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Railroads and their lagged impact on the economy: Evidence from the Russian Empire

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Author:
Kirill Safonov

Advisor:
Andrei Markevich

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Abstract

This paper examines the economic impact of railway construction in the context of Tsarist Russia. I propose using an economically optimal network derived from the general equilibrium model as an instrumental variable for estimating the economic effect of the railroad construction in the historical context. I further apply this instrument for the context of Tsarist Russia and estimate the railroad effect on urbanization for year 1897. I estimate that there is no significant effect of the railway construction on urbanization in the Russian Empire. I also estimate that there is around 2.3% welfare loss which arise from the suboptimality of the historical network configuration.

Contents

1 Introduction

Governments tend to allocate substantial funds to massive transportation initiatives. As Donaldson (2018) points out, in 2007, the World Bank dedicated nearly 20% of its loans to transportation infrastructure projects, surpassing the combined funding for education, health, and social services. Recently, Austria has announced its plans to spend almost 4% of its GDP on the expansion of the railroad network (Bovenizer, 2023). Notwithstanding significant investments and claims of their benefits to growth (World Bank, 2009), the quantitative effect of transportation projects on economy remains unclear.

This paper studies economic effects of the railroad network in the Russian Empire, one of the largest railway systems in the world[1]. The contribution of this research is 3-fold. First, I propose using the optimal transportation network model as an instrumental variable to capture micro-level economic effects of railway network in the historical context. Second, using the proposed method, I quantify the micro-level effect of railroad construction on urbanization in Tsarist Russia of the late 19^{th} century[2]. I find no statistically significant effect. Third, I evaluate the overall welfare loss in the late 19^{th} Russian Empire arising from constructing railway network for reasons other than economic. There is around 2.3% welfare loss. Also, this paper is the first attempt to exploit the general equilibrium trade model with congestion in shipping and a continuous infrastructure investment choice of Fajgelbaum & Schaal (2020) in the historical context.

Naturally, estimation of transportation network effects on economy is a subject of great interest among economists. Michaels (2008) estimates the effect of the U.S. Interstate Highway System on demand for skilled labor, Atack et al. (2010) study how the railroad transportation affects urbanization and population density. Researchers explore the economic impact of railroad construction in various settings such as the U.S. economy of the late 19^{th} century (Donaldson & Hornbeck, 2016), China (Wang & Wu, 2015), Sweden (Berger & Enflo, 2017), and colonial India (Donaldson, 2018).

However, nobody has yet aimed to estimate similar effects in the late Russian Empire. This is a blind spot in the literature since late 19^{th}-century Tsarist Russia offers a unique context to explore the impact of railroad networks. First, it was one of the major emerging economies and was undergoing industrial transformation (Zhuravskaya et al., 2023). Second, the Russian Empire, as other empires at that time, was constantly engaged in military conflicts that significantly influenced the railway network construction making it difficult but important to isolate the pure economic effect[3]. Finally, the end of the

[1]On the eve of the World War I, the Russian Empire ranks second in the world (after the U.S.) in terms of railroad network length (Anfimov, 1994).

[2]More precisely, I estimate the effect of railroad construction attributable to economically optimal railroads (IV estimates LATE)

[3]The famous example of the economically unjustified railroad in Tsarist Russia is the first railway from Saint Petersburg to Tsarskoye Selo with the only purpose of connecting the capital with the summer mansion of the tsar. For other examples of inefficiency in railway construction see Section 3.

boom in railway network construction perfectly coincided with the first and only census conducted in the Russian Empire which allows to perform a detailed analysis of this case study.

One should be careful when estimating the economic impact of infrastructure projects as the analysis may suffer from the *endogeneity* problem. Endogeneity might occur because regions with more economic potential, which are typically more developed, tend to attract higher levels of investment, including infrastructure initiatives. It can be addressed in multiple ways. Some papers argue that either their variable of interest is not contingent upon railroad presence ("market access" approach by Donaldson & Hornbeck, 2016) or that the transportation network of interest was constructed based on solely non-economic reasons (Donaldson, 2018), while others use instrumental variable approach (Atack et al., 2010, Faber, 2009, Berger & Enflo, 2017).

The instrumental variable approach may seem especially promising but in many cases (as in Atack et al., 2010, Faber, 2009, Berger & Enflo, 2017) requires specific historical documents, events or facts that are usually rare in economic history contexts. Thus, I propose using the general equilibrium trade model that constructs the synthetic economically-optimal transportation network to assess economic effects of real transportation network. It is somewhat similar to the approach taken by Lipscomb et al. (2013) who build an engineering model that simulates hypothetical electricity grids and use as an instrumental variable to estimate the effect elictrification. The model I use is the one introduced in Fajgelbaum & Schaal (2020). See more details in Section 5.

The rest of the paper is structured as follows: Section 2 covers the related literature on *economic impact of infrastructure projects* and *economic history in the Russian Empire*. Section 3 provides more details on the historical context of the late 19^{th}-century Russian Empire. Section 4 describes the data and provides descriptive statistics. Section 5 offers details on the methodology of the paper. Section 6 presents the results. Section 7 discusses the limitations of the paper, proposes ideas for further research and concludes.

2 Literature Review

My paper relates to two streams of literature: research on economic impact of transportation projects and research on the economic history of the Russian Empire.

2.1 Economic Impact of Transportation Infrastructure

The significance of transportation infrastructure in shaping economic growth has been a subject of great interest among economists. There is an extensive literature on the rapid expansion of railroads during the 19^{th} century. Originally, it was argued that railroads significantly boosted industrial and financial sectors of the U.S. economy (Jenks, 1944).

However, Fogel (1964) debunks this belief using his now well-known "social saving" approach[4]. He argues that the novel for its time railway infrastructure could have been replaced by the traditional means of transport. Fogel (1964) shows that the existence of railroads in the U.S. in 1890 increased the GNP by 2.7% which is rather insignificant.

The Fogel's framework of "social saving" later came under serious scrutiny (Nerlove, 1966, McClelland, 1968, Leunig, 2010). Nevertheless, Metzer (1973) and White (1976) apply Fogel's framework as well as its refined version to the context of the *Russian Empire*. Specifically, Metzer (1973) calculates the additional resource costs that would have occurred if both the freight and passengers moved by the next best – a combination of internal waterways and overland transportation, instead of railway. Metzer estimates the effect of railway construction on Tsarist Russia's economy is no more than 5.55% increase in GNP. Applying the same methodology, White's (1976) estimated direct impact of the railroad network on the GNP ranged from 1% to 2% in the absence of positive externalities.

Another approach to disentangling the economic impact of transportation networks is to apply difference-in-difference estimation and compare the regions, or counties, that had railroad network to the ones that didn't. Atack et al. (2010) provide difference-in-difference estimates to establish the link between railway network in the American Midwest in 1850s and urbanization. The authors show that while railroads had little or no effect on the population density, they significantly affected urbanization of the Midwest "accounting for almost half of the increase in the percent of population living in urban areas". Building on the quasi-randomness of the historical railroad construction in Sweden, Berger & Enflo (2017) use difference-in-difference methodology and estimate that towns which gained access to railway system grew considerably larger (27%) compared to the ones that did not gain access. Both authors conduct robustness checks with the instrumental variable approach. Atack et al. (2010) use historical surveys to construct an instrument for the distance to the railroad based on the straight line between the center of the "start" and "end" counties in the Midwest. Berger & Enflo (2017) construct the instrument based on low-cost routes between Stockholm and the other major terminal points of the network. Both works are inspired by Banerjee et al. (2004) where a "straight-line" instrumental variable is introduced to estimate the effect of access to transportation network on regional economic outcomes in China. The authors construct their independent variable by drawing a straight line "from each historically important city to the nearest Treaty Port and/or to the nearest other historically important city" (Banerjee et al., 2004, 2020).

The third approach to disentangling the economic impact of transportation networks

[4]Fogel's (1964) "social saving" methodology is based on estimating the cost-savings of transporting agricultural freight by railroads and comparing them to the cost-savings of the next best alternative, i.e. shipment of agricultural freight by rivers and canals

is model-based. The idea is similar to Fogel's (1964): look at the counterfactuals and analyze transportation costs under them. The model-based approach typically consists of the model that accounts for specific ties between regions where trade agents choose the least costly route to transport goods. For example, Herrendorf et al. (2009) study the effects of large transportation costs on economic development by creating a general equilibrium model that includes two regions with non-zero costs of transporting goods between them. Perez-Cervantes (2013) uses a calibrated Ricardian model to estimate the trade benefits from the railroad network construction in the second half of the 19^{th} century in the U.S. Swisher (2017) when exploring the same research question as Fogel (1964) develops a structural model that endogenizes the counterfactual canal network when railroads are unavailable.

Donaldson & Hornbeck (2016) also reconsider Fogel's (1964) research question. The authors propose using a general equilibrium trade model and looking at changes in "market access" within the region resulting from the construction of the railway network[5]. The advantage of this approach is that it captures the aggregate impact of railroads[6]. In their empirical setting, "market access" is defined as the lowest-cost county-to-county freight network. As mentioned in Section 1, looking at the "market access" variable also allows to avoid the endogeneity problem of railroad construction. Similarly, Allen & Arkolakis (2014) develop a general equilibrium model with gravity structure and labor mobility to estimate the aggregate economic effect of interstate highway construction in the U.S.

Several papers explore network optimization within the general equilibrium framework. For example, Alder (2016) employs the Ricardian model of trade and implements a heuristic algorithm to optimize India's highway network to generate counterfactual scenarios. These scenarios serve dual objective: replicating the Chinese expansion strategy and minimizing construction costs. In parallel, Fajgelbaum & Schaal (2020) develop a neoclassical trade model and solve it using efficient numeric duality techniques. The convex nature of the problem makes it numerically tractable in the proposed framework. Fajgelbaum & Schaal (2020) then apply their methodology to contemporary European data on highways to quantify the effect of the optimal additional expansion on social welfare. Their estimates of average welfare gain across countries, ranging from 1.7% to 1.8%, align closely with the findings of Fogel (1964) and White (1976). The authors validate their strategy through a comparative analysis, juxtaposing their predicted trade flows against actual data. Also, Fajgelbaum & Schaal (2020) suggest further researchers use their framework as an instrumental variable.

The general equilibrium approach has noticeable advantage in that it requires a relatively limited data, referred as primitives. For example, in the papers of Alder (2016)

[5] "Market access" is a reduced-form expression that comes from the general equilibrium model.

[6] As argued in the paper, that railroad construction may have affected U.S. counties both directly and indirectly so it is important to capture both.

and Fajgelbaum & Schaal (2020), the necessity for data is circumscribed with GDP per capita serving as primary and almost the only required variable. It makes this approach especially appealing in my research due to the scarcity of available data for the Russian Empire.

This paper focuses on the *micro-level* effects of transportation infrastructure. In doing so, I use a model-based approach by adopting the neoclassical trade model from Fajgelbaum & Schaal (2020) to the historical context. In my case, general equilibrium model approach is the only applicable one since the context does not permit the use of difference-in-difference approach as in Atack et al. (2010) and Berger & Enflo (2017), for instance. Thus, I propose using the solution from the optimization over the space of networks in a neoclassical trade model as an *instrumental variable* for analyzing the economic effect of interest. This estimation can be applied to both modern and historical contexts but is especially helpful in the historical settings. Many historical contexts are interesting case studies but lack sufficient data for exploration. While, of course, one will still need data on the output, population, transportation and building costs that are used in Fajgelbaum & Schaal's model, the proposed approach helps to avoid the need to find additional context-specific documents to address endogeneity (as in Atack et al. (2010), Atack & Margo (2011), Berger & Enflo (2017)).

Therefore, my methodological contribution to this literature is that I propose exploiting the synthetically constructed optimal transportation network as an instrumental variable to estimate the economic effects of the actual transportation network with county-level precision. My empirical contribution to this literature is two-fold. First, I estimate the effect of railway construction on urbanization in the Russian Empire in 1897 using the proposed method. Second, I compare the change in welfare that arises due to the deviation of the actual railway network in Tsarist Russia from the economically optimal one. Note also that this paper is the first attempt to adopt Fajgelbaum & Schaal (2020) model in the historical context.

2.2 Economic History of the Russian Empire

The second stream of literature that this paper relates to is the research on the economic history of the Russian Empire.

2.2.1 Data Reconstruction

This research area involves huge data reconstruction efforts. Goldsmith (1961) reconstructs the industrial and agricultural outputs in the Russian Empire from 1860 to 1913. Gregory (1982) comprehensively constructs the national income of Tsarist Russia from 1885 to 1913. Markevich & Harrison (2011) address the missing gap in the GDP of the Russian Empire and construct it for the 20^{th} century, from 1913 to 1928, thus, connecting the Imperial and Soviet GDP series. Kuboniwa et al. (2019) estimates the GDP of the Russian Empire from 1860 to 1913 based on Goldsmith (1961). In the systematic review on Russian economic history research, Zhuravskaya et al. (2023) note that the GDP of the Russian Empire was highly volatile in 1860s–1880s and did not increase much. However, from the 1890s the GDP started demonstrating growth "accompanied by a structural transformation from agriculture toward industry" (Zhuravskaya et al., 2023). Additionally, Markevich (2019) is the only existing paper that reconstructs data on per capita income among all provinces of the empire.

However, there is still a lot of data that requires digitization and reconstruction to study the Russian Empire context. This paper contributes to this literature by being the first attempt to reconstruct the railway network in the Russian Empire by 1897.

2.2.2 Economic Development in the Russian Empire

The Russian Empire, although large and densely populated, had a relatively slow pace of development and industrialization in the late 19^{th} century. Gerschenkron (1965) argue that it was the prevalence of the *communes* which were characterized by many micro-inefficiencies such as dubious property rights and limited labor mobility that restricted the industrialization[7]. Pipes (1974) contends that the inefficient regulation policies and poor protection of property rights were to be blamed. Cheremukhin et al. (2017) apply the neoclassical growth model and show that the most important reasons for "underindustrialization" of Tsarist Russia were the monopoly power and high entry barriers. There are many other potential factors such as slow accumulation of human capital, culture traits and geographical and climate reasons. For a comprehensive review on these factors see Zhuravskaya et al. (2023) and papers cited therein.

It is interesting to explore to which extent the railroads contributed to the economic development of Russia. Did railway construction produce any economically significant effects or was it cost-inefficient and just further impeding the economic development?

Railroads have been widely thought as a key determinant in the economic growth and modernization of the 19^{th}-century Russia (Lyashchenko, 1949; Florisnky, 1953; Goldsmith, 1961; Beaumont & Freeman, 2007). To the best of my knowledge, the only attempts to quantify the economic impact of railroads in Tsarist Russia were made by Metzer (1973) and White (1976) who followed Fogel's (1964) approach. They concluded that railroad effect was *modest* but did not specify the criteria for judging what falls into *modest* range. Also, Kelly (1978) notes that Metzer (1973) used a limited sample and proxies that could have been manipulated by Tsarist Government. In contrast, I aim to provide substantive measurable evidence on railways' economic effect using the most detailed data currently available and applying the cutting-edge approach, i.e. neoclassical trade

[7]Communes, or "obshchina"-s, were peasant institutions that were organized after the abolition of serfdom in 1861.

general equilibrium model with locations arranged on a graph (Fajgelbaum & Schaal, 2020). Using this model, I estimate how beneficial the built railroads were for the society and whether it was possible to increase social welfare by building them differently. The optimal graph from Fajgelbaum & Schaal's framework is used as an instrument to identify the economic effect of the railways on urbanization.

In this research area, the contribution of this paper is that it is the first attempt to quantify the railway network county-level effects on urbanization, and estimate the welfare loss from the "misallocaion" of the railway system, i.e. deviation from the economically optimal system.

3 Historical Background

In this Section, I discuss the historical details relevant for the the Russian Empire study setting.

Prior to the railway construction, the main transportation infrastructure in the Russian Empire, as in, for instance, the U.S., were canals and roads. The first "experimental" railway, Tsarskoye Selo railroad, was constructed in 1837 and connected Saint Petersburg, the capital of the empire, with the imperial residence 24 kilometers away (Westwood, 1964). Under Nikolai I's reign, two other major railway lines were built, i.e. Warsaw–Vienna (1848) and Moscow–Saint Petersburg (1852). Interestingly, Westwood (1964) underlines that all three first railways were constructed out of military purposes. For instance, in the very year when construction was completed, Warsaw–Vienna line was used to send military troops to quell unrest in the western part of the empire. In the same fashion, Moscow–Saint Petersburg railway was used for troop drills even before the end of construction.

Russia was one of the first among European countries to introduce railways[8]. However, in the 1850s, largely due to the Crimean War, railway construction was paused. Only the harsh loss of the Crimean War prompted the Russian government to see the promising military value of railroads (Bill, 1956, Neilson & Otte, 2012). In the decades after the war, the railway system would expand 12 times in size. Number-wise, in 1861 the railway system was 1408.7 miles, whereas by 1887 the network reached 17776.5 miles in size (Neilson & Otte, 2012). According to Westwood (1964), the railway construction boom continued till the end of the 19^{th} century, i.e. from 1866 to 1899. The railway network expansion has two important periods in its history: "liberal" railway policy period under Reutern, from early 1860s till late 1870s, and a more strategic policy under Witte in 1890s (Neilson & Otte, 2012)[9]. Under Reutern the railroads were mainly constructed by private

[8]The first railway in France was constructed in 1832, in Germany in 1835, in Austria in 1837, and in Italy in 1839.

[9]Mikhail Khristoforovich Reutern was a finance minister of Russia from 1862 to 1878. Sergei Yulyevich

enterprises as was common in Europe at that times. One of the largest private railway systems in the Russian empire financed by Jan Bloch, Southwestern Railway Company, covered the western Ukraine and Poland from the Baltic to the Black Sea linking them up with the German and Austro-Hungarian railways (Neilson & Otte, 2012). However, letting private enterprises build railroad networks had several shortcomings. First, they were often insufficient in funds which would force them to halt the construction of railroad lines they had previously initiated. This, in turn, would undermine the creditworthiness of Russia in the eye's of European investors from whom they usually borrowed. Second, the failure in the Russo-Turkish war in 1878 spotted that the railway system, although vast, was very incoherent and did not adequately meet the military purposes (Westwood, 1964). Therefore, Witte started reforming the railway sector in 1890s. The previously-built railway lines were massively purchased by the government[10]. Thus, both old and newly-built railroads became integral to the government policy. This period witnessed the most significant boom in railroad construction in Russia. The length of the railroad network increased by nearly 30% from 1892 till 1896, and then by additional 40% in the next 4 years (Miller, 1967). Notwithstanding enormous effort and a quite coherent policy under Witte, Heywood (2006) points out that even on the eve of the World War I the notion of "strategic railways" remained underdeveloped in Tsarist Russia: most of the railroads were single-track and the overall network was still limited relative to the country's size.

Importantly, in 1897, right at the end of the railway boom, the Russian Empire performed the first and only nation-wide census. At that time, Russia was the third largest country in the world in terms of population. I largely draw on this comprehensive data to establish the effect of the railway transportation in Tsarist Russia. The year of the census necessitates that I restrict my analysis to 1897.

4 Data

4.1 Sources

As mentioned in Section 3, the paper considers a time period around 1897 which is the only year when the census in the Russian Empire was carried out. This allows to use the largest amount of data available. Three major variables required for the analysis within the general equilibrium framework of Fajgelbaum & Schaal (2020) are: the population, the Value Added, and the graph of the *actual* railroad network. For the empirical estimation, I also need data on urbanization, i.e. percent of population present in the urban center.

Witte was the Russian Director of Railway Affairs within the Finance Ministry from 1889 to 1891, and later a finance minister (1892–1903).

[10]By 1903, 70% of all lines were state-owned (Neilson & Otte, 2012).

The data on population and urbanization is obtained from the First general census of the population of the Russian Empire in 1897[11]. Second, I use county–level data on total yearly industrial production output in year 1900. This data comes from Gregg (2020). Finally, the county–level data on winter and summer wheat and rye crop yields in 1913 is used as a proxy for total agricultural output, obtained from Dower & Markevich (2018). According to Dower & Markevich (2018), summer and winter wheat, rye, barley, and oat crop yields were the main components of the agricultural output, together accounting for about a half of the total value added in the sector. Among them, rye was the main food grain and wheat was the main export grain, so the proxy is reasonable (Goldsmith, 1961).

Note that I limit my analysis to the European part of Russia as it is the most densely populated and economically active unit. More precisely, I consider only those parts of the Russian Empire that are to the west of the 55th meridian east. It helps to mitigate the bias associated with the dynamic effects of the railroad construction in the Eastern part of Russia. For instance, consider the Trans-Siberian Railway which connects the European part of Russia with the Far East. The economic benefits of it are so lagged that no model will propose building it. Hence, the analysis of only more developed regions with established economic ties partially solves this problem. Also, I do not consider Poland and Finland in this analysis because of limited data for these countries.

4.1.1 Descriptive Statistics

Here I provide the description of the data on population, urbanization, agriculrural and industrial outputs. The dataset contains 568 counties of 61 provinces. The Figure 1 provides a snapshot of the population density and urbanization in 1897. The most densely populated cities are Saint Petersburg and Moscow with $1,317,885$ and $1,203,926$ residents respectively. The urbanization distribution is slightly less uniform with many people living in urban centers in both western, central, and south parts of Tsarist Russia. See Figure 6 in Appendix for the visualization of agricultural and industrial outputs.

Table 1 shows that agricultural and industrial outputs vary hugely across the country with industrial output having some especially outstanding outliers. The main agricultural centers are Samara governorate, Kuban region, and Kherson governorate. The main industrial centers are Saint Petersburg, Moscow, and Kharkov.

[11] The data is available here: Demoscope Weekly, www.demoscope.ru/weekly/ssp/rus$_{g}ub_{9}7.php$

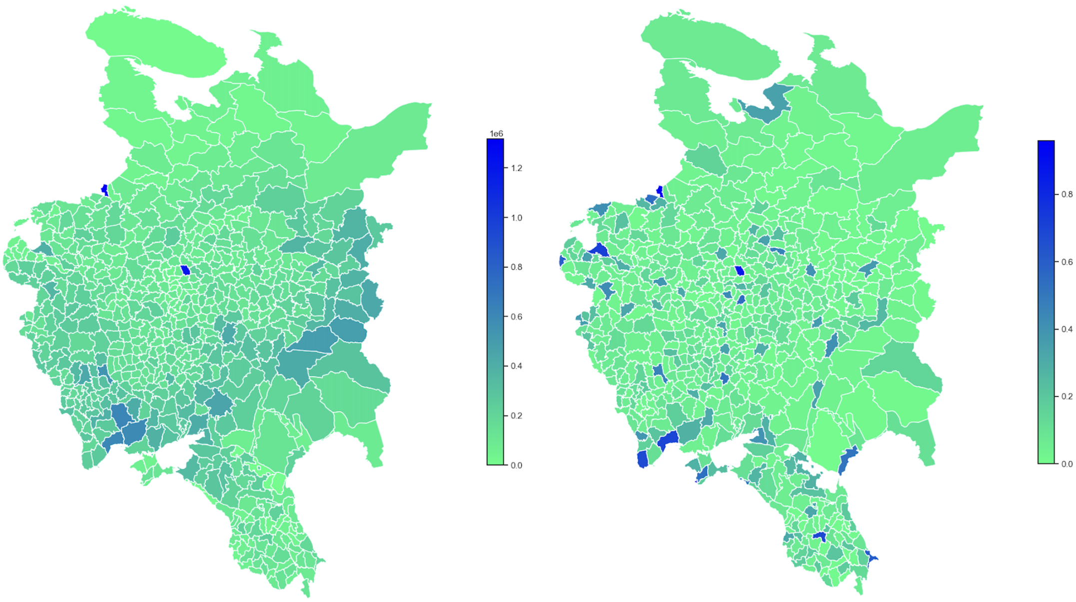

Figure 1: The distribution of population (left), the distribution of urbanization (right)

Table 1: Descriptive statistics

Statistic	Mean	St. Dev.	Q1	Median	Q3	Max
Population	172	113	105	153	220	1,318
Urban Population	23	75	4.6	8.9	18	1,265
Agricultural Ouput	4,601	6,327	1,171	2,420	5,028	53,967
Industrial Output	2,643	12,228	48	315	1,422	241,162
Urbanization	10.5%	13.1%	3.6%	6.0%	11.8 %	96.0 %

Note: The urbanization rate is in percentage points. All other measurements are in thousands. It contains data of present population which was located in the area at the time of measurement.

4.2 Construction of the Actual Network

The key independent variable in this research is the *actual* graph of the railway network of the Russian Empire in 1897. There are neither existing digital maps of the Russian Empire's railway system, nor the coordinates of the railway lines built in Tsarist Russia. This research covers this data gap and constructs the actual railway system network of the Russian Empire up to 1897. To do so, I use a two-stage approach. First, I construct the contemporary railway network of 15 post-Soviet countries (see the list of countries in Appendix A.2). Second, I match the names of railway lines found in a railroad history handbook with the corresponding lines of the contemporary graph and assign year of the construction. This approach is based on the assumption that most railway paths, if constructed at some point in time, are still present today. It is reasonable because railway construction is a very costly enterprise, so even if damaged, it is much easier to rebuild the existing one than lay a new one.

4.2.1 Contemporary Railway Network

There is no publicly available railway system network of contemporary Russia and other former Soviet Union countries in the format applicable for the research purposes.

To construct the contemporary graph, I gather data on railroad line entities in the post-Soviet countries from the manual handbook[12]. This data contains the identification numbers of all lines and railroad stations within them. Also, the data holds information on the order of stations within the line and the distances between them. In order to create a network, I need the coordinates of all stations. I get this data via web-scraping the following sources: *openstreetmap*, *wikidata*, and *alta*[13]. The data on station coordinates is filled with errors, requiring rigorous validation to ensure accuracy. There are 26,834 station entities in the data so data cleaning and processing requires some automatization. Therefore, I develop a semi-automatic algorithm to process and clean the coordinate data.

The algorithm processes the data as follows:

(1) It assesses whether the distance between any two subsequent stations provided in the manual handbook is accurate and coherent by comparing it with the real-world haversine distance between stations. Also, the algorithm accounts for missing values and omits interim stations if the actual railway line is straight.

(2) It tries to reorder stations within one line if it identifies in (1) some incoherence.

(3) If the error cannot be solved automatically, it returns data points for further manual check. Lines identified for manual check have, in turn, 3 levels of importance.

[12] Tariff Guide No. 4, www.tr4.info

[13] I would like to thank Natalya Naumenko for providing a great part of the scraped data from *wikidata* and *openstreetmap*.

The first level of importance are the lines that miss the first and/or the last station coordinates. The second level of importance are lines that have a distance mismatch identified in (1) but do not have missing interim values. The third level of importance are lines that have both distance mismatch and interim missing values.

Around 70% of errors are solved automatically via the algorithm. The rest is fixed manually by imputing missing coordinates in important cases, i.e. when the missing coordinates are the beginning or the end of the line, when the line is crooked and misses some interim coordinates. Manual imputation involves looking up the station name in location search tools (Google Maps and Yandex Maps) and assign the corresponding coordinates to it in the data. Finally, all lines and stations are double-checked to approve the algorithm's work and are corrected if necessary.

The constructed contemporary railway system contains 1,982 lines and 21,634 stations. See Appendix A.2 for a visualization of the reconstructed contemporary map.

4.2.2 Actual Historical Network

After the construction of the contemporary network, I use a railroad history handbook[14] to identify the lines on the contemporary graph that were constructed in the 19^{th} century. I look up the names of the constructed lines in each year up to 1897 from this handbook and identify the corresponding current lines. The names do change in some cases over time but it is easily handled manually. The reconstructed historical network contains 445 lines and 7166 stations. Figure 2 visualizes the reconstructed railway network of Tsarist Russia by 1897. See the larger version in the A.5.

4.3 Validation of the Network Construction

There is no complete map of the railway network in Tsarist Russia available, so it is hard to verify that the reconstruction is truthful. However, I search for network components to verify that the constructed is actually representative of the network in the Russian Empire.

Figure 3 and 4 provide a validity check of the network by comparing the reconstructed two lines, namely Saint Petersburg–Tsarskoye Selo and Moscow–Saint Petersburg, with the historical maps of these entities.

Note that although the match is striking, thus, validating our approach, in Figure 3 the reconstructed railroad deviates a bit from the one on the map. It is likely due to the inaccuracies in the surface projections of the old maps.

[14]Information about public railways from 1838 to 1917, https://istmat.org/node/42966

Figure 2: Reconstructed historical railway network of the European part of Tsarist Russia up to 1897

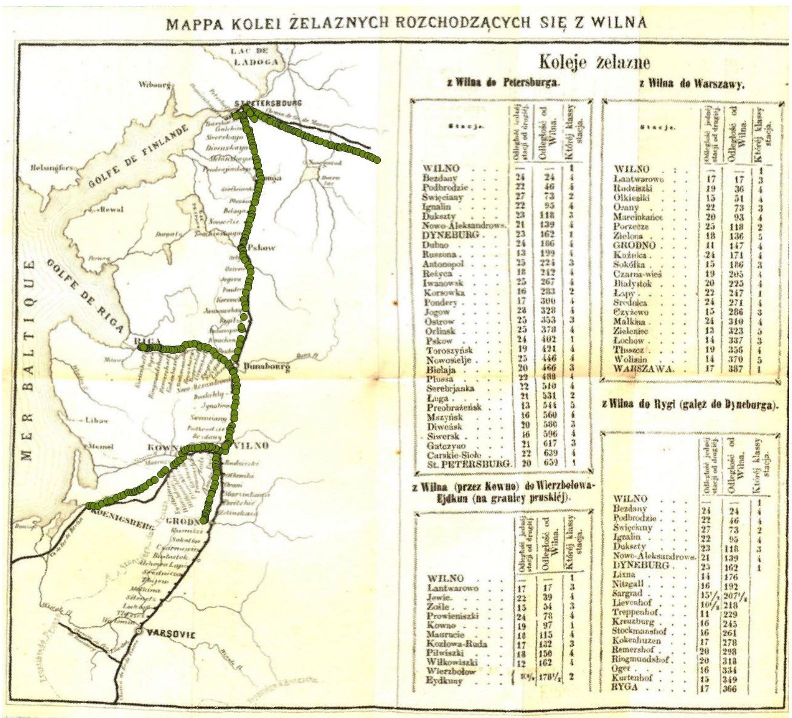

Figure 3: The historical map of the St.Petersburg–Tsarskoye Selo railroad line (black line) and the reconstructed line (green dots)

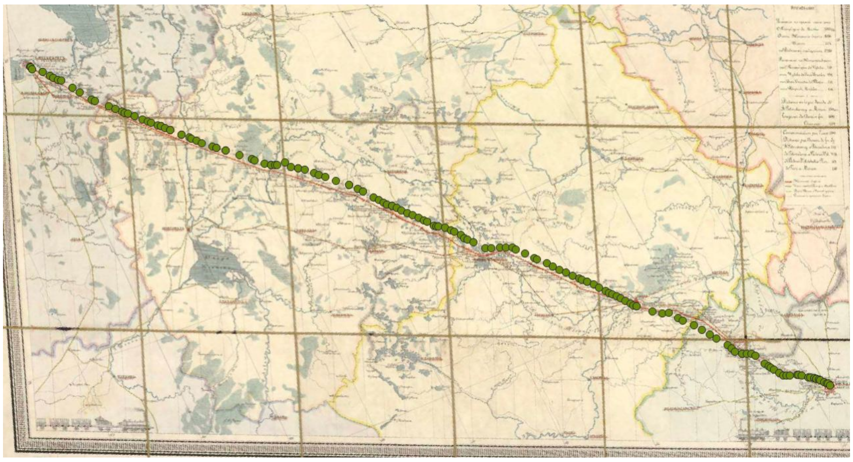

Figure 4: The historical map of the Moscow–Saint Petersburg railroad line (red line) and the reconstructed line (green dots)

5 Methodology

In this Section, I introduce the optimal transport network framework and based on it, describe an identification strategy that captures the economic effect of the railroad.

5.1 Optimal Transport Networks Framework

I apply the theoretical general equilibrium model proposed by Fajgelbaum & Schaal (2020) to construct a synthetic railroad graph that is optimal solely from an economic standpoint. I adapt the aforementioned model to the context of railroads in the Russian Empire. This Section describes the main concepts of the Fajgelbaum & Schaal's (2020) model and its application to the historical context. See a more detailed explanation of the theoretical model in the original paper, Fajgelbaum & Schaal (2020).

Within the framework of Fajgelbaum & Schaal (2020), the country is discretized by regions which are connected by roads. In my setting, the regions are connected by railroads as the railroad infrastructure is the object of interest. Fajgelbaum & Schaal (2020) suggest dividing the country into the grid which they obtain from the satellite data. My setting does not permit that, so I use the existing county (uezd) division (see Figure 10 in the Appendix). Also, I assume no labor mobility between regions in the model based on the stylized fact that population movement between regions was very limited in the Russian Empire and became active only during Stolypin's reforms (Chernina et al., 2014).

Let I_{jk} be a binary indicator of counties j and k connectivity with each other, i.e. if counties j and k have a connection, I_{jk} equals one, otherwise this binary variable is set to zero. Let L_j be the population in every province j in year 1897. Each person is simultaneously a producer and a consumer. In the model, the "social planner" maximizes the social welfare measured in utility terms. Mathematically, it is a solution to the following 3-stage nested optimization problem:

$$W = \max_{I_{jk}} \max_{Q_{jk}^n} \max_{\{c_j, h_j, D_j^n, L_j^n, z_j^n\}} \sum_j \omega_j L_j U(c_j, h_j), \tag{1}$$

where, among already described variables, ω_j is the social planner's weight assigned to each worker in region j and $U(c_j, h_j)$ is the utility of an individual worker who consumes c units of the traded goods bundle and h units of the non-traded good in location j.

For simplicity, I assume that all regions and all workers are equally important and set all ω_j equal to 1. Thus, the problem can be reformulated as follows:

$$W = \max_{I_{jk}} \max_{Q_{jk}^n} \max_{\{c_j, h_j, D_j^n, L_j^n, z_j^n\}} \sum_j L_j U(c_j, h_j). \tag{2}$$

Let us consider this optimization problem step-by-step starting from the inner part. The innermost problem $max_{\{c_j, h_j, D_j^n, L_j^n, z_j^n\}}$ is allocation of resources for production within one county under given trade flows and infrastructure built. A worker consumes a bundle of traded and non-traded goods. In my setting, traded goods are grains and the industrial production combined, and the non-traded is housing which has fixed supply. The preferences of c units of traded goods and h units of non-traded are defined by the Cobb-Douglas utility function:

$$U(c, h) = c^{\alpha} h^{1-\alpha}. \tag{3}$$

I use $\alpha = 0.4$ as proposed in Fajgelbaum & Schaal (2020). Note that both c and h are *aggregated* goods, so, for example, the model does not differentiate between housing and other non-traded services. The variation in the endowment of h as well as in productivity creates differences between counties and theoretically justifies the need for trade.

The number of tradeable sectors is $N+1$ and they are combined with the CES aggregator into one good C_j demanded in the province:

$$C_j = \left(\sum_{n=1}^{N+1} (D_j^n)^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}}, \tag{4}$$

where D_j^n is the demand in location j for the output in sector n. Each worker, therefore, consumes $c_j = C_j / L_j$. Assume that $\sigma = 5$ in the CES aggregator consistent with the Head & Mayer's (2014) findings in their meta-analysis of the international trade literature. The number of tradeable sectors, $N+1$, is predefined and equals to 6. The more N is, the more computationally intensive the task becomes. Fajgelbaum & Schaal (2020) use $N = 10$ but the number of regions in their work is ten times smaller.

Also, in each location there are *fundamentals*: the housing fixed supply H_j and a production factor z_j. The following linear production function is used:

$$Y_j^n = z_j^n L_j^n. \tag{5}$$

In this setting, Y_j^n is the output of sector n, where $n \in \{1, 2, ..., N = 5\}$, in region j. The only production factor in each sector is labor L_j, and z_j is interpreted as labor productivity. I follow Fajgelbaum & Schaal (2020) and simplify the model for the numerical application. I assume that each region can produce only one tradeable good. In the whole economy, there are $N = 5$ differentiated goods and one homogeneous good. Each of the differentiated goods can be produced only in one location, specifically in one of the 5 most populated regions. Other regions produce one homogeneous good which one can interpret for simplicity as the agricultural output. These assumptions allow to reduce the computational cost while preserving the logic of the existence of the industrial centers.

The second nested problem $max_{Q_{jk}^n}$ is the optimal flow problem. The planner chooses how the produced goods are then traded between counties. Goods are transported only via connected counties. If a good is transported from region j to region k and these two regions are not adjacent, it means that a good must transit all the interim regions between them. The diagram in Figure A.6 illustrates the configuration type of graph that permits the movement of goods between edges in the Russian Empire. Transportation from j to k is costly and is described as *iceberg* transportation costs τ_{jk}. I use the log-linear parametrization of transport costs:

$$\tau_{jk} = \delta_{jk} \frac{Q^\beta}{I^\gamma}. \tag{6}$$

The costs are proportional to the number of transported goods Q and inversely proportional to the built infrastructure. The former effect is essentially congestion, i.e. the more goods are shipped at one time, the more costly it becomes. The latter effect captures returns to infrastructure since infrastructure reduces transportation costs. Parameters β and γ control the magnitude of these two effects. I use $\beta = 0.13$ and $\gamma = 0.10$, values calibrated by Fajgelbaum & Schaal (2020). Also, the ratio betweeen β and γ defines whether this problem is convex or not. In my case, the optimization is convex which guarantees the numerical tractability and convergence to the unique global optimum.

I follow Fajgelbaum & Schaal (2020) and use the same assumption that transport costs multiplier is a linear function of the distance: $\delta_{jk} = \delta_0 \cdot dist_{jk}$ where δ_0 is set to the value calibrated by Fajgelbaum & Schaal (2020).

The outer-most nested problem $max_{I_{jk}}$ refers to choosing the optimal infrastructure network. It compares the marginal costs of building a new path and marginal gain from the infrastructure. The construction requires the scarce resource (for instance, iron in the case of railways) which cannot be used in any other way. The main computational challenge is that one additional edge in the infrastructure network changes transportation costs all over the graph.

Finally, solving network optimization problem requires some assumptions about building costs δ_{jk}^I. I exploit a modified version of the formula proposed by Fajgelbaum & Schaal

(2020). The main difference is that I do not account for the costs associated with the features of the terrain (elevation or difficult area):

$$\log\left(\frac{\delta^I_{jk}}{dist_{jk}}\right) = \log(\delta^I_0) - 0.11 \cdot \mathbb{1}(dist_{jk} > 50\ km). \tag{7}$$

Since I look at the European part of Russia, it is a rather reasonable assumption because the majority of the territory is on the flat East European Plain (see Section 7 for a discussion of other specifications).

Having introduced the main theoretical concepts and key assumptions relevant for my context, I then apply the framework. It can be divided into two stages: calibration and construction a counterfactual network.

5.2 Application

Having the fundamentals (z_j, H_j), the social planner's solution outputs GDP^{obs}_j which is an observable production output in region j. This information is next used to back out the productivity levels z_j under the existing network $\{I_{jk}\}$. Also, in my case the housing component is just normalized to one, $\frac{H_j}{L_j} = 1$, because there is no labor mobility. The result of this calibration is a set of the optimal fundamentals (z_j, H_j). Using them as inputs to the model, I get very close estimates of the observable output.

The next step is constructing a counterfactual railroad network. I use the already calibrated values of (z_j, H_j) to solve again the network optimization problem. Imposed limitation on maximization is that the optimized network uses the same amount of construction resource, e.g. iron, as does the real historical network. Thus, it is interpreted as the optimal reallocation of resources to obtain the counterfactual graph. Note that this is the most computationally intensive part which requires a lot of time for the algorithm to converge.

5.3 Identification Strategy

Here I formally introduce the model specification. The research interest in the effect of railroad infrastructure on the economic development can be viewed as follows:

$$Y_j = \alpha + \beta Z_j + \gamma X_j + \varepsilon_j. \tag{8}$$

where $j \in \mathcal{J} = \{1, .., J\}$ is a set of locations, namely counties; Z_j is a scalar identifying whether the railroad in county j exists; Y_j is a scalar representing the economic variable (urbanization) in county j; X_j is a vector of control variables for county j; ε_j is an error term for county j.

As noted in Sections 1 and 2, the above equation suffers from the simultaneous causality: while the railroad infrastructure can affect the urbanization of province j, the vice versa may also be true – the urbanization of province j can determine whether it is reasonable to build railroad infrastructure there. Perhaps, railroads are built in more flourishing and prospective provinces. In order to eliminate the endogeneity problem, I use a synthetically constructed social planner's *optimal* railroad infrastructure across all $\mathcal{J}$ locations as an instrument. Thus, I add the following equation to the above:

$$Z_j = \theta + \delta Z'_j + \pi X_j + \varphi_j, \tag{9}$$

where Z'_j is a scalar identifying whether the *optimal* railroad in province j exists; X_j is a set of controls, and φ_j is an error term.

The choice of the controls is important because it helps to mitigate bias arising from the omitted variables and establish convincing relationship between the instrument and the independent variable. I use the same set of the controls for both stages. My control variables cover geographic and economic factors, as well as those related to military railroad construction. See Section 6 for a more detailed discussion about controls.

Note, however, 2SLS is not the only way to estimate the effect. The comparison of the actual and optimal networks can be summarized in 4 cases:

(1) Both the actual and the optimal networks exist, so the decision made by the tsar was also economically optimal.

(2) The actual network exists but should have not been according to the optimal network, i.e. the decision was made out of non-economic reasoning.

(3) The actual network has not been built but should have according to the optimal network, also economically non-optimal decision.

(4) Neither the actual nor the optimal network exist, hence, the decision by the tsar coincides with the economically optimal one.

Mathematically, let us represent it in the following way:

$$\forall j : (Z_j, Z'_j) \in \{(1,1),(1,0),(0,1),(0,0)\}, \tag{10}$$

where 1 denotes the presence of Z or Z', actual network and optimal one respectively, in j, 0 denotes the absence of Z or Z' in j. I am interested in the counties where $(Z_j, Z'_j) \in \{(1,0),(0,1)\}$ as they reflect all the provinces and corresponding railways that were constructed based on non-economic rationale. Selected the sample of regions with this condition, I avoid the endogeneity problem, and equation 8 can be estimated without any additional equations.

6 Results

6.1 General Equilibrium Model

After the model is calibrated, I obtain the optimal railway network. The model estimates that the social welfare loss from the historical network suboptimality is around 2.3% which is not highly significant economics-wise. One would expect the utility to change much greater considering the distinct changes in network configurations.

The synthetic network meets expectations in terms of connecting the main economic centers. When compared to the historical one, it noticeably shifts from the borders to the center of the country. It can be partly explained by the fact that the model does not take into account international trade.

Looking at the "counterfactual" network, we see that it is much less developed in the Caucasus than in reality. Moreover, this Caucasian *component* is not connected to the main network. Also note that the model does not propose the construction of a railroad to Crimea, and the number of proposed railroads near the western border is quite small. All of these railways were most likely historically constructed due to military reasons, i.e. in response to the Crimean war, Russo-Turkish wars and the political unrest in Poland. The discrepancy between the two networks in clearly military cases validates the whole approach and justifies the following analysis.

The historical railroad network in the European part passes through 358 counties while the optimal network connects 361 regions with each other. The number of edges is 505 in the historical one and 479 in the optimal one. The counterfactual network is more compact, dense and with a smaller number of branches. Also, it is visually noticeable that the optimal graph is more connected, and there is not a large number of unconnected sections. This is likely due to the fact that some of the railway projects in 1897 were still in the process of being created, and they had not yet been connected to the rest of the railway network.

6.2 Effect on Urbanization

At first glance, the predictive power of the model-based network is very high. The two networks are very similar in many places. I evaluate the predictive power of the new graph and its quality as an instrumental variable by conducting a standard F-test. The null hypothesis of this test is that the instrument does not explain the historical railroad network. In my case, there is only one instrumental variable and, thus, the F-value is just the square of the corresponding t-value. It is frequently asserted that a robust and strong instrument is at least characterized by an F-value exceeding 10. The results of this stage, characterized in Equation 9, are reported in columns 1-4 in the Table 2.

In all first stage models, the effect of the optimal network on the historical one is

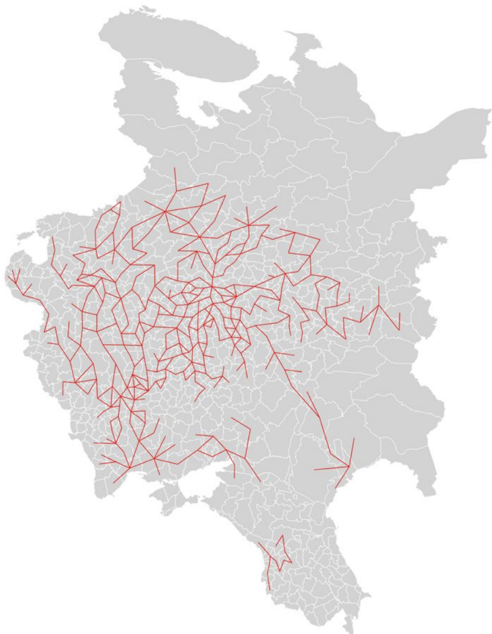

Figure 5: Model-based optimal railway network of the European part of Tsarist Russia in 1897

strictly positive and statistically important at 1 per cent level. The first OLS regression of the actual network on the model-based network gives the F-value of 15.39. At the same time, the inclusion of geographical controls greatly reduces the value of the F-test, lowering it to 5.3. A geographical region stands for a territory of 5 large areas that the country can be divided into, namely Northwestern (*Northwestern Krai*), Southwestern (modified *Southwestern Krai*), Caucasus (*Caucasus Krai*), Ostsee (*Ostsee governorates*), and Central regions (see Appendix A.4 for the list of the territories included in each region). This is an intuitive and logical division of the empire, by areas sharing common features, principles of governance, culture and language.

On the surface, the use of provinces seems to be a more intuitive set of controls, since they are in the same regional context. They are also under the same administration. I do not use this control because the variance of railroad network dummy (whether the historical network is in a county or not) is very low within one province. The rough estimate is that 80% of counties within one province on average share the same value of this dummy variable[15].

Models 3 and 4 are more plausible specifications of the first stage regression. I control for the population and its square value because this confounder directly affects both the optimal railroad network and the real one. Both historical and synthetic networks rather connect big cities (counties) than small ones. And as already mentioned, many decisions regarding the construction of railways were made due to military reasons. I add two controls to account for that: a border province dummy and the indicator whether the

[15] The equally-weighted average of the intra-group variation is 0.15.

distance is less than 1000 kilometers from the Crimean peninsula or not. They capture the effect of the two main directions of troop deployment. The model 4, which includes all the proposed controls, is the most accurate and convincing one. The F-value is 10.24 in this specification.

Using model 4 as the preferred model for the first stage, I get the final results of the 2-stage least-squares regression (Model 5). The construction of the railroad network does not create any significant effect on urbanization. This result is in line with the previous research estimates of the railway economic effect. However, one major source of bias here is that the effect of the railroad construction boom of the 1890s had not yet been fully accumulated by that time. A better approach is to conduct the same analysis at the beginning of the 20^{th} century (see also discussion in 7) but is not currently possible due data inavailability.

Table 2: Impact of the railway infrastructure on urbanization. 2SLS

	Dependent variable:				
	Actual historical network				Urbanization
	OLS				*2SLS*
	(1)	(2)	(3)	(4)	(5)
Actual historical graph					−0.001 (0.089)
Optimal network	0.163*** (0.042)	0.103** (0.045)	0.116*** (0.043)	0.138*** (0.043)	
Border				0.120 (0.080)	0.075* (0.035)
Population			3.201*** (0.483)	2.473*** (0.488)	1.036*** (0.274)
Population^2			−1.712*** (0.465)	−1.202*** (0.462)	0.408** (0.134)
$\mathbb{1}$(Crimea distance <1000 km)				0.241*** (0.045)	0.013 (0.024)
Geographical Region Control	✗	✓	✓	✓	✓
Constant	0.527*** (0.033)	0.333 (0.270)	0.051 (0.261)	0.119 (0.255)	−0.050 (0.072)
Observations	564	564	564	564	564
R^2	0.026	0.074	0.155	0.201	0.163
Adjusted R^2	0.025	0.064	0.143	0.186	0.147
F-test	15.390	5.377	7.398	10.24	

Note: *p<0.1; **p<0.05; ***p<0.01. F-test checks the weakness of the optimal network as an instrumental variable. The standard errors are clustered at the geographical region level.

7 Discussion & Conclusion

This paper aims to contribute to the literature on transportation infrastructure in three main ways. First, I propose using a model-based optimal network as an instrumental variable for establishing the economic effects of the transportation network construction in historical contexts. Second, I apply the proposed method and estimate how the construction of the railway network in Tsarist Russia affected urbanization. Finally, I provide an estimate of the welfare loss in the Russian Emprie due to the suboptimality of the historical railway network configuration.

The current work has several limitations and assumptions that can be relaxed in the further research. First, the current general equilibrium model does not account for the international trade which is an important economic reasoning for the railway construction. Second, current paper looks at the static effect for year 1897. Although almost 20 years have passed after the *first* railroad boom in Tsarist Russia, the effects of the *major* surge in construction in 1890s may have been downplayed. It would be interesting to explore the dynamic effects 10, 15, 20 years after the second boom. Third, the network discretization connects a county centroid to the overall graph even if the railroad is present in a tiny part of the county. Future research can use geospatial regression models which mitigate the discretization bias or explore other approaches such as the square grid discretization proposed by Fajgelbaum & Schaal (2020). Also, I use a proxy for output so the model does not account for such economic sectors as services, for instance. The model does not consider how different features of terrain may affect the network building. For instance, it is much more difficult to construct a network in a marshland than in the field. Additionally, general equilibrium model parametrization can be improved and it requires further research in economic history to estimate the value of important parameters such as α (expenditure share that consumers devote to tradeable goods) in the consumer preferences and σ, elasticity of substitution between varieties of goods. Also, it may be worth using historical trade flow data to better calibrate the general equilibrium model.

The proposed methodology of using a synthetically constructed economically optimal network as an instrumental variable can be applied in many other contexts, especially when the variable of interest is non-economic such as voting, protests or spread of ideology (in the Russian Empire setting, communism). In turn, the reconstructed historical graph can also be used to estimate variables of economic interest with a slightly different identification strategy. For instance, the proposed by Banerjee et al. (2004, 2020) "straight line" approach where the instrumental variable which establishes straight-line connections between large cities.

8 Acknowledgements

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Appendix

A.1 Distribution of Agricultural and Industrial Outputs

These maps show the distribution in agriculture (wheat and oat) and industrial outputs. Note that the industrial map has huge outliers such as Saint Petersburg.

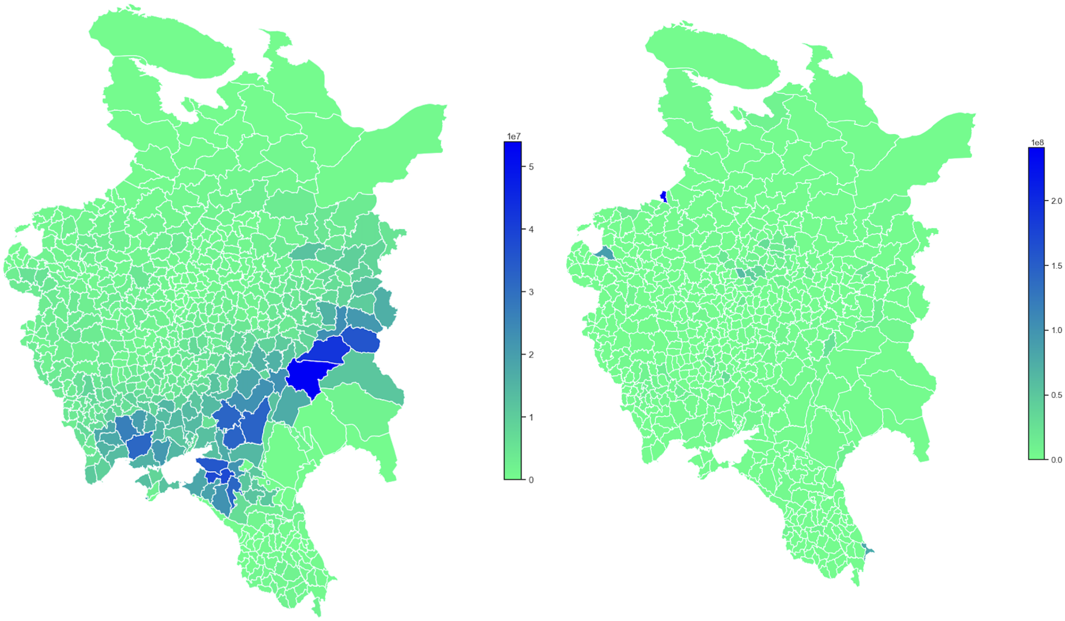

Figure 6: The distribution of agricultural (left) and industrial (right) outputs in Tsarist Russia

A.2 Contemporary Railway Network

The map of the constructed contemporary railway network for 15 countries: Armenia, Azerbaijan, Belarus, Estonia, Georgia, Kazakhstan, Kyrgyzstan, Latvia, Lithuania, Moldova, Russia, Tajikistan, Turkmenistan, Urkaine, Uzbekistan.

Figure 7: Contemporary network of the railway network in the post-Soviet countries

A.3 Network Discretization

This is a subsample of the network discretization algorithm.

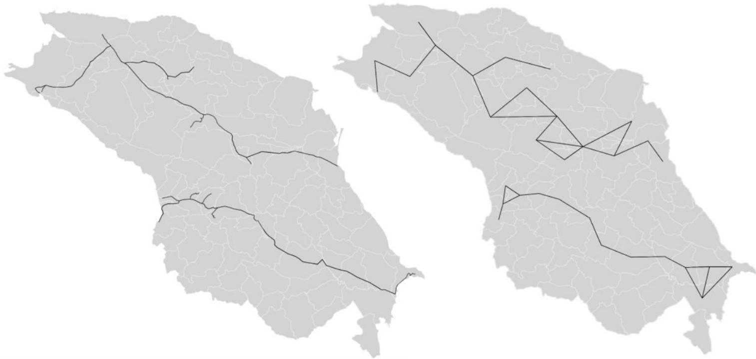

Figure 8: Example of network discretization in Tsarist Russia

A.4 List of geographical regions

(1) Northwestern Region: Grodno governorate, Kovno governorate, Minsk governorate, Mogilev governorate, Vilna governorate, Vitebsk governorate

(2) Southwestern Region: Bessarabia governorate, Kiev governorate, Podolsk governorate, Volhynian governorate

(3) Caucasus Region: Baku governorate, Black Sea governorate, Dagestan region, Elisabethpol governorate, Erevan governorate, Kars governorate, Kuban region, Kutaisi governorate, Stavropol governorate, Terek region, Tiflis governorate

(4) Ostsee (Baltic) Region: Estonia governorate, Kurland governorate, Livonia governorate

(5) Central Region: Arkhangelsk governorate, Astrakhan governorate, Chernigov governorate, Don Cossack host lands, Ekaterinoslav governorate, Kaluga governorate, Kazan governorate, Kharkov governorate, Kherson governorate, Kostroma governorate, Kursk governorate, Moscow governorate, Nizhny Novgorod governorate, Novgorod governorate, Olonets governorate, Orel governorate, Penza governorate, Poltava governorate, Pskov governorate, Ryazan governorate, Samara governorate, Saratov governorate, Simbirsk governorate, Smolensk governorate, St. Petersburg governorate, Tambov governorate, Taurida governorate, Tula governorate, Tver governorate, Ural region, Viatka governorate, Vladimir governorate, Vologda governorate, Voronezh governorate, Yaroslavl governorate

A.5 Historical Railway Network

Figure 9: Reconstructed historical railway network of the European part of Tsarist Russia up to 1897

A.6 Optimization Space

The general equilibrium model operates in the space of potential solutions. The space is a mathematical representation of the topology of the country. The graph is based on adjacency matrix of all counties. The nodes are centroids of the couties.

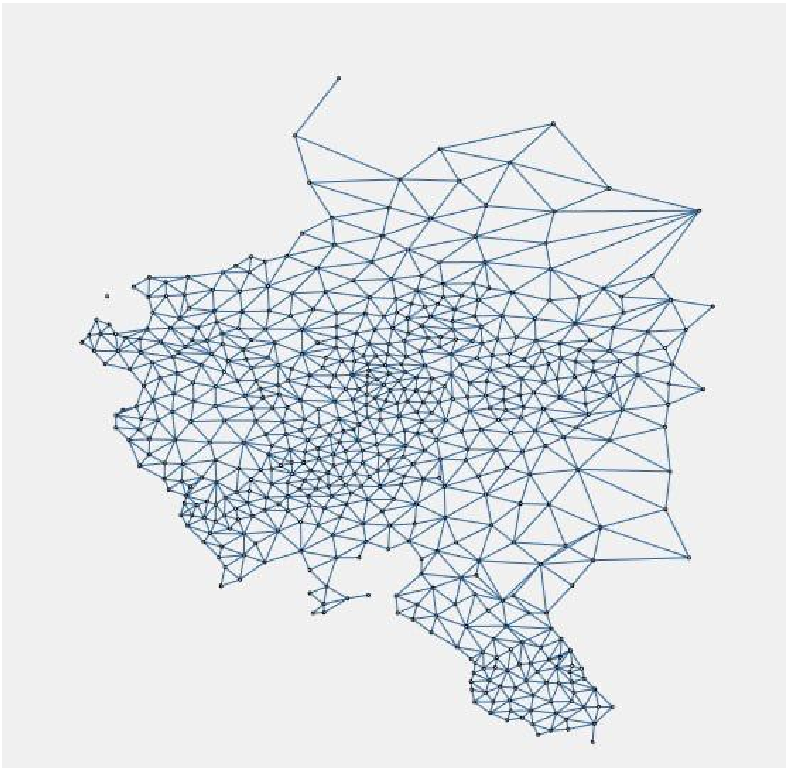

Figure 10: Space of potential solutions for infrastructure network in the general equilibrium model