), Komikado et al. (2021), Hanley et al. (2021), Sun et al. (2021), Yang et al. (2021) and (Yao and Li, 2022). Tamura (2017), Inoue and Nakajima (2017) and Komikado et al. (2021) investigate the effect of the HSR on innovation activities in Japan. The opening of the Hokuriku Shinkansen line in 1997 facilitates knowledge spillovers, as measured by patent citations (Tamura, 2017; Inoue and Nakajima, 2017) and patent collaborations (Inoue and Nakajima, 2017). Furthermore, the existence of HSR stations has a positive and statistically significant association with knowledge productivity, measured as annual patent applications divided by employees in each prefecture (Komikado et al., 2021).

Moving to the Chinese case, railway firms gain in terms of knowledge spillovers from the foreign technology transfer (Lin et al., 2015). Yet, the diffusion process did not end there. The nearby firms benefited not only in terms of more patents, but also as higher productivity and revenue growth. These results are in line with the findings of Yang et al. (2021). The authors show that the cities without a HSR station benefit from the connection of HSR in neighboring cities as they also experience an increase in their innovation activity. HSR connection contributes to the increase of innovation activities of firms (Gao and Zheng, 2020). It further enhances patent collaborations among inventors (Sun et al., 2021), patent collaborations among firms and universities (Cui et al., 2020) and between enterprises in different locations (Hanley et al., 2021). The HSR network also fosters green innovation, with the mechanism behind the main effect being the mobility of innovative factors (Huang and Wang, 2020). Finally, empirical evidence suggest a significant positive impact of HSR on research paper publications and citations which is also driven from secondary cities and not just the star cities (Dong et al., 2020).

We build on this literature and contribute to it in several ways. Starting from the benchmark analysis we use a recent, unique dataset of disambiguated Chinese inventors (Yin et al., 2020) which covers the entire universe of patent applications of the CNIPA (2017 edition). [30] We overcome endogeneity concerns by proposing a novel identification strategy, which relies on historical couriers' stations during

[30]Papers in the literature so far use a part of the CNIPA database like Cui et al. (2020) which relies only on university patents or they exclude cities from the sample because China City Statistical Yearbook does not provide accurate statistics for the same Chinese cities over time.

the Ming dynasty (1403–1644) to create exogenous variation for our main independent variable.[31] We complement our dataset with global raster files of population, cropland, grazing area from the HYDE (2020) and night light data from Li et al. (2020) to create consistent control variable in QGIS for the same Chinese cities over time. Next, we collect data about the cities that belong to high technological zones. China high-tech zones are approved by the State Council and supported by the national government. Companies located in these zones not only benefit from better infrastructure and access to talent but can also receive special incentives such as lower tax rates. We identify and control for the cities that belong to these zones. Furthermore, we geo-localize flight passenger data at the airport level as an alternative transportation network.

Equipped with this rich dataset this chapter provides causal evidence of the effect of HSR network on innovation performance. We further exploit the time availability of our dataset to run several robustness tests. We include a difference-in-differences regression with staggered treatment in which we can control for pre-trends prior to the arrival of the HSR network, a falsification test between our instrument and innovation performance before the creation of the HSR network and finally we add controls to our analysis related to the historical framework of our instrument.

As a mechanism behind the increase in the patenting activity, we investigate knowledge diffusion (which ultimately affects city innovation). First, we explore the role of the reduction of transportation costs, due to the expansion of the HSR network, on the promotion of patent co-applications and patent citations across cities. While imperfect, both are indicators of the spatial reach of knowledge diffusion. In this respect, one very recent paper which is close to our work is that of Hanley et al. (2021). The authors use gravity models and find that travel time has a significant effect on patent collaborations and citations. They define travel time as the difference in travel time between HSR and ordinary railway across cities. We add to this literature in two ways: first, our measure of transportation takes into consideration also the road network. We include three different road lines, highways, national roads and other roads. Second, we elaborate more on the effect of HSR on city pairs by distance. Thus, we find that the results are driven mainly from

[31]Previous studies use either the transportation network of 1961-1962 or 1934 as an instrument (Zheng and Kahn, 2013; Baum-Snow et al., 2017; Dong et al., 2020; Hanley et al., 2021), or a difference-in-difference (DID) approach (Lin, 2017; Qin, 2017; Dong, 2018; Gao et al., 2018; Gao and Zheng, 2020), among other approaches (Hsiao et al., 2012; Ke et al., 2017; Faber, 2014; Dong, 2018; Gao et al., 2018; Banerjee et al., 2020).

the cities that are within a certain threshold of distance. Second, using the framework of the branching literature about technological diversification (Hidalgo et al., 2007; Hausmann et al., 2007; Essletzbichler, 2015; Rigby, 2015; Boschma, 2017), we investigate the probability that a city diversifies in a new technology (develops comparative advantage) increases with the presence of related technologies in that city, in line with the principle of relatedness (Guo and He, 2017; He et al., 2017; Hidalgo et al., 2007, 2018; Gao et al., 2021; Zhu et al., 2019). Recent examples of this literature include, among others, Balland et al. (2019), who report evidence that relatedness and knowledge complexity affects the probability of a region to specialize in a given technological field. Petralia et al. (2017) investigate how the proximity of countries' existing capabilities to every technology is associated with the probability to specialize in a new technological field. Finally, Rigby (2015) documents that technological proximity has an impact on the specialization of US cities. None of these studies, however, address the issue of diversification thanks to the connections to the outside world. To our knowledge, very few studies address the issue of diversification thanks to the connections to the outside world. Bahar et al. (2020) study the effect of immigrant inventors on the technological advantage of nations, finding that countries tend to diversify in technologies brought in by migrant inventors originating in their countries of origin. Bahar et al. (2014) establishes that neighboring countries are very similar in their patterns of comparative advantage, a similarity that decays with distance. They propose knowledge diffusion is a potential underlying mechanism behind their main findings but they do not test it empirically. In our case, we explore if cities are more likely to develop comparative advantage in a new technology after increasing its connectivity, via HSR network, with other cities already specialized in that technology. Close to this approach is a very recent paper of Gao et al. (2021). The authors explore the spillovers across industries and regions in China's regional economic diversification at the province level. In their analysis, they use the HSR network as an instrument in a differences in differences design to explore whether the timing of the roll-out of HSR is associated with the industrial similarity between provinces. They find that that the introduction of HSR promoted the increase in industrial similarity among connected provinces.

The rest of the chapter is organized as follows: Section 3.2 presents the empirical strategy, section 3.3 describes the relationship between HSR network and the diffusion of knowledge across cities, section 3.4 summarizes the data, section 3.5 presents the main results, section 3.6 provides the robustness analysis, section 3.7

discuss the role of the HSR on knowledge diffusion and section 3.8 concludes.

3.2 Empirical Strategy

We begin our analysis by estimating our main model to analyse the role of HSR on the innovation performance of the Chinese cities:

$$Y_{it} = \alpha + \beta H_{it-1} + \gamma_i + \delta_t + \zeta X_{it} + \epsilon_{it} \tag{1}$$

where Y_{it} is the number of patents per capita, in line with the paper of Andersson et al. (2021), in the city i, in time period t. The main variable of interest is H_{it-1}, which contains the straight line distance of any city point with the highest population value to the closest HSR station, as computed in the previous period.[32] We include city fixed effects, γ_i and year fixed effects, δ_t. In addition, we control for the average night light activity, the average crop land area, the average grazing area, the number of flight passengers and if the city belongs to a high technological zone, X_{it}.[33] We estimate by OLS our baseline model, clustering the standard errors at the city level. We transform our main independent variable using the log transformation of the parameters.

However, there is a vast literature rising concerns regarding potential endogeneity issues in the analysis of the impact of the HSR. The most common drawback is that the placement of the HSR network could be endogenous as HSR stations are not randomly established. Because of that, transportation investments may be correlated with the outcomes of interest (Andersson et al., 2021) or assigned through the existing political process (Redding and Turner, 2015). For these reasons, we adopt an identification strategy based on instrumental variables.

3.2.1 Identification Strategy: Historical Couriers' Routes and Stations

It is a common approach in the literature the use of least cost paths between cities that serve as instruments for railway access or the use of an old infrastructure network. Two examples are the recent papers of Andersson et al. (2021) and Büchel

[32]A one-lag structure for the effect of HSR on innovation is intuitive because the stations constructed near the end of the calendar year are likely to affect innovation outcomes only in the following year (Melander, 2020).

[33]The average values of these variables are the sum divided by the number of cells in each city.

and Kyburz (2020). The least-cost path instruments allow the researchers to confront endogeneity concerns related to the placement of railway lines. The authors in both papers use geographic features, such as the slope, the river crossings and the land cover, in order to define the least cost paths. However, this approach requires from the researcher to choose the inputs for the computation of the least cost paths. This choice is endogenous to the identification strategy as it is determined by the researcher. On the other hand, an old infrastructure network has specific drawbacks already discussed in the literature (Baum-Snow et al., 2017).

In our case, we rely on couriers' routes and their stations during the Ming dynasty (1368-1644) to create exogenous variation for our analysis. We argue that the routes represent the least cost paths that the couriers were using during Ming dynasty to deliver their messages among the Chinese cities. We claim that our approach contributes to the existing ones because we do not determine the least cost paths by any mean as we do not use geographical characteristics or the location of the big urban centers. Comparing to the studies that use an old infrastructure network, we provide evidence that from the entire network our analysis includes only the routes that were being used by the couriers as they represent the fastest routes.

Twitchett and Mote (1998) describe in detail the organization of the courier services in their book and provide illustrative examples. They argue that there were 1936 operational stations established within the mainland China, defined as the major routes of the Ming dynasty. It is reasonable to assume that these routes were the fastest ones since there was a penalty for the couriers that exceeding the time limits to deliver the mails. For exceeding the time limit by a day, a courier was liable to a beating of twenty strokes, plus an additional stroke for every three days beyond that, to a maximum of sixty.[34] In line with Twitchett and Mote (1998), Zhang et al. (2021) document that when a courier was reaching to a station the arrival time must be written down on the notebook and there will be corresponding punishment if the courier was late.

The Ming dynasty is possibly the most appropriate time period because the distribution system of couriers was renovated and reached at its peak in terms of ef-

[34]In their book Twitchett and Mote (1998) provide stories which could serve as anecdotal evidence. "On 23 March, the Hangchow prefectural government assigned Ch'oe's party a different escort and issued them with a document empowering them to travel by the courier service. His escort was given an arrival deadline of 11 May, with threat of punishment should he fail to meet it. Ch'oe was told informally that the journey from Hangchow to Peking would take about forty days, though the deadline gave them forty-seven days in which to get to the capital." Using the couriers' routes they arrived in Peking two days before their travel permit expired.

ficiency. More details about the success of the Ming communication network are included in the stories of foreign visitors whose entire presence in China was overseen by a series of well-connected courier stations spaced apart by an average of 30 kilometers (Brook, 1998). In the following years after Ming dynasty, and especially during Qing dynasty, the courier system started to decline because of the wars (Ma et al., 2016). Figure 3.2 presents the routes during Ming dynasty with red lines, with the blue lines being the lines of the HSR network in 2015.

Figure 3.2: HSR lines in 2016 and Ming routes

Notes: Figure 3.2 presents the HSR lines in 2015 and Ming routes. Source: Li (2016) and World Map (2011).

We compute in QGIS the straight line distance from any city point with the highest population value to the closest courier station. Since the instrument is static, we multiple it with time dummies (Andersson et al., 2021; Melander, 2020). We expect a positive relation between the instrument and the HSR stations. A city which is far away from the courier stations during Ming dynasty should also be far away from the HSR stations in recent time periods.

Next, we form our first stage equation:

$$H_{it-1} = \alpha + \sum_{y} \kappa_t^y (Distance\, to\, Courier\, Station)_i + \gamma_i + \delta_t + \zeta X_{it} + \epsilon_{it} \qquad (2)$$

where κ_y is a variable which takes the value 1 if the year is equal to y = 2009, 2010, 2011, 2012, 2013, 2014, 2015, 2016 and 0 otherwise. We have then eight instruments, one for each year after the introduction of the HSR network (Andersson et al., 2021). Distance to courier stations is transformed using logs. Consequently, in a second stage, our main equation is:

$$Y_{it} = \alpha + \beta\hat{H}_{it-1} + \gamma_i + \delta_t + \zeta X_{it} + \epsilon_{it} \tag{3}$$

where $\hat{H}_{it-1}$ is the fitted value of HSR according to equation 2 and Y_{it} is the number of patents per capita. The rest of the control variables are the same as in the equation 1. We cluster the standard errors at the city level.

3.3 HSR and the diffusion of knowledge across cities

3.3.1 HSR and inventors' co-patenting activities and citations

In this section we look at the effect on cross-city patent co-applications and citations. Breschi and Lissoni (2009) explore the effect of mobile inventors and their co-invention networks on the diffusion of knowledge across firms and the space. They find solid evidence that the most important reason why geography matters in constraining the diffusion of knowledge is that it limits the mobility of researchers. As a result of this stickiness, their co-invention network is also localized. D'Este et al. (2013) study the effect of geographical proximity on research collaborations between universities and industry. They state that geographical proximity makes universities and industry research partnerships more likely. Breschi and Lenzi (2016) find that co-invention networks is crucial for inventive productivity in a sample of US cities. They argue that the co-invention networks matter when there is high social proximity between the members in the city and local cliques of co-inventors in which interaction is dense. A developed co-invention network facilitates the interactions among inventors. The inventors built their own knowledge by interacting with and learning from others. Interactions with better inventors are very strongly correlated with higher subsequent productivity (Akcigit et al., 2018; Tubiana et al., 2022). Finally, the mobility of the inventors enhances patent collaborations by helping them to overcome localization constraints (Miguelez, 2019).

We proceed by introducing a gravity equation such as:

$$Know_{odt} = \alpha + \beta Cost_{odt-1} + \xi_{od} + \rho_{ot} + \zeta_{dt} + \epsilon_{odt} \tag{4}$$

where $Know_{odt}$ is the number of co-applications or citations across two cities in year t. o is the symbol for origin city and d the symbol for destination city. $Cost_{odt-1}$ is the transportation cost based on HSR lines across two cities as it was computed in $t-1$ period. We include, ξ_{od}, origin - destination fixed effects, ρ_{ot}, origin - year fixed effects and ζ_{dt}, destination - year fixed effects. We double cluster the standard errors at origin and destination city. We use the OLS model of Correia (2015) to estimate the gravity equation.

Admittedly, it would be ideal to measure collaborations among inventors across different regions (co-inventorship). However, CNIPA database does not contain information of inventor's addresses but only the address of the first applicant (Yin et al., 2020). Assuming inventors from different organizations would involve in co-applications, we consider cross-regional co-application to proxy for regional co-inventorship. We fill in the address of non-first applicants with their corresponding information provided in other patents. For instance, one applicant may not be the first applicant in a given patent application i but it can be the first one in another patent application j. Then, we observe the address of this applicant from the patent application j. We then rely on the assumption that firms don't change their address frequently as to fill in the missing values in the case of non-first applicants with their address in the closest observable year in the dataset. After filling in the addresses, we geo-code the data and we identify 490,314 co-application cases in which 260,030 (about 53.03%) are cross-city collaborations until 2016.

Patent citations have been widely used as a measure of knowledge flows (Jaffe et al., 1993; Britto et al., 2020), despite the drawbacks that are highlighted by the literature (Alcacer and Gittelman, 2006; Jaffe and de Rassenfosse, 2017; Corsino et al., 2019). Using a gravity equation, Morescalchi et al. (2015) explore the impact of physical distance and country borders on inter-regional links proxied by patent citations.

3.3.2 HSR and technological diversification of cities

We complement our previous evidence by exploring the effect of the HSR network on the technological diversification of cities. To be more specific, we investigate whether the reduction of transportation costs, due to the expansion of the HSR network, has an impact on the technological specialization of cities.

With this objective in mind, we estimate the following equation by OLS (OLS with high dimensional fixed effects, as in Correia (2015)):

$$entry_{ict} = \alpha + \beta Cost_{ict-1} + \theta RelDen_{ict-1} + \lambda_{it} + \phi_{ct} + \omega_{ic} + \epsilon_{ict} \tag{5}$$

where $entry_{ict}$ is a binary variable switching to 1 if the city i starts to specialize in a given technology c in year t. $Cost_{ict-1}$ is the reduction, thanks to the HSR, in the median transportation cost to those cities that are specialized in a given technological field c. $RelDen_{ict-1}$ is the relatedness density of the city i in technology c, that is, the extent to which the knowledge base in the city is related to technology c. We include, city-year fixed effects, λ_{it}, ipc-year fixed effects, ϕ_{ct} and city-ipc, ω_{ic}, fixed effects. We cluster the standard errors at the city level.

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3.4 Data

3.4.1 Patent Data

We rely on a unique dataset of disambiguated Chinese inventors. Our source is the CNIPA (2017 edition), founded in 1980 as the Patent Office of the People's Republic of China. As Yin et al. (2020) indicate, inventor level research in East Asia suffers from the common name problem, i.e., many Chinese people share the same name. For example, a search of the name Zhang Wei hits up to 9,680 patents and 61,037 papers in Wanfang Chinese DBLP database, which clearly indicates a problem of homonymy. Our patent database does not suffer from these drawbacks. It relies on a systematic disambiguation process carried out by means of machine learning techniques, using data from 1985 to 2016. It contains the full universe of Chinese patents meaning 4,967,900 over the entire period and 4,105,238 over the sample period of this chapter (Yin et al., 2020).

The assignment of inventors to cities is based on reverse geocoding using CNIPA's addresses and Baidu Map's API (Yin et al., 2020). CNIPA collects only the first applicant's address. We allocate the inventors to their cities based on the latitude and longitude of their address. Our shapefile comes from the National Geomatics Center of China and contains 349 cities for mainland China. We aggregate patent data at the city level to have a measure of city innovation.

Given that Chinese patent applications have been criticized in previous literature due to their possible low quality (Eberhardt et al., 2017), we collect data about claims and citations to try to increase their reliability.[35] We extract the data on claims from Google patent and citations from PATSTAT. We complement our city level measure of innovation with quality indexes of innovation used in the literature: the number of patents weighted by their number of claims and the number of patents weighted by their number of citations within a 5 year window (Aghion et al., 2019) and the patents that belong to the top 50 percent of the distribution of citations for every year and for every technological class based on the citations received within a five year window.[36]

3.4.2 Technological specialization

We classify patents in technological classes according to the 4 digits IPC codes. We restrict our analysis to technological classes that appear in every year. Our final database includes 599 technological classes in total. We rely on the relative technological advantage (RTA) index for each city to define our entry variable. We define it, for each city and technology, as:

$$RTA_{ict} = \frac{pat_{ict}/\sum_c pat_{it}}{\sum_i pat_{ct}/\sum_c \sum_i pat_t} \tag{6}$$

where pat_{ict} is the number of patents that city i produced in technology c in time t. This index relies on Soete (1987) and it is similar to the Revealed Comparative Advantage (RCA) index by Balassa (1965). Based on this index we define our main independent and dependent variables as explained next.

We define the variable "entry" as a binary indicator switching to 1 if the city in a given year starts to specialize in a specific technology. It becomes 1 only when the city i in a year t has an RTA index larger or equal than 1 while in the period $t-1$ it was less than 1. If the city preserves an RTA index larger or equal than 1 the following years it becomes missing value since a city cannot enter again, by definition, before exiting. As long as a city has an RTA index less than 1 in period t

[35] We could not recover citation data in 6,471 cases out of 4,105,238. However, we believe that it is unlikely that these missed cases affect our analysis as these are patents for military purposes. Regarding the patent claims, we were not able to extract data in 239,353 patent applications out of 4,105,238. Again, this is unlikely to affect our results to a large extent.

[36] We rely on the 4 digits IPC classification to define technological classes.

as well as in period $t-1$, it preserves the zero value.

Following the literature on the technological specialization, we compute the relatedness density variable. First, we created the co-occurrence matrix across all technological fields and we normalize it using the association probability measure, proposed by van Eck and Waltman (2009). We compute one co-occurrence matrix for each of the time periods under consideration. We rely on this matrix to develop the relatedness density index for each set city-technology that indicates how close such technology is to the existing technological base of the city. The technological base of a city is considered to consist of those technologies in which a city has developed a specialization (measured using RTAs). We use the Econ Package in R to compute the relatedness density index (Balland, 2017). With this variable we measure to what extent the technological base of a city is related to technology c. The higher the degree of relatedness, the easier we expect city i to specialize in technology c.

3.4.3 Rail Data

Our chapter makes use of three different sources to construct the HSR network. We extract data on HSR stations and lines of China's HSR System from Li (2016) and World Map (2011). We explore the shapefiles of both sources to find the most precise and accurate placement of lines and stations. In addition, we extract data about the speed of each line in two different time periods.[37] Our final source of data is the official website of the National Railway Administration of the People Republic of China which contains the opening years of the HSR stations.[38]

As shown in Figure 3.1, we consider only the lines with an average speed of more than 250 kilometers per hour - in line with the definition of Dong et al. (2020). Our setting allows us to compute in QGIS the straight line distance in meters from the city's most populous point to the closest HSR station.[39] We prefer this measure over a binary variable in terms of higher variation. Huang and Wang (2020) apply a similar approach based on the spherical distance to the closest HSR station. To identify the most populous points we use the raster file of population in 2007 from HYDE (2020) database. We transform the pixels into points and we choose for every city the pixel with the highest population value. An alternative approach

[37]World Map (2011) gives information until 2011 while Li (2016) is updated until 2016.
[38]www.12306.cn, accessed in 2020
[39]We have information about the latitude and the longitude of every HSR station.

would be to select the centroids of the polygons instead of the most populous points but we believe that our choice makes the empirical setting more realistic as the most populous points represent better the center of the cities.

3.4.4 Computation of the transportation cost

We compute the accessibility of each city based on the expansion of HSR network, as follows:

1. We divide China in $0.09^o \times 0.09^o$ grids. One grid is approximately 80 square kilometers.

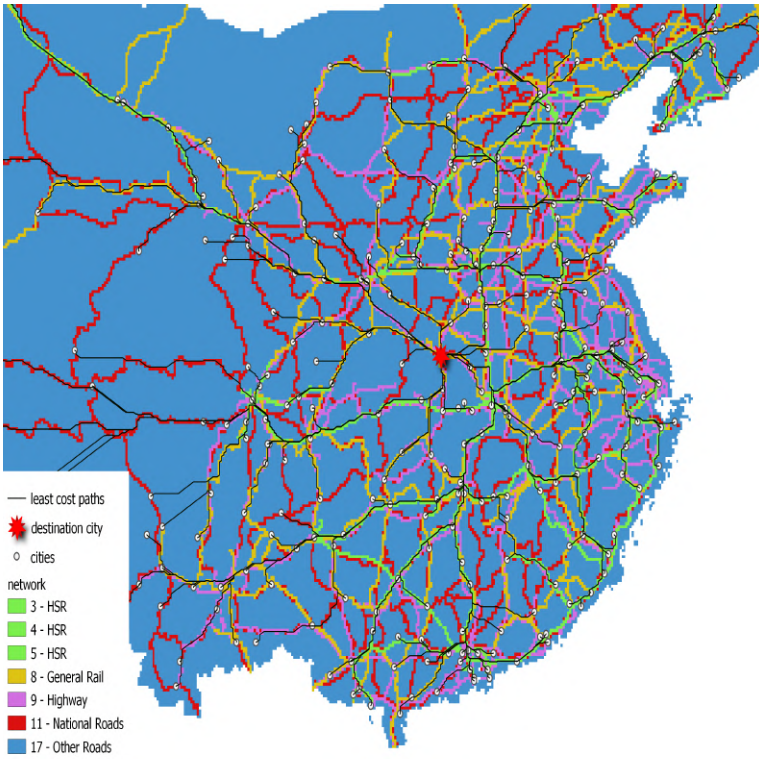
2. Our source of variation over the years is the average travel speed of each HSR line. We rely on the speed of the lines to allocate costs to our grids. We have 3 categories of HSR lines according to their travel speed. Their speed could be 200, 250 or 300 kilometers per hour, on average. Furthermore, we make use of shapefiles of the road network in 2009 and general rail network in 2007. We extract the data from the World Map (2011). Then, we create our cost values using the reverse of the average travel speed for all the lines, HSR, general rail and roads. A HSR line with an average speed of 300 kilometers per hour is assigned a value of 3, for a HSR line with 250 kilometers per hour the value of 4, for a HSR line with 200 kilometers per hour the value of 5, for a general rail line with a speed of 130 kilometers per hour the value of 8, for a highway line with an average speed of 110 kilometers per hour the value 9, for a national road line with an average speed of 90 kilometers per hour the value of 11 and we assume for the rest of the network the value 17 which is based on the average travel speed of 60 kilometers per hour. The travel speeds for the road network are assigned based on the speed limits in Asia. Regarding the general rail network, since we do not have information about the speed of each line, we assign a speed of 130 kilometers per hour, which is the average speed of all the different train lines that exist in China.[40]

Then, based on the type of line that crosses each grid, we allocate one of the values 3, 4, 5, 8, 9 or 11. If no line is intersected with a grid then the grid takes the value of 17.[41]

[40] www.chinadiscovery.com/china-trains/normal-trains.html, accessed in 2021. We compute these values for each grid by simple doing (1/average travel speed of each line)*1000.

[41] Over the period 2007-2015, Chinese government dedicated much of its effort to the construction of the HSR network. Since the other networks do not evolve much over time, their effect should be captured by the fixed effects during the regression analysis.

Figure 3.3: Example of least cost paths



Notes: This graph presents an example of the least cost paths based on the transportation network in 2015. The with dots are the . Authors' computations.

3. Next, we create our cost raster files, one for each year.

4. We apply Dijkstra (1959) algorithm to compute the least cost paths for a given city point with the highest population value i to all the other cities' most populated points except i. This is a typical minimisation problem based on the least cost surface, which selects the optimal route. Figure 3.3 presents an example of the least cost path algorithm for the year 2015. In this example the destination city is in the center. Then, the algorithm finds the least cost path from every city point, white dots, to the destination city. The result is 123,201 least cost paths, for every year, which can be summarized in the following cost matrix:

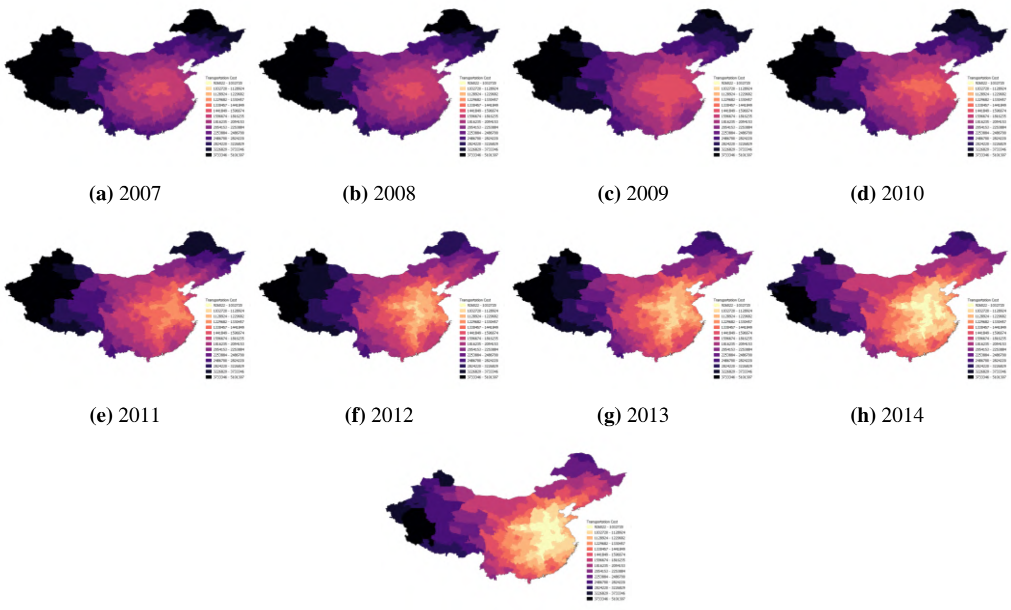
where n is the city number and θ is the trade elasticity (Donaldson and Hornbeck, 2016). For our empirical exercise we assume that θ is 1.

Figure 3.4 presents the reduction in terms of transportation cost based on the expansion of the HSR network for every Chinese city. In section 3.7, we use this transportation cost to explore to what extent its reduction thanks to the HSR increases the probability of a city to specialize in a certain technology. Specifically,

$$
C_t = \begin{bmatrix} \text{Cost}_{11}^{-\theta} & \text{Cost}_{12}^{-\theta} & \dots & \text{Cost}_{1n}^{-\theta} \\ \text{Cost}_{21}^{-\theta} & \text{Cost}_{22}^{-\theta} & \dots & \text{Cost}_{2n}^{-\theta} \\ \vdots & \vdots & \ddots & \vdots \\ \text{Cost}_{n1}^{-\theta} & \text{Cost}_{n2}^{-\theta} & \dots & \text{Cost}_{nn}^{-\theta} \end{bmatrix}_t
$$

our main independent variable, for a given city i in a given year t and for a given technology c, is the reduction of the median transportation cost to the cities that are specialized in technology c (or equally cities that have a RTA larger or equal to 1). We use the main independent variable in absolute terms. Consequently, the computation of the cost for every city, year and technological class depends also on the cities that are specialized in such a technology. Thus, we expect that a higher value of this variable implies a better connectivity with cities already specialised in technology c, with the corresponding increase in the likelihood of city i to specialize in c.

Figure 3.4: Transportation costs



(a) 2007 **(b)** 2008 **(c)** 2009 **(d)** 2010

(e) 2011 **(f)** 2012 **(g)** 2013 **(h)** 2014

(i) 2015

Notes: Following the method described in section 3.4.4. This figure presents the reduction in transportation costs. Authors' computations.

3.4.5 Other Variables

In order to control for economic activity at the city level we rely on night light data. According to the previous literature, night light data is a decent proxy for economic activity (Henderson et al., 2011; Mellander et al., 2015). In addition, Kulkarni et al. (2012) report evidence that for only a very low count of prefectures (between 5 to 10%) the night light data is not a good proxy for determining local GDP in case of China. We make use of the harmonized global nighttime light dataset in the period 1992-2018 given in Li et al. (2020).

We extract a large set of control variables from HYDE (2020) database (Goldewijk et al., 2010, 2011).[42]HYDE (2020) provides (gridded) time series of population and land use for the last 12,000 years. We use raster files to determine the population, cropland and grazing area at the city level. In addition, we collect data about the cities that are national-level high-tech zones approved by the State Council. Our source is the the official website of Ministry of Science and Technology (MOST).[43] Finally, we control for the access to airports since recent literature finds a positive association between air connectivity and patenting (Wong, 2019). We make use of the Civil Aviation Administration of China website (accessed in 2021) to obtain data regarding the number of passengers. All these data come at the airport level so that we use reverse geocoding in the names of the airports and aggregate the passenger data at the city level.

Table 3.1 separates the variables we use by estimation model and presents the summary statistics.

3.5 Results

3.5.1 The role of the HSR on innovation performance

Table 3.2 contains the first stage estimates. The effect of the instrument on the distance to the HSR station solely comes from cross-sectional variation. Based on that, the positive sign means that, for a given city, if it was close to a courier station during the Ming dynasty, it is more likely to be close to a HSR station in a more recent time period.

Next, we move to our benchmark results in Table 3.3. Panel A contains the OLS

[42]We use the baseline estimates of the version 3.2.

[43](http://www.most.gov.cn/zxgz/gxjscykfq/gxjsgxqml/, accessed in 2021)

Table 3.1: Summary statistics

Variables	Mean	Std. Dev.	Min.	Max.	N
Model of innovation performance					
Patents per 10,000 People	2.134	4.837	0	54.12	3141
Past Patents per 10,000 People	0.266	0.914	0	23.583	2792
Claims per 10,000 People	10.586	30.583	0	444.695	3141
Citations within a 5 year window per 10,000 People	4.84	13.177	0	188.509	3141
Top Cited Patents within a 5 year window per 10,000 People	2.571	5.767	0	62.557	3141
Distance to HSR stations with more than 250 average speed	670647.803	894601.049	864.921	4857224.5	3141
Distance to all HSR stations	621234.838	872179.797	242.625	4857224.5	3141
Distance to Ming stations	2271453.549	4921132.46	322.239	24786600	3141
Percentage of people that took Ming Exams	0.00002	0.0001	0	0.00176	3141
Average Population Growth during Ming Dynasty	0.177	0.008	0.057	0.179	3141
Average night light area	7.19	8.182	0.001	58.336	3141
Average crop area	18.744	12.621	0.002	44.634	3141
Average grazing area	19.13	13.349	0.324	61.634	3141
Air transportation (passengers)	1929347.21	8063795.778	0	107543629	3141
High Technological Zones	0.27	0.444	0	1	3141
Difference-in-Differences Model					
Patents per 10,000 People	1.255	3.694	0	54.12	5933
Access to a HSR station	0.131	0.338	0	1	5933
Average night light area	6.063	7.618	0.001	58.336	5933
Average crop area	18.942	12.774	0.002	47.517	5933
Average grazing area	19.131	13.348	0.324	61.634	5933
Air transportation (passengers)	1325430.271	6309835.612	0	107543629	5933
High Technological Zones	0.213	0.41	0	1	5933
Gravity Model Co-applications					
Patent Co-applications	0.217	5.428	0	1248	546534
Total transportation cost	5455.336	3690.387	24	23519.6	546534
Transportation cost for cities within 250 km	13.613	98.641	0	5055.559	546534
Transportation cost for cities from 250 to 499 km	76.053	322.252	0	4904.158	546534
Transportation cost for cities from 500 to 749 km	175.057	602.483	0	5944.213	546534
Transportation cost for cities from 750 to 999 km	278.717	869.673	0	7150.854	546534
Transportation cost for cities from 1000 to 1249 km	360.135	1109.423	0	8107.164	546534
Gravity Model Citations					
Total number of citations	17.692	227.754	0	44257	1086804
Citations within a 5 year window per	15.109	200.745	0	39235	1086804
Total transportation cost	5427.169	3673.594	24	23519.6	1086804
Transportation cost for cities within 250 km	13.674	98.883	0	5055.559	1086804
Transportation cost for cities from 250 to 499 km	76.276	322.633	0	4904.158	1086804
Transportation cost for cities from 500 to 749 km	175.873	603.714	0	5944.213	1086804
Transportation cost for cities from 750 to 999 km	280.26	871.799	0	7150.854	1086804
Transportation cost for cities from 1000 to 1249 km	361.877	1111.542	0	8107.164	1086804
Model of knowledge diffusion					
Entry	0.088	0.284	0	1	1631595
Change in the Median transportation cost X RTA	2.521	2.65	0	8.069	1631595
Relatedness density	5.425	16.745	0	100	1631595
Number of Patents X RTA	1583.432	4585.556	0	113913	1631595

Notes: Summary statistics for all the variables (Model of innovation performance: 349 cities from 2008-2016. Model of knowledge diffusion: 348 cities from 2008-2016. Gravity models: 348 cities from 2008-2016.). **Model of innovation performance:** The number of patents per capita is the number of patent applications for every city divided by the population of the city. The past number of patents per capita is the number of patent applications for every city divided by the population of the city from 2000 to 2007. The number of claims per capita is the number of patent claims for every city divided by the population of the city. The number of citations within a 5 year window per capita is the number of citations within a 5 year window for every city divided by the population of the city. Top cited patents per capita is the number of patents in the top 50% of the distribution for every year and every technological class, based on the 4 digits IPC code, according to the citations that received in a 5 year window for every city divided by the population of the city. Distance to HSR Station 250 is the computed straight line distance (in meters) from the point with the highest population value of a city to the closest HSR station with access to a line of more than 250 km per hour average speed. Distance to HSR Station is the computed straight line distance (in meters) from the point with the highest population value of a city to the closest HSR station. Instrument: Distance to Ming stations is the distance in meters from the most populous point of a city to the closest courier station during Ming dynasty. Percentage of people that took Ming Exams is the number of people that took the Ming exams divided by the average population during Ming Dynasty. Average Population Growth during Ming Dynasty is the average growth of population during Ming Dynasty. The rest of the control variables are the computed average night light area for every city, the cropland area for every city, the average land used for grazing for every city and as air transportation, we control for the number of passengers. High Technological Zones is binary indicator switching to one if the city is defined as a high technological zone. **Difference-in-Differences model:** Access to a HSR station is a binary indicator switching to one if the city has access to a HSR station with more than 250 km per hour average speed. **Gravity models:** The patent co-applications are the patent co-applications between pair of cities. Citations is the total number of citations between pair of cities. Citations within a 5 year window is the total number of citation within a 5 year window between pair of cities. The total transportation cost is the total computed transportation cost using the HSR between pair of cities. **Model of knowledge diffusion:** The entry variable is a binary indicator which switches to 1 if the city in a given year starts to specialize in a specific technology. Change in the Median transportation cost is the change from one year to the other of the median computed transportation cost using the HSR to the cities that are specialized in a given technology. The relatedness density index for each set region-technology indicates how close a technology is to the existing technological base of a city. The technological base of a city is considered to consist of those technologies in which a city has developed a specialization, measured as the Revealed Technological Advantage (RTA). Number of patents is the total number of patents in each technological field.

Table 3.2: First stage: Distance to courier stations and distance to HSR stations

Dep. var. =	Log Distance to Stations		
	(1)	(2)	(3)
Log Distance to Courier Station X 2009	0.233***	0.229***	0.218***
	[0.033]	[0.033]	[0.031]
Log Distance to Courier Station X 2010	0.468***	0.463***	0.446***
	[0.048]	[0.047]	[0.045]
Log Distance to Courier Station X 2011	0.585***	0.587***	0.562***
	[0.052]	[0.052]	[0.051]
Log Distance to Courier Station X 2012	0.543***	0.546***	0.536***
	[0.055]	[0.054]	[0.053]
Log Distance to Courier Station X 2013	0.554***	0.558***	0.558***
	[0.055]	[0.055]	[0.053]
Log Distance to Courier Station X 2014	0.605***	0.609***	0.617***
	[0.058]	[0.058]	[0.056]
Log Distance to Courier Station X 2015	0.505***	0.509***	0.517***
	[0.070]	[0.071]	[0.072]
Log Distance to Courier Station X 2016	0.453***	0.457***	0.469***
	[0.070]	[0.071]	[0.073]
Average Night Light	-0.425***	-0.399***	-0.378***
	[0.095]	[0.095]	[0.084]
Flight Passengers	-0.163***	-0.217**	-0.169
	[0.062]	[0.100]	[0.169]
Sample Size	3141	3105	2988
City FE	Yes	Yes	Yes
Year FE	Yes	Yes	Yes
Sample	Full	Second and Third	Third

Notes: First stage regression results based on equation 2. The dependent variable is the straight line distance in meters from the most populous point of a city to the closest HSR station. Distance to a courier station is the straight line distance in meters from the most populous point of a city to the closest courier station. Average night light data controls for the economic activity of a city. We control for the average cropland area and the average land used for grazing. The variables distance to a HSR station and distance to a courier station have been transformed using the log transformation. Clustered standard errors at the city level are reported in brackets. We standardize all our variables.

results and panel B the IV estimation. Both OLS and IV coefficients for the distance to HSR are significant and negative, meaning that, for a given city, a reduction in the distance to the closest station is associated with an increase in the number of patents per capita. More specifically, one standard deviation decrease in the distance to a HSR station results to 0.24 standard deviations increase in the patents per capita (panel B column 1). In the second column, we remove the first tier cities according to the definition of Fang et al. (2015) and in the final column we keep only the third tier cities. In columns 2 and 3 we observe a reduction in the IV coefficients of the distance to a HSR station which become significant at 5%, compared to column 1, where it is significant at 1%. It seems that the exclusion of the big urban centers affects the magnitude of the IV estimates. However, the fact that the coefficients are still significant at 5% shows that the effect on innovation performance is partially driven also from the second and third tier cities. Both control variables in this regression, night light activity and passengers by air, have a positive and significant effect on innovation activity. We also observe that the IV coefficient is higher than the OLS one. According to Dong et al. (2020), an explanation for this larger IV estimates is that the Chinese government intentionally planned some HSR stations in lagging areas to help them grow. This could explain the downward bias in the OLS estimates.

According to Lin (2017), the HSR network uses speeds over 200 km/h. As a robustness test we repeat the same regressions and we include in our analysis the stations with connections to lines of 200 km/h and above. As we present in the Appendix 3A Table A3.1, our results are not affected even when we include the stations with access to a line that has an average speed of 200 kilometers or more. Finally, we provide evidence in Table A3.2 in the Appendix 3A that our results are robust when we use as our key variable the distance to a HSR station lagged in time.

Next, we adjust the dependent variable to the quality of the patent so that we can explore the effect of the HSR network on the top cited patents by year and by technological class. These are patents that belong to the top 50% of the distribution according to the citations they receive within a five year window. Our results in Table 3.4 are in line with the benchmark estimates in Table 3.3 even though the coefficients are slightly lower. In the Appendix 3A we report evidence using as quality indexes of innovation the weighted number of patents based on citations received within a five year window (Table A3.3), and the weighted number of patents based on claims (Table A3.4). The results confirm our benchmark analysis.

Table 3.3: Main Results: HSR and Innovation

Dep. var. =	Patents per capita		
	(1)	(2)	(3)
Panel A	**OLS**	**OLS**	**OLS**
Log Distance to Stations	-0.118***	-0.120***	-0.122***
	[0.034]	[0.034]	[0.036]
Average Night Light	0.565***	0.598***	0.581***
	[0.167]	[0.165]	[0.172]
Flight Passengers	0.567***	0.609***	0.425**
	[0.170]	[0.148]	[0.186]
R-squared	0.83	0.77	0.75
Panel B	**IV**	**IV**	**IV**
Log Distance to Stations	-0.240***	-0.210**	-0.203**
	[0.088]	[0.086]	[0.086]
Average Night Light	0.501***	0.553***	0.542***
	[0.170]	[0.164]	[0.171]
Flight Passengers	0.544***	0.585***	0.406**
	[0.173]	[0.152]	[0.188]
First-Stage F-stat	18.52	18.47	18.96
Sample Size	3141	3105	2988
City FE	Yes	Yes	Yes
Year FE	Yes	Yes	Yes
Sample	Full	Second and Third	Third

Notes: Main results. The dependent variable is the number of patents divided by population. Distance to HSR stations contains the straight line distance in meters from the most populous point of a city to the closest HSR station. Flight passengers accounts for the effect of alternative transportation networks. Average night light data controls for the economic activity of a city. We control for the average cropland area, the average land used for grazing and we include a dummy variable switching to 1 if the city belongs to a high technological zone. The variable distance to a HSR station has been transformed using the log transformation. Panel A contains the OLS results based on equation 1 and panel B the IV estimates based on equation 3. Clustered standard errors at the city level are reported in brackets.

Table 3.4: HSR and Innovation - Top Cited Patents in a 5 year window

Dep. var. =	Top Cited Patents per capita		
	(1)	(2)	(3)
Panel A	**OLS**	**OLS**	**OLS**
Log Distance to Stations	-0.097***	-0.100***	-0.106***
	[0.029]	[0.029]	[0.030]
Average Night Light	0.503***	0.537***	0.525***
	[0.161]	[0.161]	[0.168]
Flight Passengers	0.551***	0.594***	0.413**
	[0.150]	[0.159]	[0.188]
R-squared	0.83	0.76	0.73
Panel B	**IV**	**IV**	**IV**
Log Distance to Stations	-0.184**	-0.154**	-0.156**
	[0.076]	[0.075]	[0.076]
Average Night Light	0.457***	0.510***	0.501***
	[0.165]	[0.164]	[0.171]
Flight Passengers	0.534***	0.580***	0.401**
	[0.152]	[0.162]	[0.191]
First-Stage F-stat	18.52	18.47	18.96
Sample Size	3141	3105	2988
City FE	Yes	Yes	Yes
Year FE	Yes	Yes	Yes
Sample	Full	Second and Third	Third

Notes: The dependent variable is the number most cited patents in a five years window divided by population. Distance to HSR stations contains the straight line distance in meters from the most populous point of a city to the closest HSR station. Average night light data controls for the economic activity of a city. Flight passengers accounts for the effect of alternative transportation networks. We control for the average cropland area, the average land used for grazing and we include a dummy variable switching to 1 if the city belongs to a high technological zone. The variable distance to a HSR station has been transformed using the log transformation. Panel A contains the OLS results based on equation 1 and panel B the IV estimates based on equation 3. Clustered standard errors at the city level are reported in brackets.

3.6 Robustness Analysis

3.6.1 Falsification Exercise

We begin our robustness analysis with the introduction of a falsification exercise (Autor et al., 2013; Dix-Carneiro et al., 2018). We start by collecting data on population and patents from 2000 until 2007 from the same sources as in the benchmark analysis. Then, we estimate a panel IV regression in which our key independent variable is the distance to the closest HSR station, as in Table 3.3. Now the dependent variable is the number of patents per capita from 2000 to 2007, one year before the actual arrival of HSR network. We regress past changes in the patents per capita on future changes in distance to HSR network.

Table 3.5 presents the results of our exercise. Column 1 contains the IV estimates of the benchmark analysis of Table 3.3 after we restrict our sample from 2009 to 2016 in order to have the same time span as our falsification test in column 2. In column 2, we report no significant effect of future HSR network on past patents per capita.

Based on these results we verify that we do not capture some a long-run common causal factor behind both the expansion of rail network and the rise of patent activity. According to the estimates of Table 3.5 this relationship was absent in the years immediately prior to our sample period.

3.6.2 Additional Controls

Next, we repeat the estimation strategy of our benchmark analysis, equations 1 to 3, but this time we include two additional controls related to the Ming dynasty multiplied with time dummies. The first control is defined as the share of people that took the entry exams in each Chinese city and the second is the average population growth for the Chinese cities during Ming Dynasty. We collect the data about the number of people that took the entry exams during Ming dynasty from the World Map (2011) and the total population over the Ming Dynasty from the HYDE (2020). Table 3.6 presents our results, which again, are similar to those in the benchmark analysis.

Table 3.5: HSR and Innovation - Falsification Exercise

Dep. var. =	Patents per capita	Past Patents per capita
	(1)	(2)
	IV	**IV**
Time Period	2009-2016	2000-2007
Log Distance to Stations	-0.329**	
	[0.131]	
Log Future Distance to Stations		-0.055
		[0.113]
First-Stage F-stat	11.71	11.71
Sample Size	2792	2792
City FE	Yes	Yes
Year FE	Yes	Yes

Notes: The dependent variable in column 1 is the number of patents divided by population from 2009 to 2016 and in column 2 is the past number of patents divided by population from 2000 to 2007. Distance to HSR stations contains the straight line distance in meters from the most populous point of a city to the closest HSR station. Both columns contain all the control variables as in the benchmark analysis. IV estimates based on equation 3. Clustered standard errors at the city level are reported in brackets.

3.6.3 Difference-in-Difference Model

Next, we explore a conventional difference-in-differences regression model with staggered treatment to control for pre-trends related to innovation activities before the arrival of HSR lines, which could have been attributed to the HSR in our previous analysis. By doing this, we allow for a long period of time, from 2000 to 2007, in which all the cities did not have access to a HSR station. As long as there are no systematic changes over time except for treatment, differences can be interpreted as causal.

We rely on the richness of our dataset to compare our key outcome variables within a city before and after treatment. We collect the same variables than in our benchmark analysis with the difference that now our panel starts in 2000. Our focal variable is a binary indicator, instead of the distance to a HSR station, which switches to 1 if a city gains access to a HSR station. We include all our baseline controls, like equation (1).

$$Y_{it} = \alpha + \beta Access_{it-1} + \gamma_i + \delta_t + \zeta X_{it} + \epsilon_{it} \tag{7}$$

As observed in 3.7, we find that accessibility to a HSR station has a significant

Table 3.6: HSR and Innovation - Additional Controls during Ming Dynasty

Dep. var. =	Patents per capita		
	(1)	(2)	(3)
Panel A	**OLS**	**OLS**	**OLS**
Log Distance to Stations	-0.115***	-0.117***	-0.121***
	[0.034]	[0.034]	[0.036]
Average Night Light	0.542***	0.577***	0.566***
	[0.167]	[0.164]	[0.172]
Flight Passengers	0.564***	0.607***	0.429**
	[0.171]	[0.149]	[0.186]
R-squared	0.83	0.77	0.75
Panel B	**IV**	**IV**	**IV**
Log Distance to Stations	-0.240**	-0.207**	-0.203**
	[0.093]	[0.091]	[0.090]
Average Night Light	0.487***	0.539***	0.533***
	[0.170]	[0.164]	[0.172]
Flight Passengers	0.541***	0.583***	0.408**
	[0.174]	[0.153]	[0.189]
First-Stage F-stat	16.51	16.51	17.03
Sample Size	3141	3105	2988
City FE	Yes	Yes	Yes
Year FE	Yes	Yes	Yes
Ming Controls	Yes	Yes	Yes
Sample	Full	Second and Third	Third

Notes: The dependent variable is the number of patents divided by population. Distance to HSR stations contains the straight line distance in meters from the most populous point of a city to the closest HSR station with a speed more than 250km per hour. Average night light data controls for the economic activity of a city. Flight passengers accounts for the effect of alternative transportation networks. We control for the average cropland area, the average land used for grazing and we include a dummy variable switching to 1 if the city belongs to a high technological zone. Furthermore, we control for the share of people that took the Ming Exams and the average population growth for the Chinese cities during Ming dynasty multiplied with time dummies. The variable distance to a HSR station has been transformed using the log transformation. Panel A contains the OLS results based on equation 1 and panel B the IV estimates based on equation 3. Clustered standard errors at the city level are reported in brackets.

Table 3.7: HSR and Innovation - Difference in Differences Model

Dep. var. =	Patents per capita		
	(1)	(2)	(3)
Access to a HSR Station	0.107***	0.102***	0.083***
	[0.028]	[0.027]	[0.028]
Average Night Light	1.112***	1.234***	1.266***
	[0.230]	[0.216]	[0.229]
Flight Passengers	0.560***	0.475***	0.311***
	[0.153]	[0.124]	[0.120]
R-squared	0.72	0.65	0.62
Sample Size	5933	5865	5644
City FE	Yes	Yes	Yes
Year FE	Yes	Yes	Yes
Sample	Full	Second and Third	Third

Notes: The dependent variable is the number of patents divided by population. Access to a HSR station is a dummy variable which switches to 1 if a city gains access to a HSR station. Average night light data controls for the economic activity of a city. Flight passengers accounts for the effect of alternative transportation networks. We control for the average cropland area, the average land used for grazing and we include a dummy variable switching to 1 if the city belongs to a high technological zone. Differences in differences model based on equation 7. Clustered standard errors at the city level are reported in brackets.

effect on the number of patents per capita. The positive effect means that there is an increase in the number of patent per capita after the city gains access to a HSR station. This is in line with our benchmark analysis.

3.7 The role of the HSR on knowledge diffusion

In this section we report evidence on the effect of the HSR network on different diffusion linkages among Chinese cities, as commented in the Introduction. First, Table 3.8 presents the regression results of the role of transportation cost on co-applications based on equation 4. According to column 1, we find that one standard deviation decrease in transportation costs is associated with an approximately 0.042% increase in patent co-applications across cities. In column 2, we split our focal variable in ranges of 250 km.[44] We obtain that the cities which are close in terms of distance are the ones that are most benefited by the HSR network in terms of patent co-applications.

[44]We chose these thresholds because the average speed of HSR network is 250 km per hour and it needs one hour to cover a distance of 250 km.

Table 3.8: Transportation cost and patent co-applications - OLS

Dep. var. =	Co-applications	
	(1)	(2)
Log Transportation Cost	-0.042**	
	[0.019]	
Less than 250 km		-0.676***
		[0.156]
250-499 km		-0.227
		[0.141]
500-749 km		-0.115*
		[0.066]
750-999 km		-0.052
		[0.075]
1000-1249 km		-0.208
		[0.212]
More than 1250 km		0.095
		[0.121]
R-squared	0.68	0.68
Sample Size	546516	546516
City Origin x Destination FE	Yes	Yes
Destination FE x Year FE	Yes	Yes
Origin FE x Year FE	Yes	Yes

Notes: Gravity model based on equation 4 estimated with OLS and standard errors clustered at the origin and destination city. Patent co-applications are patent co-applications between inventors in each pair of cities. The total transportation cost is the computed total transportation cost using the HSR between each pair of cities.

Second, we explore the effect of a reduction of transportation costs on the number of citations between patents in different cities. Table 3.9 summarizes these results. In line with the ones based on co-applications, we observe that the effect is basically due to the cities that are within a short distance. To be more specific, even though in Panel A we do not find a general significant effect of the HSR network on the citations between cities, we report evidence in Panel B that the diffusion process based on citation data is driven by the cities that are within less than 749 km of distance. Our results are confirmed also when we use subsequent years in columns 2 and 3. Finally, in the Appendix 3A, in Table A3.5 we restrict our index only to the citations within a 5 year window and again we find the same pattern.

We further explore the effect of HSR on knowledge diffusion by looking at the specialization patterns of Chinese cities. Table 3.10 summarizes the results of the technological specialization model. We include all the possible pairwise fixed ef-

Table 3.9: Transportation cost and patent citations - OLS

Dep. var. =	Citations	Citations t+1	Citations t+2
	(1)	(2)	(3)
Panel A - Total Cost			
Log Transportation Cost	-0.0366	-0.0304	-0.0225
	[0.0259]	[0.0250]	[0.0202]
R-squared	0.88	0.92	0.94
Panel B - Total Cost by distance thresholds			
Less than 250 km	-0.7664***	-0.6202***	-0.3409***
	[0.2028]	[0.1592]	[0.0940]
250-499 km	-0.2665***	-0.2283***	-0.1624***
	[0.0848]	[0.0785]	[0.0613]
500-749 km	-0.0986*	-0.0927*	-0.0811*
	[0.0564]	[0.0539]	[0.0425]
750-999 km	-0.0200	-0.0215	-0.0363
	[0.0583]	[0.0572]	[0.0491]
1000-1249 km	-0.2004	-0.1722	-0.1272
	[0.1311]	[0.1201]	[0.0879]
More than 1250 km	-0.0093	-0.0027	-0.0199
	[0.1598]	[0.1557]	[0.1267]
R-squared	0.88	0.92	0.94
Sample Size	1086804	1086804	1086804
City Origin x Destination FE	Yes	Yes	Yes
Destination FE x Year FE	Yes	Yes	Yes
Origin FE x Year FE	Yes	Yes	Yes

Notes: Gravity model based on equation 4 estimated with OLS and standard errors clustered at the origin and destination city. The dependent variable is the number of citations. The total transportation cost is the total computed transportation cost using the HSR between each pair of cities.

fects. Additionally, we control for the number of patents that a city has in a given technology (column 2) and the total number of patents (column 3). The latter tries to mitigate concerns related to the fact that we can observe specialization because a city has a very low number of patents. In the first column, we report strong evidence that for a given city i and a given technology c, a higher reduction in transportation costs, thanks to the better HSR network connectivity to other cities that already specialize in the technology c, affects positively the probability of the city i to start also to specialize in technology c. Thus, we observe that the probability of a city to specialize in a new technological field is associated to the specialization patterns of the cities to which the city connects through the HSR. Importantly, note that relatedness density has a positive effect, which is in line with previous literature.

Table 3.10: Technological specialization model

Dep. var. =	Entry		
	(1)	(2)	(3)
Log (Change of Median Transportation Cost+1)	0.002***	0.003***	0.002***
	[0.001]	[0.001]	[0.001]
Relatedness Density	0.002***	0.002***	0.001***
	[0.000]	[0.000]	[0.000]
R-squared	0.31	0.32	0.38
Sample Size	1629435	1629435	1629435
City*IPC FE	Yes	Yes	Yes
City*Year FE	Yes	Yes	Yes
Year*IPC FE	Yes	Yes	Yes
Patents	No	Yes	No
Log (Patents+1)	No	No	Yes

Notes: The dependent variable is binary and switches to 1 if a city has a comparative advantage in a specific technological field. Change of the median transportation cost is the reduction (in absolute terms) from one year to the other of the median computed transportation cost using the HSR to the cities that are specialized in a given technology. The relatedness density index for each set city-technology indicates how close a technology is to the existing technological base of a city. The technological base of a city is considered to consist of those technologies in which a city has developed a specialization, measured as the Revealed Technological Advantage (RTA). We include city*technology fixed effects, city*year fixed effects and year*technology fixed effects. In column 2 we control for the number of patents in every technological sector and in the third column for the log number of patents +1. OLS model based on equations 5 and 7 with clustered standard errors at the city level are reported in brackets.

3.8 Conclusion

This chapter explores the role of the expansion of the HSR on innovation activity in China. Firstly, our analysis contributes to the growing literature about the effect of transportation networks on innovation activity (Andersson et al., 2021; Agrawal et al., 2017; Perlman, 2015; Tamura, 2017; Inoue and Nakajima, 2017; Cui et al.,

2020) by using a brand new disambiguated Chinese inventors dataset (Yin et al., 2020) covering the entire universe of CNIPA patent applications. We assemble a rich dataset which allows us to overcome previous limitations in the literature. In addition, we rely on historical couriers' stations as a novel instrument, to create exogenous variation for our analysis. We report evidence that connectivity to HSR enhances the patenting activity of a city. Our results remain highly significant when we remove the large urban centers, meaning that the effect on innovation is also driven by second and third tier cities. Among several robustness analyses, we run a difference-in-differences regression with staggered treatment to control for pre-trends before the arrival of the HSR network. The main results in the chapter are maintained.

Secondly, we aim at providing evidence of some of the mechanisms that may work when analyzing the role of the HSR network on knowledge diffusion. Initially, we focus on the impact that the HSR may have on the co-applications across inventors residing in different cities. In order to do it, we compute transportation costs for every pair of cities based on the speed of HSR lines. We provide evidence that the reduction in transportation costs fosters patent co - applications across cities. Furthermore, we rely on citation data to provide evidence of knowledge flows between cities and to mitigate concerns that our results could be driven by re-distribution of the same economic activities over space. Again, we show that the reduction in transportation costs due to the HSR increases citations. Finally, we build on the branching literature and look at the technological diversification of regions (Petralia et al., 2017; Balland et al., 2019; Rigby, 2015; Bahar et al., 2020) by presenting evidence that the probability of a city to specialize in a new technological field is related to the specialization patterns of the cities to which the city connects through the HSR.

In terms of policy, our chapter contributes to a broader literature of how to smooth the consistent inequalities among mega cities and places that are left behind (Rodriguez-Pose, 2018; Balland et al., 2020). It shows that reductions in transportation costs as a result of efficient and meaningful transportation projects (Crescenzi et al., 2016) can spur knowledge diffusion. This is crucial in our days since novel ideas are getting harder and harder to find (Bloom et al., 2020) and high quality invention activity concentrates disproportionately in the super star cities (van der Wouden, 2022).

The results in this chapter need to be interpreted as the impact of a HSR network, which is a very specific infrastructure, with very specific people having access to it. According to Dobruszkes et al. (2022), the profile of HSR passengers is anything but neutral. HSR is more likely to be used by specific social groups, such as men in their thirties to fifties, with high income, high occupational position and high educational level. This is in line with findings that HSR network facilitates accessibility to the general rail network and has an uneven impact on the growth of Chinese cities (Jiao et al., 2020; Jin et al., 2020). This prevents us from generalizing our results to any kind of transportation infrastructure.

Appendix 3A: Additional Tables

Table A3.1: HSR stations with speed more than 200km per hour and Innovation

Dep. var. =	Patents per capita		
	(1)	(2)	(3)
Panel A	**OLS**	**OLS**	**OLS**
Log Distance to Stations	-0.118***	-0.120***	-0.130***
	[0.037]	[0.036]	[0.038]
Average Night Light	0.568***	0.602***	0.582***
	[0.169]	[0.167]	[0.174]
Flight Passengers	0.565***	0.601***	0.414**
	[0.170]	[0.150]	[0.183]
R-squared	0.83	0.77	0.75
Panel B	**IV**	**IV**	**IV**
Log Distance to Stations	-0.242***	-0.210**	-0.202**
	[0.090]	[0.088]	[0.086]
Average Night Light	0.506***	0.560***	0.550***
	[0.171]	[0.164]	[0.172]
Flight Passengers	0.539***	0.572***	0.392**
	[0.173]	[0.158]	[0.190]
First-Stage F-stat	23.18	23.07	22.98
Sample Size	3141	3105	2988
City FE	Yes	Yes	Yes
Year FE	Yes	Yes	Yes
Sample	Full	Second and Third	Third

Notes: The dependent variable is the number of patents divided by population. Distance to HSR stations contains the straight line distance in meters from the most populous point of a city to the closest HSR station with a speed more than 200km per hour. Average night light data controls for the economic activity of a city. Flight passengers accounts for the effect of alternative transportation networks. We control for the average cropland area, the average land used for grazing and we include a dummy variable switching to 1 if the city belongs to a high technological zone. The variable distance to a HSR station has been transformed using the log transformation. Panel A contains the OLS results based on equation 1 and panel B the IV estimates based on equation 3. Clustered standard errors at the city level are reported in brackets.

Table A3.2: HSR and Innovation - Time Lags

Dep. var. =	Patents per capita				
	(1)	(2)	(3)	(4)	(5)
Panel A	**OLS**	**OLS**	**OLS**		
Lag 1 Log Distance to Stations	-0.118***				
	[0.034]				
Lag 2 Log Distance to Stations		-0.076***			
		[0.022]			
Lag 3 Log Distance to Stations			-0.112***		
			[0.025]		
Lag 4 Log Distance to Stations				-0.090***	
				[0.019]	
Lag 5 Log Distance to Stations					-0.087***
					[0.020]
R-squared	0.83	0.85	0.88	0.91	0.94
Panel B	**IV**	**IV**	**IV**		
Lag 1 Log Distance to Stations	-0.240***				
	[0.088]				
Lag 2 Log Distance to Stations		-0.145***			
		[0.055]			
Lag 3 Log Distance to Stations			-0.163***		
			[0.053]		
Lag 4 Log Distance to Stations				-0.156***	
				[0.046]	
Lag 5 Log Distance to Stations					-0.110***
					[0.037]
First-Stage F-stat	18.52	22.08	25.77	27.41	30.13
Sample Size	3141	2792	2443	2094	1745
City FE	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes
Sample	Full	Full	Full	Full	Full

Notes: The dependent variable is the number of patents divided by population. Distance to HSR stations contains the straight line distance in meters from the most populous point of a city to the closest HSR station with a speed more than 250km per hour. Average night light data controls for the economic activity of a city. Flight passengers accounts for the effect of alternative transportation networks. We control for the average cropland area, the average land used for grazing and we include a dummy variable switching to 1 if the city belongs to a high technological zone. The variable distance to a HSR station has been transformed using the log transformation. Panel A contains the OLS results based on equation 1 and panel B the IV estimates based on equation 3. Clustered standard errors at the city level are reported in brackets.

Table A3.3: HSR and Innovation - Weighted Inventions by their Citations in a 5 year window

Dep. var. =	Citations 5 year window per capita		
	(1)	(2)	(3)
Panel A	**OLS**	**OLS**	**OLS**
Log Distance to Stations	-0.093***	-0.087***	-0.076***
	[0.022]	[0.020]	[0.021]
Average Night Light	0.462***	0.464***	0.427***
	[0.116]	[0.105]	[0.109]
Flight Passengers	0.364**	0.314***	0.209*
	[0.167]	[0.084]	[0.112]
R-squared	0.89	0.83	0.80
Panel B	**IV**	**IV**	**IV**
Log Distance to Stations	-0.228***	-0.188***	-0.149**
	[0.074]	[0.064]	[0.062]
Average Night Light	0.391***	0.413***	0.392***
	[0.129]	[0.106]	[0.111]
Flight Passengers	0.338**	0.287***	0.191
	[0.165]	[0.088]	[0.117]
First-Stage F-stat	18.52	18.47	18.96
Sample Size	3141	3105	2988
City FE	Yes	Yes	Yes
Year FE	Yes	Yes	Yes
Sample	Full	Second and Third	Third

Notes: The dependent variable is the number of patents weighted by their number of citations within a 5 year window divided by population. Distance to HSR stations contains the straight line distance in meters from the most populous point of a city to the closest HSR station with a speed more than 250km per hour. Average night light data controls for the economic activity of a city. Flight passengers accounts for the effect of alternative transportation networks. We control for the average cropland area, the average land used for grazing and we include a dummy variable switching to 1 if the city belongs to a high technological zone. The variable distance to a HSR station has been transformed using the log transformation. Panel A contains the OLS results based on equation 1 and panel B the IV estimates based on equation 3. Clustered standard errors at the city level are reported in brackets.

Table A3.4: HSR and Innovation - Weighted Inventions by their Claims

Dep. var. =	Claims per capita		
	(1)	(2)	(3)
Panel A	**OLS**	**OLS**	**OLS**
Log Distance to Stations	-0.092***	-0.086***	-0.082***
	[0.023]	[0.021]	[0.023]
Average Night Light	0.444***	0.433***	0.406***
	[0.139]	[0.123]	[0.129]
Flight Passengers	0.381**	0.391***	0.282**
	[0.162]	[0.096]	[0.138]
R-squared	0.86	0.79	0.77
Panel B	**IV**	**IV**	**IV**
Log Distance to Stations	-0.177**	-0.142**	-0.123*
	[0.070]	[0.065]	[0.067]
Average Night Light	0.400***	0.405***	0.386***
	[0.152]	[0.127]	[0.135]
Flight Passengers	0.365**	0.376***	0.272*
	[0.160]	[0.101]	[0.145]
First-Stage F-stat	18.52	18.47	18.96
Sample Size	3141	3105	2988
City FE	Yes	Yes	Yes
Year FE	Yes	Yes	Yes
Sample	Full	Second and Third	Third

Notes: The dependent variable is the number of patents weighed by the number of claims divided by population. Distance to HSR stations contains the straight line distance in meters from the most populous point of a city to the closest HSR station with a speed more than 250km per hour. Average night light data controls for the economic activity of a city. Flight passengers accounts for the effect of alternative transportation networks. We control for the average cropland area, the average land used for grazing and we include a dummy variable switching to 1 if the city belongs to a high technological zone. The variable distance to a HSR station has been transformed using the log transformation. Panel A contains the OLS results based on equation 1 and panel B the IV estimates based on equation 3. Clustered standard errors at the city level are reported in brackets.

Table A3.5: Transportation cost and patent citations within a 5 year window - OLS

Dep. var. =	Cit5	Cit5 t+1	Cit5 t+2
	(1)	(2)	(3)
Log Transportation Cost	-0.0461	-0.0367	-0.0242
	[0.0316]	[0.0288]	[0.0214]
R-squared	0.85	0.90	0.94
Less than 250 km	-0.8916***	-0.6970***	-0.3543***
	[0.2357]	[0.1781]	[0.0994]
250-499 km	-0.3160***	-0.2642***	-0.1749***
	[0.1009]	[0.0899]	[0.0661]
500-749 km	-0.1223*	-0.1120*	-0.0905*
	[0.0666]	[0.0618]	[0.0468]
750-999 km	-0.0348	-0.0343	-0.0409
	[0.0693]	[0.0662]	[0.0540]
1000-1249 km	-0.2449	-0.1987	-0.1284
	[0.1579]	[0.1363]	[0.0904]
More than 1250 km	-0.0313	-0.0180	-0.0246
	[0.1936]	[0.1774]	[0.1336]
R-squared	0.85	0.90	0.94
Sample Size	1086804	1086804	1086804
City Origin x Destination FE	Yes	Yes	Yes
Destination FE x Year FE	Yes	Yes	Yes
Origin FE x Year FE	Yes	Yes	Yes

Notes: Gravity model based on equation 4 estimated with OLS and standard errors clustered at the origin and destination city. The dependent variable is the number of citations within a five year window. The total transportation cost is the total computed transportation cost using the HSR between each pair of cities.

4 Religiosity and Innovation in 19th Century France

4.1 Introduction

Anti-scientific views expressed by religious conservatives are still present in society even though we came a long way from science. These views are being promoted directly by religious leaders or indirectly through politics. During the recent Covid-19 pandemic, religious leaders convince their congregation not to receive the vaccine, because they claim that 'can cause homosexual tendencies' and it 'controls the mind' (Galang, 2021). In the recent past, religious conservatives were critical in the election of President Trump and Vice President Pence (81% of White Evangelicals voted for the ticket), both of whom have often expressed counter-scientific attitudes about climate change, evolution, vaccines and viruses (Benabou et al., 2021). But how can anti-scientific views affect societal progress and innovation? What are the consequences when these views are generalized in a community or a society? These are the questions to which this chapter seeks to contribute.

We focus on nineteenth-century Catholicism in France, during a crucial phase of modern economic growth, the Second Industrial Revolution. We aim at exploring the relationship between the the anti-scientific agenda of the Catholic Church and technological progress. During this period, Western economies began adopting transformative, skill-intensive technologies while the Catholic Church was promoting a conservative and anti-scientific program. Local clergymen opposed any modern medical advice or intervention, rejected the efforts of public authorities who tried to introduce vaccinations, and rebuffed doctors who recommended birth control. They were against the secularization and professionalization of the education system and the use of electricity in churches (Squicciarini, 2020; Lecce et al., 2021).

In this chapter we take advantage of a new legislation introduced on July 27th 1884, which reestablished divorce in France, to propose a novel proxy for religiosity, i.e., the number of divorces per capita. We are able to exploit time and geographical variation to construct a panel dataset at the department level with information about divorces and population from the Censuses (2011). We take advantage of the intense conflict between the Catholic Church and the advocates of the divorce law to argue that divorces are a suitable proxy to measure religiosity and the intensity of Catholicism in places. We are particularly interested in the intensity of Catholicism, which in turn determined the degree to which the Catholic anti-scientific agenda was observed at the local level (Squicciarini, 2020). In order to explore the impact of the anti-scientific views on technological progress, we built a novel database containing geo-referenced information for French inventions patented at United States Patent and Trademark Office (USPTO) over the period 1838-1960 (Petralia et al., 2016). We complement this information with local patenting information from the National Institute of Industrial Property (INPI) of France, and demographic information, including several measures of religiosity of places. Previous attempts using INPI historical data have focused mainly before the 1860 to determine the factors that drive innovation, like Nuvolari et al. (2020), Galvez-Behar (2019) and Khan (2016).

Anti-scientific views can deter progress. There is a growing literature connecting the anti-scientific agenda promoted by the Church with creativity and innovation. From a historical perspective, Squicciarini (2020) finds that the Catholicism's anti-scientific approach hampers diffusion of knowledge and economic development by slowing down the adoption of the technical curriculum and pushing for religious education. Lecce et al. (2021) present evidence that more religious cantons were less likely to give birth to scientists. However, the authors report that religiosity did not play a role for their migration choices. They find that the accumulation of scientific human capital earlier in life was a key mechanism. In a more recent time period, Wang and Wang (2021) explore the impact of major religions (Christianity, Judaism, Islam and Buddhism) on innovative activities globally. The authors report evidence that Christianity and Judaism reduce innovation, while in general, Buddhism and Irreligion increase innovation. They argue that there is no significant effect of Islam on innovation while Judaism has a negative impact, except for Catholics and Orthodox Judaism. Their research relies on the effect of different religions on R&D activities. Krause et al. (2021) study about monotheistic believers' thinking about God and creativity. The authors find that believers are less creative than non-believers and this effect is strengthened when they are actively thinking about God. Using the Word Values Survery, Benabou et al. (2015) find that greater religiosity is almost uniformly and very significantly associated to less favorable views of innovation. Finally, (Benabou et al., 2021) report a robust negative relationship between religiosity and the level of patents per capita.

The rest of the chapter is organized as follows. Section 4.2 contains the historical background and section 4.3 presents the data and the empirical strategy. Finally, section 4.4 presents the main results, whereas section 4.5 the robustness analysis and section 4.6 concludes.

4.2 Historical Background

4.2.1 National Patent Office - United States Patent Office

The French patent system is one of the oldest in the world. In 1791, Boufflers' bill became the first Patent Act in France. According to the law, there were three different categories for patenting: 1) Patents for invention, 2) Patents for improvement and 3) Patents for importation. The duration of the patent could be five, ten or fifteen years. However, their cost was prohibitive. Apart from the initial cost, several taxes were added during the examination process. More specifically, the cost of a five year patent was 300 francs, for a ten year patent 800 francs and for a fifteen year patent 1500 francs. In addition, there was an initial deposit with a cost of 50 francs (Nuvolari et al., 2020). Therefore, the patent system did not facilitate the spread of patents because a lot of inventors could not afford the high cost (Galvez-Behar, 2019).

However, a subsequent law introduced in 1844 contributed to the increase of the patenting. This legislation allowed the inventors to export their patents in foreign countries and changed the method of payment for the inventors. Even though the total cost of five and ten-year patents was increased, up to 500 and 1,000 francs respectively, the new act allowed patentees to spread the payment of the tax over the entire duration of their patent. Then, the cost of a patent was 100 francs each year. In addition, inventors could stop paying the tax whenever they wanted. Even though the new legislation managed to boost patent activity, it is possible that the effect was mainly driven by short-life patents, which were likely to be "junk" ones (Galvez-Behar, 2019).

The first U.S. copyright statute was approved on May 31, 1790, "for the encouragement of learning, by securing the copies of maps, charts, and books to the authors and proprietors of such copies, during the times therein mentioned." According to the regulation, the authors (broadly defined) were able to obtain copyright protection by registering their works and paying a nominal fee (Khan and Sokoloff, 2001).

In parallel, the first modification to the existing law which allowed the foreigners to register a patent in US took place in 1800. According to the new law, patent rights were extended to foreigners living in the United States for two years who could prove that the invention was new to the world. Still, the process for the foreigners was very complicated. A series of reforms started from 1832 aimed to change that situation. In 1832, the Patent Act allowed patents to resident aliens who intended to become citizens, provided that they introduced the invention into public. In 1836, the stipulations on citizenship or residency were removed, although in fact they were replaced with extremely high patent fees. Nonresident foreigners could obtain a patent in the United States for a fee of $300, or even $500 if they were British. The patent laws that stipulated discriminatory treatment of foreign nonresidents were repealed in 1861, and utility patent rights were available to all applicants on the same basis without regard of the nationality (Khan, 2013).

The cost of patenting in US was $30 from 1793 to 1861. In that year, they were raised to $35, and the term was changed from fourteen years (with the possibility of an extension) to seventeen years (with no extensions) (Khan and Sokoloff, 2004). According to the Historical currency converter, the 35 US dollar in 1861 could buy 53.62 grams of gold which corresponds to 188 French francs.[45] As a result, the fee for obtaining a patent in US was more expensive than a patent in France for the first year without taking into consideration potential transaction costs.

4.2.2 Divorces and the Catholic Church

In this section we aim at shedding light on why we consider that the number of divorces could be a good proxy for religiosity.

The first divorce law was introduced the 20th of September of 1792, during the period of the French Revolution. The Revolution came as a result of the failure of the the existing regime to deal with the combination of social, political and economic factors. The Revolution was responsible for the massive shift of power from the Catholic Church to the state. In May 1789, widespread social distress led to the creation of the National Assembly, which passed a series of radical measures, including the abolition of feudalism, state control of the Catholic Church and extending the right to vote. The Revolution, committed to preserve the rights of the individuals and its antipathy to Roman Catholicism, promoted a law about divorces that was affordable even to poor people and it was not based on any double stan-

[45]The Historical currency converter (www.historicalstatistics.org/Currencyconverter.html, accessed in December of 2021) was developed by Rodney Edvinsson, Associate professor of Stockholm University.

dard of sexual morality that would have put women at a disadvantage. In addition, the law justified divorce for a specific cause, such as immorality, cruelty, insanity, condemnation for certain crimes, desertion for at least two years, or emigration.

In the following years, divorce became much more difficult to obtain. A series of measure reinforced the patriarchal authority of the family and they drastically reduced the number of divorces. In 1816, with the return of the monarchy to France, divorce was abolished entirely. Under Louis XVII, Roman Catholicism became once again the state religion, and judicial separation became the only option for unhappy couples. However, even this restricted form of divorce was unacceptable to the Catholic church (McBride, 1992).

The conflict between the Catholic Church and the advocates of the divorce revived in 1880 with the establishment of the Third Republic. Between 1875 and 1884, Alfred Naquet, a former radical socialist and deputy from the Vaucluse, as well as other supporters of the new law about divorces planned conferences in towns throughout France. During these conferences they were explaining the need for a new divorce law. The reaction of the Catholic Church to these conferences was instantaneous. An example of the reaction is the speech of Charles Freppel, Bishop of Angers. In his speech, Freppel referred to the divorce as a "grave attack on Christian civilization," and called the divorce law "anti-French," "anti-Catholic," and a "Semitic campaign" (McBride, 1992). According to the American historian Gordon Wright, it was the "last religious war" between the clerics and the anti-clerics (Wright, 1987).

In 1876, Naquet attempted to introduce a divorce law like the one in 1792. However, the deputies refused even to form a committee to discuss it. After several attempts, the new law passed on July 27 1884, with a more conservative format than the one in 1792, because there were still Catholics whose moral consciences did not permit them to divorce and legislators' reluctance to render divorce too easily (McBride, 1992).

4.2.3 Catholicism and Science

The Catholic Church was not always against scientific progress, but had a positive although complex attitude toward scientific and technological progress (Squicciarini, 2020). However, everything changed dramatically after the French Revolution.

Two major events contributed to this rapid change. The first one was the French invasion of Italy in 1796. As a result, Rome introduces a serious anti-modern and anti-scientific agenda: all French laws and norms were abolished, and science was accused of the revolutionary events. Quickly, the conservative program of the Church in Rome spread in France. The second event which exacerbated the conflict between the Church and science was the unstable relationship between Napoleon and Pope Pius VII. These two events triggered the culture conflict between supporters of the traditional order, embodied in the Catholic Church, and advocates of the new order, who promoted secular and scientific point of view (Squicciarini, 2020).

The effect of the anti-scientific agenda of the Catholic Church started to appear during the Bourbon Restoration (1815–1830). As an example in the medical sector, local clergymen opposed any modern medical advice or intervention, rejected the efforts of public authorities who tried to introduce vaccinations, and rebuffed doctors who recommended birth control (Squicciarini, 2020). In the case of education, the production of religious books rose sharply (from 300 to 600 per year) and the scientific instruction that many clergy members had acquired in the pre-revolutionary period was replaced by religious texts (Minois, 1991; Jacob, 2014).

During the central decades of the 19th century (1833–1870), the conflict between science and religion remained stable, and was only present in political, social, and educational contexts (Lecce et al., 2021). In the last years of the Second Empire (1866–1870) and after the facts of the Third Republic (1870), the situation between the Church and science exacerbated as a consequence of the adoption of an anticlerical agenda by the Republican government, which gradually undermined the role of the Church in French society and reached its peak in the Jules Ferry Laws. The Jules Ferry Laws are a set of French laws which made education free and mandatory (Lecce et al., 2021). Thus, the history of 19th century France is a history of constant confrontation between the Catholic Church and scientific progress.

4.3 Data and Empirical Strategy

4.3.1 Historical INPI database

The historical database of INPI contains all the patent applications (409,324 applications with their additions) covering the period 1791-1902. The database includes the application number of the patents, the filing year, the name of the applicant(s), the commune, the street and number of the applicant(s), the title of the patents and the expiration date of the patent applications.[46] Additional details are included in the database, like the number of additions (small improvements based on the initial design of a patent application) of every patent application and, in some cases, the profession of the applicant.

We remove applications that belong only to firms using key words.[47] Next, we exclude applications without a filing date, 116 in total. In addition, when one application has several improvements, we do not take into account the improvements, but only the initial design. We end up with 308,926 patent applications over the entire period. With this information, we construct our main dependent variable as the sum of the patents for every year from 1885 to 1897 at the department level.

4.3.2 Historical USPTO database

We build a novel database containing geographical information of patents granted by the USPTO to French residents in the period 1838-1960. To do so, we modify the original algorithm used to construct the Histpat database (Petralia et al., 2016) to identify French locations in patent documents.[48] Since the number of observations were not too high, we manually filled in the missing values when the algorithm identified that a patent was from France but could not identify the place of precedence within France. After doing so, we applied geo-coding techniques as in Zeigermann (2018) to harmonize the name of the French communes over this time period.[49]

For every patent, the algorithm returns the name of the commune where the patent is registered. The location of the patent is determined by the location of the inventor or the location of the assignee.[50] However, on several occasions, the commune name is not enough for the determination of the location of the patents because some of the communes' names are similar or even exactly the same. For these locations, the name of the department is also required. For the patents that are registered to communes that suffer from this problem, we proceed by reporting manually from the patent documents the name of the department. When the location of the inventor cannot be determined (many communes with the same name and no information

[46] This information is available only until 1844 and the reform

[47] We exclude all the applications that have the words "COMPAN", "COMPAGNI", "SOCIETA", "SOCIET", "GESELLSCHAFT", "SYNDICAT", "GESELLSCHAF" and "MANUFACTUR" in the applicant name.

[48] Refer to the original paper for detailed description of the algorithm.

[49] Communes are the cities in the case of France.

[50] The owner of the patent could be "Inventor" or "Assignee". Assignee corresponds to a firm.

about the department), we check which of the communes are more close to the location of the assignee, if there is an assignee, and we report this as a location. If a given patent i suffers from all the problems mentioned above and there is not any information about the assignee, we search for the name of the inventor in the google patents database. We do so because it is possible to locate the inventor based on another patent document that was filled in during the same year or a close one to that of the given patent i. If there is not any additional information that could help us to identify unequally the location of the inventor, we report the name of the commune found by the geo-coding.

As a robustness check, we check manually the name of the communes which appear only once or twice in the database. The probability of these names to be wrong is higher as they appear only few times in the database. We find that sometimes the algorithm reports the name of the inventor as a commune especially when the surname of the inventor is Franco, France, or Francois. Most of these times, the patent is not even from France, so that we exclude them.

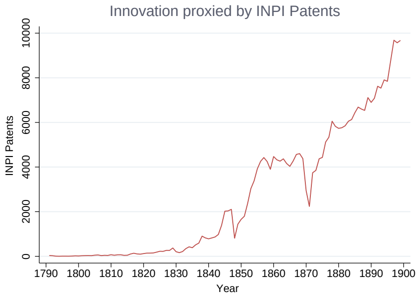
The database consists of a unique publication number for every patent, details regarding the owner of the patent, the name of the city in which the owner of the patent lived, the year the patent was granted and the name and surname of the owner of the patent. Like in the case of INPI patents, we compute the sum of the patents for every year from 1885 until 1897 at the department level.

Figure 4.1 presents the evolution of innovation through time as by INPI and USPTO patents owned by inventors. The drop in 1870 is due to the Franco-Prussian War. As it can be observed, one major difference in these two databases is the different level of total number of patents, much higher in the INPI. Overall, both graphs present a similar evolution, with a general upward trend.

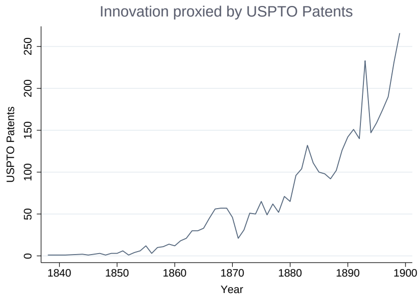
4.3.3 Divorces

We rely on the census data processed by INSEE (Censuses, 2011) to extract information about the number of divorces in each French department for the period 1885-1897. The data are available for every year. Figure 4.2 presents the number of divorces per 10,000 inhabitants for the French departments in 1885, 1890 and 1895. Given that 98 percent of the French population was Catholic (Squicciarini, 2020), this variable would not offer variability enough in the space. Therefore we use divorces as a proxy for religiosity because it is important that our measure to

Figure 4.1: Innovation through time



(a) INPI

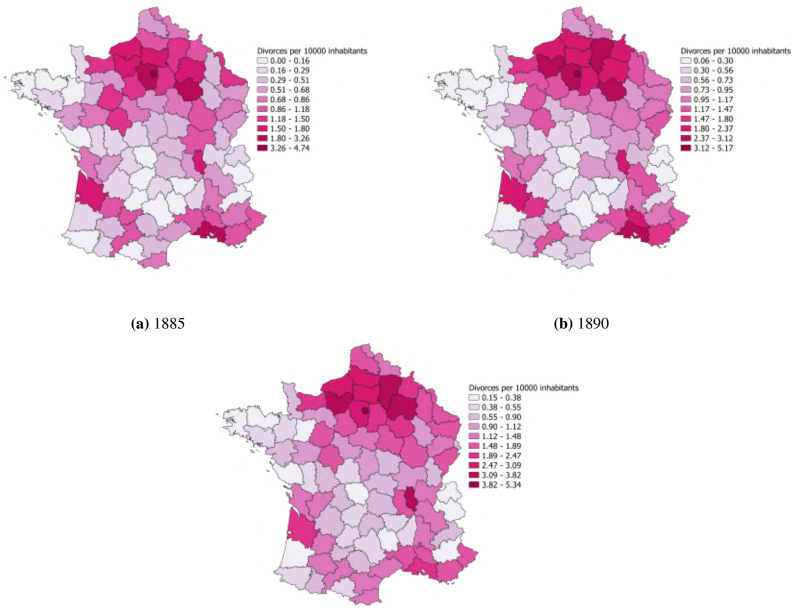


(b) USPTO

Notes: These figures show the evolution of innovation through time in 19th century France. Figure (a) proxies innovation with INPI patents and Figure (b) with USPTO patents.

capture regional variation among the French departments.

Figure 4.2: Divorces per 10,000 inhabitants



(a) 1885 **(b)** 1890

(c) 1895

Notes: This figure shows the divorces per 10,000 inhabitants for the departments of France for the years 1885, 1890 and 1895.

4.3.4 Control Variables

We collect the rest of the control variables, number of marriages and population, from the Census (Censuses, 2011). We have annual data for the variable marriages and the variable divorces. However, population is available in five year intervals, so that we use linear interpolation to overcome this limitation. In the robustness section of this chapter, we report evidence that our benchmark results hold even if we do not use linear interpolation. We complement the data with the share of refractory clergy in 1790 (Squicciarini, 2020), in a cross section analysis, and we compare our proxy of religiosity with a measure that has been already used in previous literature. Table 4.1 reports summary statistics for our variables in the panel and cross section models. The USPTO Patents 1874-1886 and USPTO Patents 1874-1886 per 10000 inhabitants as well as the variables for the cross section model are used during the robustness analysis.

4.3.5 Empirical Strategy

In this section we present our empirical strategy. We apply a fixed-effects panel model. More specifically,

Table 4.1: Summary statistics

Variable	Obs	Mean	Std. Dev.	Min	Max
Panel Analysis					
INPI Patents	1118	92.017	723.953	0	8462
INPI Patents per 10000 inhabitants	1118	0.527	2.252	0	25.101
USPTO Patents	1118	1.934	13.703	0	189
USPTO Patents per 10000 inhabitants	1118	0.014	0.046	0	0.553
USPTO Patents 1874-1886	1118	0.943	7.125	0	90
USPTO Patents 1874-1886 per 10000 inhabitants	1118	0.007	0.028	0	0.311
Divorces per 10000 inhabitants	1118	1.087	0.886	0	5.911
Divorces per marriages	1118	0.015	0.012	0	0.068
Population	1118	443055.7	369615.9	79758	3420082
Marriages per 10000 inhabitants	1118	71.81	5.649	52.36	93.141
Cross Section Analysis					
INPI Patents per 10000 inhabitants	82	0.537	2.299	0.035	20.814
USPTO Patents per 10000 inhabitants	82	0.014	0.043	0	0.38
Divorces per 10000 inhabitants	82	1.105	0.822	0.092	4.747
Population	82	451654.5	376999.7	116242.4	3185628
Marriages per 10000 inhabitants	82	0.007	0	0.006	0.009
Share Refractory Clergy	82	0.425	0.229	0.04	0.875

$$Y_{it} = \alpha_0 + \beta DivPC_{it-2} + \gamma_i + \delta_t + \zeta X_{it-2} + \epsilon_{it} \tag{1}$$

where Y_{it} is the dependent variable which can be either the number of patents or the number of patents per capita in a department i, in time period t.[51] The main variable of interest is $DivPC_{it-1}$, which contains the number of divorces per capita in a department as computed in the previous period. We include department fixed effects, γ_i, and year fixed effects, δ_t. X_{it} contains the controls at the department level, such as the population and number of marriages per capita. We lag all our variables by two years as an attempt to reduce reverse causality and we cluster the standard errors at the department level.

4.4 Results

Table 4.2 explores the effect of anti-scientific attitudes proxied by the religiosity of the place on innovation proxied by the number of patents in INPI database. For interpretation reasons we have re-scaled all our variables to have a mean of 0 and a standard deviation of 1. We find that the divorces per capita as a proxy for religiosity has no effect on the invention rate proxied by patents in INPI database, column 1. The same applies when we use the patents per capita as a dependent variable in

[51] The dependent variable could be either the patents from INPI database or USPTO database.

column 2. Our results show that only population has a positive effect on innovation activity, in line with prior literature.

Table 4.2: Religiosity and INPI Patents

Dep. var. =	INPI Patents	INPI Patents p.c.
	(1)	(2)
Divorces p.c.	0.025	0.007
	[0.021]	[0.018]
Population	2.903***	2.065***
	[0.862]	[0.615]
Marriages p.c.	-0.008	-0.009
	[0.012]	[0.010]
Within R-squared	0.69	0.58
Between R-squared	0.67	0.69
Overall R-squared	0.67	0.68
Sample Size	1118	1118
Department FE	Yes	Yes
Year FE	Yes	Yes

Notes: OLS results based on equation 1. Clustered standard errors at the department level are reported in parentheses.

Next, we report the results of religiosity on patenting proxied by USPTO patents. In contrast to Table 4.2, we find a strong positive effect of divorces per capita on innovation in Table 4.3. According to panel A, we find that one standard deviation increase in the number of divorces per capita results into an increase of 1.093 standard deviations in the USPTO patents according to column 1 and an increase of 0.128 standard deviations on the patents per capita according to column 2. The positive relationship between our main variable of interest and the dependent variable means that less religious departments (departments with a higher number of divorces per capita) experience higher levels of innovation activity, both in absolute and in per capita terms.

In Panel B we exclude the Seine department, where Paris is located, and we observe a significant drop in the magnitude of the coefficients. The crucial information in panel B is that our results hold, meaning that the effect is not only driven by the Seine department.

One explanation for the different results we obtain when we use the INPI and the USPTO patent databases is the reform of 1844. As we already mentioned in the historical background section, the reform introduced in 1844 reduced the cost for a patent application in INPI database to 100 francs per year. As a result, this re-

Table 4.3: Religiosity and USPTO Patents

Dep. var. =	USPTO Patents	USPTO Patents p.c.
	(1)	(2)
Panel A	**Full Sample**	**Full Sample**
Divorces p.c.	1.093*	0.128***
	[0.601]	[0.042]
Population	61.841***	3.151***
	[14.720]	[0.533]
Marriages p.c.	-0.052	-0.023
	[0.210]	[0.016]
Within R-squared	0.57	0.22
Between R-squared	0.69	0.71
Overall R-squared	0.65	0.60
Sample Size	1118	1118
Panel B	**No Seine**	**No Seine**
Divorces p.c.	0.249*	0.095**
	[0.127]	[0.040]
Population	11.268***	1.416*
	[3.691]	[0.795]
Marriages p.c.	-0.039	-0.025*
	[0.039]	[0.013]
Within R-squared	0.14	0.06
Between R-squared	0.38	0.18
Overall R-squared	0.22	0.07
Sample Size	1105	1105
Department FE	Yes	Yes
Year FE	Yes	Yes

Notes: OLS results based on equation 1. Clustered standard errors at the department level are reported in the parenthesis.

form boosted short-life patents, which were likely to be “junk” ones (Galvez-Behar, 2019). In addition, from 1844, the patents were delivered without any governmental guarantee and even without any governmental serious regard. Given that, we believe that USPTO database captures better inventions that were meaningful for technological progress.

4.5 Robustness Analysis

4.5.1 Falsification Test

In this section, we regress past USPTO patents on future changes in the number of divorces per capita. This exercise allows us to explore if our model captures some long-run common causal factor behind both the number of divorces and USPTO patent activity (Dix-Carneiro et al., 2018; Autor et al., 2013). As we mention in the historical background section, before 1836 it was not possible for a French citizen to apply for a USPTO patent. In addition, from 1816 until 1884, there was not any law on divorces. However, given that Alfred Naquet started his campaign around 1874, our concerns focus basically on the period before the establishment of the law in 1884.

To further mitigate these concerns, Table 4.4 presents the results of the regression of future divorces per capita on USPTO patents from 1874-1886, in absolute and per capita terms. In both cases, the coefficient is negative and non-significant, meaning that our model is not associated with pre-trends regarding the patent activity, at least in the years immediately prior to the sample period.

Table 4.4: Religiosity and USPTO Patents - Falsification Test

Dep. var. =	USPTO Patents 1874-1886	USPTO Patents p.c. 1874-1886
	(1)	(2)
Future Divorces p.c.	-0.027	-0.014
	[0.062]	[0.079]
Within R-squared	0.48	0.14
Between R-squared	0.67	0.68
Overall R-squared	0.64	0.57
Sample Size	1118	1118
Department FE	Yes	Yes
Year FE	Yes	Yes
Controls	Yes	Yes

Notes: OLS results based on equation 1. Clustered standard errors at the department level are reported in the parentheses.

4.5.2 Share of Refractory Clergy

The analysis performed in this section aims at comparing our proxy for anti-scientific attitude, which is based on religiosity in the 19th century, with the share of refractory clergy in 1790. The latter measure was used also as a proxy for reliogiosity in Squicciarini (2020). Therefore, in this subsection we replicate her empirical framework in order to understand if our results are in line with other measures already used in previous studies. In such paper, the author explores the effect of the share of refractory clergy in 1790 on the share of industry workers in 1901 and machines per capita in 1891. By doing that, she reports solid evidence that religiosity is negatively associated with economic development. Since the author uses machines per capita as the dependent variable, we treat our dependent variable in a similar way and we use patents per capita. Before we go into the detail of the results, we have to acknowledge specific data limitations as we do not possess the same control variables as in Squicciarini (2020). From the controls that this paper uses, we only have population, which we include in the regression model.

We proceed by taking the average value of our main variables over the period 1885-1897 and we restrict the sample to the 82 departments in both datasets.[52] We estimate by OLS the following cross section equation,

$$PatPC_i = \alpha_0 + \beta M_i + \zeta X_i + \epsilon_i \tag{2}$$

where the dependent variable, $PatPC_i$ could be the number of INPI or USPTO patents per capita and the main independent variable, M_i, the number of divorces per capita or the share of refractory clergy. X_i includes the same control variables as in equation 1. We cluster the standard errors at the department level.

Table 4.5 presents the results. In column 1 and 2 we explore the effect of divorces per capita on patents per capita. In line with the benchmark analysis, we also find a stronger effect of the number of divorces per capita on USPTO patents. Moving to column 3 and 4, we find a negative and significant impact of the share of refractory clergy on patents per capita. The negative effect means that departments with a high level of religiosity are associated with low levels of inventive activity. Similarly to the case of using the proxy of divorces per capita, the share of refractory clergy has a stronger effect in the case of considering USPTO patents.

[52] In 1790, there were only 83 departments. The number of departments changed in 1876 because of the Franco-Prussian War.

Table 4.5: Religiosity and Innovation per capita - Replication Test

Dep. var. =	INPI Patents p.c.	USPTO Patents p.c.	INPI Patents p.c.	USPTO Patents p.c.
	(1)	(2)	(3)	(4)
Divorces p.c.	0.169*	0.242***		
	[0.095]	[0.089]		
Share Refractory Clergy			-0.177**	-0.209***
			[0.074]	[0.070]
R-squared	0.73	0.77	0.73	0.76
Sample Size	82	82	82	82
Controls	Yes	Yes	Yes	Yes

Notes: OLS cross section results based on equation 2. Clustered standard errors at the department level are reported in the parenthesis.

4.5.3 Population without Linear Interpolation

In this section, we provide some additional findings without using linear interpolation for the variable population. We replicate the estimation of model 1, but this time we do not include population as a control variable and we divide the number of patents, divorces and marriages for the years 1885 to 1889 over population in 1885, for the years 1890 to 1894 over population in 1890 and for the years 1895 to 1897 over population in 1895. Table 4.6 summarizes the results.

Table 4.6: Religiosity and Innovation per capita - Without Linear Interpolation

Dep. var. =	INPI Patents p.c.	USPTO Patents p.c.
	(1)	(2)
Divorces p.c.	0.065	0.233*
	[0.071]	[0.124]
Marriages p.c.	-0.001	-0.008
	[0.003]	[0.017]
Within R-squared	0.03	0.07
Between R-squared	0.30	0.37
Overall R-squared	0.27	0.29
Sample Size	1118	1118
Department FE	Yes	Yes
Year FE	Yes	Yes

Notes: OLS results based on equation 1. Clustered standard errors at the department level are reported in the parentheses.

Again, we report evidence that divorces per capita has an effect on USPTO patents per capita, in line with our benchmark results. Main conclusions are, therefore, maintained.

4.5.4 Divorces per marriages

As a last robustness check, as a proxy for religiosity we use the number of divorces per marriage instead of divorces per capita, and estimate the model in 1 with this new proxy. Table 4.7 presents our findings.

Table 4.7: Religiosity and Innovation - Divorces per marriages

Dep. var. =	INPI Patents	INPI Patents p.c.	USPTO Patents	USPTO Patents p.c.
	(1)	(2)	(3)	(4)
Divorces p.m.	0.017	0.002	0.820*	0.116***
	[0.020]	[0.017]	[0.490]	[0.039]
Population	2.832***	2.066***	62.387***	3.192***
	[0.841]	[0.617]	[15.078]	[0.555]
Within R-squared	0.68	0.57	0.57	0.22
Between R-squared	0.67	0.69	0.69	0.71
Overall R-squared	0.67	0.68	0.65	0.59
Sample Size	1118	1118	1118	1118
Department FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes

Notes: OLS results based on equation 1. Clustered standard errors at the department level are reported in parentheses.

In line with the results we report in Table 4.2, we find an effect only for innovation proxied by USPTO patents, in columns 3 and 4, whereas the coefficients in the case of INPI patents are non-significant.

4.6 Concluding Remarks and Next Steps

This chapter exploits an episode from French history, the establishment of a law on divorces, to study the relationship between anti-scientific attitudes and technological progress, a question which is relevant still today. 19th century France constitutes an interesting case study in that perspective. It is a country that experienced a great conflict between the Catholic Church and the political powers that were trying to promote technological progress.

A main value added of this chapter consists of the construction of the dataset needed to analyze the main question in mind. We combine data of two unique patent databases to answer our questions. Our preliminary results suggest that religiosity, proxied by the number of divorces per capita, has an adverse effect on patenting activity proxied with USPTO patents registered by French inventors residing in France. In addition, we do not find evidence when we use the domestic patents from the INPI database.

Despite the evidence provided in this chapter is interesting enough, there are several improvements that should be taken fully consideration in the near future. First, we are planning to further explore the effect of religiosity on innovation at a different territorial level. We will make use of time variant arrondissement level data which are available for both divorces and marriages but also for innovation. France had approximately 300 arrondissements during the 19th century.

In addition, we will make a step further by shedding light on the type of innovations that the Catholic Church was trying to slow down. Our analysis will be able to reveal which technological sectors were affected the most by religiosity by exploiting the advantage of the technological classes provided in patent data documents and the profession of the inventors. By doing this, we aim to provide the first empirical evidence that the Catholic Church wanted to hamper progress in the medical sector, the professionalization in general, and the use of technologies related to electricity. Examples of inventions that the Catholic Church was against were the bicycle, as it was representing "dangerous instrument of female emancipation", as well as electric lamps, because they could cause "theatrical effects" (Minois, 1991).

Last but not least, we plan to make an additional step into exploring the underlying mechanisms behind our main results. Our preliminary results suggest a stronger effect in the case of using USPTO inventions comparing to INPI inventions. We believe that this is due to the fact that USPTO patents capture, with higher precision, the ideas that are related to economic and technological progress. The places less affected by the anti-scientific agenda of the Catholic Church were able to diffuse the ideas that are crucial for economic development more easily (Heldring et al., 2021).

5 Concluding Remarks

5.1 Summary of findings and key lessons

The idea that innovation is at the heart of economic growth goes back as far as Schumpeter (1942). Over the years, theoretical and empirical literatures have incorporated Schumpeter's ideas and confirmed the relationship between innovation and economic growth (Aghion and Howitt, 1992; Grossman and Helpman, 1991; Akcigit et al., 2017). The key actors in the center of this process are the inventors. Inventors build their knowledge over time by interacting with others and learning from them. There are several places where inventors can acquire new knowledge like universities, companies and other research institutions and a variety of events in which they can participate, like international conferences, seminars or even a coffee room (Akcigit et al., 2018). Despite all these opportunities, recent literature has shown that there is a growth slowdown because the generation and exchange of new ideas is becoming more costly (Kortum, 1993; Griliches, 1994; Kogan et al., 2017; Bloom et al., 2020).

This Ph.D. thesis provided new empirical findings of the effect of transportation networks and religiosity on innovation performance from a historical and a recent perspectives. In doing so, it sheds light on the underlying mechanisms related to knowledge spillovers behind the main results. Specifically, it provides consistent evidence that higher connectivity can reduce the cost of exchanging ideas. New inventions are more likely to emerge with the stimulation of the flow of ideas. With this taken into consideration, Chapter 2 studies the effect of railroads in 19th century France on technological progress. Chapter 3 documents that the roll-out of the high speed rail in China fosters innovation activity. Whereas finally, Chapter 4 explores the impact of anti-scientific opinions, promoted by the Catholic Church, on the invention rate of 19th century France.

Throughout this Ph.D. thesis, we contribute with the creation of unique databases, specifically tailored for the purposes of this dissertation. For the second chapter, we merge the historical patent database of the French National Institute of Industrial Property (INPI) with a brand new database of rail stations during the 19th century France at the canton level (Mimeur et al., 2018). We complement this dataset with the extraction of geographical controls from raster files, the digitization of historical maps of navigable waterways, the geo-location of universities and the use of historical data about the location of the post offices (Verdier and Chalonge, 2018). For the third chapter, we create a new dataset based on the unique disambiguated Chinese patent database of CNIPA (2017, edition) (Yin et al., 2020) and we match it with the distance to HSR stations at the city level. We complement these data with a historical instrument based on the location of the couriers' routes and stations during Ming dynasty (Li, 2016; World Map, 2011). We further build other geographical controls, such as the accessibility of a city to an airport (CAAC, 2021) and we identify the Chinese cities that belong to high technological zones. Last but not least, for the fourth chapter, we collect historical data about divorces, marriages and population from the Census of France, (Censuses, 2011), and we merge them with the historical American patent database for the French inventors residing in France.

Chapter 2, *"Transportation Networks and the Rise of the Knowledge Economy in 19th Century France"*, focuses on the impact of the expansion of railroads on the rise of the knowledge economy in 19th century France. This chapter provides solid evidence that rail stations work as gates providing access to the network for the citizens of France. This chapter contributes to the prior literature by showing that for a given canton, the access to the network is crucial as it leads to higher connectivity with other cantons inhabited by inventors. The increase in the connectivity of a given canton translates into a higher number of inventions. In addition, inventors that reside in places with a strong connection to the global city of Paris, via the transportation network, have a high probability to innovate in a new technology. The intuition is that Paris can work as a gatekeeper of knowledge that connects the national innovation systems to global innovation networks. A time variant instrumental variable approach is used, based on the three different French rail plans to tackle any endogeneity concerns. Finally, the findings are robust to several robustness exercises such as Poisson regressions, a difference-in-differences approach, a falsification test and an inconsequential units approach.

Chapter 3, *"Rails and innovation: Evidence from China"*, establishes a relationship between the roll-out of the HSR network and patenting activity in China. We apply a novel historical instrument based on courier's routes and stations during Ming dynasty to create exogenous variation for our main independent variable and to provide causal evidence showing that the opening of a HSR station is associated with the increase of innovation performance at the city level. In a second stage, we argue that cities are more likely to develop comparative advantage in a new technology after increasing its connectivity, via HSR network, with other cities already specialized in that technology. We complement these findings with gravity equations using cross city co-applications and patent citations. Our results from the gravity equations reveal that the diffusion process is mainly driven from the cities that are within the threshold of 750 kilometers. Again, our benchmark analysis is robust to a battery of robustness tests such as a difference-in-differences approach, a placebo test and additional controls regarding the historical era of our instrument.

In Chapter 4, *"Religiosity and Innovation in 19th Century France"*, we investigate the relationship between religiosity and technological progress. We take advantage of a law that re-established divorces in 1884 to propose the number of divorces per capita as a novel proxy for religiosity. Our variable allows us, for the first time, to create a panel dataset and to explore variation between departments over time. Our results provide evidence of a negative effect of the anti-scientific agenda, proxied by religiosity, on innovation performance, proxied by USPTO patents. The findings are robust to a falsification test and comparable with prior results in the literature.

Three key lessons arose from this Ph.D. thesis. First, transportation projects are important determinants of innovation performance and knowledge diffusion. According to Chapter 2, connecting places that are inhabited by inventors has a positive effect on innovation performance. Chapter 3 complements these findings by showing that transportation connectivity fosters technological specialization and diffusion linkages such as cross city patent citations and co-applications. The findings of chapter 3, in a sense, justify the enormous amounts of money invested by the Chinese government to achieve economic growth and prosperity.[53] Finally, Chapter 4 presents evidence that religiosity can hamper technological progress when an anti scientific agenda is being promoted by the Church. A recent example of this refer to the way that religious leaders acted during the Covid-19 pandemic when they convinced their congregation not to receive the vaccine (Galang, 2021).

5.2 Policy implications and limitations

Top wage shares not just recovered from the World War II shock in the late 1960s, but they are now even higher than before World War II. The increase in top wages leaded to an increase in the top income shares in the last decades (Piketty and Saez,

[53] The state planned to spend $300 billion to build a 25,000 km HSR network by 2020. Source: Environmental and energy study institute, 2018.

2003). High skilled people receive top wages, like inventors (Aghion et al., 2019), and they are disproportionately concentrated in big cities. This unequal distribution of people with skills in space tend to create regional inequalities between star cities and places lagging behind (Rodriguez-Pose, 2018).

In the last decades, several policy plans have been applied to Europe, such as Lisbon Strategy 2000 and Europe 2020, with the purpose to reducing the regional disparities between places that are left behind and star cities (Iammarino et al., 2019). The Lisbon Agenda and the Europe 2020 Strategy focused on making Europe the world's leading innovation economy. Both plans aimed to create the appropriate circumstances for every region to start to specialise in knowledge-related sectors (McCann and Ortega-Argilés, 2015). The plans support several policies such as the 3% RD-based innovation policy for the small and medium-sized enterprises, the promotion of efficient connectivity and infrastructure improvements, and the establishment of good institutions (Hervás-Oliver et al., 2021; Iammarino et al., 2019).[54]

The findings of chapter 2 and 3 add to the ongoing debate regarding the efficiency of the transportation projects and to what extent are capable to reduce the regional inequalities among urban and rural areas. We find that transportation networks can trigger technological progress. The results hold even when we exclude from the sample all the big cities, meaning that also the small and medium size cities are getting benefited from the transportation connectivity. These findings support the intuition that the investments in efficient and meaningful transportation projects (Crescenzi et al., 2016) can spur the knowledge diffusion process. Knowledge diffusion can contribute to the reduction of inequalities among mega cities and places that are left behind (Rodriguez-Pose, 2018; Balland et al., 2020).

However, there is literature that rises concerns regarding the impact of transportation connectivity. An increase in connectivity is not always translated into more jobs, greater productivity or economic growth (Crescenzi and Rodríguez-Pose, 2012). Transportation networks may also lead to further inequality and concentration of economic resources as they contribute to channel physical and human capital and resources to the more dynamic cities (Glaeser, 2011; Iammarino et al., 2019). For instance, a HSR line between two very unequal territories often reinforces centralisation (Puga, 2002).

We believe that it is important to acknowledge specific limitations of the empiri-

[54]The 3% RD-based innovation policy for the small and medium-sized enterprises it is a policy documenting that 3% of the EU's GDP should be invested in RD (European Commission, 2010).

cal analysis in chapters 2 and 3. Given the nature of the empirical setting, we are not able to draw conclusions regarding the degree of centralization that it is been promoted by the transportation networks. It is true that the increase in connectivity facilitates the movements of economic resources from small cities to star cities. To illustrate an example: small cities may experience a marginal increase in their invention rate while star cities, like Paris, an enormous growth in their invention rate. Future research could contribute to the literature on innovation and inequalities by finding a way to include these two opposite effects in the same empirical model. In addition, in Chapter 2, due to data limitations, we were not able to further explore if the relationship between access to knowledge and innovation is driven by knowledge spillovers created through collaborations or through competition among inventors. Finally, we have to acknowledge the fact that China and 19th century France are unique case studies, for different reasons, and possibly it is not safe to generalize the results. In the case of China, HSR is a particular case of infrastructure network which is not accessible to everyone (Dobruszkes et al., 2022). Recent evidence suggests that HSR is more likely to be used by specific social groups, such as men in their thirties to fifties, with high income, high occupational position and high educational level (Dobruszkes et al., 2022). In the case of France, we have to highlight that it is a historical setting and railroads as a major invention was the dominant network of transportation. To what extent the same applies to a recent time period is an open question.

The preliminary findings of chapter 4 suggest that places which were less affected by the anti-scientific agenda of religious institutions experience a higher increase in the ideas more closely related to economic and technological progress. We believe that the inventors located in these places get benefited from the institutional setting which stimulates the flow of crucial ideas. In terms of policy, the findings of this paper confirm that institutions shape changes in productivity to a considerable extent (Rodriguez-Pose and Ganau, 2022). Good institutions can ameliorate the opportunities for small firms to survive and to compete against the technological giants without changing their location in order to attract more costumers. This fact will reduce the concentration and clustering of firms in super star cities (Feldman et al., 2021).

Last but not least, additional research is needed regarding the mechanisms in Chapter 4 on how anti-scientific agenda, promoted by the Catholic Church, hampers technological progress and knowledge diffusion.

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