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Document de Travail n° 2026 – 22

Juin 2026

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Networks of Change: Infrastructure and Steam Diffusion in 19th-Century France

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Tuesday 23rd June, 2026

Abstract

This paper examines how transport infrastructure shaped the diffusion of steam power across French departments between 1840 and 1911. Using a newly constructed annual departmental panel of steam engine stocks, firms, and installed horsepower, we reconstruct regional diffusion trajectories and estimate the causal impact of transport connectivity on mechanization. We combine department and year fixed effects with an instrumental-variable strategy based on successive French railway planning laws to address the endogeneity of railway expansion. The results reveal substantial territorial heterogeneity in the timing and speed of adoption, indicating that industrialization unfolded unevenly across space. Railway expansion exerted a positive and increasingly strong effect on steam adoption from the mid-1860s onward. An additional 100 kilometers of railway is associated with roughly six additional steam engines per 10,000 inhabitants around 1865 and more than nine by 1900. Navigable waterways also promoted adoption, though their role evolved from complementing railways to becoming progressively substituted by them as the rail network matured. To identify the mechanisms underlying these effects, we construct time-varying measures of accessibility to coal markets and engineering expertise. The results indicate that improved access to coal significantly increased steam adoption throughout the second half of the nineteenth century, while access to engineering knowledge became important only in the 1890s as steam technology grew more complex. The findings suggest that the diffusion of general-purpose technologies depended not only on relative prices and local endowments but also on the infrastructures that reduced economic and informational frictions across space.

Keywords: Technological diffusion · Transport infrastructure · Steam power · French industrialisation · Regional inequality

JEL code: N93 ; N73 ; O33 ; C23

Introduction

The adoption of steam power was one of the defining technological transformations of the nineteenth century, yet its diffusion was neither uniform nor seamless. Even within national economies undergoing rapid industrialisation, such as Britain or the United States, the spread of this general-purpose technology unfolded at markedly different rates across regions, reflecting unequal access to markets, energy sources, and technical knowledge (Mokyr, 1990; Nuvolari et al., 2011; Yamasaki, 2025). More broadly, the diffusion of general-purpose technologies cannot be understood solely through factor prices or local endowments. What mattered was the geography of effective access: access to energy, access to markets, and access to the technical capabilities required to adopt and operate new technologies. Industrialisation was therefore not simply uneven across space; it was uneven because access itself was unevenly transformed.

In France, the question of how and why regions diverged in their industrial trajectories has long occupied a central place in the historiography of industrialisation, but existing scholarship has been constrained by the absence of systematic longitudinal data at the regional level (Chanut et al., 2000). Studies of steam diffusion in France have relied primarily on two cross-sectional enquêtes industrielles, Le Chapelain and Wilke (2025) being the latest and only exception, while broader accounts of regional industrialisation have typically drawn on business tax records or other indirect evidence (Bazot, 2014; Juhász et al., 2020). The result is a literature rich in descriptions of spatial heterogeneity, but more limited in its ability to explain how that heterogeneity emerged dynamically and how transport infrastructure contributed to structuring it over time.

This paper addresses that gap directly. It argues that the diffusion of steam power in nineteenth-century France was fundamentally shaped by connectivity. Transport infrastructure did not simply accompany industrialisation; it transformed the economic and informational conditions under which mechanisation became viable, thereby structuring when, where, and how rapidly steam technology spread. More specifically, the paper argues that infrastructure altered the geography of feasible industrialisation by compressing the effective distances that separated firms from the resources and capabilities required for adoption.

To investigate this process, we exploit a newly constructed annual departmental panel on steam engine stocks, firms, and installed horsepower covering the period from 1840 to 1911 — a longitudinal structure that has not previously been available for systematic analysis of French steam diffusion — in order to estimate departmental diffusion trajectories and assess the role of transport infrastructure in shaping adoption dynamics. Our central argument is that connectivity restructured the conditions for adoption in two complementary ways: first, by reducing the effective cost of coal, the principal fuel of steam engines; and second, by reducing effective distances to engineering expertise, thereby facilitating the circulation of technical knowledge and capabilities. Both channels reflected a common underlying process: infrastructure reduced the economic and informational frictions that would otherwise have made mechanisation less profitable and less feasible in peripheral territories. Yet these two channels did not operate with the same intensity throughout the period. Coal accessibility exerted its strongest influence during the earlier phases of diffusion, while knowledge accessibility became increasingly important as steam technology itself grew more complex and engineering-intensive during the late nineteenth century.

The empirical strategy proceeds in two steps. We first estimate diffusion curves at the departmental level in order to extract comparable parameters describing the timing, speed, and ultimate intensity of adoption across territories. The resulting heterogeneity is striking: take-off years span more than half a century across the eighty-nine departments in our sample, and the variation in diffusion speed and saturation levels is equally pronounced. These diffusion dynamics already suggest that infrastructure shaped not only the intensity of adoption, but also its temporal structure. Departments connected earlier to the national transport system tended to experience both earlier take-off and faster diffusion, pointing toward a systematic relationship between connectivity and the geography of mechanisation.

We then estimate a panel fixed-effects model relating steam adoption intensity to time-varying railway and waterway stocks, allowing the effects of each transport mode to evolve as networks consolidated. A remaining concern is that railway expansion may itself have followed anticipated industrial growth rather than caused it. We address this issue in two complementary ways. First, we exploit the sequencing of infrastructure development and diffusion trajectories, showing descriptively that departmental steam take-off typically occurred only after the installation of substantial railway infrastructure. Second, following Tsiachtsiras (2025), we construct a straight-line synthetic network derived from successive French railway planning legislation — the Legrand plan, the Migneret law, and the Freycinet plan — which provides exogenous variation in the intended structure of the network and serves as an instrument for actual railway stock. To further strengthen the causal interpretation, we complement the baseline fixed-effects and instrumental-variable specifications with a series of additional robustness checks.

The results establish a clear and evolving role for transport infrastructure. Railway expansion exerted a statistically significant and progressively strengthening effect on steam adoption from the mid-1860s onward, consistent with a network mechanism in which the returns to connectivity increased as the national rail system became more integrated. Navigable waterways display a positive and relatively stable effect throughout the period, operating primarily as infrastructures for bulk coal transportation. Over time, however, the relationship between the two transport modes shifted from coexistence toward functional substitution, as railways progressively absorbed the bulk-transport role previously performed by canals.

Taken together, these results indicate that industrialisation in nineteenth-century France unfolded as a spatially structured process in which connectivity shaped not only whether regions mechanised, but when and how rapidly they did so. Mechanism-based analysis using constructed accessibility scores — measuring effective freight costs to coal mines and effective travel times to engineering institutions — confirms both channels empirically. Coal accessibility shows a strong and persistent association with steam adoption from the 1860s onward, while knowledge accessibility becomes significant only from the 1890s, consistent with a later-stage diffusion of technical expertise as railway integration progressively reduced the effective distance between peripheral territories and centres of engineering competence.

More broadly, steam power belongs to the class of general-purpose technologies whose transformative effects unfolded gradually across sectors and regions over long periods of time. Existing work on such technologies has largely focused on aggregate productivity gains or factor-price incentives, while paying comparatively limited attention to the territorial conditions governing diffusion itself. Our analysis shifts attention toward the infrastructures that conditioned access to the energy, markets, and technical capabilities required for adoption. In this perspective, infrastructure was not merely a consequence of industrialisation; it was one of the mechanisms through which industrialisation itself became territorially possible.

The paper contributes to three bodies of literature. First, it advances the historiography of French industrialisation by providing the first quantitative account of departmental diffusion trajectories over the full period, showing that the variance across departments was at least as informative as the national mean and that connectivity constituted a primary organising principle of that variance (Bazot, 2014; Schwartz et al., 2011). Second, it extends the literature on steam engine diffusion — largely centred on Britain and the United States and focused on factor prices as the dominant determinant of adoption (Atack et al., 1980; Nuvolari et al., 2011; Lintsen and Stcenaard, 1991 — by introducing infrastructure-mediated accessibility as a mechanism shaping not only whether firms adopted steam power, but also when and how rapidly diffusion occurred. Third, it contributes to the growing literature linking transport infrastructure to technological adoption and innovation diffusion (Américo, 2024; Tsiachtsiras, 2025; Yamasaki, 2025), offering the first joint treatment of railways and navigable waterways across the full period of steam diffusion in France while tracing their evolving and partially substitutable roles.

The remainder of the paper is organised as follows. Section 1 situates the analysis within the historical and economic literatures on French industrialisation, steam engine diffusion, and transport infrastructure. Section 2 presents the data and methodology. Section 3 reports the diffusion-curve estimates and documents the spatial heterogeneity of adoption. Section 4 presents the econometric results on the role of infrastructure. Section 5 develops the mechanism-based interpretation and introduces the accessibility measures. Section 6 reports robustness checks. Section 7 concludes.

1 Historical background and state of the literature

Industrialisation in nineteenth-century France cannot be understood through national aggregates alone. Historical and economic research increasingly emphasises that development was spatially uneven and shaped by patterns of connectivity, market integration, and access to technical capabilities (Bazot, 2014; Fox and Weisz, 2020). The key issue is therefore not simply whether France industrialised "slowly" or "late" in aggregate terms, but how different territories entered industrial modernity under highly unequal conditions of access to energy, markets, and engineering expertise. Focusing on the elements most relevant to our argument, this section examines the territorial heterogeneity of development, the uneven geography of steam adoption, and the role of transport infrastructure in mediating access to economic and technical resources. Bringing together the literatures on French industrialisation, steam engine diffusion, and transport infrastructure, it argues that the diffusion of steam power depended not only on local endowments or relative prices, but also on the evolving transport networks that transformed access to markets, knowledge, and mechanisation across space.

1.1 Industrialisation and regional heterogeneity in France

The historiography of French industrialisation has undergone significant transformation, moving from a stagnationist interpretation — summarised in the charge that France's industrial transformation was "almost ludicrously slow" — toward a more nuanced assessment of a distinctive French path of development (Crouzet, 2003, p.216). For decades, this debate was conducted primarily at the national level, with scholars comparing aggregate growth rates and capital formation against British or German benchmarks. The limitations of this approach are now widely recognised. National aggregates concealed a deeply differentiated geography of industrialisation, in which access to markets, transport networks, technical expertise, and mechanised production capabilities varied dramatically across territories. Industrial dynamism was concentrated in a limited number of regional poles, while large parts of the country remained only weakly integrated into the emerging industrial economy.

The territorial dimension of this unevenness is documented most directly by Bazot (2014), who uses the patente (business tax) to show that non-agricultural value-added was heavily concentrated in a relatively small number of departments. Paris (Seine) exercised a strong polarising influence throughout the period, growing at a rate far above the national norm and continuously concentrating wealth and non-agricultural activity. Outside the capital, dynamic hubs including Bouches-du-Rhône (Marseille), Gironde (Bordeaux), Nord (Lille), Rhône (Lyon), and Seine-Maritime (Rouen) dominated industrial output.

These territories thrived through commercial integration, industrial specialisation, and the progressive adoption of mechanised production. By contrast, departments such as Creuse, Haute-Marne, and Morbihan remained far behind, with local incomes in some cases depending heavily on seasonal out-migration of workers toward larger urban and industrial centres.

A further dimension of this uneven geography concerned the territorial organisation of technical knowledge and engineering capacity. In nineteenth-century France, engineering expertise was not distributed spontaneously through markets alone, but was strongly structured by state institutions, grandes écoles, and applied science institutes whose expansion progressively extended the geography of technical competence beyond Paris. During the late nineteenth century, France's system of state-led engineering education expanded through a network of applied science institutes attached to provincial faculties in cities such as Grenoble, Nancy, Lille, and Toulouse. These institutes specialised in fields closely aligned with local industrial structures, including mechanical and electrical engineering and industrial chemistry, and developed rapidly in response to the evolving needs of regional economies (Fox and Weisz, 2020). While contemporaries sometimes criticised their orientation toward short-term industrial demands, they played a central role in supplying the technical capabilities required for the acceleration of industrial growth during the Belle Époque (1896–1913).

This institutional expansion formed part of a broader transformation of the French economy after 1890. As documented by Bazot (2014), this period marked a shift from increasing regional divergence toward gradual convergence, with previously lagging départements growing more rapidly than established industrial centres. The mechanisms behind this catching-up process — including the spread of manufacturing and services, improvements in transport infrastructure, and the expansion of technical education — all point toward the central importance of access. Departments that became better connected not only to national markets but also to centres of engineering expertise were progressively able to overcome earlier structural disadvantages. Industrial convergence therefore depended not only on capital accumulation or natural-resource endowments, but also on the territorial transformation of economic and cognitive accessibility. Evidence from Schwartz et al. (2011) similarly highlights the role of railway expansion in reducing disparities between northern and southern regions.

Seen in this light, the French pattern of industrialisation — often characterised as a "regional path" combining local specialisation with a state-supported engineering tradition (Crouzet, 2003) — reinforces the centrality of spatially mediated access to both economic and technical resources. The key question is therefore not whether France industrialised "late" in aggregate terms, but how different territories became progressively integrated into the infrastructural and institutional networks that made mechanised production economically and technically feasible. These divergent trajectories suggest that regional industrialization was not a uniform race toward steam, but a series of locally optimal technological choices. For instance, while the French path was increasingly defined by infrastructure-mediated connectivity, the Prussian experience reveals that a persistent reliance on water power was an economically rational strategy that cultivated the artisanal skill base necessary for subsequent industrial catch-up (Hinrichs, 2026). Steam power provides a particularly revealing lens through which to examine this process. Steam engines were not adopted uniformly across France; they diffused through territories whose access to fuel, markets, transport systems, and engineering capabilities differed profoundly across space and over time.

1.2 The geography of steam engine diffusion

A substantial body of literature has examined the regional diffusion of steam engines, with factor prices — above all the cost of coal — generally identified as the primary determinant of adoption. In Britain, Nuvolari et al. (2011) show that the relative price of coal shaped both the timing and the spatial pattern of adoption across English counties, influencing which engine designs became economically viable in different territories. In the United States, Atack (1979) and Atack et al. (1980) demonstrate that firms treated steam power as an alternative to water power and based adoption decisions largely on the cost of accessing fuel. The comparison between Belgium and the Netherlands illustrates the same mechanism at the national scale: Lintsen and Stcenaard (1991) trace Belgium's much more intensive adoption of steam technology directly to its access to economically exploitable coal deposits, while the neighbouring Netherlands, lacking such endowments, lagged substantially behind.

Taken together, these contributions establish that geography mattered profoundly for steam adoption. Yet they conceptualise geography primarily in terms of natural-resource endowments and relative factor prices. What remains comparatively underexplored is the role of transport infrastructure in mediating access to those resources and, more broadly, in transforming the economic and technical conditions under which adoption became feasible. Two territories may possess similar underlying access to coal deposits while facing radically different effective costs of mechanisation depending on whether they are connected to waterways, railway networks, or neither. Infrastructure, in this perspective, did not simply reflect geography; it actively reshaped the geography of industrial feasibility by altering the effective accessibility of fuel, markets, and technical capabilities across space.

This distinction is particularly important in the case of steam power as a general-purpose technology. The diffusion of such technologies depended not only on the existence of profitable applications, but also on the territorial infrastructures that enabled firms to access the inputs, markets, and knowledge required for adoption. Existing research on general-purpose technologies has often focused on aggregate productivity effects or factor-price incentives, while paying comparatively less attention to the spatial and infrastructural conditions governing diffusion itself. Steam engines did not spread automatically once invented; their adoption depended on the infrastructures that transformed mechanisation from a theoretical possibility into an economically and technically viable choice within specific territories.

France has remained comparatively understudied in this literature, largely because of data constraints. The principal sources available until recently — the two enquêtes industrielles of 1840–47 and 1860–65 — while exceptionally rich in detail, provided only cross-sectional snapshots, thereby limiting the possibility of analysing regional diffusion trajectories dynamically. The most direct predecessor to our work is Le Chapelain and Wilke (2025), who draw on the same newly reconstructed source base to show that physical distance from early adopters significantly impeded diffusion across French regions. Their contribution demonstrates clearly that diffusion unfolded unevenly across space. Yet physical distance alone remains only an imperfect proxy for connectivity. It cannot fully capture the infrastructural links that determined how firms accessed coal markets, transport systems, engineering expertise, and information networks at different moments of the nineteenth century. Our analysis extends this line of inquiry by incorporating time-varying transport infrastructure directly and by exploiting an annual panel structure that allows us to reconstruct diffusion trajectories rather than static snapshots.

The figures of steam adoption at the national level confirm that France was not a laggard within continental Europe[1]. Although Britain and the United States dominated in absolute terms, France compared favourably with both Germany and Belgium throughout much of the mid-nineteenth century. Prussia only began to surpass France in installed horsepower from the mid-1870s onward, while the Dutch case — with fewer than 300 engines as late as the 1840s — illustrates the substantial variation that existed even among relatively prosperous European economies. These aggregate comparisons also suggest a distinctively French pattern of mechanisation: a relatively large number of comparatively low-powered engines, consistent with an industrial structure more oriented toward skilled-labour-intensive and quality-based production than toward heavy industrial concentration. What these aggregate figures cannot reveal, however, is the profoundly uneven territorial distribution of steam adoption within France itself. The key issue was not simply whether France adopted steam technology, but how different regions became integrated — at different moments and under highly unequal conditions — into the infrastructural and economic networks that made mechanised production feasible. It is precisely this geography of differential access that motivates the analysis developed in the remainder of the paper.

1.3 Transport infrastructure, market access, and knowledge diffusion

Transport infrastructure shaped industrialisation and technology adoption through two analytically distinct but deeply interconnected channels. The first concerned market accessibility: by lowering transport costs, infrastructure expanded the effective demand available to firms and reduced the delivered price of critical inputs, thereby altering the expected profitability of adopting capital-intensive technologies. The second concerned knowledge accessibility: improved connectivity reduced the cost of moving people, ideas, and technical expertise across space, lowering the informational and organisational barriers that often slowed the recognition, adaptation, and implementation of new technologies.

[1] See Table A.1, which situates France within the broader international context of steam adoption.

Both channels were central to the diffusion of steam power, and both were profoundly influenced by the uneven and time-varying expansion of railways and navigable waterways across nineteenth-century France.

The market-access channel is well established in the literature. Yamasaki (2025) provides perhaps the closest parallel to our analysis, documenting rapid but spatially uneven steam adoption in Meiji Japan and showing that distance to railways explains a substantial share of regional variation in adoption rates. In his framework, rail connectivity reduced barriers to mechanisation primarily by enlarging accessible markets and lowering coal transport costs — the two factors most directly affecting the expected profitability of steam adoption. Américo (2024) identifies a similar mechanism in the development of mechanised cotton spinning in Brazil, where municipalities located closer to railway lines expanded spinning capacity more rapidly as railways connected agricultural areas to overseas machinery suppliers. Bogart et al. (2022) likewise associate steam adoption in Britain with proximity to turnpike roads and inland waterways, emphasising the role of improved market accessibility in facilitating adoption decisions.

These studies demonstrate convincingly that infrastructure influenced adoption by transforming the economic geography of production. Yet they also suggest a broader point that remains comparatively underdeveloped in the literature: infrastructure did not simply reduce transport costs in a narrow sense, but altered the effective accessibility of industrialisation itself. By compressing economic distance, transport networks reshaped the territorial conditions under which mechanisation became profitable and sustainable. The issue was therefore not merely whether coal existed, markets existed, or technologies existed, but whether firms could access them under sufficiently favourable conditions to justify adoption.

The knowledge-access channel has received comparatively less attention in the literature on technology adoption *per se*, although it is well established in research on innovation and regional development more broadly (Bai et al., 2023; Baruffaldi and Poege, 2025). For France specifically, Tsiachtsiras (2025) shows that railway expansion significantly increased patenting activity by intensifying interactions between neighbouring inventor clusters and extending the spatial reach of localised knowledge spillovers. His counterfactual exercise suggests that invention rates would have been approximately 24% lower in the absence of railways. The mechanism operates through reduced travel costs, which facilitated face-to-face interaction, the circulation of technical expertise, and the transmission of practical engineering knowledge across space.

This channel is particularly relevant in the French context, where technical expertise was strongly structured by state institutions, grandes écoles, and engineering networks whose influence remained geographically mediated. Engineering knowledge did not circulate frictionlessly across the national territory. Departments that were effectively connected to centres of technical competence faced lower informational barriers to adoption than territories that remained infrastructurally isolated, even when geographical proximity alone was relatively small. In this sense, infrastructure altered not only the movement of goods, but also the geography of feasible interaction between firms, engineers, institutions, and industrial knowledge.

More broadly, these two channels — market accessibility and knowledge accessibility — should not be understood as independent mechanisms operating in parallel. They formed complementary dimensions of the same underlying process: the territorial transformation of access. Steam engines were not adopted simply because firms faced favourable relative prices. Adoption also required the practical capability to recognise the profitability of mechanisation, acquire technical information, access engineering expertise, organise installation, and maintain increasingly complex machinery over time. Infrastructure reduced both economic and informational frictions, thereby reshaping the geography of feasible mechanisation across France.

Existing work on infrastructure and technology adoption has generally focused on single transport modes and has only rarely examined the evolving relationship between competing networks over time. In the French case, no study has jointly analysed railways and navigable waterways across the full period of steam diffusion, nor explicitly modelled how the relative contributions of these two infrastructures changed as the national railway system consolidated. This is precisely the gap our analysis addresses. By combining an annual departmental panel with time-varying measures of railway and waterway infrastructure, we are able to trace not only whether connectivity mattered, but how its effects evolved across different phases of industrialisation — including the transition from an early period in which waterways provided the principal infrastructure for bulk coal transportation to a later phase in which railways progressively absorbed, extended, and ultimately transformed that function.

2 Data and Methodology

2.1 Data sources

The analysis combines several datasets of different nature in order to reconstruct the territorial conditions under which steam diffusion unfolded across nineteenth-century France. The core information on steam adoption comes from official French administrative statistics, while infrastructure and spatial data are drawn from the COMMUNES project[2], a large-scale historical GIS initiative reconstructing commune boundaries, transport networks, and territorial transformations since the eighteenth century. These sources are complemented by additional datasets on population, coal geography, and the spatial organisation of engineering education. Taken together, these materials make it possible to analyse not only where and when steam engines diffused, but also how changing infrastructures transformed access to markets, fuel, and technical expertise across space.

2.1.1 Steam engine panel

Data on steam engines by French department originate from two consecutive administrative series: the *Compte rendu des travaux des ingénieurs des mines* and, from 1848 onward, the *Statistique de l'industrie minérale et des appareils à vapeur*. These statistics were compiled in response to the French authorities' need to monitor and regulate steam technology for safety purposes following the regulatory framework established in 1823 (see Le Chapelain and Wilke, 2025, for further details). Beyond their administrative purpose, these sources provide a uniquely detailed longitudinal record of mechanisation across the French territory.

For each department and year, the statistics report the number of stationary steam engines in industrial use, the number of steam-powered firms, and the total installed horsepower. The resulting panel covers eighty-nine departments annually from 1840 to 1911, provid-

[2]See the website here. The website was last visited on 26 May 2026

ing a temporal and spatial continuity that remains exceptionally rare among nineteenth-century industrial datasets. Unlike the cross-sectional enquiries traditionally used in the literature, this structure makes it possible to reconstruct departmental diffusion trajectories dynamically and to analyse how the timing, speed, and intensity of adoption varied across territories over time.

The panel reveals substantial spatial heterogeneity throughout the period (see Figure A.1 in Appendix). Although this heterogeneity diminishes progressively over time, it remains pronounced even in the final decades of the sample, reflecting the deeply uneven geography of French industrialisation discussed in Section 1.

2.1.2 Population data

Population data at the departmental level are drawn from the *Annuaire Statistique de la France* (1878–1899) and from the COMMUNES project for earlier census years. Both sources compile information from the five-yearly *recensements* conducted between 1841 and 1911. Following Fernihough and O'Rourke (2021)), intercensal years are interpolated by modelling the natural logarithm of population as a linear function of time. Commune-level population figures are likewise obtained from the COMMUNES project, allowing demographic information to be integrated directly into the construction of accessibility measures described below.

2.1.3 Infrastructure data

Railways and navigable waterways are treated as the two principal transport infrastructures through which goods, energy, and technical knowledge circulated across nineteenth-century France. Both series are derived from the COMMUNES project and cover the full study period on an annual basis. Starting from GIS files geo-localising each network, we aggregate the relevant measures to the departmental level.

For railways, the data include the opening and closing dates of individual lines and stations as well as decade-specific information on average travel speeds. For navigable waterways, the database records the type of infrastructure (river or canal) and, for artificial waterways, the year of entry into service. The evolution of both transport systems over time is illustrated in Figure A.2 in the Appendix.

These data are particularly important for our analysis because they allow infrastructure to be treated not simply as a static territorial characteristic, but as a dynamic process of spatial integration unfolding over time. This makes it possible to reconstruct how the geography of effective accessibility evolved as transport networks expanded and became increasingly interconnected across the national territory.

Decadal freight-cost data (centimes per tonne-kilometre) by transport mode are taken from Toutain (1968, p.279) and are used in the construction of the coal accessibility measure described in Section 5.

2.1.4 Other variables

To operationalise the market-access and knowledge-access channels identified in Section 1, we incorporate two additional datasets: the locations and founding dates of grandes écoles awarding engineering degrees, and the locations of coal mines. The geo-localisation of these sites is presented in Figure A.3 in the Appendix.

The list of grandes écoles was compiled from the public website of the *Conférence des Grandes École*s (CGE), restricted to institutions authorised to award the *titre d'ingénieur*[3]. Incorporating the founding dates of these institutions allows the knowledge-accessibility measure to capture changes over time in the territorial organisation of advanced technical expertise, reflecting the progressive expansion of engineering capacity beyond Paris and major industrial centres.

Information on mine locations and extracted minerals comes from the COMMUNES project. We restrict the dataset to coal mines, as coal constituted the principal fuel source for steam engines throughout the period. Data on departmental coal-bearing areas are drawn from Fernihough and O'Rourke (2021). Combined with transport-cost information, these data allow us to reconstruct the changing geography of coal accessibility across French territories.

[3]The website was last consulted on 13 January 2026.

2.2 Diffusion modeling

The temporal completeness of the panel makes it possible to analyse diffusion trajectories at the departmental level in a way that has not previously been feasible for nineteenth-century France. Our objective is not primarily to adjudicate between competing diffusion models, but rather to extract comparable and interpretable parameters that allow us to reconstruct the territorial structure and temporal dynamics of mechanisation across departments.

To this end, we rely on a classical and well-established framework from the literature on technological diffusion. Following Griliches (1957), we estimate a symmetric logistic curve, while Dixon (1980) provides the asymmetric alternative considered alongside it. These specifications have consistently proven effective in capturing the characteristic sigmoid pattern associated with innovation diffusion while retaining a parsimonious and transparent structure[4].

The underlying logic of these models is particularly relevant in our context. Diffusion processes are assumed to operate through the gradual spread of information and adoption incentives among potential users. In the case of steam power, transport infrastructure likely accelerated this process by reducing both economic and informational frictions across space. Our approach is therefore close in spirit to that of Nuvolari et al. (2011), who analyse regional heterogeneity in steam diffusion across England. Similar to their strategy — and to Atack et al. (1980) for the United States — we use standard sigmoid models to obtain comparable diffusion parameters across territories and thereby reconstruct the uneven temporal geography of industrial mechanisation.

We first estimate the symmetric logistic growth equation (Eq. 1):

$$\text{Stock}_t = \frac{K}{1 + e^{-a(t-b)}} \tag{1}$$

where t denotes time; Stock_t the number of engines in use at time t; K the estimated saturation level (carrying capacity); a the diffusion speed parameter; and b the midpoint (the

[4]Even if recent contributions develop more advanced techniques, more in line with real world interactions (e.g. Sidorov et al., 2021; Sziklai et al., 2025), nevertheless, logistic and Gompertz specifications remain widely used in applied studies of technology diffusion (see for example Bacha et al., 2024; Jha and Saha, 2020; Lartey, 2020; Sultanov et al., 2016; Gupta and Jain, 2012).

year at which the process reaches $K/2$). The logistic specification provides a benchmark representation of balanced acceleration and deceleration phases.

We then estimate the Gompertz model (Eq. 2):

$$\text{Stock}_t = K \exp\left[-e^{-a(t-b)}\right] \tag{2}$$

This asymmetric formulation allows for more rapid initial growth and a longer tail as the diffusion process approaches saturation, a pattern frequently observed when early adopters play a disproportionate role in initiating technological change or when diffusion progressively slows in more peripheral territories.

Parameters are estimated using non-linear least squares. For each department, we retain the specification providing the best fit according to the R^2 criterion. Importantly, our objective lies less in identifying the "correct" functional form of diffusion than in extracting comparable parameters capable of summarising the temporal structure of mechanisation across territories.

Beyond the estimated saturation level, diffusion speed, and midpoint/inflection year, we compute several additional indicators designed to characterise regional diffusion trajectories more precisely. First, we estimate the year of take-off, defined as the year in which adoption reaches 10% of the estimated saturation level, following Pezzoni et al. (2022, Appendix D). Second, we compute Δ_t corresponding to the number of years required to move from 10% to 90% of saturation, following Grübler (1990) and in line with Nuvolari et al. (2011). Finally, we calculate the compound annual growth rate (CAGR), which provides a synthetic measure of the intensity and pace of adoption over the diffusion period.

Taken together, these parameters allow us to compare not only when diffusion began across departments, but also how rapidly mechanisation unfolded and how complete the diffusion process ultimately became. More broadly, they make it possible to reconstruct the uneven temporal geography of industrialisation across nineteenth-century France. The emphasis is therefore placed on identifying systematic territorial differences in the timing, speed, and scale of mechanisation rather than on refining the underlying mathematical specification itself.

By reconstructing departmental diffusion trajectories in this way, the analysis moves beyond static measures of industrial development and instead captures industrialisation as a dynamic and spatially differentiated process. The diffusion of steam power was not a single national transition unfolding uniformly through time, but a succession of territorially uneven entries into mechanised production, shaped by changing conditions of economic and technical accessibility across space.

2.3 Econometric analysis

After characterising the diffusion process at the departmental level, we turn to the econometric analysis of the mechanisms underlying these territorial differences in mechanisation trajectories. More specifically, we estimate a panel regression model relating steam adoption intensity to the development of transport infrastructure at the department-year level (Eq. 3):

$$\begin{aligned}
\text{SteamEnginesPC}_{d,t} = & \underbrace{\sum_{\tau} \delta_{1\tau} \left(\text{RailStock}_{d,t-1} \times \mathbf{1}[t=\tau]\right) +}_{\text{Rail effect over time}} \\
& \underbrace{\sum_{\tau} \delta_{2\tau} \Big(\text{WaterwayStock}_{d,t-1} \times \mathbf{1}[t=\tau]\Big) +}_{\text{Water effect over time}} \\
& \underbrace{\sum_{\tau} \delta_{3\tau} \Big(\text{RailStock}_{d,t-1} \times \text{WaterwayStock}_{d,t-1} \times \mathbf{1}[t=\tau]\Big) +}_{\text{Complementarity/Substitution effect over time}} \\
& \beta_1 \text{RailStock}^2_{d,t-1} + \\
& \beta_2 \text{CitiesWithStations}_{d,t-1} + \beta_3 \text{CitiesWithPorts}_{d,t-1} + \\
& \beta_4 \text{WaterDensity}_{d,t-1} + \\
& \beta_5 \ln(\text{pop}_{d,t}) + \gamma_t + \lambda_d + \epsilon_{d,t}
\end{aligned} \tag{3}$$

The dependent variable, *SteamEnginesPC*, measures the number of steam engines per 10,000 inhabitants and captures the territorial intensity of mechanisation in a form that remains comparable across departments of different demographic sizes. Rather than focusing solely on aggregate engine counts, this specification allows us to analyse how deeply steam technology penetrated local economies across space.

The principal explanatory variables, $RailStock$ and $WaterwayStock$, measure the active kilometres of railway lines and navigable waterways within each department, expressed in units of 100 kilometres. Both variables are interacted with calendar years in order to allow the effects of infrastructure to evolve over time as transport networks expanded, densified, and became progressively integrated at the national scale. Their interaction term captures potential complementarities or substitution effects between railways and waterways, thereby allowing the relationship between the two transport modes to change as the geography of connectivity evolved throughout the nineteenth century.

$RailStock$ additionally enters the specification in squared form in order to account for potential nonlinear returns to railway connectivity[5]. This allows for the possibility that the effects of rail integration intensified once networks reached sufficient density to generate broader market integration and stronger interregional linkages.

To complement these aggregate stock measures, we also include indicators capturing the local diffusion of network access within departments. $WaterDensity$ measures kilometres of navigable waterways per square kilometre of departmental area, while $CitiesWithStations$ and $CitiesWithPorts$ correspond respectively to the shares of communes served by an active railway station or inland port. These variables are intended to capture the territorial depth of infrastructural integration beyond the mere presence of major transport corridors. Infrastructural accessibility depended not only on the existence of networks at the departmental level, but also on the extent to which firms and local communities could effectively connect to them within everyday economic space.

Department fixed effects, λ_d, absorb all time-invariant characteristics likely to influence a department's propensity to adopt steam technology, including natural-resource endowments, inherited industrial structures, geographical constraints, and baseline levels of engineering capability. Year fixed effects, γ_t capture the broader expansion of steam technology over time as well as macroeconomic and institutional conditions common to all departments in a given year. The logarithm of population is included to control for time-varying demographic dynamics at the departmental level.

All infrastructure variables are lagged by one year in order to reduce concerns regarding simultaneity between infrastructure expansion and steam adoption. The estimation sam-

[5]The specification with the square of also $WaterStock$ was discarded, as it consistently showed non-significant result for this variable.

ple covers the period from 1850 to 1911, excluding the sparse first decade of the panel during which the diffusion process remained highly limited across much of the national territory. Standard errors are clustered at the departmental level throughout.

More fundamentally, the fixed-effects structure allows the analysis to focus on changes in connectivity within departments over time rather than on static cross-sectional differences between territories. The identifying variation therefore comes from the progressive transformation of infrastructural accessibility as railway and waterway networks expanded across France. In this sense, the econometric framework is designed to capture industrialisation not as a fixed regional characteristic, but as a dynamic process of territorial integration unfolding unevenly through time.

To address remaining concerns regarding the potential endogeneity of railway construction, we employ an instrumental-variable strategy widely used in the infrastructure literature (Banerjee et al., 2020; Hodgson, 2018; Atack et al., 2010). Following Tsiachtsiras (2025), we exploit successive phases of French railway planning legislation — the Legrand plan (1840–1860), the Migneret law (1865), and the Freycinet plan (1878) — to construct a straight-line synthetic network connecting cities, ports, and administrative centres according to the intended logic of state railway planning rather than the realised geography of economic activity. Department-level measures derived from this synthetic network are then used as instruments for observed railway stock.

The relevance of the instrument is supported by historical evidence showing that the *Corps des ponts et chaussées* prioritised geometric directness and engineering considerations in route planning, often independently of local industrial demand or short-term commercial profitability (Dunham, 1941; Smith, 1990), and is confirmed by the first-stage results reported in the Appendix, where F-statistics comfortably exceed conventional thresholds. More broadly, this strategy exploits the strongly centralised and technocratic character of nineteenth-century French railway planning, in which major infrastructural decisions were shaped to a significant extent by state engineering logics rather than solely by decentralised market forces.

The construction of the synthetic network and the corresponding first-stage results are reported in the Appendix (Figure A.5 and Table A.3).

3 Results I: Diffusion Dynamics Across Departments

The estimation of department-level diffusion curves confirms the pronounced spatial heterogeneity already suggested by the raw panel data. At the national level, the aggregate adoption rate reaches 7.57%, with a take-off year estimated at 1848. Yet this national trajectory conceals a remarkably uneven territorial distribution spanning more than half a century of divergence across departments. The full set of estimated diffusion parameters is reported in Table A.2.

Figure 1 maps this geography of unequal mechanisation by displaying the distribution of departmental take-off years — defined as the year in which adoption reaches 10% of estimated saturation. The earliest quintile corresponds closely to the industrial core identified in the historical literature. Paris (Seine), Nord (Lille), Rhône (Lyon), and Seine-Maritime (Rouen) all emerge as early adopters, consistent with their dominant positions in non-agricultural value-added, commercial integration, and early specialisation in mechanised production (Bazot, 2014). More broadly, the concentration of early take-off departments in the Northeast reflects proximity to coalfields, whose importance for steam adoption has been extensively documented in the comparative literature (Nuvolari et al., 2011).

Yet factor endowments alone cannot fully account for the spatial pattern observed in Figure 1. When compared with the chronology of railway expansion, the progressive extension of early-adoption zones toward the interior of the country appears closely associated with the expansion of the rail network during the 1850s and 1860s. As transport integration advanced, many of the bottlenecks that had previously constrained mechanisation in less connected territories were progressively reduced. In this respect, the spatial structure of diffusion provides direct support for Grantham's (1997) argument that industrialisation depended fundamentally on connectivity and proximity to urban and commercial centres.

Departments located in the Massif Central, Brittany, and the Southwest — including Creuse, Morbihan, and several departments of the far South — consistently appear among the latest adopters. Their delayed entry into mechanised production reflects not only their greater distance from coal-producing regions, but also their relatively late integration into the national transport system. In several of these territories, delayed take-off additionally reflects the industrial dislocation of the 1880s and 1890s, during which traditional activities increasingly struggled to compete against more connected and more heavily mechanised industrial regions (Crouzet, 2003).

More fundamentally, Figure 1 suggests that the diffusion of steam power unfolded not as a uniform national process, but as a territorially differentiated sequence of industrial transitions shaped by changing conditions of accessibility. Departments entered the age of mechanised production at different moments because they became connected to the infrastructures supporting industrial modernity at different moments. The geography of diffusion therefore appears inseparable from the geography of transport integration itself.

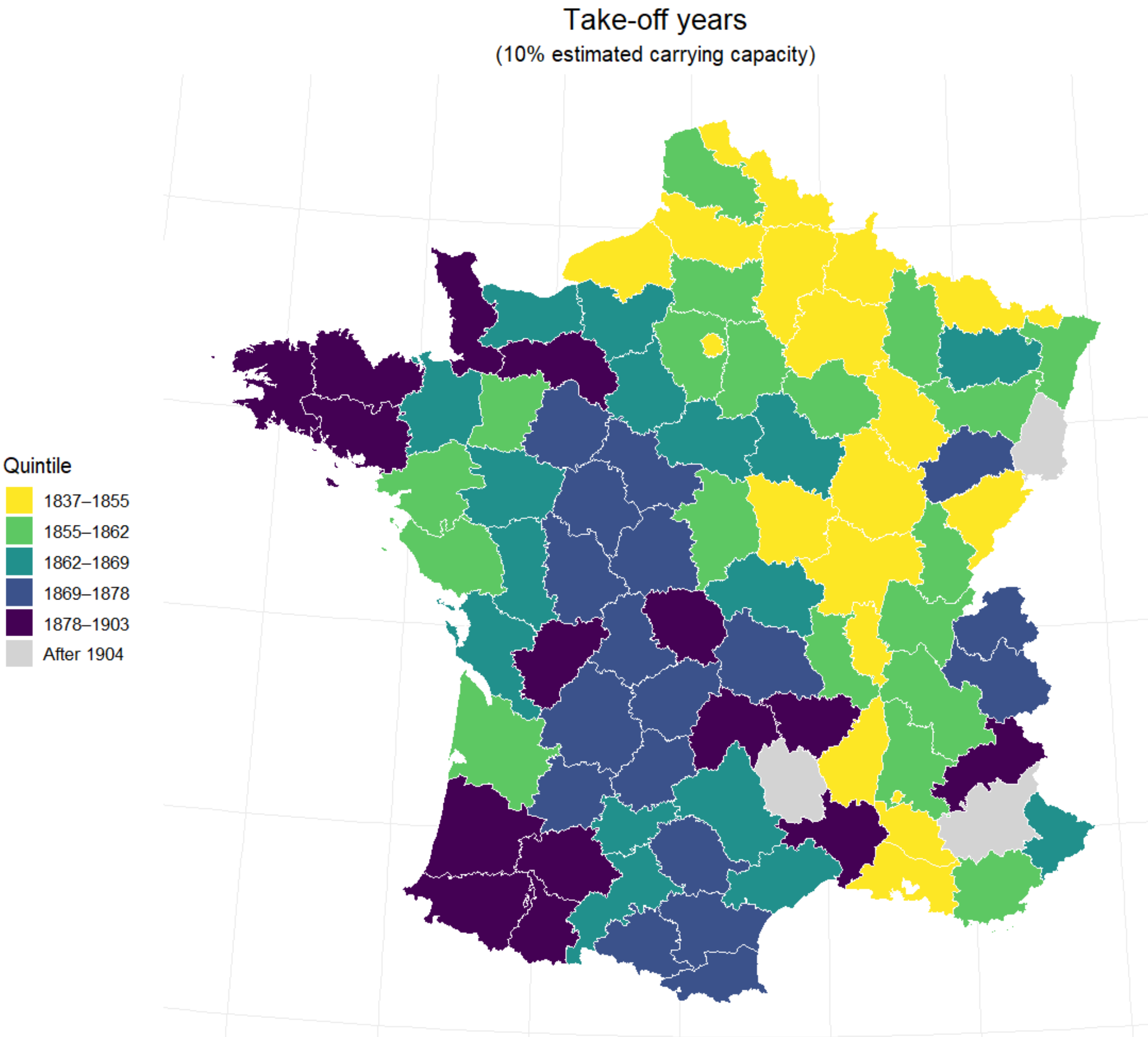

Figure 1: French departments map of the distribution of the take-off years, i.e. reach of 10% saturation as proposed by Pezzoni et al. (2022); source: own elaborations on steam engine panel by Le Chapelain & Wilke (2025); base map of French departments in 1770 by Gay (2022)

A preliminary investigation of the relationship between infrastructure and diffusion dynamics points toward a strikingly consistent pattern. Departments connected earlier to the railway network tend to display both earlier take-off years and shorter Δ_t — that is, more rapid transitions from initial adoption to mature mechanisation. Quantitatively, the estimated take-off year occurs, on average, approximately seven years after the installation of the first 100 kilometres of railway within a department, and this sequencing characterises roughly half of all territories in the sample. The temporal ordering is particularly important: in many cases, substantial railway integration precedes industrial take-off rather than emerging as a consequence of it. While descriptive evidence alone cannot establish causality, this sequencing is consistent with a mechanism running from connectivity to mechanisation and therefore provides preliminary grounds for mitigating concerns regarding reverse causality before turning to the econometric analysis.

Beyond the timing of take-off, the duration parameter Δ_t (Figure A.4) reveals a second dimension of territorial heterogeneity that the spatial distribution of take-off years alone cannot fully capture. Departments with the shortest diffusion durations — including Aude (13.8 years), Pyrénées-Orientales (13.1 years), and Haute-Marne (23.4 years) — tend to correspond to relatively compact industrial systems in which concentrated sectoral demand generated rapid saturation of a comparatively limited adoption potential. By contrast, departments displaying the longest diffusion durations — including Basses-Alpes, Gard, and Haute-Saône — reflect either very late starts combined with slow subsequent growth or estimated carrying capacities substantially exceeding observed adoption levels within the sample period. In these cases, mechanisation appears to have remained incomplete when the panel ends in 1911.

Taken together, the joint distribution of take-off years and Δ_t values suggests the existence of at least two distinct territorial regimes of industrialisation. The first corresponds to an early-integrating industrial core characterised by rapid and relatively complete mechanisation. The second corresponds to a more peripheral France marked by delayed, slower, and often incomplete diffusion processes. Strikingly, this division maps closely onto the geography of transport integration documented in the following sections. Industrial modernity therefore appears to have spread through the national territory not as a homogeneous process of technological convergence, but through successive waves of infrastructural integration that progressively transformed the accessibility conditions of mechanisation across space.

Descriptive evidence alone cannot, however, determine the magnitude, persistence, or precise timing of infrastructure effects. Nor can it establish whether railways complemented or substituted for pre-existing waterway systems, or whether the influence of connectivity intensified as transport networks became denser and more integrated over time. The following section addresses these questions using a panel framework designed to estimate the evolving impact of transport infrastructure on steam adoption across French departments.

4 Results II: Role of Infrastructure in Steam Engines Adoption

Table 1 summarises the year-specific marginal effects of RailStock and WaterwayStock on the number of steam engines per 10,000 inhabitants, evaluated at the mean level of the alternative infrastructure variable. The full coefficient estimates and yearly marginal effects are reported in the Appendix (Tables A.4 and A.5). Point estimates are displayed together with standard errors clustered at the departmental level.

Railway expansion begins to exert a statistically significant and economically meaningful influence on steam adoption from the mid-1860s onward. Around 1865, an additional 100 kilometres of railway is associated with approximately six additional steam engines per 10,000 inhabitants, evaluated at mean levels of waterway access and holding all other covariates constant. The magnitude of this effect becomes clearer when situated within the broader scale of mechanisation during the period. In 1860, the median French department possessed fewer than three steam engines per 10,000 inhabitants; by 1870 this figure had risen to 4.3, by 1880 to 7.3, and by 1900 to 14.9. The estimated railway effect therefore corresponds to a substantial share of observed territorial variation in mechanisation intensity.

More importantly, the influence of railway connectivity strengthens progressively over time. The marginal effect rises from roughly seven additional engines per 10,000 inhabitants during the 1870s to nearly eight during the 1880s, before exceeding nine by the end of the century. This gradual intensification is highly consistent with a network mechanism. As the railway system expanded, densified, and became increasingly integrated at the national scale, the economic advantages associated with connectivity appear to have grown correspondingly larger and more persistent. Railways therefore did not simply reduce transport costs at a fixed rate; they progressively transformed the territorial conditions under which mechanisation became economically viable.

Navigable waterways display a markedly different temporal profile. Their marginal effect remains positive and comparatively stable throughout the entire period, corresponding to approximately 17–18 additional steam engines per 10,000 inhabitants per additional 100 kilometres of navigable waterways. Although larger in point estimate than the railway effect, this coefficient applies to a substantially narrower empirical range. The bottom quartile of departments never exceeds 45 kilometres of navigable waterways, while even the upper quartile remains below 140 kilometres. Consequently, the practical contribution of waterways to cross-sectional variation in mechanisation is smaller than the coefficient magnitude alone might suggest.

This contrast reflects important historical differences in the development of the two transport systems. Unlike railways, the navigable waterway network was already largely established by the middle of the nineteenth century. Most major canal-construction efforts predated our sample period, and relatively few new waterways were opened after 1850. As a result, cross-departmental variation in waterway accessibility was effectively fixed relatively early, whereas railway connectivity evolved dynamically throughout the second half of the century.

The stable waterway coefficient therefore appears to capture a persistent structural advantage enjoyed by departments endowed with established navigable connections, particularly in sectors highly dependent on bulk coal transportation where freight costs remained a chronic constraint on mechanisation. Railways, by contrast, progressively extended and transformed these accessibility conditions through a more flexible and spatially expansive technological system. In this interpretation, waterways provided an initial infrastructural foundation for industrial connectivity, while railways gradually absorbed, augmented, and ultimately reconfigured that function as the national transport system became increasingly integrated. This interpretation is consistent with the substitution pattern suggested by the interaction terms and explored further in the canal-specific specification below.

More broadly, the contrast between the railway and waterway effects reinforces the central argument of the paper: transport infrastructure mattered not simply because it existed, but because different transport systems transformed accessibility in fundamentally different ways across time. The geography of steam diffusion was therefore shaped not only by the presence of infrastructure, but by the evolving capacity of transport networks to integrate territories into increasingly dense economic and technical systems of exchange.

The interaction between railway and waterway stock is not statistically significant in the baseline specification, nor in the alternative lag structures considered. This absence of precision should not, however, be interpreted as evidence that the relationship between the two infrastructures was historically unimportant. The interaction terms are fully incorporated into the computation of the yearly marginal effects, meaning that the estimates reported in Table 1 reflect the combined contribution of all relevant components of the specification rather than isolated coefficients taken independently.

Although estimated imprecisely, the interaction coefficients consistently point toward an increasingly substitutive relationship between railways and waterways as the nineteenth century progresses — a pattern to which we return in greater detail in Section 5. This evolution is historically plausible. Early in the period, waterways and railways often operated as partially complementary systems within a fragmented transport geography. Over time, however, the progressive expansion and densification of the railway network increasingly allowed rail transport to replicate and extend many of the bulk-transport functions previously performed by canals and navigable rivers.

The non-interacted infrastructure coefficients, corresponding to the baseline year of the specification, are themselves not individually significant once the time interactions are introduced. This does not imply that infrastructure exerted no influence on steam adoption. Rather, the economically meaningful quantities are the year-specific marginal effects, which jointly incorporate the time interactions and the cross-infrastructure interaction terms. Substantively, this result reinforces one of the central themes of the paper: the influence of transport infrastructure on mechanisation was not fixed through time, but evolved alongside the expansion, integration, and changing functional roles of transport networks across nineteenth-century France.

Given the particular importance of canals in the French case — where canal systems were often designed explicitly to facilitate the bulk transportation of coal and industrial raw materials, and where parts of the network were developed in partial coordination with early railway expansion — we estimate an alternative specification replacing the general waterway variables with canal-specific measures. The results are reported in Table 1 (Model B) and, complete in Table A.5.

The positive and statistically significant effect of railway expansion remains robust throughout the period. Canal infrastructure also displays positive marginal effects from the mid-1870s onward, although these estimates do not reach conventional levels of statistical significance. Importantly, when the marginal effect is evaluated at relatively low levels of railway access — corresponding to departments where rail integration remained weak or arrived comparatively late — the canal effect becomes substantially larger. This suggests that canals continued to play an important infrastructural role in territories that remained only partially integrated into the expanding railway system. The absence of significance in the canal specification reflects limited within-department variation after network completion rather than the absence of a substantive role — a measurement constraint inherent to a network built largely before the sample period begins.

More broadly, the relationship between the two infrastructures appears to evolve progressively from weak complementarity toward substitution. In the earlier phases of industrialisation, canals and railways contributed jointly to territorial integration by reducing transport frictions and facilitating access to coal and markets. As the railway network matured, however, rail transport increasingly absorbed and extended the connectivity functions previously associated with waterways. The diffusion of steam power therefore unfolded within a changing infrastructural ecology in which successive transport technologies reshaped the territorial organisation of accessibility across France.

Table 1: Marginal effects by year of Rail, Water, and Canal variables on steam engines per 10k inhabitants for selected years; variables lagged one year; standard errors clustered at department level (complete Table A.5)

	Model A: Rail + Water		Model B: Rail + Canal	
Year	Rail	Water	Rail	Canal
1851	5.3705 (3.8187)	17.4688** (7.5522)	5.8853 (3.8131)	-2.4576 (3.8806)
1855	5.5182 (3.6924)	17.4917** (7.5906)	5.8770 (3.6336)	-2.1639 (3.8245)
1860	5.6258 (3.4215)	17.6153** (7.5174)	5.9480* (3.3415)	-1.5955 (3.6551)
1865	6.2526* (3.3513)	17.6416** (7.5103)	6.5367** (3.2806)	-1.1137 (3.5493)
1870	6.8138** (3.2979)	17.8256** (7.5406)	7.1498** (3.2368)	-0.1719 (3.3557)
1875	7.3411** (3.1710)	17.8581** (7.4811)	7.6842** (3.1942)	-0.1109 (3.2712)

1880	7.9067** (3.1538)	18.2866** (7.4194)	8.5530*** (3.2150)	-0.1302 (3.3839)
1885	8.2181*** (3.1037)	18.2214** (7.3636)	8.7319*** (3.1874)	1.3878 (3.2969)
1890	8.8835*** (3.0533)	17.9080** (7.3891)	9.2605*** (3.1315)	1.4534 (3.2680)
1895	8.7170*** (3.0625)	18.0946** (7.3621)	9.1337*** (3.1374)	1.9257 (3.3428)
1900	9.3466*** (3.0680)	17.9863** (7.3463)	9.7208*** (3.1630)	1.6643 (3.3791)
1905	9.3430*** (3.1511)	17.8704** (7.3807)	9.8162*** (3.1915)	0.5208 (3.4115)
1910	8.6468*** (3.0440)	18.0972** (7.3320)	9.4593*** (3.1609)	-0.4566 (3.2775)

5 Mechanisms

The econometric results establish a strong relationship between transport infrastructure and steam adoption, but the magnitude of this relationship can only be fully understood by clarifying the mechanisms through which connectivity altered firms' incentives and capacities to mechanise. The argument developed in this paper is that infrastructure mattered not simply because it increased movement in a generic sense, but because it transformed the effective accessibility of mechanisation along distinct yet closely interconnected dimensions.

This section develops two complementary mechanism-based interpretations. The first concerns access to input markets, specifically coal, whose effective cost varied substantially across French territories depending not only on geological endowments but also on the transport infrastructures linking departments to producing areas. The second concerns access to technical knowledge through the network of engineering institutions whose territorial reach was itself progressively transformed by railway expansion.

Although analytically distinct, both channels operated through the same underlying logic: transport infrastructure reduced the effective distances separating firms from the economic and technical resources required for mechanisation. Connectivity lowered the delivered cost of fuel, reduced informational frictions, facilitated access to engineering expertise, and ultimately altered the practical feasibility of adopting steam technology in territories that would otherwise have remained comparatively peripheral.

To evaluate these mechanisms empirically, we construct two time-varying accessibility measures at the departmental level. The first captures accessibility to coal markets through the evolving transport-cost structure linking communes to active coal mines.

The second captures accessibility to engineering expertise through the changing geography of travel times to institutions awarding engineering qualifications. We then estimate the relationship between these accessibility measures and steam adoption intensity before turning to a joint assessment of their respective contributions to the territorial diffusion of mechanisation.

5.1 Coal access and the reduction of operating costs

Steam engines required large and continuous supplies of coal, and the cost of accessing that fuel varied enormously across nineteenth-century France. Coal deposits were heavily concentrated geographically — particularly in the Nord, Pas-de-Calais, the Loire basin, and several southern mining districts — meaning that departments located outside these regions depended almost entirely on transport systems to supply industrial fuel. In this context, the economic viability of steam adoption depended not simply on the existence of coal deposits at the national scale, but on the capacity of firms to access coal at sufficiently low effective cost.

Before the expansion of railways, navigable waterways — and canals in particular — fulfilled much of this function. Canal systems had been designed explicitly to facilitate bulk freight transportation, and coal rapidly became one of their principal cargos. The expansion of railways progressively transformed this geography of fuel access by extending the spatial reach of coal markets and, in many cases, reducing effective transport costs relative to existing alternatives. The coal-access channel therefore captures something more specific than connectivity in the abstract: transport infrastructure reshaped the geography of a critical input market whose accessibility directly affected the variable operating costs of mechanisation.

In this perspective, infrastructure altered not only the movement of goods, but the territorial economics of steam power itself. Departments that became better connected to coal-producing regions faced lower operating costs, broader fuel accessibility, and therefore stronger incentives to adopt and sustain steam-intensive production systems.

To operationalise this mechanism, we construct a coal-market accessibility score defined as the minimum freight cost between each commune and the nearest active coal mine, before aggregating the resulting values to the departmental level. For each year t, mine

m, and commune c, the freight cost is defined as:

$$C_{mct} = \begin{cases} \tau_t^H \cdot d(m,c), & \text{if no network path to } m, \\ \min\left(\tau_t^H \cdot d(m,c), M_{mt} + P_{mct} + L_{ct}\right), & \text{otherwise.} \end{cases}$$

where $d(m, c)$ is the Euclidean distance between mine m and the centroid of commune c, and τ_t^H is the per-metre road freight rate in year t, taken from Toutain (1968). When a network path exists, total cost decomposes into M_{mt}, the mine access cost; P_{mct}, the least-cost path on the combined rail and waterway network computed via Dijkstra's algorithm; and L_{ct}, the commune last-mile cost. The road alternative is always available as a fallback, so the cases formulation takes the minimum of the two options whenever the network is reachable.

Commune-level accessibility is the minimum cost to any active mine[6]:

$$A_{ct} = \min_{m \in \mathcal{M}t} C_{mct}$$

and department-level accessibility is the arithmetic mean across communes[7]:

$$\widetilde{A}_{d,t} = \frac{1}{|\mathcal{C}_d|} \sum_{c \in \mathcal{C}_d} A_{c,t}$$

The coal accessibility score is then the negative of the standardised value of this measure:

$$\text{Coal Accessibility}_{d,t} = -\frac{\widetilde{A}_{d,t} - \mu_A}{\sigma_A}$$

where μ_A and σ_A denote the mean and standard deviation of $\widetilde{A}_{d,t}$

The inclusion of both rail and waterway paths in the least-cost algorithm means the measure reflects the comparative advantage of each mode for bulk freight at each point in time, with canals tending to define least-cost paths in the early period and railways increasingly dominant as the network densified.

[6] See a visual representation across decades in Figure A.9.
[7] See a visual representation across decades in Figure A.10.

5.2 Knowledge diffusion and access to technical capabilities

The second channel through which infrastructure shaped steam adoption is less immediately visible than coal access, yet arguably no less important. The decision to adopt steam power was not triggered mechanically by relative input prices alone. Mechanisation required technical knowledge: knowledge of the technology itself, of its suitability for particular production processes, of how to install, operate, and maintain engines, and of where to obtain machinery, expertise, and skilled labour. These capabilities were unevenly distributed across the French territory, and one of the central effects of transport integration was to reduce the effective distance separating peripheral firms from their sources.

In nineteenth-century France, engineering knowledge of this kind was strongly institutionalised. The *grandes écoles* — and particularly those authorised to award the *titre d'ingénieur* — constituted the principal centres for the formation and dissemination of technical expertise relevant to industrial mechanisation. Their role extended far beyond formal teaching alone. Through alumni networks, state administrative functions, professional corps, and the industrial activities of their graduates, these institutions acted as nodes within a broader system of technical circulation linking the industrial economy to the scientific and engineering frontier (Day, 1978; Jarrige, 2021). The manuals and technical materials produced within these institutions explicitly addressed the industrial applications of steam technology and frequently framed mechanisation as a practical engineering solution to industrial production problems (Jacqmin, 1870).

This mechanism is particularly plausible in the French case because engineering expertise was strongly organised through state institutions, technical corps, and educational networks whose territorial influence remained geographically uneven. The expansion of transport infrastructure likely increased firms' exposure to centres of scientific and engineering competence both directly — through lower travel times — and indirectly through denser professional, commercial, and informational interactions. In this sense, infrastructure reduced not only transport frictions but also informational frictions that might otherwise have delayed or discouraged mechanisation in more peripheral territories.

The knowledge-access mechanism also helps explain why simple geographic distance remains insufficient as a measure of connectivity. Two departments located at comparable physical distance from major centres of expertise could nevertheless face radically different effective distances once actual transport conditions are taken into account. What infrastructure transformed was therefore not merely the map of transportation, but the geography of feasible interaction itself. By bringing firms into closer functional proximity with engineers, skilled workers, technical institutions, and early adopters, transport integration likely accelerated the recognition, adaptation, and practical implementation of steam technology across space.

More broadly, this interpretation highlights an important distinction between the diffusion of technology and the diffusion of the capabilities required to use that technology effectively. Steam engines could be purchased, but successful mechanisation also depended on access to maintenance knowledge, technical advice, engineering judgement, and skilled operational labour. The diffusion of steam power was therefore simultaneously a process of technological diffusion and a process of territorial learning.

A natural objection to this interpretation is that engineering institutions may themselves be endogenous to industrial development, since schools were often established in economically dynamic territories or in regions where the state anticipated industrial expansion. Several features of the institutional history nevertheless mitigate this concern. The oldest and most influential institutions — including the École Polytechnique, the École des Mines in Paris, and the earliest provincial mining schools — predated the major phase of steam diffusion and were founded primarily for reasons related to military organisation, state administration, and Napoleonic educational reform rather than immediate local industrial demand (Day, 1978). This is not to suggest that institutional geography was random. Paris, Lyon, and other major urban centres undoubtedly benefited from their economic and political importance. However, the timing and spatial distribution of engineering education were sufficiently shaped by broader administrative and state-building logics to generate meaningful variation in territorial exposure to technical expertise that cannot be reduced entirely to pre-existing industrial intensity.

The time-varying structure of our accessibility measure further strengthens this identification strategy. Exposure is assigned only from the year an institution begins operating and evolves according to changes in transport infrastructure and travel speeds over time. The resulting variation therefore exploits both the staggered territorial expansion of engineering capacity and the progressive reduction of effective travel times generated by railway integration. To operationalise this mechanism, we construct a departmental knowledge-accessibility score based on estimated travel times to the nearest open grande école awarding an engineering qualification. Commune-specific access time, $Access_{i,t}$ is defined as:

$$\text{Access}_{i,t} = \begin{cases} \dfrac{d_{i,g}}{v_w}, & \text{if no rail path to } g, \\ \min\left(\dfrac{d_{i,g}}{v_w}, \dfrac{d_{i,s}}{v_w} + \dfrac{d_{s,s_g}}{v_r} + \dfrac{d_{s_g,g}}{v_w}\right), & \text{otherwise.} \end{cases}$$

Here $d_{i,g}$ is the Euclidean distance between commune i and institution g; $d_{i,s}$ is the walking distance to the nearest active station; d_{s,s_g} is the rail distance to the station closest to g; and $d_{s_g,g}$ is the final walking segment. Walking speed v_w is fixed at 4 km/h and rail speed v_r is line-specific and varies by decade.

The department-level measure[8] is a population-weighted average:

$$\widetilde{K}_{d,t} = \frac{\sum_{i \in d} \left(\text{Pop}_{i,t} \cdot \text{Access}_{i,t}\right)}{\sum_{i \in d} \text{Pop}_{i,t}}$$

The knowledge accessibility score is defined as the negative of the standardised value of this measure:

$$\text{Knowledge Accessibility}_{d,t} = -\frac{\widetilde{K}_{d,t} - \mu_K}{\sigma_K}$$

where μ_K and σ_K denote the mean and standard deviation of $\widetilde{K}_{d,t}$ over the sample. As with the coal measure, this transformation ensures that higher values correspond to better accessibility,that is, shorter effective travel times to centres of technical expertise, while allowing direct comparison across specifications.[9] The score thus captures the reduction in effective distance to technical expertise generated by the joint expansion of engineering institutions and the railway network, and changes over time both as new schools open and as new rail connections reduce travel times to existing ones.

[8]See a visual representation across decades in Figure A.12

[9]We use $-\ln(\widetilde{K}_{d,t})$ as a robustness check, with consistent results (Table A.10).

5.3 Results: accessibility and steam adoption

We estimate the relationship between each accessibility measure and steam adoption intensity using the same panel structure as in the main specification. Because the principal variation in the accessibility scores occurs at a decadal frequency, however, we replace yearly fixed effects with decade fixed effects while retaining department fixed effects, the logarithm of population, and standard errors clustered at the departmental level. The raw infrastructure-stock variables used in Section 4 are replaced by the constructed accessibility measures in order to evaluate directly whether the infrastructural effects identified previously operate through the proposed mechanisms.

This framework allows us to assess whether the variation in mechanisation intensity associated with transport infrastructure is consistent with the mechanism-based interpretation developed throughout the paper. If connectivity mattered because it transformed access to fuel markets and engineering expertise, then departments experiencing improvements in coal accessibility and knowledge accessibility should display faster and more intensive steam adoption, over and above the direct infrastructural effects already identified in the baseline specifications.

This interpretation does not imply that infrastructure constituted the sole determinant of mechanisation. Local industrial structures, urbanisation, natural-resource endowments, commercial traditions, and pre-existing technical capabilities undoubtedly also shaped adoption trajectories. The argument advanced here is instead that connectivity played a central enabling role by transforming the economic and informational environment within which adoption decisions became feasible.

The results, reported graphically in Figure 2, support both channels and confirm that distinct dimensions of accessibility contributed to steam diffusion, although with different magnitudes and temporal profiles[10].

Coal accessibility displays a progressively strengthening association with mechanisation intensity throughout the second half of the nineteenth century. A one-standard-deviation improvement in coal accessibility is associated with approximately 1.78 additional steam engines per 10,000 inhabitants during the 1860s, rising to 2.22 during the 1870s, 3.11

[10]See Table A.9 for the complete results; consistent results for an alternative normalisation (with switched-polarisation of logarithms) are proposed in Table A.10

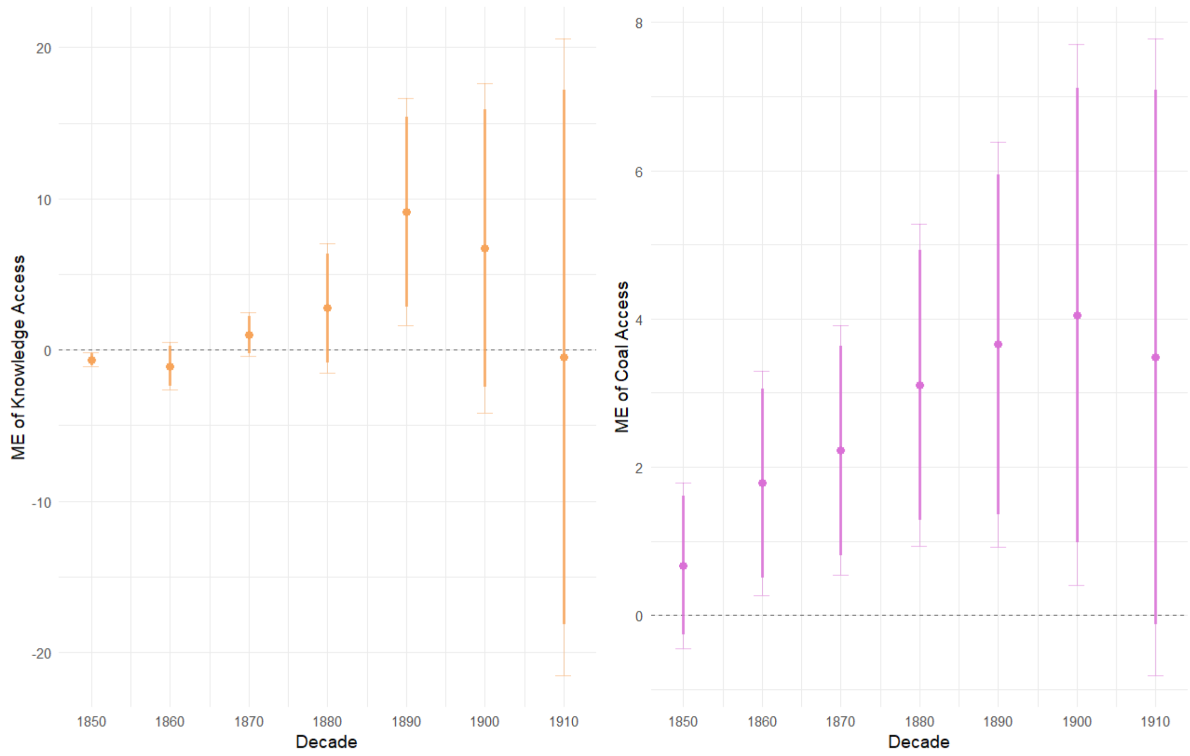

Figure 2: Decadal marginal effects of the Knowledge Access and Coal Access scores on steam engines per 10 k inh.; source: own elaborations on multiple sources, see text for more details

during the 1880s, 3.66 during the 1890s, and exceeding 4 additional engines per 10,000 inhabitants at the beginning of the twentieth century.

Knowledge accessibility follows a markedly different trajectory. Its effect becomes positive and statistically significant only during the 1890s[11], when a one-standard-deviation improvement in access to engineering expertise is associated, ceteris paribus, with an increase of approximately 9.1 steam engines per 10,000 inhabitants. Because both accessibility measures are expressed in standard deviations, the coefficients are directly comparable across channels and periods.

Taken together, these estimates suggest that coal accessibility constituted the more stable and continuously operative mechanism throughout the industrialisation process, particularly during the earlier phases of mechanisation when fuel costs represented a major constraint on adoption. Knowledge accessibility, by contrast, appears to have become in-

[11]The negative coefficient in the 1850s reflects the highly fragmented state of the railway network during this period, when the accessibility measure captures primarily proximity to Paris rather than genuine access to engineering expertise distributed across the territory. As both the rail network and the provincial grandes écoles expanded, the measure progressively shifted toward capturing meaningful reductions in effective distance to technical knowledge — consistent with the channel's emergence as significant only once that territorial expansion was sufficiently advanced.

creasingly important during the later stages of diffusion, once mechanisation itself became more technologically complex and more dependent on engineering expertise, maintenance capabilities, and technical coordination.

The more limited statistical precision associated with the knowledge-accessibility estimates likely reflects the intrinsic difficulty of isolating informational spillovers from the correlated effects of market integration in a context where engineering institutions and industrial centres were themselves unevenly distributed across the territory. This limitation does not invalidate the existence of a substantive knowledge channel. Rather, it reflects the limits of identification achievable using departmental-level variation in a highly interconnected process of industrial transformation. Importantly, the directional consistency of the knowledge-accessibility estimates across specifications strongly supports the broader interpretation advanced in this paper.

The temporal sequencing of the two accessibility channels — coal accessibility becoming significant from the 1860s onward, while knowledge accessibility emerges only during the 1890s — reflects an important substantive feature of how steam technology diffused as it matured and of how the institutional environment supporting mechanisation evolved alongside it.

During the early and intermediate phases of diffusion, the principal constraint facing less-connected departments was the cost of fuel. Steam engines consumed large quantities of coal, and the effective delivered price of coal largely determined whether mechanisation was economically viable. Infrastructure capable of reducing freight costs — initially navigable waterways and progressively railways — therefore relaxed a binding operational constraint directly affecting the profitability of adoption. This helps explain why the coal-accessibility channel appears early and remains relatively stable throughout the entire period.

By the final decades of the nineteenth century, however, two reinforcing transformations altered the relative importance of the knowledge-accessibility channel.

The first transformation was technological. The spread of high-pressure engines and the progressive integration of steam power with early electrical-generation systems required substantially greater engineering expertise than the comparatively simple low-pressure engines characterising earlier phases of mechanisation. The marginal adopter of the 1890s therefore faced a considerably more technically demanding decision than the marginal adopter of the 1860s. Successful mechanisation increasingly depended not only on access to fuel, but also on access to trained engineers capable of specifying, installing, adapting, and maintaining more complex industrial systems.

The second transformation was institutional. The economic dislocation of the 1880s exposed the fragility of departments that remained only weakly integrated into national industrial networks. One response — both from the state and from regional authorities — was the deliberate expansion of applied engineering education into provincial centres. In this context, the grandes écoles and associated engineering institutes did not function merely as passive repositories of technical knowledge. They became active instruments of territorial modernisation by equipping regional economies with the engineering capabilities required to industrialise, adapt, and recover (Fox and Weisz, 2020; Day, 1978).

The expansion of engineering institutions into cities such as Grenoble, Nancy, Lille, and Toulouse during the Belle Époque should therefore not be interpreted solely as a passive response to existing industrial demand. It also reflected a broader effort to create the institutional conditions necessary for industrial modernisation in territories that had previously lagged behind. Transport infrastructure played a crucial enabling role in this process. Railway integration reduced the effective distance between these emerging centres of expertise and the firms requiring technical assistance, thereby transforming the geographical expansion of engineering education into a practical reduction in the cost of accessing industrial knowledge across the territory.

The growing importance of knowledge accessibility from the 1890s onward therefore reflects the convergence of these two transformations: a technology becoming progressively more knowledge-intensive meeting an institutional landscape increasingly organised to diffuse technical expertise beyond the traditional industrial core. Infrastructure mattered throughout the diffusion process, but it mattered for different reasons at different moments. The significance of the 1890s lies precisely in the fact that the knowledge-accessibility channel became sufficiently important to emerge clearly in the empirical results.

To illustrate more concretely how cross-sectional variation in accessibility translated into differences in mechanisation intensity, Figure 3 presents predicted levels of steam adoption

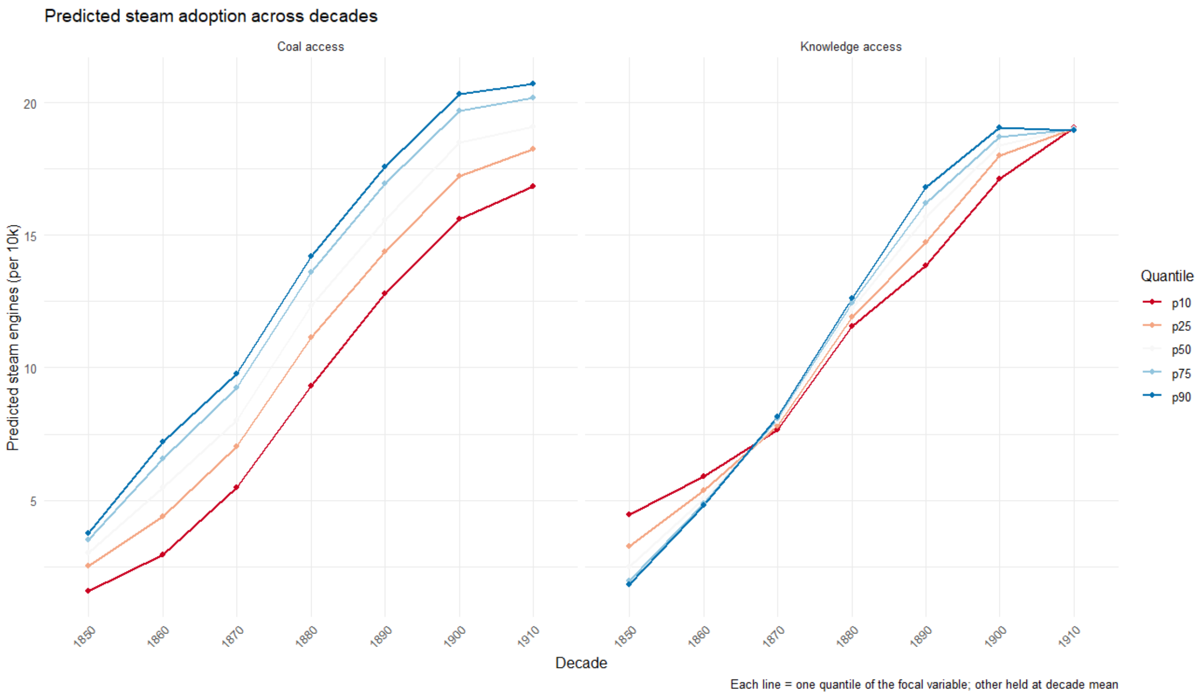

Figure 3: Decadal predictions of steam engines per 10k inh. based on the quantile distribution of the Knowledge Access and Coal Access scores, holding the other at their decadal mean level; source: own elaborations of multiple sources, see text for mre details

across accessibility quantiles by decade, holding the alternative accessibility measure at its decadal mean. The results reveal clear and distinct patterns across the two channels.

Because the estimated effect of knowledge accessibility emerges relatively late, substantial differences between quantiles become visible only during the 1890s. During this decade, the gap between the least and most well-connected departments in terms of engineering accessibility reaches approximately three additional steam engines per 10,000 inhabitants, holding coal accessibility constant at its decadal mean.

The coal-accessibility channel displays a stronger and more persistent gradient throughout the period. Departments enjoying better access to coal markets consistently exhibit approximately five additional steam engines per 10,000 inhabitants relative to less-connected territories, ceteris paribus. These differences reinforce the interpretation advanced throughout this section: transport infrastructure altered mechanisation not only through generic improvements in connectivity, but by reshaping the territorial accessibility of the economic and technical resources required for industrial adoption.

6 Robustness checks

We subject the main findings to a series of robustness checks addressing the measurement of steam adoption, the specification of the lag structure, the possibility of anticipatory investment, and the presence of spatial spillovers. Taken together, these exercises aim to assess whether the relationship identified between transport infrastructure and mechanisation reflects a stable and substantively meaningful diffusion process rather than a consequence of a particular modelling choice.

Our baseline dependent variable — steam engines per 10,000 inhabitants — captures the territorial intensity of mechanisation in a transparent and comparable way across departments of different demographic sizes. Nevertheless, this measure does not account for differences in engine size or productive capacity. We therefore consider two alternative specifications.

First, we replace the engine count with installed horsepower per 10,000 inhabitants, introducing decadal interactions in order to accommodate the additional volatility present in the horsepower series. The resulting estimates, reported in Figure A.8, remain fully consistent with the baseline interpretation. The marginal effects of railway expansion remain positive throughout the period and become statistically significant during the final decades of the sample, when mechanisation increasingly involved larger and more technically sophisticated installations.

Second, we estimate a fixed-effects negative binomial specification using the raw number of steam engines per department. This model is particularly appropriate for count data characterised by substantial overdispersion and provides an additional test focused on the extensive margin of adoption. The corresponding yearly marginal effects, presented in Figure A.7, display the same temporal profile and sign structure as the baseline results, confirming that the central findings do not depend on a particular operationalisation of mechanisation intensity.

To evaluate more directly the possibility of reverse causality — namely that railway construction occurred preferentially in departments already following faster industrial trajectories — we augment the baseline specification with one- and two-period leads of the railway and waterway variables. The estimated lead coefficients are individually small and statistically insignificant (Table A.6) Although the joint F-test rejects the null hypothesis at the 5% level (F=2.46, p=0.044), the lead coefficients themselves are negative and economically negligible, which is difficult to reconcile with a genuine anticipation mechanism whereby future railway construction would simply follow pre-existing adoption trends. We therefore interpret the joint significance result as more likely reflecting multicollinearity among the lead variables than substantive anticipatory effects.

Extending the lag structure to two and five years further reinforces this interpretation. In these specifications, the onset of statistically significant railway effects shifts toward earlier calendar years (Figure A.6), consistent with the idea that sustained and reliable railway integration — rather than the mere arrival of an isolated first line — was what ultimately triggered irreversible investment in steam-intensive production systems.

Finally, we investigate the possibility of spatial spillovers by replacing own departmental railway stock with the average railway density of neighbouring departments in an otherwise identical specification. The results, reported in the spatial first-differences table in the Appendix (Table 6), reveal a positive and statistically significant spillover effect. Departments surrounded by territories experiencing more rapid railway expansion also display faster steam adoption, even after controlling for their own infrastructure levels. This result is particularly important for the interpretation of the paper. It suggests that the diffusion of mechanisation followed the broader structure of territorial connectivity rather than responding exclusively to local industrial characteristics. Railway integration generated benefits extending beyond departmental borders through wider processes of market integration, informational circulation, and interregional interaction. More fundamentally, the presence of these spillovers reinforces the interpretation of transport infrastructure as a network mechanism transforming the geography of industrial feasibility across France.

Taken together, the robustness checks strongly support the central argument advanced throughout the paper. The relationship between infrastructure and mechanisation remains stable across alternative measures of adoption, alternative temporal specifications, and alternative spatial structures. The evidence therefore points consistently toward a process in which transport integration reshaped the territorial conditions under which steam technology could diffuse across nineteenth-century France.

Conclusion

This paper has examined the diffusion of steam power across French departments between 1840 and 1911 and has shown that the spread of this general-purpose technology was both gradual and profoundly uneven across space. By combining a newly constructed annual departmental panel with diffusion modelling and panel econometrics, we document substantial territorial heterogeneity in the timing, speed, and intensity of mechanisation. Steam diffusion in nineteenth-century France did not unfold as a uniform national transition. Rather, it proceeded through a sequence of spatially differentiated industrial trajectories shaped by unequal conditions of connectivity and access.

Our results identify transport infrastructure as a central mechanism structuring this process. Departments integrated earlier and more effectively into railway and navigable-waterway networks experienced faster and more intensive adoption of steam technology, although the relative importance of different transport systems evolved significantly over time. Waterways provided an early and persistent infrastructural foundation, particularly in sectors where access to bulky inputs such as coal remained crucial. Railways, however, became progressively more decisive as the national network expanded, densified, and integrated regional markets into an increasingly unified economic space.

More fundamentally, the findings suggest that infrastructure mattered not simply because it facilitated the movement of goods in a narrow sense, but because it transformed the broader economic and technical conditions under which mechanisation became profitable and feasible. By reducing freight costs, expanding market accessibility, lowering informational frictions, and strengthening access to engineering expertise, transport networks altered the territorial geography of industrial possibility itself.

The mechanism-based analysis reinforces this interpretation. Coal accessibility emerges as a stable and continuously important determinant of mechanisation throughout the second half of the nineteenth century, reflecting the central role of fuel costs in shaping the profitability of steam adoption. Knowledge accessibility, by contrast, becomes significant only during the later stages of industrialisation, when steam technology itself had become more technically demanding and when the expansion of engineering institutions increasingly connected peripheral territories to centres of scientific and industrial expertise. The temporal sequencing of these channels suggests that the conditions supporting technological diffusion evolved alongside the maturation of the technology itself.

More broadly, the paper contributes to the historiography of French industrialisation by offering a more spatially differentiated interpretation of nineteenth-century economic development. The evidence does not support a simple narrative of uniform backwardness or delayed industrialisation. Instead, it points toward a territorially uneven process in which some departments entered the age of mechanised production substantially earlier than others and in which connectivity played a decisive role in structuring these divergences. In this perspective, France appears less as a uniformly "slow" industrialiser than as a country marked by strong regional inequalities in access to the infrastructures, markets, and technical capabilities required for industrial modernity.

The paper also contributes to the broader literature on the diffusion of general-purpose technologies. Steam power did not spread automatically once invented, nor did diffusion depend solely on factor prices or local resource endowments. Adoption depended critically on the territorial infrastructures that linked firms to fuel markets, commercial networks, engineering expertise, and systems of technical circulation. Understanding technological diffusion therefore requires attention not only to prices and aggregate growth trajectories, but also to the spatial organisation of economic and institutional life.

In nineteenth-century France, infrastructure was not merely a consequence of industrialisation. It was one of the mechanisms through which industrialisation itself became territorially possible.

Appendix

Table A.1: Summary table with available information concerning steam engines' counts and horse power installed in selected countries according to multiple sources (see Notes)

Period	UK	US	Germany	Belgium	France	Netherlands
1700–1800	2,191 built 1,000 in use 10,000 hp	1 engine (RI, 1776)	1st German-built (1791)	67 engines (61: mines)		<5 engines
1830s	59,000 hp (textiles)	1,420 (manufact.)	231 3,670 hp	1,044	38,173 hp	293 4,000 hp
1840s			26,400 hp	38,000 hp	2,901 37,296 hp	
1850s	487,500– 500,000 hp	8,598 181,000 hp		2,013 50,436 hp	5,489 66,552 hp	
1860s		25,577 806,500 hp			14,875 34,883 hp	
1870	3,297,150 hp	40,191 1,215,711 hp			27,921 336,031 hp	
1875			28,783 632,067 hp		32,079 400,756 hp	
1890					58,917 863,007 hp	
1900		155,724 (manufact.)			74,879 116,704 hp	

Notes: Information for UK comes from Landes (1969), Nuvolari et al. (2011) and Bottomley (2024); for USA from Atack et al. (1980); for France from Le Chapelain and Wilke (2025, same panel as us) and Landes (1969); for Germany from Landes (1969) and Becker et al. (2026); for Belgium and the Netherlands from Lintsen (1991) for information on ordered Boulton and Watt engines (1775-1825) see Tann and Breckin (1978)

Data cartography

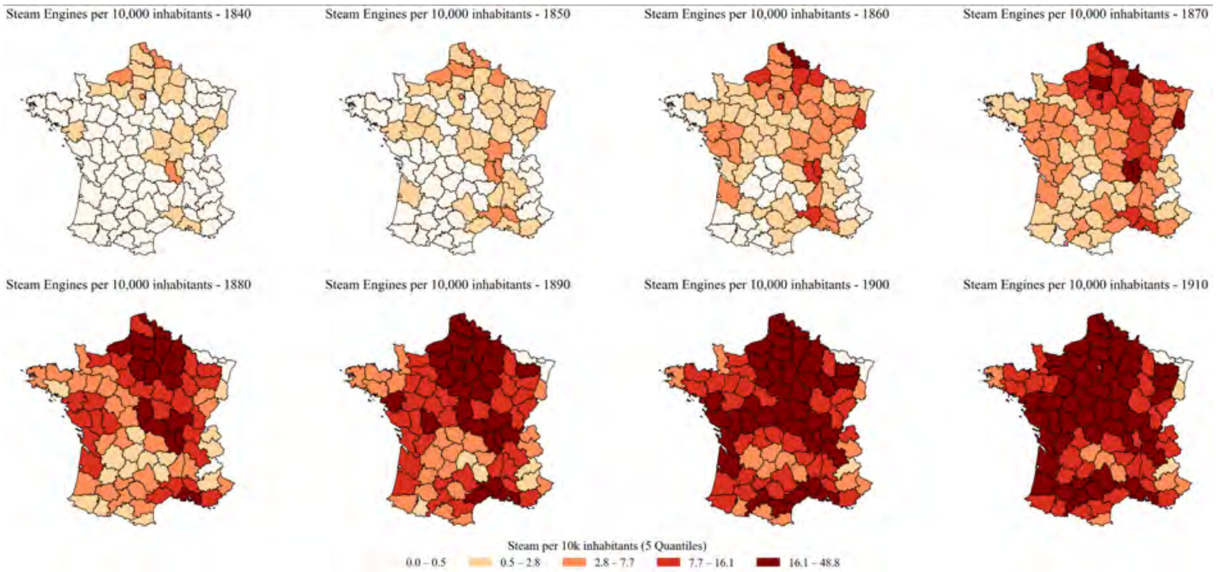

Figure A.1: Steam engines per 10k inhabitants for selected years - own elaborations on steam engines' panel and census data (interpolation), map of 1870's departments from Gay (2020)

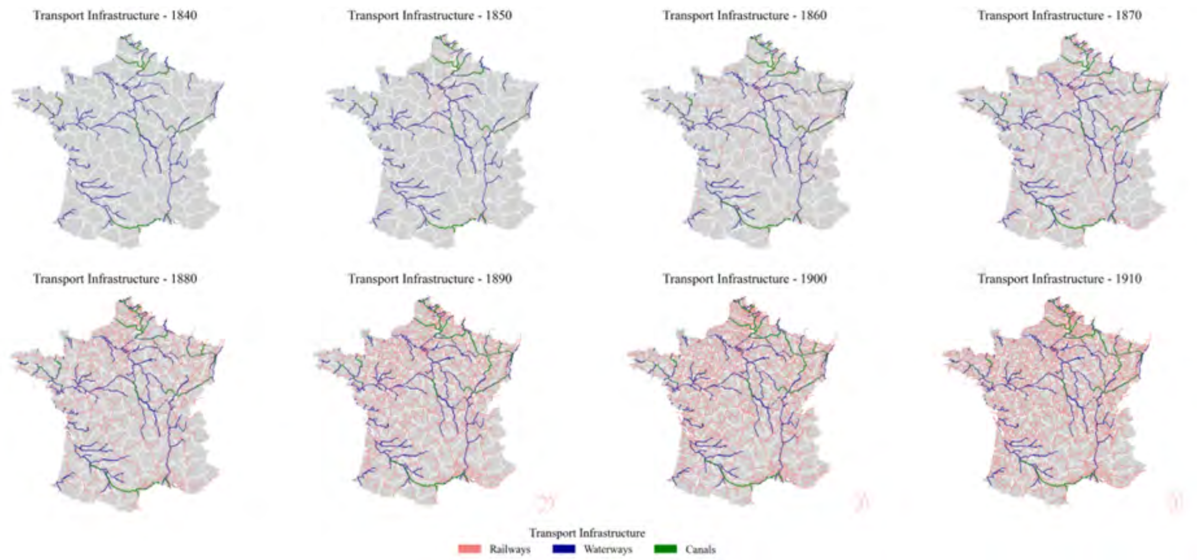

Figure A.2: Transport infrastructure's development (railways and navigable waterways) for selected years - own elaborations on COMMUNES data, map of 1870's departments from Gay, 2020

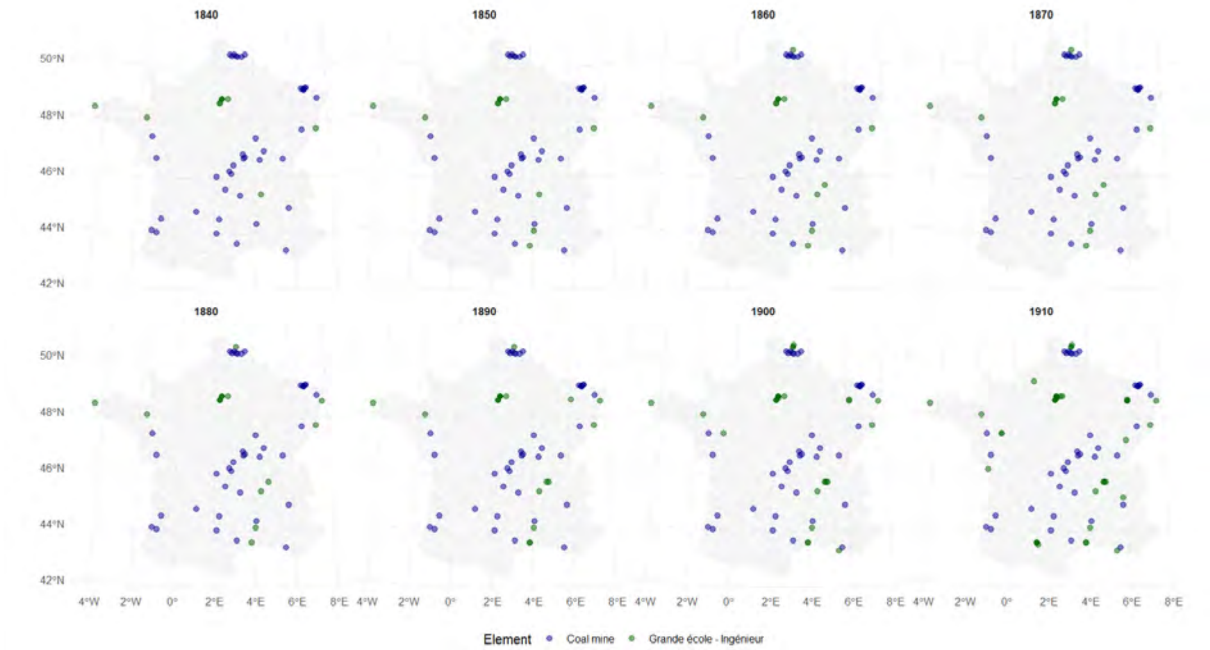

Figure A.3: Geo-localisation of engineering schools (grandes écoles awarding ingénieur title) and coal mines for selected years - own elaborations on COMMUNES data (mines) and CGE website (grandes écoles), maps of 1870's department from Gay (2020)

Complete results of the diffusion modeling

Table A.2: Estimated logistic and Gompertz diffusion parameters for steam-engine adoption by department. Columns report maximum capacity, inflection point, take-off year, estimated adoption rate, diffusion duration Δ_t, model fit (R^2), and compound annual growth rate (CAGR). Source: authors' calculations based on multiple historical datasets (see text).

Department	Maximum capacity	Midpoint / Inflection (b)	Take-off	Adoption rate % (a)	Δ_t	R^2	CAGR %	Model
Allier	1649	1892	1863	7.405	59.348	0.98	6.571	Logistic
Aube	675	1876	1861	14.624	30.049	0.992	7.936	Logistic
Aude	543	1883	1876	31.944	13.757	0.984	9.097	Logistic
Aveyron	845	1889	1864	8.902	49.362	0.993	7.002	Logistic
Bouches-du-Rhône	1796	1877	1853	9.241	47.554	0.987	5.61	Logistic
Cantal	224	1899	1879	11.253	39.052	0.993	43.914	Logistic
Charente-Inférieure	1154	1888	1865	9.85	44.616	0.991	9.17	Logistic
Cher	1002	1879	1862	12.716	34.558	0.986	6.803	Logistic
Corrèze	281	1898	1878	11.247	39.07	0.994	44.605	Logistic
Côte-d'Or	630	1873	1849	9.303	47.238	0.993	5.024	Logistic

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Table A.2 (continued)

Department	Maximum capacity	Midpoint / Inflection (b)	Take-off	Adoption rate % (a)	Δ_t	R^2	CAGR %	Model
Côte-du-Nord	1403	1900	1879	10.344	42.482	0.997	10.217	Logistic
Dordogne	583	1897	1878	11.734	37.45	0.995	9.116	Logistic
Doubs	466	1883	1854	7.371	59.62	0.991	4.795	Logistic
Drôme	591	1885	1859	8.343	52.67	0.99	6.255	Logistic
Garonne (Haute)	977	1886	1867	11.551	38.045	0.995	8.055	Logistic
Gers	729	1906	1881	8.811	49.872	0.989	8.955	Logistic
Gironde	1875	1890	1862	8.008	54.878	0.993	6.522	Logistic
Hérault	807	1877	1864	17.681	24.854	0.97	5.831	Logistic
Loire (Haute)	624	1906	1880	8.439	52.071	0.995	5.702	Logistic
Loire-Inférieure	1645	1883	1859	9.139	48.084	0.982	4.872	Logistic
Lot-et-Garonne	407	1898	1870	8.013	54.843	0.991	45.121	Logistic
Manche	1478	1919	1883	6.137	71.609	0.99	7.164	Logistic
Marne	890	1871	1854	13.205	33.277	0.995	4.263	Logistic
Marne (Haute)	392	1867	1855	18.768	23.415	0.964	7.617	Logistic
Meurthe (avec Moselle, 1871)	1635	1887	1866	10.541	41.688	0.995	7.584	Logistic
Moselle	418	1859	1846	17.658	24.886	0.992	11.566	Logistic
Nièvre	675	1877	1855	10.279	42.753	0.965	5.363	Logistic
Oise	2305	1880	1858	10.019	43.863	0.962	6.69	Logistic
Pas-de-Calais	4032	1889	1860	7.6	57.82	0.988	5.99	Logistic
Pyrénées (Basses)	669	1897	1881	13.321	32.989	0.997	46.331	Logistic
Pyrénées (Hautes)	260	1897	1881	13.001	33.8	0.995	44.415	Logistic
Pyrénées-Orientales	133	1883	1877	33.505	13.116	0.991	43.616	Logistic
Rhin (Bas)	782	1871	1856	14.271	30.793	0.992	10.901	Logistic
Rhône	1923	1863	1844	11.653	37.712	0.864	3.906	Logistic
Saône-et-Loire	1999	1875	1853	9.873	44.508	0.997	4.474	Logistic
Sarthe	1608	1905	1873	6.924	63.463	0.995	7.094	Logistic
Seine	5912	1868	1846	9.8	44.84	0.992	3.768	Logistic
Seine-et-Oise	1771	1875	1857	12.213	35.981	0.985	5.488	Logistic
Seine-Inférieure	2133	1869	1837	6.804	64.584	0.987	2.928	Logistic
Somme	1906	1875	1853	10.082	43.585	0.994	5.403	Logistic
Tarn	868	1899	1875	9.008	48.784	0.997	7.3	Logistic

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Table A.2 (continued)

Department	Maximum capacity	Midpoint / Inflection (b)	Take-off	Adoption rate % (a)	Δ_t	R^2	CAGR %	Model
Vaucluse	427	1876	1848	7.868	55.854	0.98	7.63	Logistic
Vienne (Haute)	554	1891	1874	13.175	33.353	0.996	46.39	Logistic
Vosges	1051	1883	1859	9.357	46.966	0.969	7.784	Logistic
Yonne	943	1887	1867	11.163	39.367	0.995	47.409	Logistic
Ain	787	1871	1856	5.699	54.119	0.975	8.143	Gompertz
Aisne	2528	1872	1854	4.811	64.108	0.99	5.011	Gompertz
Alpes (Basses)	6306	2081	1985	0.87	354.487	0.977	42.207	Gompertz
Alpes (Hautes)	139	1934	1897	2.241	137.638	0.934	40.464	Gompertz
Alpes-Maritimes	339	1887	1869	4.411	69.923	0.955	44.195	Gompertz
Ardèche	720	1882	1855	3.131	98.513	0.975	6.205	Gompertz
Ardennes	1304	1868	1854	6.078	50.744	0.996	5.25	Gompertz
Ariège	217	1884	1873	7.972	38.69	0.961	44.498	Gompertz
Calvados	1601	1905	1865	2.094	147.263	0.985	4.743	Gompertz
Charente	2422	1917	1882	2.39	129.034	0.997	9.752	Gompertz
Creuse	2334	1927	1895	2.654	116.217	0.998	46.1	Gompertz
Eure	2049	1889	1864	3.232	95.438	0.994	6.282	Gompertz
Eure-et-Loir	952	1880	1869	7.562	40.786	0.991	7.069	Gompertz
Finistère	1453	1903	1879	3.449	89.43	0.982	7.345	Gompertz
Gard	11369	1986	1903	1.013	304.573	0.975	4.061	Gompertz
Ille-et-Villaine	1630	1897	1869	2.969	103.899	0.993	8.861	Gompertz
Indre	1248	1891	1877	6.171	49.978	0.996	7.937	Gompertz
Indre-et-Loire	2325	1904	1878	3.247	94.988	0.997	7.289	Gompertz
Isère	1568	1881	1861	4.219	73.113	0.991	7.551	Gompertz
Jura	406	1870	1859	7.047	43.771	0.992	7.037	Gompertz
Landes	3547	1929	1894	2.366	130.34	0.991	46.877	Gompertz
Loire	5319	1904	1856	1.73	178.307	0.976	2.963	Gompertz
Loiret	1687	1888	1869	4.31	71.572	0.981	7.31	Gompertz
Loir-et-Cher	1129	1899	1875	3.412	90.398	0.992	9.431	Gompertz
Lot	318	1889	1877	7.546	40.876	0.986	44.924	Gompertz
Maine-et-Loire	1893	1895	1863	2.562	120.381	0.993	5.687	Gompertz
Mayenne	702	1889	1861	2.948	104.627	0.987	5.716	Gompertz
Meuse	424	1867	1856	7.418	41.581	0.986	6.536	Gompertz
Morbihan	2033	1907	1884	3.57	86.395	0.996	8.841	Gompertz
Nord	8099	1867	1847	4.271	72.226	0.993	3.76	Gompertz
Orne	1641	1909	1879	2.805	109.943	0.992	7.513	Gompertz

Continued on next page

Table A.2 (continued)

Department	Maximum capacity	Midpoint / Inflection (b)	Take-off	Adoption rate % (a)	Δ_t	R^2	CAGR %	Model
Puy-de-Dôme	1880	1914	1874	2.117	145.666	0.994	5.799	Gompertz
Saône (Haute)	1545	1921	1871	1.646	187.381	0.98	4.407	Gompertz
Savoie	338	1892	1877	5.367	57.468	0.995	9.16	Gompertz
Savoie (Haute)	362	1887	1875	7.118	43.334	0.987	7.855	Gompertz
Seine-et-Marne	1601	1872	1860	6.969	44.257	0.99	8.046	Gompertz
Sèvres (Deux)	1799	1900	1869	2.72	113.387	0.992	8.944	Gompertz
Tarn-et-Garonne	397	1882	1869	6.252	49.338	0.996	6.907	Gompertz
Var	506	1874	1862	6.93	44.511	0.961	5.409	Gompertz
Vendée	1617	1885	1860	3.406	90.569	0.989	8.621	Gompertz
Vienne	1274	1886	1875	7.371	41.847	0.997	10.328	Gompertz
TOTAL	93268	1883	1854	7.567	58.072	0.998	5.022	Logistic

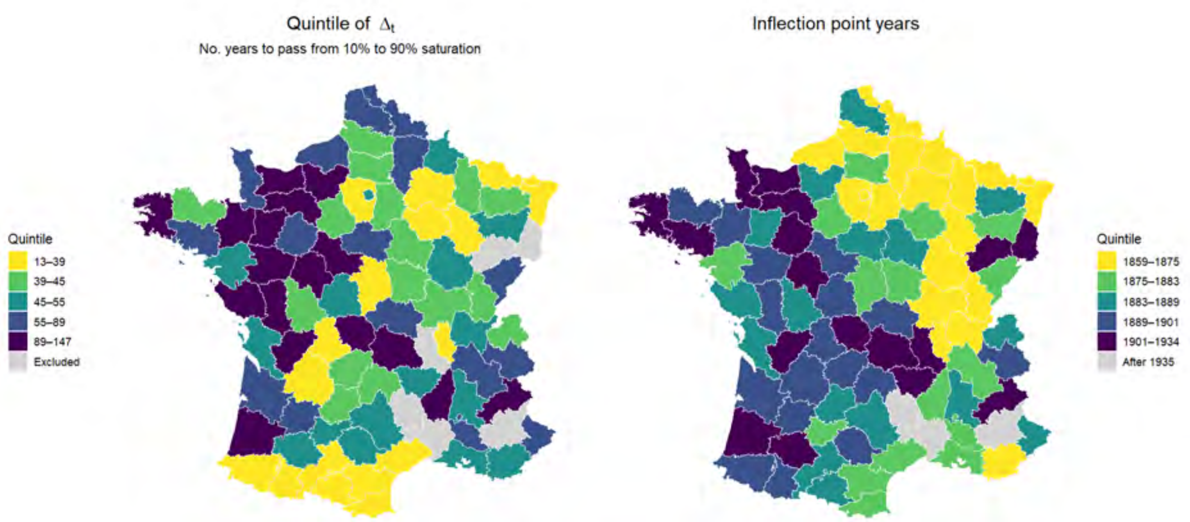

Figure A.4: French departments maps of Δ_t (sx) and midpoints years (dx); source: own elaborations on steam engine panel by Le Chapelain and Wilke (2025); base map of French departments in 1770 by Gay (2022)

Straight-line synthetic network

The simultaneous reading of the Legrand Plan, the Migneret Law, and the Freycinet Plan guided the construction of the synthetic railway network at each stage of its development.

The resulting network closely resembles that obtained by Tsiachtsiras (2025), while remaining grounded in the engineering and territorial logic underlying nineteenth-century French railway planning.

For the period 1840–1850, the synthetic network consists primarily of radial lines departing from Paris toward the principal regional centres of France. These centres include Lille, Amiens, Rouen, Caen, Rennes, Nantes, Angers, Tours, Orléans, Reims, Nancy, Strasbourg, Dijon, Besançon, Clermont-Ferrand, Lyon, Marseille, Montpellier, Toulouse, Bordeaux, Poitiers, and Limoges. This initial configuration reflects the highly centralised logic of the early railway system, which was designed to integrate major administrative and economic centres into a national network structured around Paris.

Between 1850 and 1860, the network expands toward major ports and customs centres. These locations are identified using a distance rule based on departmental chefs-lieux, the French ports recorded in the COMMUNES project, and the customs centres identified through the cartographic material presented in Lévêque et al. (2024). This second stage captures the increasing importance of maritime trade integration and external commercial connectivity within the broader development of the railway system.

For the period 1860–1870, the synthetic network is extended using a minimum spanning tree (MST) connecting the major regional centres, ports, customs centres, and the remaining departmental *chefs-lieux*. This phase reflects the progressive densification of the national transport system and the growing objective of territorial integration beyond the initial radial structure centred on Paris.

The next stage, corresponding broadly to the 1880s and associated with the Freycinet era, introduces a finer level of territorial disaggregation by incorporating arrondissement *chefs-lieux*. These additional nodes are connected to the nearest point on the pre-existing network linking already integrated centres. This phase captures the transition toward a more locally articulated railway geography aimed at extending connectivity into secondary and peripheral territories.

The final stage of the network construction involves a second minimum spanning tree applied to the complete set of nodes identified during the previous phases. The resulting synthetic network therefore reproduces the successive territorial logics underlying nineteenth-century French railway expansion: initial centralisation around Paris, integration of strategic commercial and maritime centres, progressive territorial densification, and eventual extension toward more peripheral administrative units.

The result of this process is graphically visible in Figure A.5 and in Table A.3.

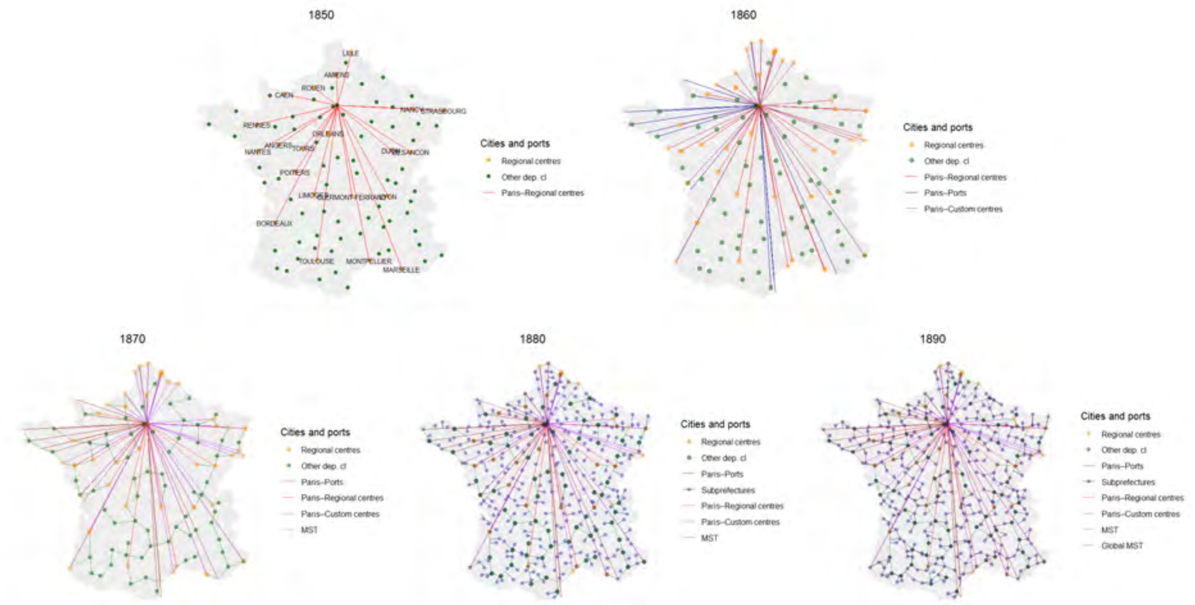

Figure A.5: Evolution across time of the straight-line synthetic network used as IV in the analyses - own elaborations on the basis of the Migneret Law, the Freycinet Plan and the Legarand Plan

Table A.3: Estimation of the first stage of the 2SLS: use of the synthetic network measures to estimate RailStock and RailDensity - source: own estimation

	Dependent variable:	
	RailStock	RailDensity
	(1)	(2)
IV_RailStock	0.001***	
	(0.0004)	
IV_RailDensity		0.115***
		(0.011)
Constant	−159.011***	−2.647***
	(8.421)	(0.089)
Department FE	Yes	Yes
Year FE	Yes	Yes
Observations	440	440
R^2	0.865	0.935
Adjusted R^2	0.830	0.919
Residual Std. Error (df = 350)	0.776	0.013
F Statistic (df = 89; 350)	25.116***	56.695***
Note:	*p<0.1; **p<0.05; ***p<0.01	

Complete estimates and robustness checks

Main specification and all considered lags: 1y, 2y and 5y

Table A.4: Overall coefficients of the main specification, yearly marginal effects of interest variables in Table A.5; source: own elaborations on multiple sources, see text for more details

	Model Rail + Water			Model Rail + Canal
	Lag 1	Lag 2	Lag 5	Lag 1
Communes w/ stations	2.327	2.111	1.970	3.925
	(3.836)	(3.768)	(3.634)	(3.895)
Communes w/ ports	-75.926	-75.936	-83.053	-6.659
	(82.916)	(84.514)	(91.623)	(80.017)
Waterway density	-8.604*	-8.951*	-9.897*	-1.024
	(4.438)	(4.543)	(4.989)	(3.486)
log(Population)	-4.261	-4.756	-6.273	-7.526
	(5.060)	(5.076)	(5.064)	(4.613)
Observations	5280	5192	4928	5280
R^2	0.886	0.888	0.893	0.886
Within R^2	0.293	0.289	0.280	0.293
Département FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Year interactions	Yes	Yes	Yes	Yes

*Significance levels: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$; Clustered SEs at the département level; Year-specific interactions for lags 2 and 5 are estimated but reported graphically (Figure A.6). The estimation of the yearly marginal effects for lag 1 (the main specification) is in Table A.5 together with yearly marginal effects of the model with canal measures instead of general waterway measures*

Table A.5: Marginal effects by year of Rail, Water, and Canal variables on steam engines per 10k inhabitants; variables lagged one year; standard errors clustered at department level

	Model A: Rail + Water		Model B: Rail + Canal	
Year	Rail	Water	Rail	Canal
1851	5.3705 (3.8187)	17.4688** (7.5522)	5.8853 (3.8131)	-2.4576 (3.8806)
1852	5.4422 (3.7774)	17.4015** (7.5614)	5.9080 (3.7555)	-2.5288 (3.8706)
1853	5.4845 (3.7623)	17.4162** (7.5561)	5.8923 (3.7366)	-2.5658 (3.8854)
1854	5.5517 (3.7430)	17.4347** (7.5965)	5.9156 (3.6938)	-2.2584 (3.8405)
1855	5.5182 (3.6924)	17.4917** (7.5906)	5.8770 (3.6336)	-2.1639 (3.8245)
1856	5.5085 (3.6445)	17.5546** (7.5763)	5.8652 (3.5756)	-1.9812 (3.7700)
1857	5.4844 (3.6053)	17.6716** (7.5468)	5.8876* (3.5129)	-1.7594 (3.7112)
1858	5.5465 (3.5445)	17.6735** (7.5421)	5.9169* (3.4526)	-1.7271 (3.6774)

1859	5.6036 (3.4844)	17.6613** (7.5225)	5.9695* (3.3983)	-1.6551 (3.6672)
1860	5.6258 (3.4215)	17.6153** (7.5174)	5.9480* (3.3415)	-1.5955 (3.6551)
1861	5.6508* (3.3543)	17.6430** (7.5123)	5.9774* (3.2830)	-1.4571 (3.6281)
1862	5.8059* (3.3436)	17.6087** (7.5142)	6.0977* (3.2773)	-1.3375 (3.6101)
1863	5.9519* (3.3438)	17.6102** (7.5184)	6.2677* (3.2779)	-1.4237 (3.6180)
1864	6.1037* (3.3578)	17.6366** (7.5149)	6.4293* (3.2853)	-1.3894 (3.6059)
1865	6.2526* (3.3513)	17.6416** (7.5103)	6.5367** (3.2806)	-1.1137 (3.5493)
1866	6.4292* (3.3398)	17.6435** (7.5101)	6.7155** (3.2730)	-1.1104 (3.4958)
1867	6.4608* (3.3259)	17.7865** (7.5417)	6.8204** (3.2502)	-0.5952 (3.4030)
1868	6.6725** (3.3156)	17.7214** (7.5361)	6.9859** (3.2492)	-0.5336 (3.3826)
1869	6.7836** (3.3061)	17.7715** (7.5353)	7.1056** (3.2433)	-0.3552 (3.3656)
1870	6.8138** (3.2979)	17.8256** (7.5406)	7.1498** (3.2368)	-0.1719 (3.3557)
1871	6.6541** (3.1981)	17.9091** (7.4973)	7.1046** (3.1837)	-0.6571 (3.3159)
1872	6.7736** (3.1935)	17.9839** (7.4980)	7.2179** (3.1817)	-0.3450 (3.2980)
1873	7.0318** (3.1838)	17.9561** (7.4950)	7.4391** (3.1842)	-0.2672 (3.2860)
1874	7.2257** (3.1750)	17.8906** (7.4977)	7.5848** (3.1837)	-0.2020 (3.2805)
1875	7.3411** (3.1710)	17.8581** (7.4811)	7.6842** (3.1942)	-0.1109 (3.2712)
1876	7.4805** (3.1735)	17.9360** (7.4287)	7.8304** (3.1985)	0.2257 (3.3170)
1877	7.5628** (3.1723)	18.0185** (7.4219)	7.9574** (3.1961)	0.2087 (3.3368)
1878	7.6543** (3.1672)	18.0835** (7.4136)	8.0834** (3.2038)	0.3022 (3.3178)
1879	7.7127** (3.1586)	18.3329** (7.4328)	8.3573*** (3.2106)	0.0238 (3.3729)
1880	7.9067** (3.1538)	18.2866** (7.4194)	8.5530*** (3.2150)	-0.1302 (3.3839)
1881	8.0051** (3.1453)	18.2453** (7.3978)	8.6253*** (3.2171)	0.0775 (3.3517)
1882	8.1769*** (3.1264)	18.2269** (7.3897)	8.8120*** (3.2228)	0.0433 (3.3327)
1883	8.2491*** (3.1137)	18.2910** (7.3846)	8.9026*** (3.2137)	0.5570 (3.3077)
1884	8.3024*** (3.1016)	18.3642** (7.3627)	8.9653*** (3.2122)	0.9924 (3.3193)
1885	8.2181*** (3.1037)	18.2214** (7.3636)	8.7319*** (3.1874)	1.3878 (3.2969)
1886	8.5042*** (3.0932)	17.9784** (7.3775)	8.9320*** (3.1756)	1.1663 (3.2896)
1887	8.5516*** (3.0824)	17.9661** (7.3803)	8.9588*** (3.1681)	1.1586 (3.3123)
1888	8.5841*** (3.0617)	17.9311** (7.3849)	8.9374*** (3.1326)	1.4875 (3.2454)
1889	8.6762*** (3.0574)	17.9891** (7.3762)	9.0658*** (3.1350)	1.6083 (3.2531)
1890	8.8835*** (3.0533)	17.9080** (7.3891)	9.2605*** (3.1315)	1.4534 (3.2680)
1891	8.6289*** (3.0633)	18.0192** (7.3706)	9.0366*** (3.1293)	1.5434 (3.3017)
1892	8.6128*** (3.0690)	18.0703** (7.3689)	9.0586*** (3.1352)	1.5952 (3.3262)
1893	8.6810*** (3.0591)	18.0515** (7.3602)	9.0905*** (3.1285)	1.9460 (3.3306)
1894	8.7764*** (3.0540)	18.0253** (7.3623)	9.1662*** (3.1333)	1.8359 (3.3249)
1895	8.7170*** (3.0625)	18.0946** (7.3621)	9.1337*** (3.1374)	1.9257 (3.3428)
1896	8.8720*** (3.0528)	18.0530** (7.3606)	9.2645*** (3.1361)	1.8443 (3.3661)
1897	8.8783*** (3.0546)	18.0221** (7.3659)	9.2829*** (3.1383)	1.7161 (3.3561)

1898	8.9919*** (3.0622)	17.9364** (7.3518)	9.3865*** (3.1426)	1.5169 (3.3378)
1899	9.1597*** (3.0601)	18.0623** (7.3472)	9.5737*** (3.1461)	1.7924 (3.3606)
1900	9.3466*** (3.0680)	17.9863** (7.3463)	9.7208*** (3.1630)	1.6643 (3.3791)
1901	9.3454*** (3.0705)	17.9431** (7.3454)	9.7216*** (3.1581)	1.3812 (3.3832)
1902	9.4221*** (3.1365)	17.9280** (7.3503)	9.8034*** (3.1860)	1.1648 (3.4021)
1903	9.3067*** (3.1404)	17.9238** (7.3625)	9.7432*** (3.1781)	0.9212 (3.4376)
1904	9.3635*** (3.1442)	17.8721** (7.3705)	9.8011*** (3.1813)	0.7104 (3.4219)
1905	9.3430*** (3.1511)	17.8704** (7.3807)	9.8162*** (3.1915)	0.5208 (3.4115)
1906	9.1832*** (3.1392)	17.9102** (7.3802)	9.7521*** (3.1890)	0.0647 (3.2974)
1907	8.5157*** (3.0521)	18.4190** (7.3249)	9.3670*** (3.1714)	0.2801 (3.3148)
1908	8.7700*** (3.0471)	18.1715** (7.3225)	9.5660*** (3.1619)	-0.1971 (3.3287)
1909	8.6955*** (3.0448)	18.1352** (7.3279)	9.5048*** (3.1610)	-0.2958 (3.3113)
1910	8.6468*** (3.0440)	18.0972** (7.3320)	9.4593*** (3.1609)	-0.4566 (3.2775)

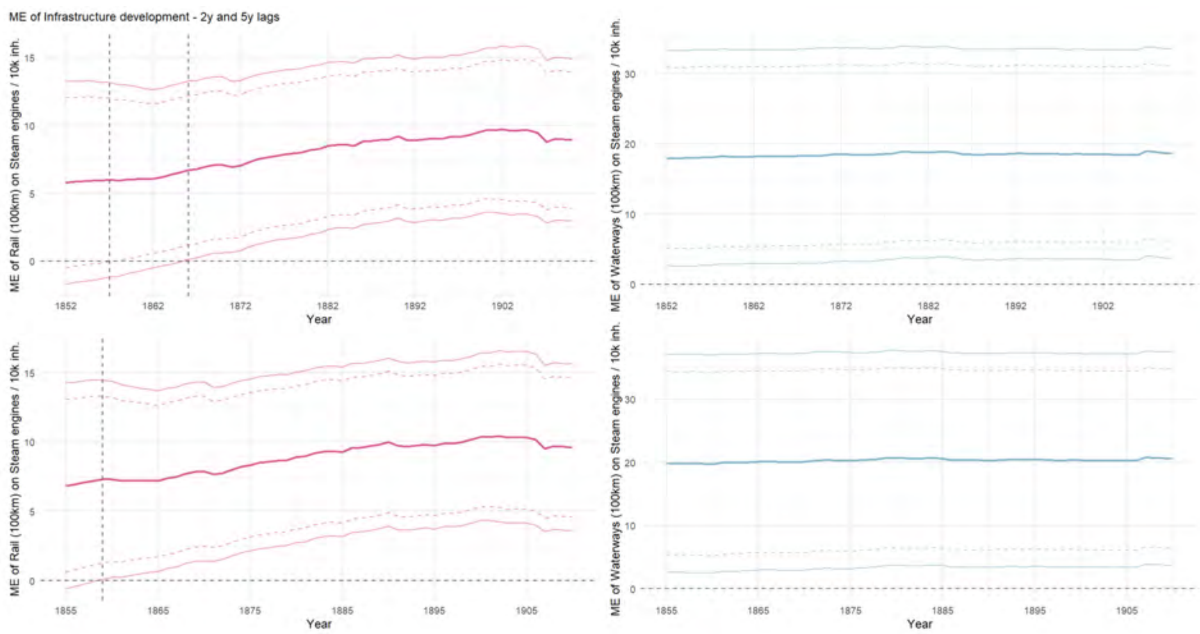

Figure A.6: Yearly marginal effects of Rail, Water and Rail × Water, evaluated at mean levels; 1y lag in the main text; source: own elaborations on multiple data sources, see text for more detail

Placebo tests with leads in the main specification

While individual leads are insignificant, the joint F-test rejects at the 5% level ($F = 2.46$, $p = 0.044$). However, the lead coefficients are negative and economically negligible, inconsistent with an anticipation mechanism. We interpret this as limited evidence against the parallel trends assumption. The joint result is likely driven by multicollinearity among the leads rather than a genuine pre-trend.

Table A.6: Main specification with leads as placebo test; other controls and main variables retain the same sign and statistical power as the main specification without leads; source: own elaborations on multiple data, see text for more details

Dependent Variable:	Steam engines per 10k inh.
Model:	(1)
Leads Rail (2y)	-17.342 (23.648)
Leads Rail (1y)	-47.023 (33.763)
Leads Water (2y)	-0.51606 (1.4197)
Leads Water (1y)	-0.34349 (0.35267)
Department FE	Yes
Year FE	Yes
Year interactions	Yes
Other variables	Yes
Observations	5,104
R^2	0.89003
Within R^2	0.31812

Clustered (Department) standard-errors in parentheses
*Signif. Codes: ***: 0.01, **: 0.05, *: 0.1*

Alternative models: spatial first differences

Departments whose neighbors got rail should show differential steam adoption, controlling for own rail. If identification comes from genuine infrastructure rollout rather than pre-existing industrial dynamism, the spatial spillover should be positive and lagged, as is. This supports the infrastructure story (steam follows rail networks, not just local industrial demand).

Dependent Variable:	Steam engines per 10k inh.
Model:	(1)
Variables	
Rail (100km)	-1.4486
	(4.8722)
Neighbour Rail (100km)	8.6381**
	(3.9865)
Rail (100km) square	0.56191***
	(0.12473)
Communes with stations (ratio)	2.8786
	(3.6669)
Communes with internal waterway access (ratio)	-65.093
	(87.774)
Waterway density	-8.2595**
	(3.8841)
Waterway (100km)	16.375**
	(7.3089)
log(Population)	-8.8902*
	(5.0588)
Fixed-effects	
Department	Yes
Year	Yes
Fit statistics	
Observations	5,192
R^2	0.88439
Within R^2	0.26766

Clustered (Department) standard-errors in parentheses
*Signif. Codes: ***: 0.01, **: 0.05, *: 0.1*

Alternative models: negative binomial on steam engines count

$$\text{SteamCount}_{d,t} \sim \text{NegBin}(\mu_{d,t}, \theta) \tag{4}$$

$$
\begin{aligned}
\log(\mu_{d,t}) = {} & \beta_1 \text{Rail}_{d,t-1} + \beta_2(\text{Rail}^2_{d,t-1}) + \beta_3 \text{CommunesWithStations}_{d,t-1} \\
& + \beta_4 \text{CommunesWithPorts}_{d,t-1} + \beta_5 \text{WaterDensity}_{d,t-1} \\
& + \sum_{\tau} \delta_{1\tau} \left(\text{Water}_{d,t-1} \times \mathbf{1}[t = \tau]\right) \\
& + \sum_{\tau} \delta_{2\tau} \left(\text{Rail}_{d,t-1} \times \mathbf{1}[t = \tau]\right) \\
& + \sum_{\tau} \delta_{3\tau} \left(\text{Water}_{d,t-1} \times \text{Rail}_{d,t-1} \times \mathbf{1}[t = \tau]\right) \\
& + \log(\text{Pop}_{d,t}) + \alpha_d + \gamma_t
\end{aligned}
$$

The negative binomial captures the extensive margin (number of engines) while the main specification captures intensity per capita, so the count model's declining coefficient is consistent with market saturation at the level of individual departments even as intensity per capita continues to grow as larger engines replace smaller ones.

Table A.7: Negative Binomial Estimates with the same regressors as the main specification

	Neg. Binomial
Rail (100km)$_{t-1}$	1.342***
	(0.239)
[Rail (100km)]$^2_{t-1}$	0.184***
	(0.040)
Communes with stations$_{t-1}$	0.127
	(0.133)
Communes with ports$_{t-1}$	-8.580***
	(2.499)
Water density$_{t-1}$	-1.023***
	(0.174)
Water (100km)$_{t-1}$	1.512***
	(0.368)
Water × Rail$_{t-1}$	0.019
	(0.111)
log(Population)	-1.991***
	(0.148)
Département FE	Yes
Year FE	Yes
Year interactions	Yes
Observations	5,280
Pseudo R^2	0.867

Notes: Standard errors in parentheses. $^{*}p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$. Département and year fixed effects included. Year-specific interactions for Water, Rail, and Water×Rail are estimated but reported graphically (Figure A.7).

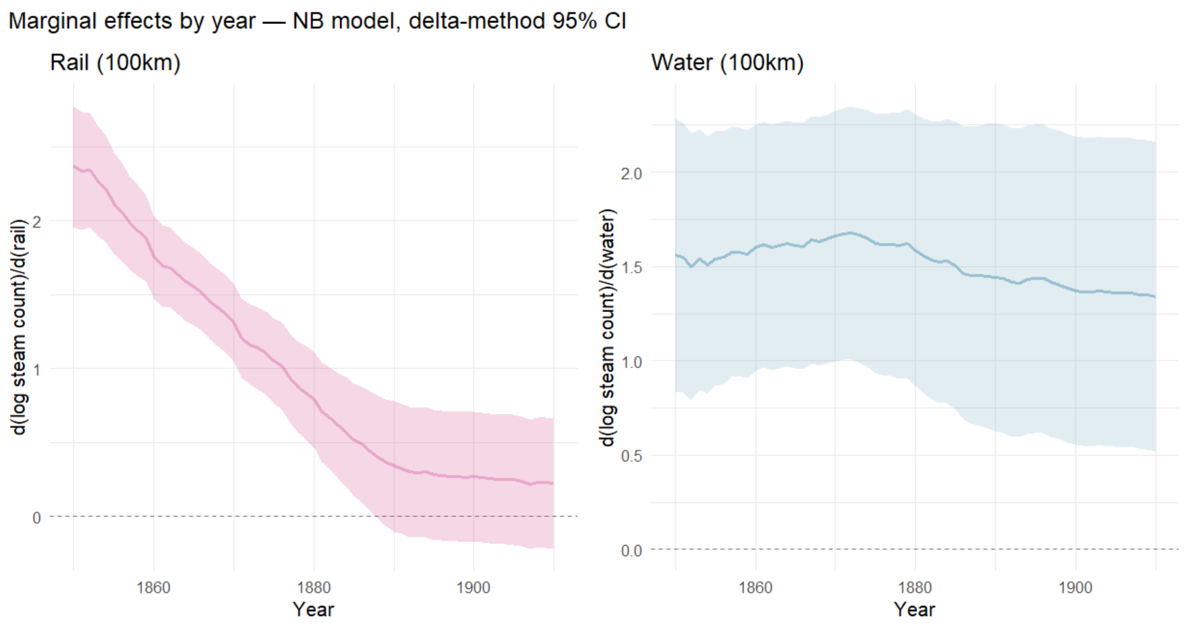

Figure A.7: Marginal effects by year of Rail and Water development, evaluated each at the mean level; source: own elaborations on multiple sources, see text for more details

Alternative models: horsepower per capita as dependent variable

We use decadal instead of yearly interaction to harmonise the temporal bins with the changes in travel speed on the lines and the freight costs by transport mode.

Dependent Variable:	HP per 10k inh.
Communes with stations (ratio)	-40.693
	(175.46)
Communes with internal waterway access (ratio)	-3,465.0
	(2,477.8)
Waterway density	-41.633
	(196.64)
log(Population)	695.85***
	(220.33)
Department FE	Yes
Decade FE	Yes
Decade interactions	Yes
Observations	5,173
R^2	0.78653
Within R^2	0.42022

Clustered (Department) standard-errors in parentheses

*Signif. Codes: ***: 0.01, **: 0.05, *: 0.1*

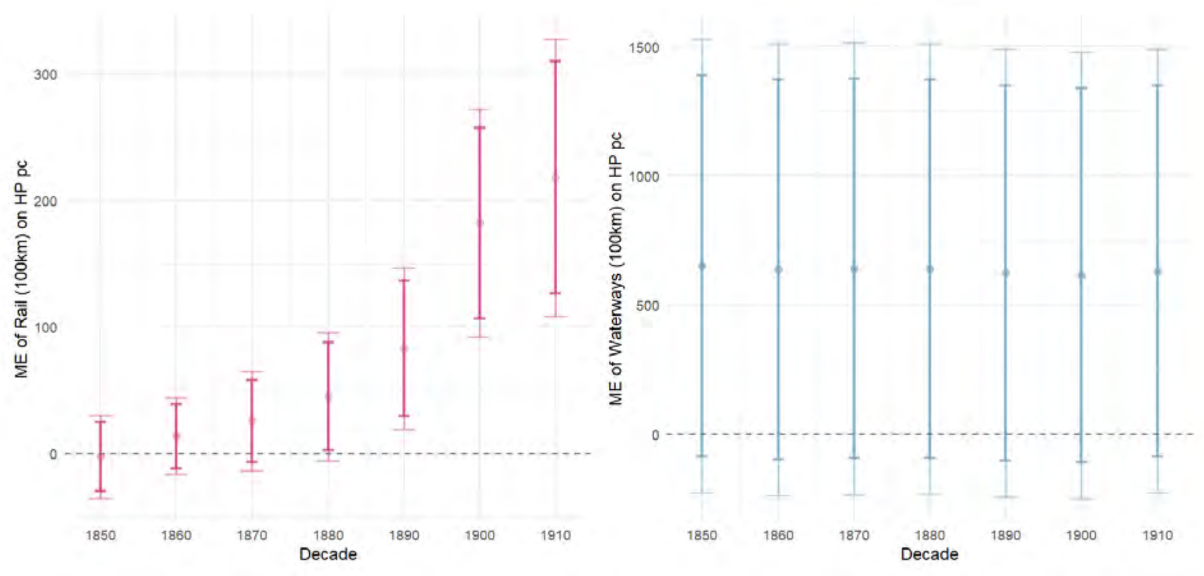

Figure A.8: Decadal marginal effects of Rail, Water and their interaction on horsepower per 10k inhabitants; source: own elaborations on multiple data source, see text for more details

Complete results of the mechanisms exploration

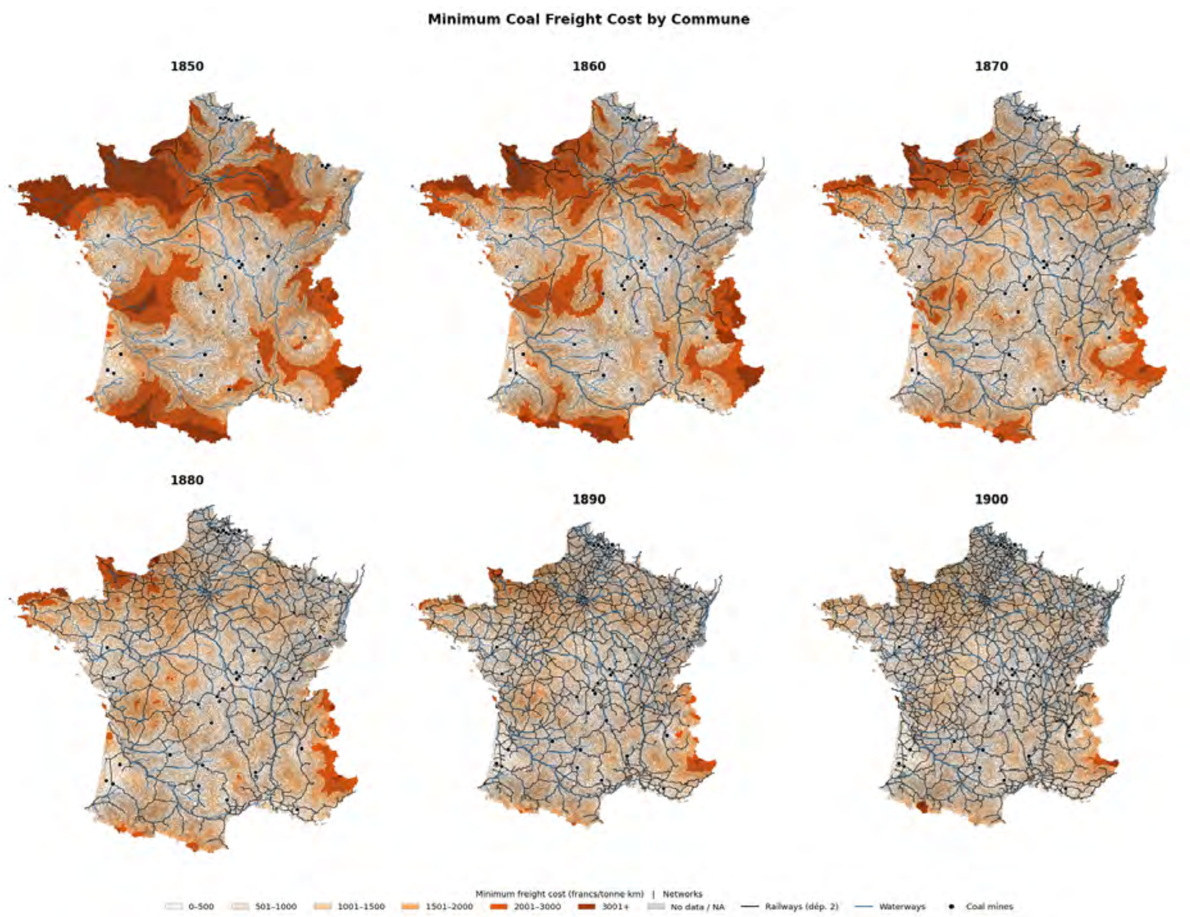

Figure A.9: Multi-modal access: freight cost (cents per ton/km) to closest coal mine for selected years - own elaborations on COMMUNE data

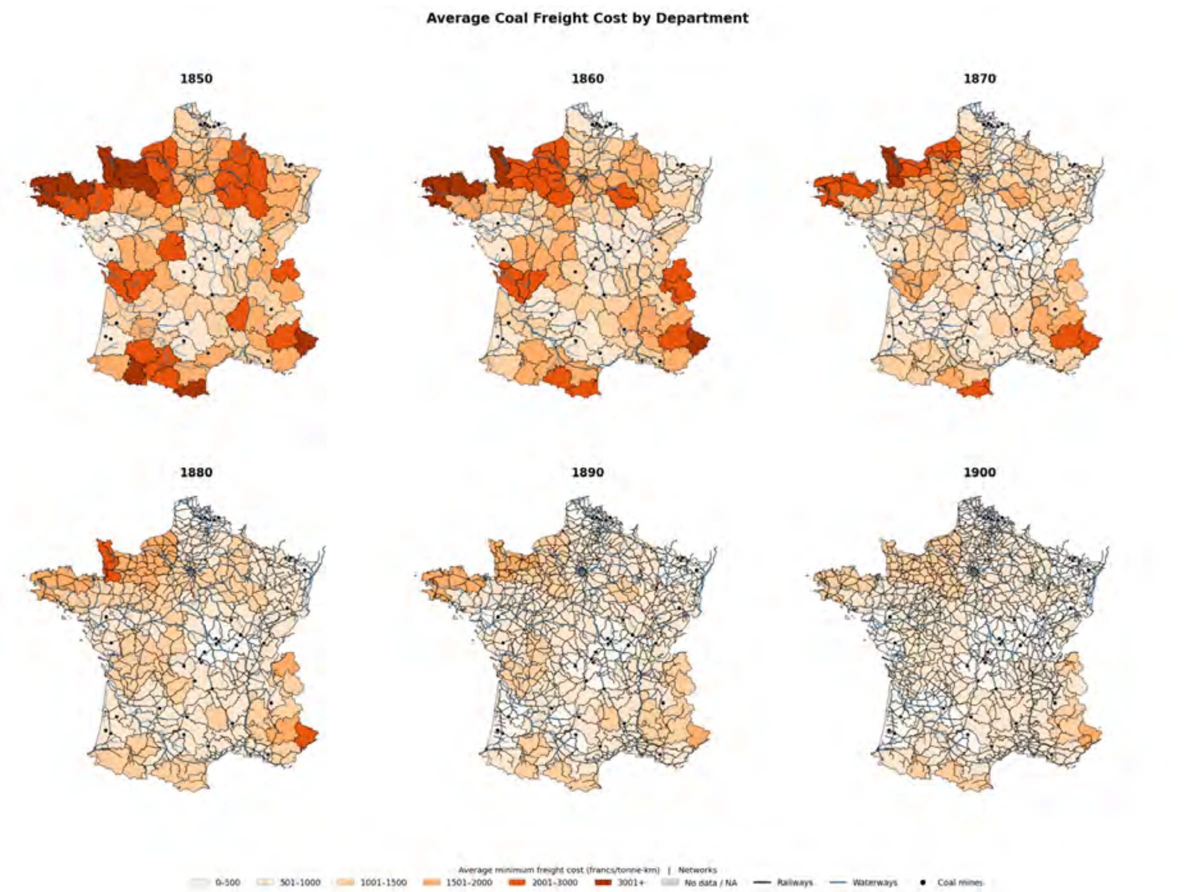

Figure A.10: Multi-modal access: freight cost (cents per ton/km) to closest coal mine for selected years - own elaborations on COMMUNE data, 1870's department boundaries from Gay, 2020

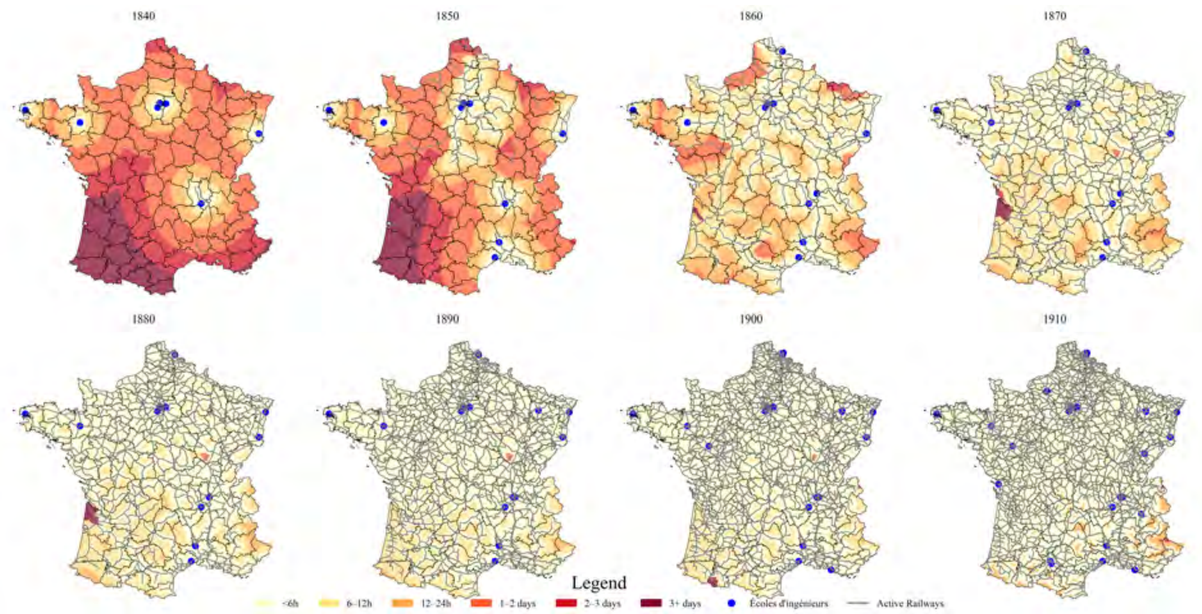

Figure A.11: Multi-modal access: hours from any commune to closest Ingénieur grande école for selected years - own elaborations on CGE and COMMUNES data

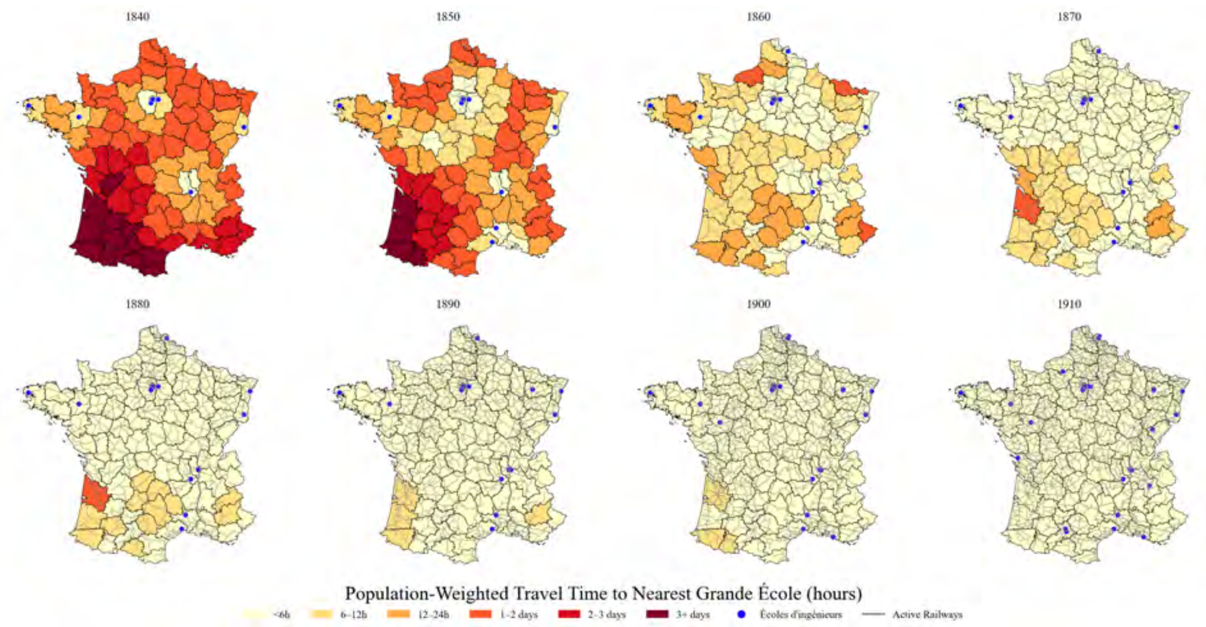

Figure A.12: Multi-modal access: weighted hours to closest Ingénieur grande école for selected years - own elaborations on CGE and COMMUNES data, 1870's department boundaries from Gay, 2020

Table A.9: Marginal effects of knowledge and coal access by decade

Decade	Knowledge	Coal
1850	-0.6412*** (0.2433)	0.6706 (0.5699)
1860	-1.0680 (0.7914)	1.7808** (0.7723)
1870	1.0096 (0.7392)	2.2214*** (0.8586)
1880	2.7562 (2.1873)	3.1058*** (1.1073)
1890	9.1387** (3.8284)	3.6560*** (1.3934)
1900	6.7203 (5.5688)	4.0497** (1.8622)
1910	-0.4721 (10.7363)	3.4837 (2.1908)

Note:
* p<0.10 ** p<0.05 *** p<0.01. SEs clustered at département level.

Table A.10: Marginal effects of knowledge and coal access (in ln form) by decade

decade	Knowledge	Coal
1850	-1.2424* (0.7233)	4.4158** (2.0443)
1860	-0.4776 (1.0513)	5.9528*** (2.0490)
1870	1.0739 (0.9038)	5.6540*** (1.8640)
1880	2.1531* (1.1410)	5.7023*** (2.0331)
1890	2.0342 (1.3963)	5.8691*** (2.2458)
1900	0.8115 (1.6953)	5.9784** (2.5396)
1910	-0.6672 (2.0363)	5.3100** (2.6457)

Note:
* p<0.10 ** p<0.05 *** p<0.01. SEs clustered at département level.

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