Old But Gold: Historical Pathways and Path Dependence

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Abstract

Following the discovery of gold in 1694 in Brazil, pathways were constructed to connect coastal settlements to mining regions in the unpopulated interior. While these pathways initially facilitated the creation of road towns, their influence faded by the late nineteenth century. With the mid-twentieth-century demographic and industrial transition, regions with higher historical road density experienced renewed population growth and greater migrant inflows. We argue that this resurgence reflects the role of road towns in fostering early urbanization and structural transformation. Using an extended Rosen-Roback-Glaeser framework, we estimate strong agglomeration spillovers, suggesting that Brazil's spatial economy exhibits multiple steady states and historical path dependence.

Keywords: Historical Roads, Geography, Multiple Equilibria, Path Dependence, Persistence, Population Density
JEL Codes: R12, N96, O18, O43

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1 Introduction

What drives the spatial distribution of economic activity and population? The literature extensively documents the role of location advantages and historical shocks in shaping economic geography. Some studies emphasize the persistence of location advantages as the main factor (*e.g.*, Davis and Weinstein, 2002), while others highlight the importance of historical events in determining where people settle (*e.g.*, Bleakley and Lin, 2012). A growing consensus suggests that "location fundamentals may be key when differences across locations are large, but other factors dominate as locations become more similar" (Hanlon and Heblich, 2022). Or, as put succinctly: "history matters only when it matters little" (Rauch, 1993).

In this paper, we study the long-run effects of historical roads on the distribution of population within Brazil and contribute to the existing literature by revealing a dynamic pattern of spatial development that initially grows and falls, laying dormant, but that later resurges, creating agglomeration economies in a pattern consistent with a path-dependent effect driven by early urbanization and structural transformation. Our analysis centers on a pivotal event in the late seventeenth century: the sudden discovery of gold around 1694, which led to the construction of "gold roads" connecting coastal settlements to the then unpopulated interior, which in turn drove the creation of "road towns," a new type of urban settlement with a mostly non-rural mix of initial population. These routes eventually transformed into a national "mule road" network, vital for internal transportation until the introduction of railroads in the late nineteenth century.

While both types of roads eventually became obsolete with the advent of modern transportation in the twentieth century, our findings demonstrate that they continue to influence population density and economic activity today. Specifically, a 10-percentage-point increase in gold road density today is linked to a 20% increase in local population density, along with significant rises in other indicators, such as nightlight intensity and urban population. Mule roads also show a similar, though somewhat weaker, effect.These findings underscore the enduring impact of historical infrastructure on contemporary settlement patterns and economic activity.

Beyond modern outcomes, we find that the impact of the historical roads on population distribution initially faded by the early twentieth century, suggesting a return to the trend similar to the temporary effects observed in Davis and Weinstein (2002).[1] However, intriguingly, this influence reemerged in the mid-twentieth century, coinciding with the country's rapid urbanization and industrialization with large-scale internal migration. Areas with higher gold road density saw faster population growth, not only because the remnants of these roads may have lowered migration costs but also because the original gold routes supported early urban development with the road towns, which then acted as agglomeration seeds to support early industrialization.[2] Mule roads also played a role in this later growth, although their influence was somewhat smaller.

To quantitatively interpret these patterns, we estimate net agglomeration effects in an extended version of the Rosen-Roback-Glaeser framework derived by Allen and Donaldson (2022), using exogenous topographic least-cost paths as instruments for population density. Our estimates reveal that net agglomeration forces are not strong enough to sustain shocks indefinitely, yet they are sufficient to generate multiple spatial equilibria. In other words, convergence to a single uniform outcome is unlikely; instead, path-dependent equilibria remain possible, which means that the resurgence of historically advantageous regions could permanently reshape Brazil's long-term spatial configuration.

Gauging the effects of historical roads on current economic development involves several challenges. First, acquiring historical data is complex. We digitize gold roads from historical maps in Simonsen (1977), depicting routes connecting coastal settlements to gold mines discovered in Brazil's hinterlands in the last decade of the seventeenth century. For mule roads, we build a unique origin-destination network from nineteenth-century archival documents and government reports. Integrating these sources improves the external validity and provides robust empirical strategies.

[1] Davis and Weinstein (2002) document that Japan's population distribution returned to its pre-World War II state after the destruction of physical capital during the war.

[2] We rule out the possibility that the placement of modern transportation infrastructure explains this dynamic. Notably, railroad infrastructure was already significant by 1920, when historical roads had no effect on population density. Additionally, less than 10% of the highway network had been constructed by 1960, yet the positive relationship between historical roads and population density was already apparent. Moreover, the coefficients associated with this relationship remain robust when controlling for the Minimum Spanning Tree network originating from Brasília, an exogenous predictor of highway expansion proposed by Morten and Oliveira (2024).

Using georeferenced trails, we compute road density as the area of a 5-kilometer buffer around the road divided by the region's total area. Outcome variables for population are constructed from censuses spanning 1920–2010.

Second, inferring causality between historical roads and modern development requires careful methods to address nonrandom factors such as pre-existing towns and exploration strategies. We employ optimal least-cost paths based on exogenous topography as instruments for road placement, combined with the inconsequential units approach (Redding and Turner, 2015). This mitigates omitted variable bias by isolating areas crossed due to topographical convenience. Additional sample restrictions – such as excluding pre-existing locations and limiting comparisons to municipalities near the roads – further strengthen causal inference. Finally, we isolate the effects of geography from our estimates by controlling for factors such as temperature, rainfall, elevation, proximity to rivers and the coast, and terrain ruggedness. A placebo test using optimal paths between municipalities with no historical connections confirms that our geography controls are an effective proxy for location advantages.

This study engages with the broader debate on whether spatial distribution is shaped predominantly by location fundamentals or path dependence. While some research highlights the enduring role of location fundamentals (*e.g.*, Davis and Weinstein, 2002, 2008; Lee and Lin, 2017), others emphasize the significance of historical events in shaping current spatial configurations (*e.g.*, Redding, Sturm and Wolf, 2011; Bleakley and Lin, 2012, 2015; Maloney and Valencia Caicedo, 2016; Michaels and Rauch, 2017; Hanlon, 2017). Our findings add to the latter by demonstrating that historical roads have had long-lasting effects on population distribution through path dependence in Brazil—a country that has a geography that is not as rugged as Japan, but at the same time is more rugged and has higher transportation costs than the United States.

A rich strand of research documents how historical infrastructure and settlement patterns can exert lasting influence on modern economic geography. For instance, Jedwab and Moradi (2016) and Jedwab, Kerby and Moradi (2017) show that railroads and settler cities established during colonization in sub-Saharan Africa shaped the spatial distribution of population long after the original infrastructure waned. Similarly, Dalgaard, Kaarsen, Olsson and Selaya (2022) demonstrate that Roman roads strongly predict current road networks and economic outcomes in Europe, a persistence that did not hold where wheeled transport was abandoned. In the Brazilian context, Barsanetti (2021) finds that pre-Columbian trails continue to shape modern urbanization mediated by railroads but not paved roads, with early settlements playing a potential role, while Portugal and Barsanetti (2023) compare the divergent economic impacts of two of the first gold roads, highlighting the importance of historically driven trade intensities. Likewise, Paik and Shahi (2022) underscores how ancient nomadic migration routes in Asia persist in shaping population density, while Bosker and Buringh (2017) and Cermeno and Enflo (2019) highlight the interplay between first-nature geography and second-nature agglomeration effects in Europe's urban evolution.

These empirical findings resonate with broader theoretical insights from Allen and Donaldson (2022) and Allen and Donaldson (2020), who show that historical shocks can produce multiple spatial equilibria when agglomeration spillovers are sufficiently strong. Our paper advances this literature on several fronts by providing both a richer temporal analysis and a deeper investigation of both the causal mechanisms of the contemporaneous outcome and of the agglomeration spillover (see, *e.g.*, Lin and Rauch, 2022).

We also move beyond standard long-run outcome comparisons by tracking population changes across multiple census decades, unveiling a dynamic pattern wherein the influence of the historical roads dissipates by the early twentieth century, only to reemerge during Brazil's rapid mid-century urbanization and industrialization. This temporal lens allows us to pinpoint the role of early urban formation, subsequent industrialization, and internal migration in generating the observed path dependence—highlighting that our findings capture not only current outcomes but also the causal channels that drive them. Finally, by embedding these reduced-form results in an extended Rosen-Roback-Glaeser framework, we quantify historical and contemporaneous agglomeration spillovers and show how these forces may generate multiple equilibria and reshape spatial equilibria in the long run.

Our study also contributes to the literature estimating productivity spillover effects. First, we introduce a novel instrumental variable tailored to the Brazilian context, whereas much of the existing literature directly estimate population density or instrument it using lagged population (*e.g.* Barufi, Haddad and Nijkamp, 2016; Chauvin, Glaeser, Ma and Tobio, 2017; Ehrl and Monasterio, 2021; Dingel, Miscio and Davis, 2021). A notable exception is Almeida, Neto and Rocha (2023), who apply a shift-share instrumental variable approach to estimate the agglomeration coefficient, though their focus is on different outcomes. Additionally, we are able to disentangle contemporaneous spillovers from historical spillovers, such as in Allen and Donaldson (2020).

2 Gold, mules, and historical pathways

In this section, we briefly explore the history of urban agglomerations in Brazil, emphasizing the significance of the gold roads in facilitating early movements toward the interior and the development of the ground transportation network in the mid-nineteenth century.

Following their initial contact in 1500, Portuguese colonizers established settlements along the Brazilian coast. For an extended period, they avoided venturing into the hinterlands due to the challenges posed by the indigenous population, geographical barriers, and high transportation costs.[3] The main incursions into the Brazilian hinterlands consisted of Jesuit missions and slave-raiding expeditions, known as *Bandeirantes*, which primarily followed indigenous trails and relied on enslaved individuals as porters (Abreu, 1998; Kok, 2009). Despite these efforts, the missions and *bandeirante* expeditions failed to significantly alter the population's concentration along the coast (Deffontaines, 1938; Morse, 1974).

[3]In 1627, the Franciscan friar Vicente de Salvador famously likened the Portuguese presence on the coast to crabs scratching the shores (Salvador, 2010, p. 70). Later in the 1700s, the Benedictine friar Gaspar da Madre de Deus observed that the essential reason why the Portuguese had decided to settle only on the coast was transportation costs: King John III of Portugal (1502–1557) knew that all goods produced along the coast could be easily transported to Europe, while those of the hinterland would never get to the ports and if they did the costs would be such that the farmers would not sell for the prices offered to them (Deus, 1920, p. 179).

In the late sixteenth century, Brazil had only three towns and fourteen villages, mostly scattered along the coastline.[4] São Paulo, founded in 1554, was a notable exception, as it was located inland (Azevedo, 1956). The establishment of São Paulo required arduous expeditions to penetrate the country's interior, carving paths through dense rainforests and the coastal mountain range while navigating conflicts and negotiations with the indigenous population.[5]

Gold mines were discovered around 1694 in Minas Gerais and later in Goiás and Mato Grosso, shifting the focus of Brazil's economy from coastal sugarcane plantations to the mining regions of the interior.[6] Several pathways were established to connect the mines with coastal settlements, facilitating the transport of agricultural provisions to the mining areas and the shipment of precious metals back to the coast (Morais, 2010). During the gold mining era, the main transportation system was the *mule train*, which proved an excellent option to trail irregular pathways (Borges, 2016).

To accurately depict the spatial distribution of settlements in colonial Brazil, we rely on two primary sources. First, Azevedo (1956) provides a comprehensive list of villages and towns, along with their foundation years, from 1500 to 1822. To complement this list and expand it to include other years, we use historical data on current municipalities made available by the Brazilian Institute of Geography and Statistics (IBGE). This information, presented as brief histories of municipalities and their administrative evolution, is collected through programmatic data extraction. This additional data enables us to identify settlements that were not officially classified as villages by the Portuguese crown.[7] Details about the data extraction procedure are available in the Appendix B.

[4] We use the following terms to categorize settlements: towns (*cidades*), villages (*vilas*), and other settlements (*distritos*, *freguesias*, *povoados*, and *arraiais*). Towns and villages are similar to modern municipalities. Other settlements refer to other communities lacking administrative autonomy.

[5] For instance, enslaved porters carrying 30-kilogram loads needed four to five days to complete the 70-kilometer round trip between the port city of Santos and São Paulo, a route that crossed the imposing *Serra do Mar* mountain range (Reis, 2023).

[6] The exact date of discovery is uncertain, but historical accounts suggest that gold was found between 1693 and 1695 in various parts of Minas Gerais (Boxer, 2003, p. 35).

[7] For instance, relying solely on Azevedo (1956), the capital of Pernambuco, Recife, appears in our list only in 1709, when it was officially elevated to village status. However, historical records indicate that the settlement existed as early as 1561. Additionally, Azevedo (1956) omits several villages that the programmatic data extraction successfully identifies and includes.

Figure 1 illustrates the spatial distribution of settlements in Brazil, along with the gold roads, both before (1694) and after (1822) the gold rush era. The gold roads' trace was georeferenced from Simonsen (1977). For context, we also highlight major rivers and the states where gold was discovered. In addition to towns and villages, the map includes districts, parishes, and other smaller settlements. In Panel A, we identify 48 villages and towns scattered along the Brazilian coast before 1694, as noted earlier, along with 15 other settlements also located on the coast. Notable exceptions include settlements in the north, along the Amazon River, and *Jacobina* in the interior of Bahia, which was founded in 1677 as part of expeditions searching for gold.

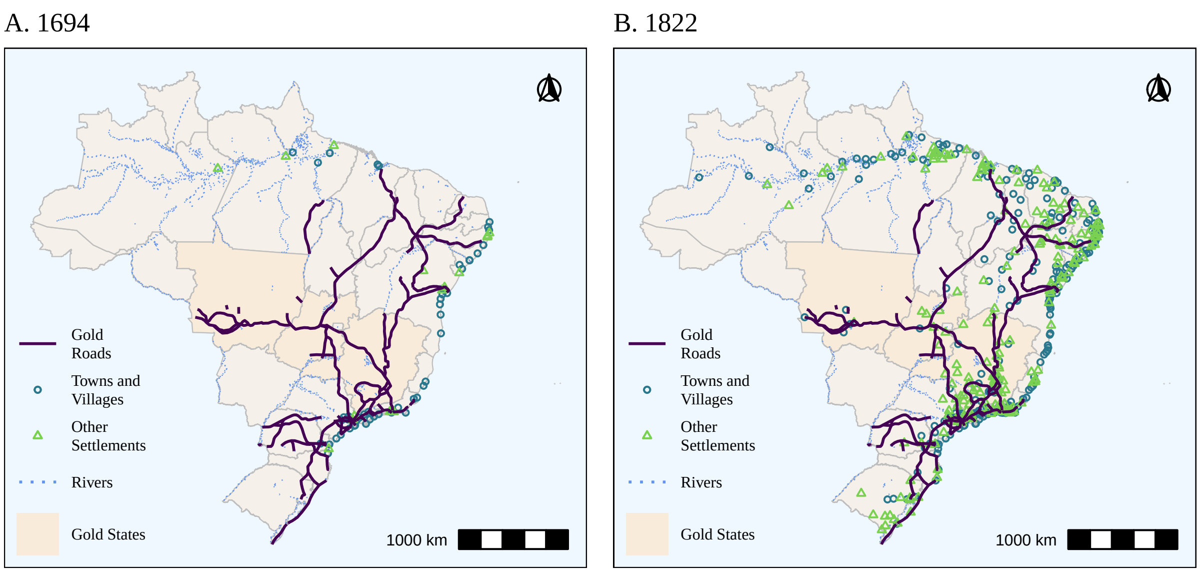

Figure 1: **Gold roads and population settlements.** *Notes:* Spatial distribution of settlements in Brazil before (1694) and after (1822) the gold rush era. The Gold States are Minas Gerais, Goiás, and Mato Grosso. Gold roads were georeferenced from maps in Simonsen (1977). Settlements and their classification are from Azevedo (1956) and current municipalities' history from IBGE.

Figure 1B shows the spatial distribution of agglomerations in 1822, the year of Brazil's independence, providing a snapshot of the landscape left by Portuguese colonization. This date also enables a meaningful comparison with 1694, as the administrative structure remained largely unchanged. By 1822, gold mines were largely depleted, and gold had lost much of its economic significance compared to a century earlier. Our data identifies 217 villages and towns, along with

200 smaller settlements. The eastern coast is densely populated with settlements, while those in the interior are concentrated along the gold roads, the Amazon River, and the far southern regions.

The gold cycle in Brazil lasted approximately 50 years. However, from 1730 to 1875, mule trains dominated long-distance inland transport. Over time, the gold roads evolved into a nationwide mule road network, particularly after the 1830s, when the number of pathways expanded rapidly (Morais, 2010). To assess the relationship between the gold roads and the broader mule road system, we calculate the density of these roads within present-day municipalities. Road density is defined as the area within a five-kilometer buffer around roads in a municipality, relative to the municipality's total area.

Gold road density can be directly calculated using the maps from Simonsen (1977). However, maps showing the exact routes of mule roads are not available. The data used in this analysis come from manuscripts and official documents issued by the Brazilian imperial government in 1863 and 1873. These documents provide information on distances between municipality pairs, primarily traveled via ground transportation dominated by mule trains.[8] While the documents specify the distances traveled, they do not detail the precise routes. To address this, we construct least-cost paths for all municipality-pair connections mentioned in the documents. The resulting network is shown in Figure 2B. Details regarding data sources, methodological procedures, the relationship between reported and estimated distances, as well as maps illustrating historical road density, are provided in Appendices A and B.

In Panel A of Figure 2, we also display the least-cost paths for gold roads, which are used to compute an instrumental variable for gold road density. The least-cost paths are calculated using detailed terrain topology data to estimate the travel time required to traverse the terrain on foot, based on slope, following the methodology of Barjamovic et al. (2019). See Appendix B for details. The underlying assumption is that while animals such as horses and mules accompanied humans during these journeys, they did not impose significant constraints on travel time. Furthermore, they were unlikely to speed up travel, given historical accounts indicating that wheeled transportation

[8]Some of the municipality-pair connections were reported in a Post Office report by the imperial government. Including an indicator for roads that were official mail routes does not affect the main regression results.

A. Gold Roads

B. Mule Roads

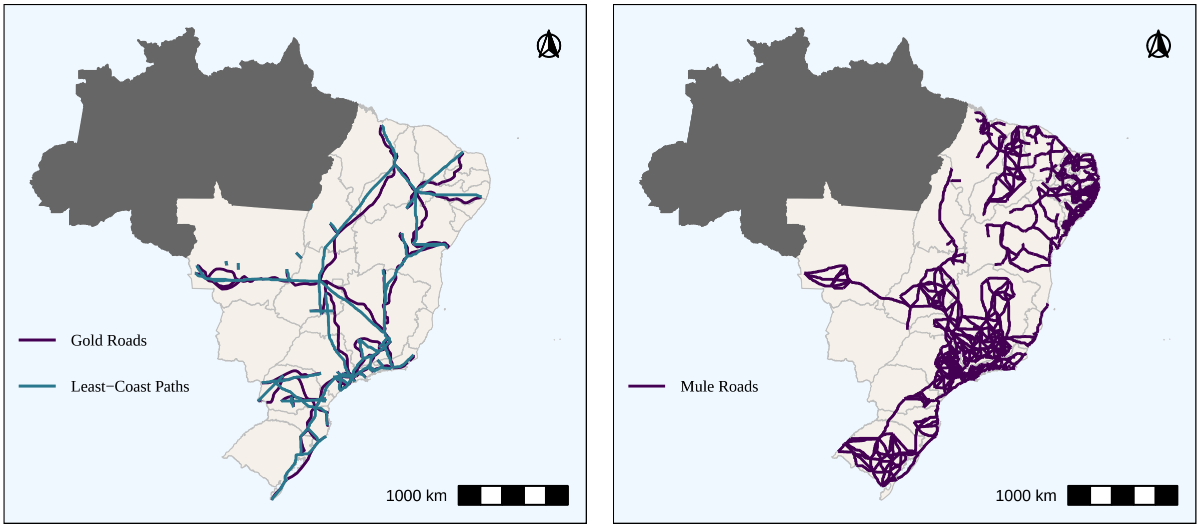

Figure 2: **Gold roads and mule roads least-cost paths.** *Notes:* Panel A shows the traces of gold roads and their equivalent least-cost paths, while Panel B displays inferred mule roads based on least-cost paths. The least-cost paths minimize travel time by accounting for terrain topology, following the approach of Barjamovic et al. (2019). The grey-shaded areas represent states heavily influenced by the Amazon River, which are excluded from the analysis.

was infeasible due to poor road quality and that many participants in the *mule trains* traveled on foot rather than riding horses.

Table 1 presents the relationship between gold road density and mule road density. All estimates include state fixed effects, with standard errors clustered at the level of 1872 Minimum Comparable Areas (MCAs).[9] In columns 4 to 6, least-cost paths of gold roads are used as instrumental variables in a Two-Stage Least Squares (2SLS) estimation. Columns 2 and 5 include geography controls to mitigate spurious correlations arising from advantageous geographic features. Columns 3 and 6 restrict the sample to municipalities crossed by gold roads and their direct neighbors, ensuring a more homogeneous sample.[10] The results indicate a positive and statistically significant relationship between gold road density and mule road density. Ordinary Least Squares (OLS) estimates tend to underestimate this relationship, while excluding geography controls leads

[9]The 1872 MCAs, as defined by Reis, Pimentel, Alvarenga and Santos (2011), are areas with stable boundaries corresponding to the municipalities of 1872. These MCAs group geographical locations from 2010 that historically shared common administrative borders.

[10]These choices are examined in greater detail in the following section.

to overestimation. Overall, the findings align with anecdotal evidence, suggesting that mule roads were, to some extent, built upon the foundations of gold roads.

Table 1: Gold roads and mule roads

	OLS			2SLS		
	(1)	(2)	(3)	(4)	(5)	(6)
Dep. Var.: Mule Road Density						
Gold Road Density	0.3694***	0.2223***	0.1396***	0.7378***	0.4698***	0.3810***
	(0.0683)	(0.0479)	(0.0391)	(0.1231)	(0.1029)	(0.1229)
Observations	5,197	5,197	2,088	5,197	5,197	2,088
Cluster Groups	404	404	260	404	404	260
Kleibergen-Paap F:				133.88	130.74	94.796
Fixed-Effects:	State	State	State	State	State	State
Geography Controls		✓	✓		✓	✓
Only Neighbors			✓			✓

Notes: Standard errors, clustered at the level of 1872 Minimum Comparable Areas, are shown in parentheses. The sample includes 2010 municipalities, excluding those in states heavily influenced by the Amazon River basin (Amazonas, Pará, Roraima, Rondônia, Acre, and Amapá) and municipalities with settlements that existed prior to 1694. Mule (gold) road density is defined as the area within a five-kilometer buffer around mule (gold) roads within a municipality, relative to the municipality's total area. The 2SLS specification uses least-cost path density as an instrumental variable for gold road density. *Geography Controls* include the log-transformed median values of precipitation, temperature, elevation, terrain ruggedness, area, distance to rivers, and distance to the coast, along with a second-order latitude-longitude polynomial. *Only Neighbors* restricts the sample to municipalities intersected by gold roads and their first-order neighbors. $^{*}p < 0.1, ^{**}p < 0.05, ^{***}p < 0.01$

This section detailed the development of early transport infrastructure in previously unpopulated areas, spurred by the discovery of gold, and its subsequent evolution into a broader network of ground transportation known as mule roads. These historical pathways remained the primary means of facilitating movement in the Brazilian hinterland until the late nineteenth century when railroads were introduced. In the next section, we examine the relationship between these pathways and the current population distribution.

3 Historical pathways and the current population distribution

Having established the significance of historical roads, particularly the gold roads, in shaping the spatial distribution of settlements during the colonial era, we now examine whether these roads continue to influence population distribution today despite having been rendered obsolete by the advent of modern transportation technologies. We model the relationship between historical roads and current agglomeration using the following linear regression equation:

$$y_i = \alpha_s + \beta \text{Road Density}_i + \mathbf{X}_i' \boldsymbol{\gamma} + \epsilon_i, \tag{1}$$

where y_i represents a measure of agglomerations at municipality i in 2010. Specifically, y_i denotes the log-transformed values of population density, nightlight incidence, or urban population density. Population density is defined as population over area, while urban population density is urban population over area. Nightlight incidence is the median value of nightlights captured from satellites. The variable Road Density$_i$ captures the influence of historical roads measured as the area within a five-kilometer buffer around the roads within a municipality relative to the municipality's total area. The term ϵ_i denotes the error term.

As outlined in the introduction, it is crucial for our analysis to isolate the effects of roads on the current population distribution from the effects of geography. Neglecting geography would lead to biased interpretations of the results, as the placement of roads is likely influenced by geographic factors. To avoid conflating the influence of roads with that of location fundamentals, the column vector $\mathbf{X}_i$ includes a set of geographical covariates.

As expected and shown in Figure 1, proximity to rivers and the coast tends to attract settlements. Therefore, we control for the distance to rivers and the coast in our estimates. Additionally, we include median temperature, precipitation, terrain ruggedness, and elevation, as these factors affect local amenities and agricultural productivity. The area is also included as a control to account for the potential endogenous division of municipalities due to agglomeration effects. Finally, a second-order latitude-longitude polynomial is included to flexibly account for the spatial location of municipalities. To ensure a more homogeneous comparison group, we include state fixed effects, denoted by α_s, and in some specifications, we restrict the sample to municipalities traversed by roads and their direct neighbors.

Another source of concern is the potential endogeneity in the placement of roads along pre-existing settlements. To address this, we combine an instrumental variables approach using least-cost paths with a variant of the inconsequential units approach (Redding and Turner, 2015), restricting our sample to exclude endpoints where pre-established population settlements existed. The optimal least-cost path strategy similar to Barjamovic et al. (2019) leverages exogenous variation in the region's topography to create the instrument independent of the existing economy. Additionally, we remove municipalities where pre-existing settlements are located, making the remaining areas inconsequential for the route choice and ensuring that they are only traversed because they lie on a convenient path.[11]

Gold Roads Our final gold road sample excludes municipalities in the northern states where transportation is primarily influenced by the Amazon River. These states include Amazonas, Acre, Rondônia, Roraima, Amapá, and Pará. The sample consists of 5,197 municipalities, with population densities ranging from 0.23 to 12,512 individuals per square kilometer and gold road density varying from zero to one. This distribution is highly skewed, with more than 75% of the sample having zero gold road density. On average, municipalities exhibit a gold road density of 5%. Detailed descriptive statistics are provided in Table B.1 in Section B.2. When restricting the sample to municipalities traversed by gold roads and their direct neighbors, the sample size reduces to 2,088 observations. The average population density increases, indicating that we are sampling more developed areas, and the distribution of gold road density becomes less skewed, averaging 13%.

The main results are presented in Table 2. All estimates include state fixed effects, with standard errors clustered at the level of 1872 MCAs. In columns 4 to 6, the least-cost paths of gold roads are used as instrumental variables in a 2SLS estimation. Columns 2 and 5 account for geography controls, while columns 3 and 6 restrict the sample to municipalities crossed by gold roads and their immediate neighbors. Overall, the results indicate a positive relationship between access

[11] Along these lines, Barsanetti (2023) emphasizes the enduring role of railroad endpoints in determining city size and "agglomeration shadows."

to gold roads and population concentration, as measured by population density (Panel A), nightlights (Panel B), and urban population density (Panel C). Although the effect slightly diminishes with the inclusion of geographic controls, it remains both statistically and economically significant. This reduction likely reflects potential bias from location fundamentals. According to the specification in Column (6), a ten-percentage-point increase in road density is associated with a 22% increase in population density, a 14.3% rise in nightlight intensity, and a 25.4% increase in urban population density.

As our model is exactly identified, the Kleibergen-Paap F statistic is equivalent to the effective first-stage F statistic proposed by Montiel-Olea and Pflueger (2013). In Table 2, we see that our F statistic substantially exceeds the critical value (37.42) corresponding to a 5% 2SLS bias (Montiel-Olea and Pflueger, 2013). Therefore, we can confidently apply the conventional 2SLS method with no concerns about weak instrument issues, as discussed by Andrews, Stock and Sun (2019).

Moreover, the bias introduced by the OLS estimation is substantial, leading to an underestimation of the effect of historical roads. The larger 2SLS estimates relative to the OLS estimates may suggest the presence of measurement error in the historical map used to construct the gold roads, which would explain the downward bias in the OLS results. Since our instrument accounts for key topographical features, it is likely that measurement error in the digitized gold roads causes the naive OLS estimates to underestimate the true impact of the roads.

In Appendix C, we demonstrate the robustness of our results through various extensions and alternative specifications. Specifically, we show that the results remain unchanged when we reduce the sample to exclude municipalities where the seat is located within 100 kilometers of the coast. This case addresses concerns that the dynamics of coastal cities, which were the main population settlements before 1694, may drive our results. In this scenario, estimates are smaller but still statistically and economically significant. We also demonstrate that our results are robust to using the inverse hyperbolic sine transformation in our variable of interest. This transformation alleviates concerns related to the right-skewness of gold road density, which may include zero-valued observations.

Table 2: Gold roads and current agglomerations

	OLS			2SLS		
	(1)	(2)	(3)	(4)	(5)	(6)
Panel A - Dep. Var.: Population Density:						
Gold Road Density	1.650***	1.006***	0.8388***	3.305***	2.308***	2.222***
	(0.3686)	(0.2373)	(0.2023)	(0.6256)	(0.4943)	(0.5759)
Observations	5,197	5,197	2,088	5,197	5,197	2,088
Cluster Groups	404	404	260	404	404	260
Panel B - Dep. Var.: Nightlights:						
Gold Road Density	1.170***	0.5673***	0.5071***	2.428***	1.466***	1.429***
	(0.2219)	(0.1321)	(0.1193)	(0.4085)	(0.2930)	(0.3802)
Observations	5,197	5,197	2,088	5,197	5,197	2,088
Cluster Groups	404	404	260	404	404	260
Panel C - Dep. Var.: Urban Population Density						
Gold Road Density	1.900***	1.177***	0.9944***	3.776***	2.674***	2.536***
	(0.3790)	(0.2483)	(0.2164)	(0.6666)	(0.5369)	(0.6419)
Observations	5,196	5,196	2,087	5,196	5,196	2,087
Cluster Groups	404	404	260	404	404	260
Kleibergen-Paap F:				133.88	130.74	94.796
Fixed-Effects:	State	State	State	State	State	State
Geography Controls		✓	✓		✓	✓
Only Neighbors			✓			✓

Notes: Standard errors, clustered at the level of 1872 Minimum Comparable Areas, are shown in parentheses. The sample includes 2010 municipalities, excluding those in states heavily influenced by the Amazon River basin (Amazonas, Pará, Roraima, Rondônia, Acre, and Amapá) and municipalities with settlements that existed prior to 1694. *Population Density*, *Nightlights*, and *Urban Population Density* are the log-transformed values of population over area, median nightlight incidence, and urban population over area, respectively. *Gold Road Density* is defined as the area within a five-kilometer buffer around gold roads within a municipality, relative to the municipality's total area. The 2SLS specification uses least-cost path density as an instrumental variable for gold road density. *Geography Controls* include the log-transformed median values of precipitation, temperature, elevation, terrain ruggedness, area, distance to rivers, and distance to the coast, along with a second-order latitude-longitude polynomial. *Only Neighbors* restricts the sample to municipalities intersected by gold roads and their first-order neighbors. $^{*}p < 0.1, ^{**}p < 0.05, ^{***}p < 0.01$

Moreover, the effect remains positive and significant when our explanatory variable indicates whether road density is positive. Again, this mitigates concerns about the choice of measures for gold roads.[12] The results are similar but somewhat weaker within 1872 MCAs. We acknowledge there can be a potential presence of spatial correlation among the units, thus we cluster errors at the level of 1872 MCA. As an alternative approach, we also calculate spatially robust standard errors (Conley, 1999). Importantly, Conley standard errors are similar to the ones clustered at the level of 1872 MCAs, suggesting that clustered standard errors at this level already accounts for spatial correlation.

Mule Roads We now turn our attention to mule roads, broadening the scope of our analysis. This exercise addresses the concern that our earlier findings may be context-specific or dependent on unique characteristics of the gold rush-era roads and regions studied. By expanding our focus to include the entire transportation network of the late nineteenth century, we incorporate a more comprehensive geographical area and provide a broader perspective on the relationship between historical infrastructure and contemporary outcomes.

The mule roads exercise also provides an opportunity to evaluate whether our empirical strategy effectively disentangles the influence of location fundamentals from our main estimates by examining "missing" routes. These routes are deemed "missing" because no mule roads directly connecting certain municipality pairs were documented in historical records, suggesting that these municipalities lacked direct connections. By testing whether least-cost paths through these nonexistent connections impact today's population distribution, we assess whether our results are driven by the construction of optimal paths – potentially correlated with favorable geographic features – or whether the actual presence of routes is necessary. This exercise serves as a placebo test to validate the robustness of our findings.[13]

[12] One point of concern may be that a large gold road density reflects more rugged terrain, leading to spurious interpretations. Although we control for terrain ruggedness, it is essential to show that the effects are still positive when using this alternative measure of gold road influence.

[13] To put it differently, consider a triangle with vertices A, B, and C. Suppose roads historically connected the edges AB and BC, but not AC. If historical roads indeed influence current population agglomerations, we would expect areas traversed by AB and BC to exhibit higher population density today, while areas along AC, which lacked a historical

Although the analysis of mule roads provides valuable insights, it introduces a new concern. Unlike the gold roads, mule roads were not the result of random exploration of Brazil's hinterlands but were intentionally constructed to integrate a newly independent, continental nation. When connecting points within a polygon, central points are more likely to be traversed by these connections. This could lead to a higher likelihood of being crossed by mule roads in 1872 and having greater market access in 2010, introducing a potential confounding factor.[14]

To address this issue, our previous analysis implemented two measures. First, state fixed effects help mitigate this concern by ensuring that comparisons are made within states, as municipalities that are central at the national level may not be central within their respective states. Second, we include a second-order latitude-longitude polynomial to account for the spatial positioning of municipalities. Now, we go a step further by incorporating a measure of centrality proposed by Borusyak and Hull (2023) into our set of geography controls to provide a more robust adjustment.[15]

Our centrality measure, referred to as expected mule road density, is derived by generating random samples of mule road networks and averaging their influence across these samples. There are 1,766 potential connections between the 1872 municipality seats, of which 1,090 were realized.[16] We randomly generate 1,000 samples by combining existing mule roads with "missing" roads while maintaining a total of 1,090 connections per sample. The underlying intuition is that each connection is assigned an equal probability of being constructed in each sample. For every draw, we compute the mule road density and then average these values across all draws to obtain the expected mule road density.

road, should not. In our placebo exercise, we construct a least-cost path along AC and test whether areas traversed by this hypothetical route show any significant increase in population density today.

[14]We believe centrality is not a significant concern in the context of gold roads. These roads were not constructed with the purpose of national integration, meaning central locations were not inherently more likely to be traversed. At the time, there were no pre-existing points of interest in Brazil's interior to connect, and the emergence of settlements along these roads is more plausibly a consequence of the roads rather than their cause. Moreover, when we include a centrality measure as a control in our analysis of gold roads, the results remain unchanged, further supporting this interpretation.

[15]Since the counterfactual shocks are not given by a randomization protocol (such as in a RCT), it is more efficient to control for the expected treatment instead of instrumenting the treatment, which also removes the residual variation in the outcome that is correlated with the expected treatment, as recommended by Borusyak and Hull (2023).

[16]Connections are determined by linking municipality seats with their immediate neighbors and iterating outward, following the actual observed spatial and topographical constraints of Brazil's economy at the time. This approach avoids unrealistic assumptions of direct connections between all municipalities or distant municipalities.

As with the gold roads analysis, results are presented for both full and restricted samples. The full sample excludes only municipalities in the northern states and those containing 1872 municipality seats, resulting in 4,660 municipalities. The restricted sample further excludes municipalities that are not direct neighbors of those traversed by mule roads, leaving 3,343 municipalities. The mule road sample shares similar characteristics with the gold road sample but exhibits a less skewed distribution of mule road density, with an average density of 0.17. Detailed summary statistics are provided in Table B.1. For the placebo test, municipalities traversed by existing connections are also excluded.

The results are summarized in Table 3. All columns include state fixed effects, with standard errors clustered at the 1872 MCA level. Columns 1 through 3 examine the relationship between mule road density and current population agglomerations. Column 2 incorporates geography controls, including our centrality measure, while column 3 restricts the sample to municipalities that are direct neighbors. The findings reveal a positive and statistically significant relationship between mule roads and indicators such as population density, nightlight intensity, and urban population density. Consistent with the gold roads analysis, the coefficients decrease substantially when geography controls are included, highlighting the correlation between location fundamentals and road placement. This positive association remains robust across various alternative specifications, as presented in Table C.2, mirroring the robustness checks conducted in the gold roads analysis.

Although the coefficients are noticeably smaller than those in the previous analysis, a direct comparison is not feasible, as Table 3 reflects the effects of least-cost path densities rather than actual road densities. However, when comparing the coefficients in Table 3 to the reduced-form coefficients from the gold road analysis, we observe a smaller but still significant difference, with the gold road coefficients being consistently larger.[17] This difference is expected, given the distinct characteristics of these two historical road networks. The gold roads spearheaded the movement into the Brazilian hinterland, laying the groundwork for the urban landscape, while the mule roads primarily connected the already established urban framework. Remarkably, despite their differing

[17] For least-cost paths associated with gold roads, the coefficients corresponding to Column (3) in panels A, B, and C are 0.921 (0.19), 0.592 (0.128), and 1.05 (0.21), respectively, with standard errors in parentheses.

Table 3: Mule roads and current agglomerations

	Existing Connections			Non-Existing Connections		
	(1)	(2)	(3)	(4)	(5)	(6)
Panel A - Dep. Var.: Population Density:						
Mule Road Density	1.339***	0.3570***	0.2339**	0.3254*	-0.3625	-0.2986
	(0.1570)	(0.1096)	(0.0968)	(0.1705)	(0.5280)	(0.5233)
Observations	4,660	4,660	3,343	2,466	2,466	1,775
Cluster Groups	356	356	354	223	223	207
Panel B - Dep. Var.: Nightlights:						
Mule Road Density	1.185***	0.4072***	0.2575***	0.1837	0.1603	0.3609
	(0.0940)	(0.0974)	(0.0950)	(0.1362)	(0.6362)	(0.6338)
Observations	4,660	4,660	3,343	2,466	2,466	1,775
Cluster Groups	356	356	354	223	223	207
Panel C - Dep. Var.: Urban Population Density						
Mule Road Density	1.489***	0.4232***	0.2939**	0.3283*	-0.3540	-0.2215
	(0.1652)	(0.1302)	(0.1172)	(0.1945)	(0.6977)	(0.6892)
Observations	4,659	4,659	3,342	2,466	2,466	1,775
Cluster Groups	356	356	354	223	223	207
Fixed-Effects:	State	State	State	State	State	State
Geography Controls		✓	✓		✓	✓
Only Neighbors			✓			✓

Notes: Standard errors, clustered at the level of 1872 Minimum Comparable Areas, are shown in parentheses. The sample includes 2010 municipalities, excluding those in states heavily influenced by the Amazon River basin (Amazonas, Pará, Roraima, Rondônia, Acre, and Amapá) and municipalities with municipality seats that existed 1872. *Population Density*, *Nightlights*, and *Urban Population Density* are the log-transformed values of population over area, median nightlight incidence, and urban population over area, respectively. *Mule Road Density* is defined as the area within a five-kilometer buffer around mule roads within a municipality, relative to the municipality's total area. In columns 1 to 3, mule roads are the least-cost paths between contiguous municipality pairs with existing connections. In columns 4 to 6, mule roads are the least-cost paths between contiguous municipality pairs with non-existing connections. The sample in columns 4 to 6 exclude municipalities traversed by existing connections. *Geography Controls* include the log-transformed median values of precipitation, temperature, elevation, terrain ruggedness, area, distance to rivers, and distance to the coast, along with a second-order latitude-longitude polynomial and the expected mule roads density computed using Borusyak and Hull (2023). *Only Neighbors* restricts the sample to municipalities intersected by mule roads and their first-order neighbors. $^{*}p < 0.1, ^{**}p < 0.05, ^{***}p < 0.01$

roles and magnitudes of impact, both types of historical infrastructure continue to shape the spatial distribution of population centuries after their decline.

Columns 4 to 6 present the results from the placebo test, which is essential for distinguishing between location fundamentals and the existence of roads (a historical shock). We find a small but statistically significant positive relationship at the 10% level between areas with a larger density of non-existing roads and current population agglomerations. This suggests that being along optimal paths between historical settlements is beneficial, even when historical routes do not actually exist. This result could be linked to advantageous geography that influenced the creation of optimal paths. However, in column 5, the coefficients shrink substantially and become statistically insignificant after controlling for geography, indicating these controls are crucial to properly isolate the effect of historical roads on current population distribution.

Overall, the evidence presented in this section suggests that historical factors have a significant influence on the spatial distribution of population in Brazil. The location of historical pathways, particularly gold roads, is strongly associated with higher population densities in municipalities in 2010. In the following sections, we delve deeper into this connection. First, we examine how the strength of these effects varies across different periods of time. Then, we investigate potential mechanisms and the nature of the spatial economy in which this historical shock operates. Specifically, we explore whether this represents a positive shock within a dynamic spatial system with a single equilibrium that will eventually be reestablished or whether multiple equilibria exist, with the positive shock potentially leading to a new steady state.

4 Historical pathways and the dynamics of agglomeration

In this section, we examine the evolving impact of historical roads on population density over time. Specifically, we seek to determine whether these effects are strengthening or diminishing. A declining effect would suggest a historical shock operating within a highly persistent autoregressive spatial system, gradually fading over time. Conversely, a persistent or increasing effect would indicate the presence of multiple steady states, where the historical shock may have initiated a transition toward a new equilibrium.

In the analysis that follows, we focus on gold roads because their actual historical paths are known, enabling a two-stage least squares estimation. Additionally, gold roads provide a more compelling case study; analogous results for mule roads are presented in Appendix D, with key differences highlighted in the main text. To maintain consistent boundaries over time, the units of observation in this analysis are the 1920 MCAs. While this choice reduces the number of observations (there are 953 MCAs) and increases the geographical scale of analysis, it allows for a more consistent comparison across years. Reassuringly, the 2010 estimates based on the 1920 MCAs align closely with those in Table 2.[18]

Figure 3 illustrates the effects of gold roads on population density from 1920 to 2010 using a 2SLS specification where least-cost path density is the instrumental variable for gold road density. The full sample includes 1920 MCAs, excluding those in states heavily influenced by the Amazon River basin (Amazonas, Pará, Roraima, Rondônia, Acre, and Amapá) and MCAs with settlements predating 1694, resulting in 856 observations.[19] The only neighbors sample focuses on MCAs traversed by gold roads and their immediate neighbors, totaling 604 observations. All estimates account for state fixed effects and geography. Given the limited number of observations per cluster when clustering errors at the level of 1872 MCAs, we present spatially corrected confidence intervals following Conley (1999), using a cutoff of 190 kilometers. Circles represent point estimates, and lines denote the 95% spatially corrected confidence intervals.

The influence of gold roads on population density becomes increasingly pronounced over the twentieth century. In 1920, the effect is minimal, with a coefficient of less than 0.3 and statistically insignificant. By 1940, the point estimate rises but remains below 0.5 and does not achieve statistical significance, even at the 10% level. The effect becomes statistically significant for the first

[18] The 1920 MCAs are used because 1920 is the earliest year with reliable population data and a sufficient number of observations. The 1872 census, though earlier, reduces the sample to 454 MCAs, significantly lowering statistical power. Results using 1872 MCAs are in Table D.2 in Appendix D. The 1890 and 1900 censuses are avoided due to known reliability issues (Oliveira and Simões, 2005).

[19] A full set of descriptive statistics is available in Panel C of Table B.1.

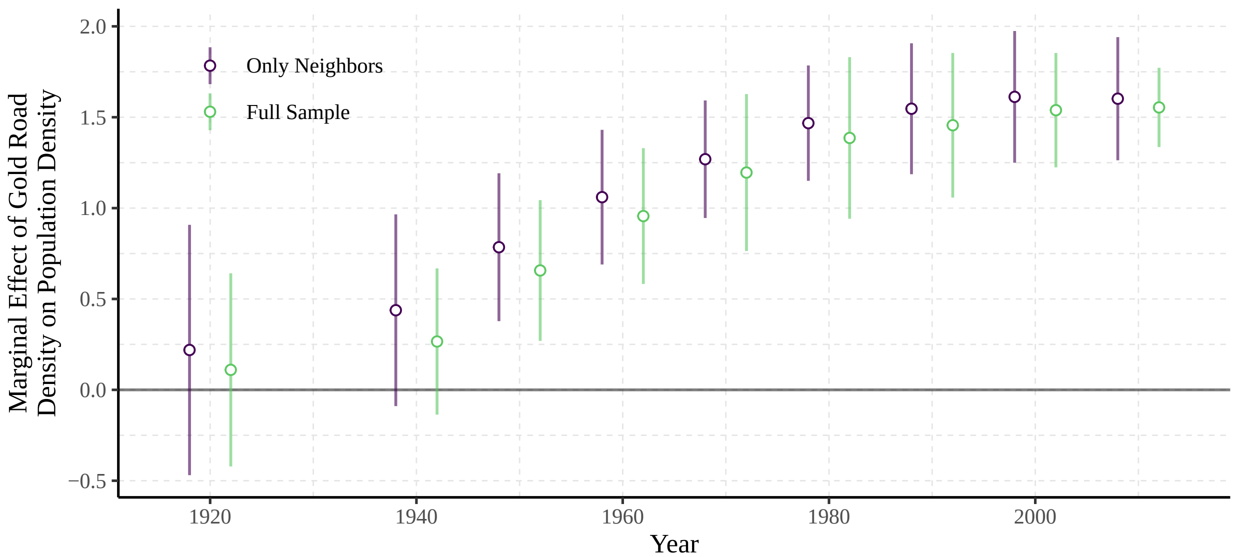

Figure 3: **Gold roads and population density over time.** *Notes:* The marginal effects of gold roads on population density are analyzed across different years using two samples and a 2SLS specification where least-cost path density is the instrumental variable for gold road density. The *Full Sample* consists of 1920 MCAs, excluding those in states heavily influenced by the Amazon River basin (Amazonas, Pará, Roraima, Rondônia, Acre, and Amapá) and MCAs with settlements predating 1694, resulting in 856 observations. The *Only Neighbors* sample includes only MCAs traversed by gold roads and their immediate neighbors, amounting to 604 observations. All estimates incorporate state fixed effects and geography controls. In all cases, the Kleibergen-Paap F is above 75. Point estimates are represented by circles, with 95% spatially corrected confidence intervals (Conley, 1999) shown as lines. Exact values are detailed in Table D.1.

time in 1950, with the coefficient peaking at approximately 1.5 in 1990, followed by only a slight increase in subsequent decades. Between 1920 and 2010, the effect of gold roads on population density grows by a factor of three. Estimation details are provided in Table D.1. Similar estimates for mule roads are also presented in Table D.1. While the pattern of increasing influence is evident for mule roads—particularly after 1960—the coefficients are only statistically significant starting in 1970. This aligns with earlier findings, which highlight the secondary importance of mule roads compared to gold roads.

The trend depicted in Figure 3 is somewhat unexpected. The first half of the twentieth century was dominated by railroad transportation, although mule roads still played a role in connecting cities. As noted in Simonsen (1977), mules continued to be vital for intercity connections in Brazil even as late as 1937. However, their freight rates were significantly higher – ranging from three to eight times those of railroads – during the period between 1860 and 1915, as documented by Reis (2023). The second half of the century, however, saw the rapid expansion of highway networks, which diminished the importance of mule troops, a point we will explore in greater detail below. Given these historical developments, one might have expected the influence of historical roads to decline over the century.

Moreover, the results presented thus far raise the question of whether historical pathways had a significant impact before the second half of the twentieth century. Investigating this earlier period is challenging due to the limited availability of population data. However, some evidence is provided in Table D.2, where we replicate the previous analysis using 1872 MCAs. While the reduced sample size limits statistical power, the point estimates for 1872 are comparable in magnitude to those observed in 1960. This finding suggests that gold roads may have played a more critical role in the past.

To extend the analysis, we utilize data on the existence of population settlements from 1570 to 1920, using the number of settlements as a proxy for agglomerations. Figure D.1 in Appendix D shows a strong positive correlation between population density and settlement density in 1920, which validates this analysis. For each year, at 50-year intervals, we calculate settlement density as the ratio of the number of settlements to the area for each 1920 MCA. Given the prevalence of zeros, particularly in earlier years, we apply an inverse hyperbolic sine transformation to this variable. Using this transformed variable as the dependent variable, we replicate the estimation from Figure 3, maintaining identical specifications and the same samples, except for years before 1694, where MCAs with pre-existing settlements are not excluded. The results are illustrated in Figure 4, with detailed estimates provided in Table D.3.

Unlike the trend observed in Figure 3, the pattern depicted in Figure 4 is unsurprising. Gold roads exhibit positive effects on settlement density for over a century and a half. The positive effect seen in 1670 likely reflects the early search for gold, as exemplified by the case of *Jacobina*, discussed in Section 2. It is important to emphasize that the coefficients before and after 1694 are not directly comparable due to differences in the samples, as indicated by the shaded area in the

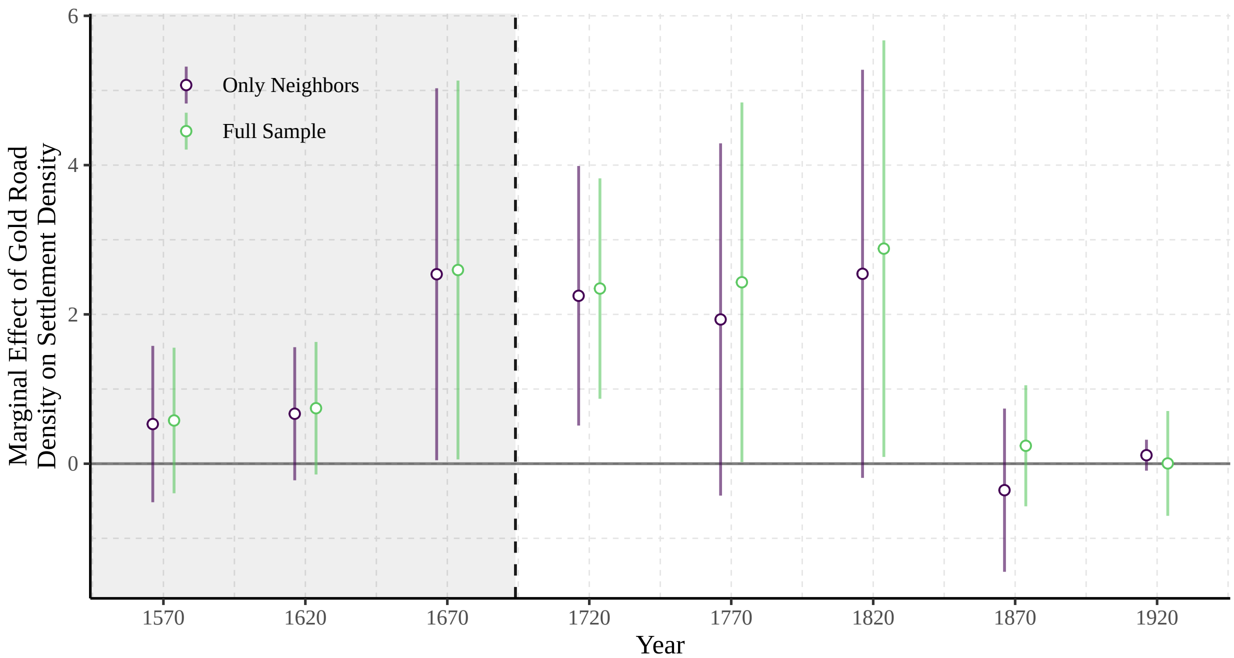

Figure 4: **Gold roads and settlement density over time.** *Notes:* The marginal effects of gold roads on settlement density are analyzed across different years using two samples and a 2SLS specification where least-cost path density is the instrumental variable for gold road density. The *Full Sample* consists of 1920 MCAs, excluding those in states heavily influenced by the Amazon River basin (Amazonas, Pará, Roraima, Rondônia, Acre, and Amapá) and MCAs with settlements predating 1694 (except in years before 1694 in the shaded area), resulting in 856 observations. The *Only Neighbors* sample includes only MCAs traversed by gold roads and their immediate neighbors, amounting to 604 observations. All estimates incorporate state fixed effects and geography controls. In all cases, the Kleibergen-Paap F is above 67. Point estimates are represented by circles, with 95% spatially corrected confidence intervals (Conley, 1999) shown as lines. Exact values are detailed in Table D.3.

figure. The peak of the gold rush occurred during the first half of the seventeenth century, and the prominent role of gold roads persisted until the end of the colonial period in 1822. These findings align with the spatial distribution of settlements shown in Figure 1B. Following independence, the focus on national integration spurred an increase in the number of settlements, independent of gold roads, such that by 1870, these roads were no longer associated with a higher density of settlements.[20] This trend continued into 1920.

A limitation of this analysis is the absence of data on population, although it is plausible that, prior to industrialization, the number of settlements serves as a reasonable proxy for population. To

[20] According to our data, the number of settlements rose from 102 in 1720 to 407 in 1820, and then to 1,055 in 1870.

address this issue, we assign different weights to various types of settlements. In Panels C and D of Table D.3, we demonstrate that the results remain consistent when assigning towns and villages weights ten times larger than those of other settlements.[21]

The trend depicted in Figure 4 reflects a spatial system with weak agglomeration forces, where the effects of historical shocks gradually dissipate. Specifically, the agglomerations formed along the gold roads did not generate additional advantages, such as more capital or stronger institutions, that could spur further population growth. By 1870, settlement density in these areas had not become significantly higher or lower than in other regions. This trend continued into the first half of the next century. However, surprisingly, the effect of gold roads on population density reverses in the latter half of the twentieth century, showing a positive and growing impact, as illustrated in Figure 3.

The limited impact of gold roads on sustained population growth can partly be attributed to the transitory nature of the gold boom and the poor quality of the roads themselves. Population movements to the hinterlands were not driven by reduced transportation costs induced by these roads but rather by the high value-to-weight ratio of gold and precious minerals. This characteristic rendered transportation costs negligible for commodity outflows but not for the inflow of goods needed by local populations. For instance, prohibitive transportation costs often triggered speculative crises in the supply of foodstuffs: the prices of foodstuffs in *Ouro Preto*, the mining center, were 10 to 30 times higher than in *São Paulo* at the beginning of the eighteenth century (Reis, 2023). With the depletion of gold towards the end of the eighteenth century, the issue of high transportation costs became more acute. Consequently, Brazil evolved into what is often described as an archipelago of self-sufficient islands lacking integration (Deutsch, 1996).

In the following sections, we delve deeper into the puzzling "revival" of the advantages associated with gold roads in the mid-twentieth century. Noticeably, we rule out the possibility of direct

[21] However, the size of towns and villages likely varied significantly within this category. Azevedo (1956) notes that *Rio de Janeiro* and *Salvador* had populations of around 100,000 by the end of the colonial period. Medium-sized settlements, with populations ranging from 10,000 to 30,000, included cities like *Cuiabá*, *São Paulo*, and *Recife*. Smaller centers, with populations between 5,000 and 10,000, were common in the gold-producing regions, such as *Mariana* and *Diamantina*.

benefits from these roads, as any such advantages clearly diminished in the nineteenth century, and there is no plausible reason to believe that individuals simply started reusing these roads a century later without any associated major change in the environment. Instead, we propose that the structural changes associated with the emergence of a modern economy before 1950 triggered the resurgence of latent advantages tied to the gold roads and their settlements. Additionally, we investigate whether this new economic shock led to strong or weak agglomeration spillovers, shedding light on the equilibrium properties of this spatial system.

5 Connections with modern transportation

One possible interpretation of the patterns observed earlier is the connection between gold roads and the development of modern transportation networks. In other words, while gold roads may no longer provide direct benefits to nearby areas in recent times, they might have influenced the spatial distribution of modern transportation infrastructure. In this section, we explore this hypothesis by analyzing the timing of the observed effects alongside the emergence and expansion of modern transportation technologies, as illustrated in Figure 5. Subsequently, we assess whether the observed results persist after accounting for the presence of modern transportation infrastructure.

In Figure 5A, the evolution of railroad length aligns with historical accounts indicating that, during the latter half of the nineteenth century and the early twentieth century, the Brazilian central government actively promoted a railroad network to foster national integration. By 1920, over 60% of the total railroad network was already constructed, with this figure exceeding 90% by 1946. Additionally, Panel B shows that the significance of railroads for transporting goods was substantially higher in the early decades of the twentieth century than in later periods. Consequently, if gold roads influenced population density through the placement of railroads, we would expect to observe strong effects early in the century that diminish over time. However, the observed pattern contradicts this expectation, as the effects intensify later in the century.

The evolution of highways aligns more closely with our observations. In 1940, only a limited number of highway kilometers connected key cities, such as São Paulo and Rio de Janeiro,

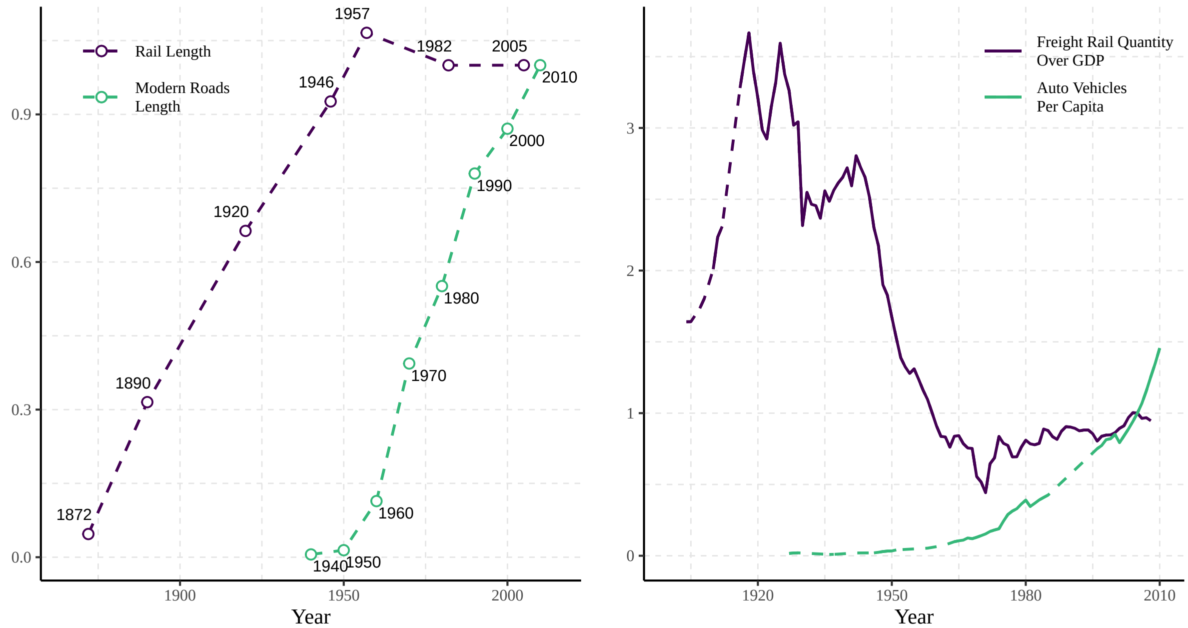

Figure 5: **Evolution of modern transportation.** *Notes:* Panel A illustrates the length of railroads and modern highways as a proportion of their respective lengths in the final year of the sample. Panel B displays the ratio of the quantity of goods (in tons) transported by railroad to real GDP, as well as the number of automotive vehicles per capita, both normalized to their values in 2005. Dashed lines represent linear interpolations between data points.

accounting for approximately 0.5% of the total highway network today. By 1950, this share had risen modestly to 1.4%. In 1951, the central government began prioritizing motorized vehicle roads as the primary strategy for national integration. However, substantial expansion occurred only during the second half of the 1960s and throughout the 1970s. According to our data, by 1960, only about 10% of the highway system had been constructed, but this share increased to 60% by 1980. Furthermore, Panel B highlights a significant inflection point in the late 1970s, marked by a sharp increase in the number of automobiles per capita.

Nonetheless, the expansion of paved roads and highways shows minimal overlap with the historical gold and mule roads, except in areas where these routes clearly represented the optimal path for any mode of transportation. Overall, these historical pathways were not well-suited for modern transportation needs. Even the "Royal Road," the most famous historical route connecting the mining regions of Minas Gerais to the court in Rio de Janeiro, demonstrates limited integration into modern infrastructure. Currently, only 20% of the Royal Road is paved, while 74% remains dirt roads, and 6% consists of trails.[22]

To evaluate whether the effect of gold roads on population density is influenced by the presence of modern highways, we would include modern highway density as a control variable in our regressions. A key concern with this approach is that the placement of modern highways may be indirectly influenced by historical pathways through their impact on population density, potentially making highway density a "bad control." To mitigate this concern, we instead control for the distance to the Minimum Spanning Tree (MST) network emanating from Brasília. As noted by Morten and Oliveira (2024), the Brazilian highway network was designed with the primary goal of national integration, with Brasília serving as its central hub. The radial highways originating from Brasília and connecting to key state capitals played a critical role in reducing travel times across the country.

To address the issue of endogenous highway placement, Morten and Oliveira (2024) divided Brazil into eight pie-shaped regions and constructed a predicted road network using least-cost paths that connect Brasília to the state capitals within these regions. This predicted network is referred to as the MST network. By using travel time along the MST network as an instrument for travel time along the actual highway network, Morten and Oliveira (2024) provide a framework to isolate the exogenous components of highway placement. Building on this MST-based approach, our analysis incorporates controls derived from this network to address potential biases and produce more robust estimates of the effect of gold roads on population density.

The results are presented in Table 4. These regressions replicate columns 2 through 9 of Panels A and B in Table D.1, with the addition of the log-transformed distance to the MST network as a control.[23] As expected, MCAs located farther from the MST network exhibit lower population densities, with this negative correlation becoming stronger over time. Crucially, including this control has minimal impact on the coefficients associated with the gold roads. If anything, the

[22] We examine a total of 1,780 kilometers of the *caminhos novo*, *velho*, *diamante*, and *sabarabuçu*. See https://institutoestradareal.com.br/en/ for detailed maps and photographs.

[23] We use the log-transformed distance to the MST network following Barsanetti (2024), who leverage the MST network to account for highway expansion. When we instead use the MST network density, the results remain consistent.

magnitude of these coefficients slightly increases, reinforcing the robustness of the observed effects of gold roads on population density shown in Figure 3, even after accounting for the MST network.

Table 4: Gold roads, modern roads and agglomerations over time

	Year							
	1940 (1)	1950 (2)	1960 (3)	1970 (4)	1980 (5)	1991 (6)	2000 (7)	2010 (8)
Panel A - Full Sample - Dependent Variable: Population Density								
Gold Road Density	0.290	0.681***	0.982***	1.23***	1.43***	1.51***	1.59***	1.61***
	(0.248)	(0.253)	(0.271)	(0.291)	(0.316)	(0.337)	(0.339)	(0.346)
Dist. to MST	-0.066**	-0.067**	-0.072**	-0.088**	-0.117***	-0.141***	-0.155***	-0.162***
	(0.032)	(0.031)	(0.034)	(0.035)	(0.038)	(0.040)	(0.042)	(0.043)
Observations	856	856	856	856	856	856	856	856
Kleibergen-Paap F	81.431	81.431	81.431	81.431	81.431	81.431	81.431	81.431
Panel B - Neighbors Only - Dependent Variable: Population Density								
Gold Road Density	0.478*	0.825***	1.10***	1.32***	1.53***	1.62***	1.69***	1.69***
	(0.276)	(0.268)	(0.276)	(0.279)	(0.314)	(0.355)	(0.369)	(0.386)
Dist. to MST	-0.088**	-0.089***	-0.094**	-0.109***	-0.141***	-0.164***	-0.180***	-0.186***
	(0.034)	(0.034)	(0.039)	(0.041)	(0.045)	(0.048)	(0.052)	(0.055)
Observations	604	604	604	604	604	604	604	604
Kleibergen-Paap F	68.067	68.067	68.067	68.067	68.067	68.067	68.067	68.067

Notes: Spatially corrected standard errors are shown in parentheses. All columns report 2SLS estimates, using least-cost path density as an instrumental variable for gold road density. Each specification includes state fixed effects and geography controls, including the log-transformed median values of precipitation, temperature, elevation, terrain ruggedness, area, distance to rivers, and distance to the coast, as well as a second-order latitude-longitude polynomial. The *Full Sample* consists of 1872 MCAs, excluding those in states predominantly influenced by the Amazon River basin (Amazonas, Pará, Roraima, Rondônia, Acre, and Amapá) and MCAs with settlements predating 1694. The *Neighbors Only* sample includes only MCAs traversed by historical roads and their immediate neighbors. *Population Density* is calculated as the log-transformed population per unit area. *Gold Road Density* is defined as the proportion of a municipality's area within a five-kilometer buffer surrounding gold roads. *Dist. to MST* is the log-transformed distance from the MCA's centroid to the minimum spanning tree from Brasília computed by Morten and Oliveira (2024). $^{*}p < 0.1, ^{**}p < 0.05, ^{***}p < 0.01$

In Appendix E, we present additional results. Specifically, Table E.1 shows that the correlation between MST distance and population density is somewhat weaker and statistically insignificant in the mule roads sample, providing further evidence of the reduced statistical power of this smaller sample. Nevertheless, the reduction in the coefficient linking mule roads to population density over time is larger – though still positive and significant – compared to the gold roads case. This suggests that the overlap between mule roads and modern transportation infrastructure may not be negligible.

For comparison, Table E.2 presents the results when we control for highway density instead of distance to the MST network. Initially, highway density exhibits no significant correlation with population density in 1940 and 1950, likely reflecting the limited extent of the highway network during these years. However, starting in 1960, this correlation becomes positive and progressively stronger over the subsequent decades. Notably, while the importance of highway density increases, the effect of gold roads on population density diminishes but remains both statistically and economically significant. For example, in 2010—the most extreme case—the coefficient for gold roads decreases from 1.55 to 1.07. Interestingly, the effect on the mule road coefficient moves in the opposite direction, increasing slightly when highway density is included as a control.

The results presented in this section challenge the hypothesis that modern transportation infrastructure is the primary mechanism linking gold roads to population density in recent times. In the next section, we investigate an alternative explanation proposed by historians, which suggests that towns established along historical pathways may have conferred enduring advantages that facilitated modern development.

6 Road towns and the seeds of agglomeration

Historians suggest that the primary benefit of the ground transportation system created from the gold economy lies not in the roads themselves but in the type of settlements established along these pathways. These distinctive settlements were more numerous and widespread than before, representing a new urban configuration. While estate-based settlements were dispersed and lacked a discernible urban center, the so-called "road towns" featured a main street lined with shops, cattle ranches, fairs, inns, and hotels. Naturally, these road towns attracted a different type of settler compared to agriculture-based towns, including craftsmen, workmen, merchants, and innkeepers, resulting in a distinctly different initial population mix (Deffontaines, 1938; Morse, 1974).[24]

There is no shortage of examples connecting the roads to modern settlements. *Campinas*, founded by an expedition connecting São Paulo to the mines in Goiás in 1722, had a density of manufacturing workers three times larger than the national average in 1872 (Rossetto, 2006). *Piracicaba* has a similar history: although the area began to be explored due to the presence of

[24]Deffontaines (1938) also argues that road towns were more stable than the mining towns themselves, as "mining colonization left only a devastated country strewn with dead or lethargic towns."

the *Piracicaba* River, with the first accounts dating back to 1693, it was only with the construction of the road leading from São Paulo to the mines in Goiás that the area received its first settlers (IBGE, 1957). By 1920, *Piracicaba* had twice as many manufacturing workers as the national average. Table 5 generalizes the anecdotal evidence presented above, showing that higher gold road density was associated with greater worker density and a larger share of workers in non-agricultural sectors.

Table 5: Gold roads and industrial composition in 1920

	Density			Share		
	Agriculture (1)	Manufacturing (2)	Services (3)	Agriculture (4)	Manufacturing (5)	Services (6)
Panel A - Full Sample						
Gold Road Density	-0.242	0.799**	0.920**	-0.221***	0.110***	0.112***
	(0.334)	(0.404)	(0.430)	(0.057)	(0.029)	(0.034)
Observations	856	856	856	856	856	856
Kleibergen-Paap F	81.564	81.564	81.564	81.564	81.564	81.564
Panel B - Neighbors Only						
Gold Road Density	-0.111	0.838*	1.11**	-0.220***	0.097***	0.122***
	(0.379)	(0.477)	(0.444)	(0.027)	(0.020)	(0.018)
Observations	604	604	604	604	604	604
Kleibergen-Paap F	75.872	75.872	75.872	75.872	75.872	75.872

Notes: Spatially corrected standard errors are shown in parentheses. All columns report 2SLS estimates, using least-cost path density as an instrumental variable for gold road density. Each specification includes state fixed effects and geography controls, including the log-transformed median values of precipitation, temperature, elevation, terrain ruggedness, area, distance to rivers, and distance to the coast, as well as a second-order latitude-longitude polynomial. The *Full Sample* consists of 1920 MCAs, excluding those in states predominantly influenced by the Amazon River basin (Amazonas, Pará, Roraima, Rondônia, Acre, and Amapá) and MCAs with settlements predating 1694. The *Neighbors Only* sample includes only MCAs traversed by historical roads and their immediate neighbors. The dependent is indicated in the column. *Density* refers to the log-transformed population working in a given industry per unit area. *Share* is defined as the population working in a given industry divided by the population working in all industries. *Gold Road Density* is defined as the proportion of a municipality's area within a five-kilometer buffer surrounding gold roads. $^{*}p < 0.1, ^{**}p < 0.05, ^{***}p < 0.01$

The hypothesis is that road towns did not hold much significance in an agrarian economy characterized by a small and sparse population. Nonetheless, as the population grew and the focus of production shifted toward non-agricultural activities, these settlements became attractive spots for migrants. Figure 6 illustrates the significant changes in the Brazilian socioeconomic structure over the twentieth century. In 1920, the population was only 16% of what it was in 2010, with significant growth occurring during the 1950s and 1960s when population growth peaked at around 3% per year.

Internal migration accelerated in the 1930s, making the early dislocations caused by the sugar and gold economies appear less significant (Furtado, 1968). This shift was precipitated by the structural transformation that began during the Great Depression years (Wagner and Ward, 1980). Over the century, population density increased substantially, rising from an average of 24 individuals per square kilometer in 1920 to 130 individuals per square kilometer in 2010, using 1920 MCAs as observations. This trend is reflected in the rapid increase in urbanization rates from the 1950s to the 1980s. In the 1940s, the urbanization rate grew by only 3 percentage points, while in the subsequent decades, it increased by approximately 10 percentage points per decade.

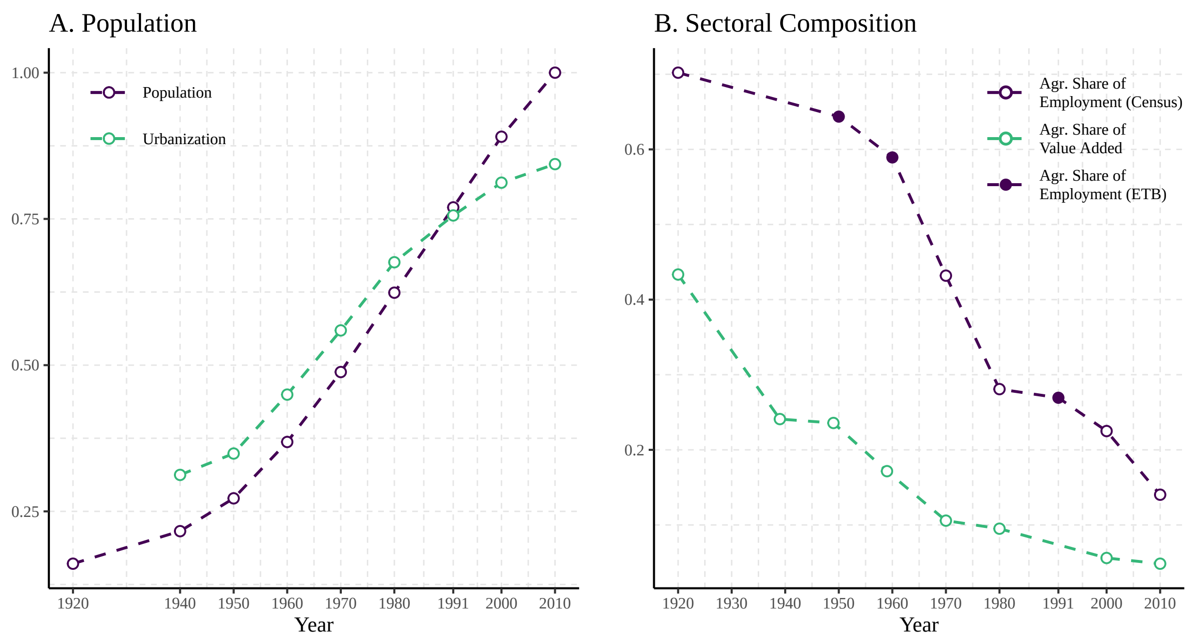

Figure 6: **The structural transformation of the Brazilian economy** *Notes:* Panel A illustrates the population size relative to 2010 and the share of population living in urban areas. Panel B displays the share of value-added and employment allocated in the agricultural sector. There are two sources of employment data: the Brazilian Census and the Economic Transformation Database. Dashed lines represent linear interpolations between data points.

Figure 6B illustrates the rapid process of industrialization, particularly between 1960 and 1980, when the share of workers in the agricultural sector decreased from about 60% to less than 30%.[25] The evolution of the share of value added from agriculture reveals a similar trend, with a significant decline first between 1920 and 1940, and then again from 1950 to 1970.

The overall pattern highlights the transition from an economy based on raw material exports to one that, by 1930, adopted an import substitution paradigm. The large influx of rural-urban migrants resulting from this shift found road towns to be attractive destinations, likely due to their already established urban infrastructure and well-developed service sector. Figure 7 supports this hypothesis. Panel A illustrates the effect of gold road density on population growth across different decades, while Panel B focuses on migrant density. The coefficients are derived from regressions using 1920 MCAs, excluding those influenced by the Amazon River and those with settlements predating 1694. All estimates control for geography and state fixed effects, with standard errors spatially corrected following Conley (1999).

The coefficients presented in Figure 7A indicate that higher gold road density increased population growth during the decades between 1940 and 1970. The effect between 1920 and 1940 was also positive but much smaller, likely due to the initial industrialization surge in the 1930s. In the 1940s, a 10-percentage-point increase in gold road density implied approximately a 0.4-percentage-point increase in population growth. However, this effect diminished over the century, becoming negligible after 1980. The faster population growth between 1940 and 1980 contributed to a higher migrant density, as shown in Figure 7B. Relevant data are only available starting in 1970. Gold road density is associated with more residents born in other states and municipalities per square kilometer, suggesting that the road towns did, in fact, attract migrants.

More details are provided in Appendix F. Concerning gold road towns, Table F.4 shows that gold roads are associated with higher urbanization rates in all years for which we have data (1940 to 2010). These results show that gold road density is linked to modern settlements, and migration did not disrupt this pattern. However, additional results in Appendix F reveal a stark contrast between

[25] Whenever possible, the data presented are from the decennial census. We supplement the information for 1950, 1960, and 1991 using the Economic Transformation Database (Kruse, Mensah, Sen and de Vries, 2023).

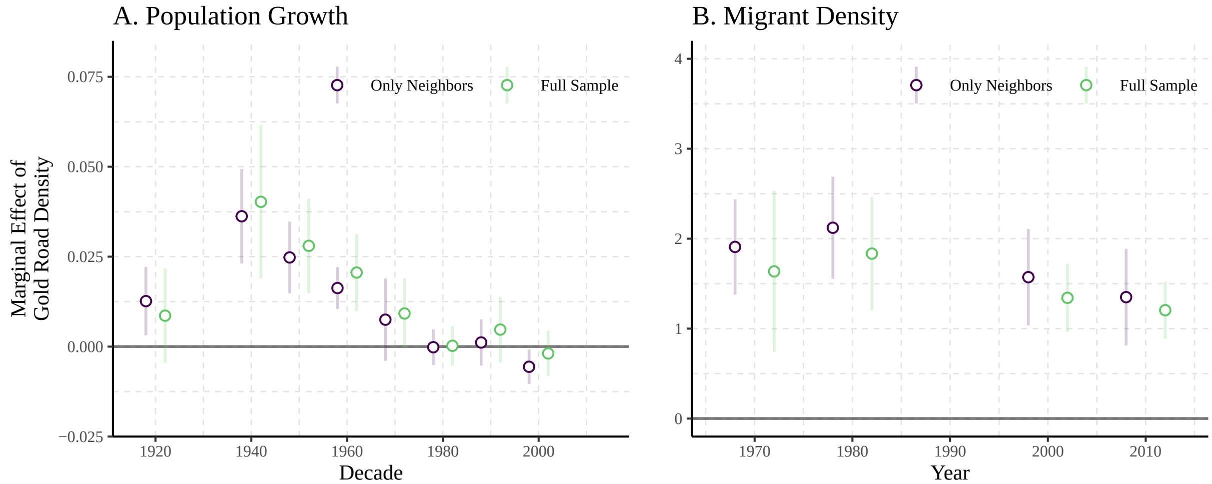

Figure 7: **Population growth and migration.** *Notes:* Panel A illustrates the effect of gold roads on average yearly population growth per decade, conditional on the initial population density. In 1920, it represents the average yearly population growth between 1920 and 1940. Panel B shows the effect of gold roads on the density of migrants from other municipalities. The *Full Sample* consists of 1920 MCAs, excluding those in states heavily influenced by the Amazon River basin (Amazonas, Pará, Roraima, Rondônia, Acre, and Amapá) and MCAs with settlements predating 1694 (except in years before 1694 in the shaded area), resulting in 856 observations. The Only Neighbors sample includes only MCAs traversed by gold roads and their immediate neighbors, amounting to 604 observations. All estimates incorporate state fixed effects and geography controls. In all cases, the Kleibergen-Paap F is above 76. Point estimates are represented by circles, with 95% spatially corrected confidence intervals (Conley, 1999) shown as lines. Exact values are detailed in Tables F.2 and F.3.

gold roads and mule roads. The relationship between mule roads and modern labor composition in 1920 is weaker than that of gold roads. The only coefficient statistically significant at the 10% level is associated with the share of workers in manufacturing. Furthermore, population growth is not significantly affected by mule roads until 1950, and the effect on migrant density from other states is either statistically insignificant or negative. These findings reinforce the hypothesis that mule roads were of secondary importance, as we exclude MCAs containing municipalities from 1872 from the sample.

In general, the results presented in this section demonstrate how historical roads, particularly gold roads, laid the foundation for agglomeration during demographic and structural transitions. Settlements along these roads were characterized by prototypical cities and attracted workers from other regions. In the mid-twentieth century, rapid urbanization was nationally attributed equally to natural population growth and internal migration (Wagner and Ward, 1980). In contrast, our findings reveal that areas with historical roads grew faster and had a larger stock of migrants.

7 Path Dependence

At this stage, we have demonstrated that historical roads constituted an initial shock to Brazil's spatial system—one that dissipated by the late nineteenth century. However, these roads left a lasting imprint through the formation of road towns, which later positioned these regions to benefit from demographic and structural transitions. The dynamics of this second shock suggest not merely persistence but a shift from one steady state to another, indicating a path-dependent process.

This section provides additional evidence supporting the path-dependent nature of population spatial distribution, as described in the framework by Allen and Donaldson (2022). According to their model, the dynamics of agglomeration can lead to multiple stable outcomes, or "steady states", depending on the strength of both current and past agglomeration spillovers. This means that the spatial distribution of population can be influenced by a region's historical development, making it path-dependent. In what follows, we present only the key elements in their model, leaving the technical details to the original paper.[26]

The economy consists of several regions, indexed by i, where a representative firm produces a homogeneous output Y_{it} at time t using labor L_{it}, following a linear production technology: $Y_{it} = A_{it}L_{it}$. Labor productivity A_{it} is exogenous and is composed of intrinsic productivity $\bar{A}_{it}$ and agglomeration spillovers. Specifically, $A_{it} = \bar{A}_{it}L_{it}^{\alpha_1}L_{it-1}^{\alpha_2}$, where α_1 and α_2 represent the strength of contemporaneous and historical productivity spillovers, respectively. Regions engage in costly trade.

[26] The model bridges two traditional strands of literature in spatial economics. One strand focuses on path-dependent geographies, agglomeration forces, and forward-looking behavior, but typically in low-dimensional settings (*e.g.* Krugman, 1991; Matsuyama, 1991; Rauch, 1993). The other involves high-dimensional models that incorporate more realistic geographies, though they often lack forward-looking agents and local agglomeration spillovers (*e.g.* Roback, 1982; Glaeser, 2008; Desmet, Nagy and Rossi-Hansberg, 2018).

Individuals make location decisions to maximize their utility. The utility function consists of amenity-adjusted real wages $w_{it}u_{it}$ and idiosyncratic preferences about locations, which are drawn from a Fréchet distribution with shape parameter $\theta > 1$. Real wages w_{it} are determined in a competitive labor market, while amenities u_{it} are determined by both the intrinsic amenity $\bar{u}_{it}$ and amenity spillovers. Specifically, $u_{it} = \bar{u}_{it} L_t^{\beta_1} L_{t-1}^{\beta_2}$, where β_1 and β_2 denote the strength of contemporaneous and historical amenity spillovers, respectively. Once individuals have chosen a location, they decide how many children to have based on their expected utility and child-rearing costs, which are assumed to be convex, governed by the parameter $\lambda > 1$.

Individuals' and firms' optimization yields an extended version of the labor supply and demand system in the Rosen-Roback-Glaeser spatial equilibrium tradition, where lagged population acts as a shifter in both equations:

$$\ln w_{it} = \alpha_1 \ln L_{it} + \alpha_2 \ln L_{it-1} + \ln \bar{A}_{it}, \tag{2}$$

$$\ln w_{it} = \left(\frac{1}{\theta} - \beta_1\right) \ln L_{it} + (-\beta_2) \ln L_{it-1} + \frac{1}{\theta} \ln IMMA_{it} - \ln \bar{u}_{it}, \tag{3}$$

where, using the simplifying parameter restriction $\theta(\lambda - 1) = 1$, the inward migration market access is given by $IMMA_{it} = \sum_j \mu_{jit}^{-\theta} L_{jt-1}$, and μ_{jit} denotes the cost of moving from j to i in period t.

Solving the system formed by Equations (2) and (3) for all L_{it} yields the key dynamic system:

$$L_{it}^{1-\theta(\alpha_1+\beta_1)} = (\bar{A}_{it}\bar{u}_{it})^{\theta} \times L_{i,t-1}^{\theta(\alpha_2+\beta_2)} \times \sum_j \mu_{jit}^{-\theta} L_{j,t-1}, \tag{4}$$

from which Allen and Donaldson (2022) draw the following qualitative implications: for any given geography $\{\bar{A}_{it}, \bar{u}_{it}, \mu_{jit}\}$, (1) if $\theta(\alpha_1 + \beta_1) < 1$, then there exists a unique and stable equilibrium path; (2) if $\theta(\alpha_1 + \alpha_2 + \beta_1 + \beta_2) < 1$, then there is convergence in partial equilibrium (i.e., considering $IMMA_{it}$ exogenous); (3) if $\theta(\alpha_1 + \alpha_2 + \beta_1 + \beta_2) < 0$, then there is convergence in general equilibrium (uniform convergence); and (4) if $0 < \theta(\alpha_1 + \alpha_2 + \beta_1 + \beta_2) < 1$, there may exist multiple steady states.[27] Figure 8 shows these qualitative implications for many combinations of $\alpha_1 + \alpha_2$ and $\beta_1 + \beta_2$, assuming $\theta = 4$ as estimated by Monte, Redding and Rossi-Hansberg (2018).

Next, our goal is to estimate the net agglomeration spillovers to identify the properties of the system we are studying. We use the least-cost path of gold and mule roads as instruments for population density in a regression on hourly wages to estimate the productivity spillovers from Equation (2). The assumption is that, as discussed above, historical roads gave birth to small urban settlements that eventually, during the process of structural transformation, attracted workers. This labor supply shock allows us to identify the elasticity of labor demand α_1. The exclusion restriction is that contemporaneous population density is the only channel through which historical roads affect contemporaneous wages, which is strengthened by the fact that we use data from 1980, 2000, and 2010, with a time interval of 60 years. Thus, historical population density is measured in the early decades of the twentieth century, when historical roads had little influence.

Consistent with the literature (*e.g.,* Bleakley and Lin, 2012; Chauvin et al., 2017), we utilize individual-level census data on workers aged between 25 and 65 years old to estimate the agglomeration effects. We have all the information needed for the 1980, 2000, and 2010 censuses. Hourly wages are set as the dependent variable, while contemporaneous and historical population density are computed at the 1920 MCA level, along with the usual geography variables. Lagged population density is measured 60 years prior to the census year. All regressions include individual-level controls such as age, age squared, and binary variables indicating the worker's race, sex, marital status, industry, and education attained. Table 6 shows the results pooling all censuses and adding state and year fixed effects. Aside from the contemporaneous and historical productivity spillovers α_1 and α_2, the table also presents the total productivity spillovers and their standard errors, which are computed using the delta method.

Contemporaneous agglomeration coefficients range from 0.086 to 0.141, depending on whether gold roads or mule roads are used as instruments or if geography controls are included. These numbers are small compared to the 0.19 estimated by Allen and Donaldson (2020) for the US.

[27] Multiple steady states may also arise if $1 < \theta(\alpha_1 + \alpha_2 + \beta_1 + \beta_2) < 2$, but there is no convergence.

Table 6: Contemporaneous and historical productivity spillovers

	Gold Roads			Mule Roads		
	(1)	(2)	(3)	(4)	(5)	(6)
Panel A - Full Sample - Dependent Variable: Hourly Wage						
Pop. Density	0.0998***	0.1245***	0.0980***	0.0914***	0.1416***	0.0941***
	(0.0119)	(0.0239)	(0.0340)	(0.0093)	(0.0162)	(0.0302)
Lagged Pop. Density		-0.0491*	-0.0185		-0.0858***	-0.0573***
		(0.0264)	(0.0306)		(0.0233)	(0.0199)
Implied Total		0.075**	0.079*		0.056**	0.037
Produc. Spillovers		(0.0356)	(0.0457)		(0.0284)	(0.0362)
Observations	11,039,347	11,039,347	11,039,347	3,646,433	3,646,433	3,646,433
Kleibergen-Paap F	44.630	23.335	20.135	15.290	11.613	7.9698
Panel B - Only Neighbors - Dependent Variable: Hourly Wage						
Pop. Density	0.0983***	0.1322***	0.1026***	0.0901***	0.1398***	0.0862***
	(0.0110)	(0.0204)	(0.0281)	(0.0093)	(0.0164)	(0.0290)
Lagged Pop. Density		-0.0612***	-0.0299		-0.0838***	-0.0527***
		(0.0216)	(0.0211)		(0.0234)	(0.0191)
Implied Total		0.071**	0.073**		0.056*	0.033
Produc. Spillovers		(0.0298)	(0.0351)		(0.0286)	(0.0348)
Observations	8,957,715	8,957,715	8,957,715	3,599,221	3,599,221	3,599,221
Kleibergen-Paap F	44.323	33.362	23.687	15.628	11.846	7.9765
Geography Controls			✓			✓

Notes: Spatially corrected standard errors are shown in parentheses. All columns report 2SLS estimates, using the least-cost path density of gold roads or mule roads as an instrumental variable for population density at the 1920 MCA level. The *Full Sample* consists of individual data for years 1980, 2000, and 2010, excluding those in states predominantly influenced by the Amazon River basin (Amazonas, Pará, Roraima, Rondônia, Acre, and Amapá) and those in MCAs with settlements predating 1694. The *Neighbors Only* sample includes only individuals in MCAs traversed by historical roads and their immediate neighbors. Each specification includes state and year fixed effects and individuals characteristics such as age (and age squared) and binary variables indicating race, sex, industry, marital status, education attained. Columns 3 and 6 controls for geography controls, including the log-transformed median values of precipitation, temperature, elevation, terrain ruggedness, area, distance to rivers, and distance to the coast, as well as a second-order latitude-longitude polynomial. The dependent is indicated in the column. *Hourly Wage* refers the log-transformed ratio of wages to hours worked. *Pop. Density* is defined as the population divided by the MCA's area. *Lagged Pop. Density* is the log-transformed value of population density 60 years before the reference year. *Implied Total Productivity Spillover* is the sum of coefficients associated with *Pop. Density* and *Lagged Pop. Density*. Standard errors are computed using the delta method. $^{*}p < 0.1, ^{**}p < 0.05, ^{***}p < 0.01$

The variation in the estimates of historical productivity effects is larger. It ranges from -0.018 to -0.085, with smaller values associated with the 2SLS using mule roads. Allen and Donaldson (2020) estimate $\alpha_2 = -0.041$, which falls close to our preferred estimates in columns (3) and (6) of Table 6. Finally, total productivity spillover effects $\alpha_1 + \alpha_2$ range between 0.033 and 0.08, again smaller than the 0.15 estimated by Allen and Donaldson (2020).

Considering that the literature often estimates $\alpha_1 + \alpha_2$, our estimates are close to the typical range found in the literature, which falls between 0.03 and 0.08 in the reviews by Rosenthal and Strange (2004) and Combes and Gobillon (2015) and equals 0.09 in Bleakley and Lin (2012). However, our estimates are somewhat higher than those from other papers studying Brazil; for example, Chauvin et al. (2017) estimate it at 0.026, while Ehrl and Monasterio (2021) finds it equal to 0.01. One possible reason for our higher estimates is related to the instrument capturing the influence of road towns that were comparatively more likely to develop urban and non-agricultural agglomerations throughout the twentieth century, which generated larger agglomeration effects in a country where historically the unit of settlement was dispersed agricultural estates. This argument also explains the smaller values associated with using mule roads as instruments since, as shown previously, mule roads had a much more limited effect on the rise of modern settlements when compared with the gold roads.

To connect our findings with the model, we need values for $\beta_1 + \beta_2$. Instead of estimating these parameters, we interpret our findings by assuming feasible values of $\beta_1 + \beta_2$. As discussed by Allen and Donaldson (2022), β_1 is expected to be negative if there is a fixed supply of local goods, such as land or housing (congestion effects), while β_2 must be positive if early investments in local factors are durable. Assuming that contemporaneous housing congestion is represented by its share in household expenditure and that the housing stock remains stable over the period of one generation, we have $\beta_1 = -\beta_2 = -0.15$ in Brazil (Chauvin et al., 2017). Moreover, in their empirical exercise for the US, Allen and Donaldson (2020) find $\beta_1 = -0.26$ and $\beta_2 = 0.31$. Thus, feasible values of $\beta_1 + \beta_2$ must be close to zero. We set $\theta = 4$ following Allen and Donaldson (2020).

Figure 8 shows the equilibrium properties of possible combinations of $\alpha_1 + \alpha_2$ and $\beta_1 + \beta_2$ when $\theta = 4$. The circles represent point estimates of $\alpha_1 + \alpha_2$ from column (3) of Table 6, assuming $\beta_1 + \beta_2 = 0$. The dashed rectangle represents a confidence region where $\alpha_1 + \alpha_2$ ranges within 1.96 standard errors above and below the point estimates, and $\beta_1 + \beta_2$ ranges between -0.05 and 0.05.

First, note that for our point estimates of α_1 around 0.1 and assuming $\beta_1 = -0.15$, the system exhibits a unique and stable equilibrium path, as $\theta(\alpha_1 + \beta_1) < 1$. Turning to net agglomeration effects, our point estimates of $\alpha_1 + \alpha_2$ around 0.07 imply that $0 < \theta(\alpha_1 + \alpha_2 + \beta_1 + \beta_2) < 1$. This condition guarantees partial convergence while allowing for potential path dependence. In other words, net agglomeration effects are strong enough to prevent uniform convergence and permit the existence of multiple steady states, but they are not strong enough to cause divergence.

Finally, using $\alpha_2 = -0.03$ and $\beta_2 = 0.15$, we compute the rate of population persistence in partial equilibrium as $\frac{\theta(\alpha_2+\beta_2)}{1-\theta(\alpha_1+\beta_1)} = 0.4$, indicating that shocks dissipate relatively quickly. Therefore, it is not surprising that if gold roads initially influenced population distribution, this effect would be negligible 200 years later unless there is path dependence. Specifically, given the persistence parameter of 0.4, less than 6% of the initial shock would persist.

The implications discussed above hold for a wide range of feasible values of $\beta_1 + \beta_2$. In extreme cases where $\beta_1 + \beta_2$ is close to -0.05, the system may exhibit a unique steady state and uniform convergence. The level of uncertainty regarding the equilibrium properties is greater when we use mule roads as instrumental variables. In this case, the values of $\alpha_1 + \alpha_2$ are smaller, and the confidence region has a larger area that intersects the uniform-convergence region. As mentioned earlier, this is likely due to the weaker agglomeration spillovers associated with mule roads compared to gold roads.

The results presented in this section reinforce the argument made earlier. Road towns established along mule roads, and particularly gold roads, were historically well positioned to participate in the structural transformation process and attract migrants. These towns had a non-agricultural population mix from the outset and were already organized around urban centers with a history of providing catering and accommodation services. Since industry and services are inherently

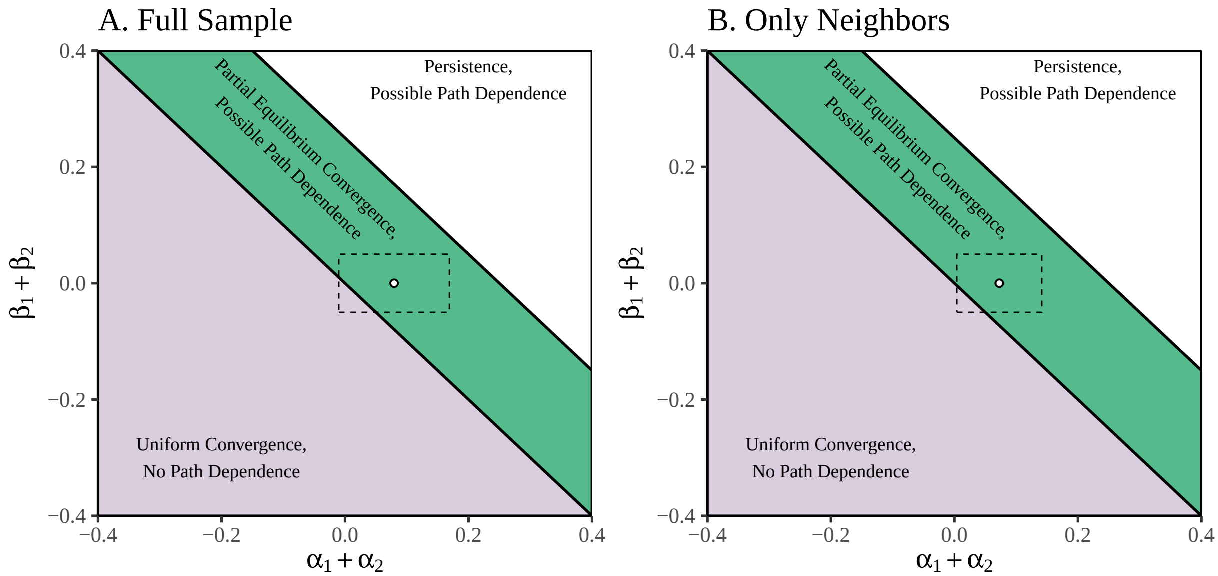

Figure 8: **Equilibrium properties and spillover estimates.** *Notes:* Both panels illustrate the equilibrium properties of the model for different combinations of productivity ($\alpha_1 + \alpha_2$) and amenity ($\beta_1 + \beta_2$) spillovers. Circles represent points estimates of $\alpha_1 + \alpha_2$ in column 3 of Table 6 (panels A and B) assuming $\beta_1 + \beta_2 = 0$. conditional on the initial population density. The dashed line rectangle represents a confidence region where $\alpha_1 + \alpha_2$ ranges 1.96 standard errors below or above the point estimate, and $\beta_1 + \beta_2$ is assumed to range between -0.05 and 0.05.

urban-oriented activities, urban sites naturally attracted firms (Wagner and Ward, 1980). Structural transformation then fueled population growth, leading to higher population densities and a smaller share of agricultural workers, which in turn drove increasing urbanization (Michaels, Rauch and Redding, 2012). This process directed the economy toward the basin of attraction of the long-run equilibrium, where places with historical pathways exhibit higher population densities. The agglomeration effects estimated in Table 6, driven by these higher densities, subsequently solidified the economy's trajectory toward the new steady state.

8 Conclusions

In this paper, we examined the long-run impact of historical roads on Brazil's population distribution. Specifically, we analyzed the construction of pathways that connected the Brazilian coast to the gold-mining regions of the interior following the discovery of gold around 1694. We find that the density of these historical routes is a strong predictor of modern agglomeration, as measured by population density, urban population density, and nightlight intensity.

Our analysis uncovers an intriguing dynamic pattern. Initially, historical roads facilitated population growth, but by the late nineteenth century, their influence on agglomeration had largely disappeared. However, following Brazil's demographic and industrial transitions after the 1930s, regions with higher historical road density experienced faster population growth and attracted a larger share of migrants. This suggests that the settlements established along these routes played a crucial role in shaping future urbanization and economic activity.

Throughout the twentieth century, the impact of historical roads strengthened, indicating that these early transportation networks contributed to a long-term shift in Brazil's spatial equilibrium. To support this interpretation, we estimate net agglomeration effects and show that Brazil's spatial economy exhibits no uniform convergence, allowing for multiple steady states. This evidence suggests that the historical roads helped shape a persistent pattern of spatial development, with long-lasting implications for regional economic dynamics.

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Online Appendix to

Old But Gold: Historical Pathways and Path Dependence

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B Details: Data

B.1 Variables and procedures

Units of observations The analysis was conducted at two primary levels: municipalities and minimum comparable areas (MCA). Municipalities are defined as administrative boundaries established by each state legislature. We utilized municipal boundaries from 2010. To ensure consistency when comparing different years, we employed 1920 Minimum Comparable Areas (MCAs) as defined by Reis et al. (2011), Figure B.1 shows these units. The shapes and seat locations of each municipality in 2010 were obtained from Pereira, Goncalves, Carabetta and Furtado (2019), and the MCAs are aggregations of these shapes.

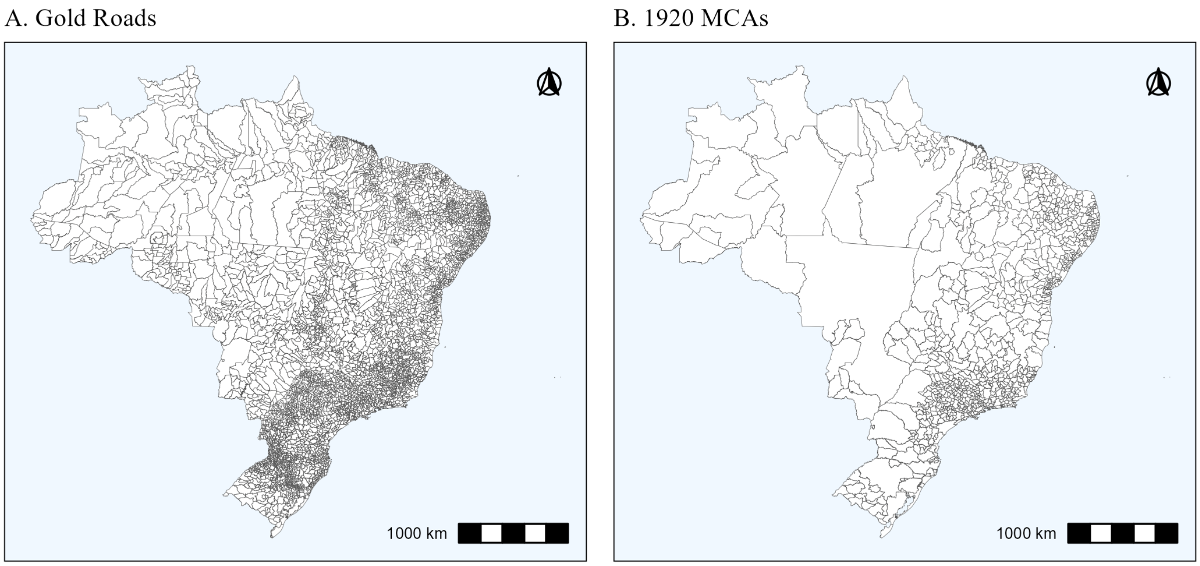


Figure B.1: **Primary units of observations**

Historical roads The gold roads were georeferenced using a map compiled by Simonsen (1977). The trace is displayed in Figure 2A and the density on 2010 municipalities is shown in Figure B.2A. We use ArcMap to represent the roads accurately using linestrings.

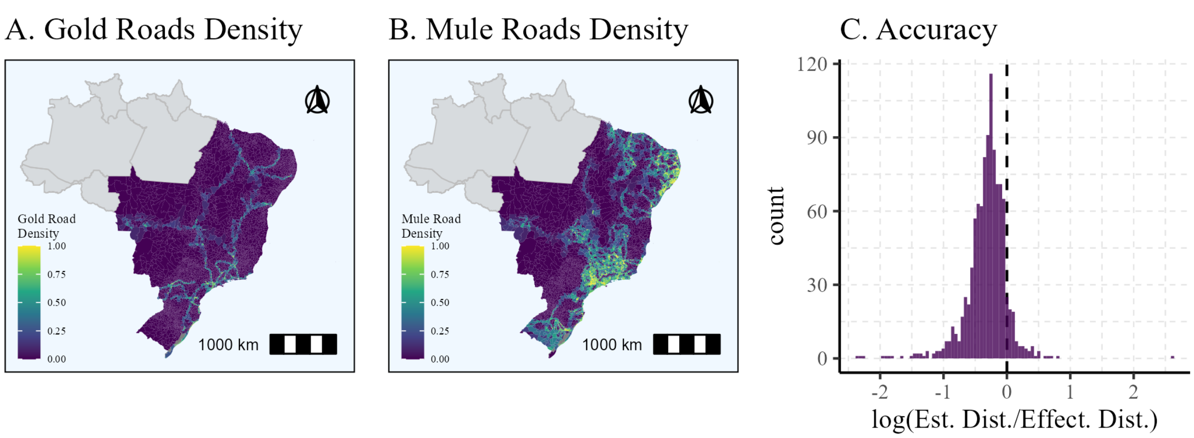
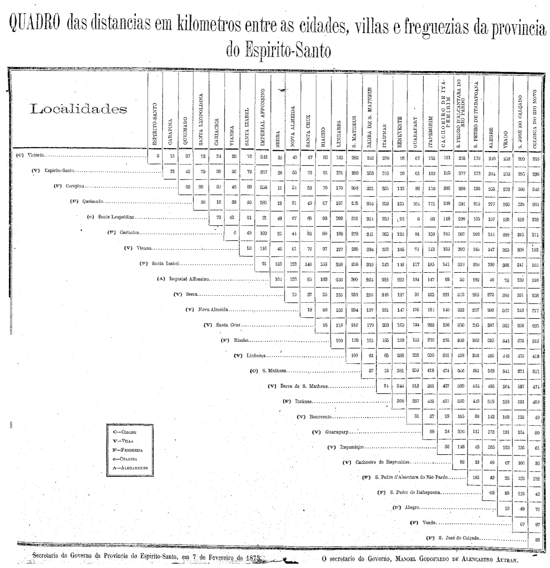
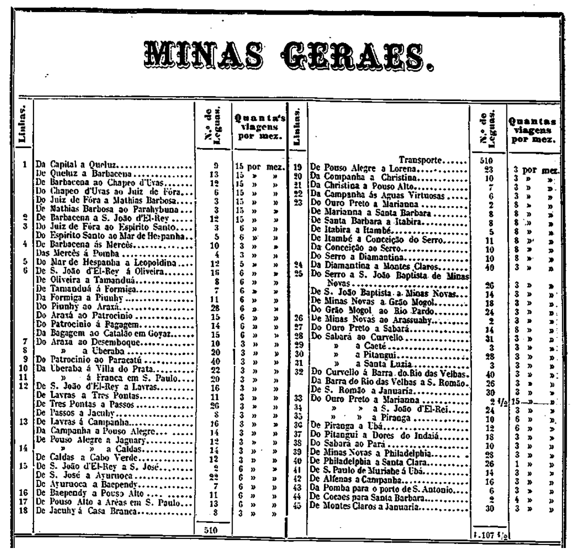


Figure B.2: **Historical road density and comparison between effective distances and estimated distances of mule roads.**

The network data used in this study is derived from historical statistical reports produced in 1863 and 1873. These reports contain information about the municipalities that were connected by the transport network, as well as the actual distances covered between these locations. The provincial governments were responsible for preparing and reporting the data on effective distances, following instructions from the Empire's Business Secretariat. Examples of these historical reports are presented in Figure B.3, which displays a sample of the matrices available in the statistical reports for the province of *Espírito Santo* and the post office report for the province of *Minas Gerais*, respectively.



(a) 1873 Statistical Report, Distance between the locations of the province of *Espŕito Santo*



(b) 1863 Post office Report, Distance between the locations of the province of *Minas Gerais*

Figure B.3: Historical Documents

After digitizing the reports, several steps and verification processes were undertaken before the data could be utilized. Firstly, it was crucial to identify the municipalities by their old names and georeference them to determine the geographic coordinates of their headquarters. Subsequently, we converted the distances initially measured in leagues to kilometers for consistency. Finally, we constructed the distance matrices between the municipal seats based on the 1872 administrative division, utilizing both the historical pathways and the postal routes. To fill in any missing information, we digitized additional historical official records from provincial governments, which allowed us to capture distances between locations in different provinces. This complementary data enabled us to establish interconnections between paths, resulting in an origin and destination matrix that covered a significant portion of the national territory.

Least-cost paths For the gold roads, we calculate least-cost paths between the connecting population centers of the paths in the Simonsen map. For the mule roads, we calculate least-cost paths between each pair of municipal seats that appear connected in the documents described above. We adopt the approach used by Barjamovic et al. (2019). Namely, we divide the country into grid cells of 30 arc-seconds with information about the elevation of each grid cell. Then, after computing the slope between cells, we assume that it takes 0.72 seconds to travel one meter horizontally. It takes an additional 6 seconds for each vertical meter uphill, while going downhill one vertical meter on a gentle slope (less than or equal to 21.25%) saves 2 seconds per vertical meter and going downhill on a steep slope (more than 21.25%) adds an additional 2 seconds per vertical meter. With that, we have a cost matrix between grid cells measuring the time it takes to move from one cell to another. We use this cost matrix to construct the least-cost paths using Dijkstra's method. These paths allowed connections through all eight adjacent cells. The final output of this process is displayed in Figure 2. Figure B.2B shows the mule road density in 2010 municipalities. Differently from goad roads, where we can compare least-cost paths with the actual path, for the mule roads we can only compare the estimated distance with the distance estimated by least-cost paths. This comparison is displayed in Figure B.2C. It shows that, in general, least-cost paths are shorter than effective distances, suggesting that these paths are more direct than the actual paths. Nonetheless, estimated distance is a good predictor of effective distance. A linear regression between them confers an R-squared equal to 0.82, suggesting that the variation in estimated distance explains 82% of the variation in the effective distance.

Historical Settlements We reconstruct the historical development of Brazilian cities over time using the foundation dates of current municipalities. Our primary data source for these foundation dates is Azevedo (1956). However, this source only documents villages and towns officially recognized by the Portuguese crown up to 1822, and it omits or provides incomplete records for many municipalities, likely due to the limitations of historical documentation.

To complement this dataset, we gather additional information from the website *IBGE Cidades* (`https://cidades.ibge.gov.br/`), which provides historical details about Brazilian municipalities, including their administrative formation. Using the *python* library *BeautifulSoup*, we extract text from the website and identify the first year following the term *Formação Administrativa*. To ensure accuracy, we exclude any numbers that appear directly after the terms *decreto(s)*, *lei(s)*, and *no*, as these typically refer to law numbers rather than foundation years. This process yields the earliest year for which we have information indicating that a municipality was officially recognized.

Next, we identify the year when a municipality was classified as a parish, district, village, or municipality. This is done by extracting years associated with terms indicating foundation, such as *criado*, *instalado*, or *elevado*, combined with terms referring to these classifications, such as *freguesia*, *vila*, *distrito*, or *cidade*. We then define the foundation date as the earliest year among those identified. If the earliest year corresponds to a settlement classification, we assign this classification to the foundation year. For villages specifically, if the information is available in Azevedo (1956), we prioritize this source.

Economic activity Our primary indicators of economic activity consist of population density, nightlight incidence, and urban population density. At the municipality and MCA levels, (urban) population density is derived by dividing the (urban) population data obtained from the Brazilian census between 1920 and 2010 by the corresponding area. Additionally, we employed nighttime lights as a supplementary metric, which is determined by calculating the median intensity of nighttime lights in cloudless skies using satellite data provided by the Earth Observation Group.

Economic Sectors Broad sectors are defined to match (as closely as possible) Revision 4 of the International Standard Industrial Classification (ISIC Rev. 4). Particularly, in our classification, agriculture equals "Agriculture, Fishing, and Forestry (code A)"; industry equals "Mining (B)", "Manufacturing (D)", "Utilities (D+E)", and "Construction (F)"; and, services aggregates

"Trade Services (G+I)," "Transport Services (H)," "Business Services (J+M+N)," "Financial Services (K)," "Real Estate (L)," "Government Services (O+P+Q)," and "Other Services (R+S+T+U)."

Geography Geographic variables, including temperature, precipitation, and elevation, were acquired through satellite data sourced from the National Institute for Space Research. These variables represent the median values within each municipality, MCA, or grid cell. Furthermore, we calculated the distances to the coast and rivers based on data from the same sources. All distances were measured in kilometers.

Modern transportation Information about the location of railway, train stations, and roadways are from shapefiles provided by the Brazilian Ministry of Transportation, except the highway shape files for 1940 and 1950, which are from Morten and Oliveira (2024).

Spatial operations Most spatial operations were computed using R's simple features package (Pebesma, 2018). Areas were constructed using South America Albers Equal Area Conic projection, whereas distances were computed using South America Albers Equidistant Conic projection. Least-coast paths were constructed using the geopandas library for Python.

B.2 Summary statistics

Below, we present descriptive statistics for a range of variables related to our municipality sample, as shown in Panel A. The variables include demographic and geographic measures, with each row presenting statistics such as the mean, standard deviation, minimum, maximum, and key percentiles (25th, 50th, and 75th). For example, the "Population Density" variable has a mean of 100.82, with a high standard deviation of 523.64, indicating considerable variation across municipalities. The "Urbanization Rate" has a mean of 0.64 and a standard deviation of 0.22, suggesting relatively moderate urbanization across the sample, with most municipalities concentrated around the middle values, as seen in the percentiles.

Other variables, such as ”Gold Roads Density” and ”Distance to River,” exhibit more skewed distributions. The ”Gold Roads Density” has a mean of 0.05, but its distribution is heavily concentrated at 0, with very few municipalities exhibiting higher values. Similarly, the ”Distance to River” has a large standard deviation of 76,462.76, indicating considerable variation in proximity to rivers, with distances ranging from 20 to over 485,000 meters. The diversity in these variables, from physical geography (such as ”Elevation” and ”Ruggedness”) to infrastructure (such as ”Gold Roads Density” and ”Nightlights”), reflects the complexity of the factors that can affect a municipality’s characteristics.

Table B.1: Summary Statistics

Variables	Count	Mean	Std. Dev.	Min	Percentile 25th	Percentile 50th	Percentile 75th	Max
Panel A - Municipality - Gold Sample :								
Population Density	5197	100.82	523.64	0.23	12.67	25.24	53.11	12512.49
Log(Nightlights)	5197	1.91	1.06	0.04	1.19	1.64	2.37	4.61
Urbanization Rate	5196	0.64	0.22	0.06	0.48	0.65	0.82	1
Gold Roads Density	5197	0.05	0.15	0	0	0	0	1
Ruggedness	5197	45.43	32.57	2.19	21.46	33.57	61.59	187.45
Elevation	5197	462.85	283.81	1.86	240.94	443.77	665.31	1640.35
Precipitation	5197	1318.36	381.15	367.23	1101.09	1357.84	1565.58	2789.36
Temperature	5197	22.24	2.93	13.75	19.9	22.42	24.57	27.8
Area	5197	940.03	2049.97	3.57	195.39	382.97	876.53	64961.41
Distance to River	5197	96298.93	76462.76	20	39892.62	80306.51	134824.42	485309.82
Distance to Coast	5197	322306.63	293762.47	16.76	106725.14	250726.54	439163.64	1719448.87
Panel B - Municipality - Mule Sample								
Population Density	4660	97.87	549.27	0.23	12.25	24.44	48.59	12998.98
Log(Nightlights)	4660	1.89	1.03	0.04	1.19	1.63	2.32	4.61
Urbanization Rate	4659	0.63	0.22	0.06	0.47	0.64	0.82	1
Mule Roads Density	4660	0.17	0.26	0	0	0	0.28	1
Ruggedness	4660	45.93	32.75	2.19	21.77	33.79	62.55	184.33
Elevation	4660	469.06	277.29	1.86	257.7	448.26	664.06	1640.35
Precipitation	4660	1324.84	382.16	367.23	1116.37	1361.24	1573.95	2789.36
Temperature	4660	22.16	2.92	13.75	19.85	22.32	24.42	27.8
Area	4660	845.21	1773.9	3.57	183.76	347.55	781.87	27946.46
Distance to River	4660	97606.34	76680.49	20	40612.24	81549.46	136712.09	473148.58
Distance to Coast	4660	334765.79	295750.58	50	117102.69	265455.54	448578.72	1719448.87
Expected Mule Density	4660	0.2	0.21	0	0	0.15	0.33	1
Panel C - 1920 MCA - Gold Sample								
Pop. Density 1920	856	22.11	31.11	0.13	5.94	14.47	30.97	642.73
Pop. Density 1940	856	25.58	45.89	0.26	7.97	17.91	33.1	1061.36
Pop. Density 1950	856	29.01	60.69	0.33	9.8	20.56	34.67	1388.56
Pop. Density 1960	856	35.5	90.09	0.51	11.4	23.39	39.74	1812.48
Pop. Density 1970	856	44.52	138.38	0.66	13.56	25.72	43	2721.36
Pop. Density 1980	856	57.04	200.33	0.66	14.65	28.77	51.04	4147.5
Pop. Density 1990	856	71.78	258.17	0.72	16.54	32.06	60.97	5609.81
Pop. Density 2000	856	84.08	305.35	0.75	17.72	35.62	68.73	6792.15
Pop. Density 2010	856	95.1	346.58	0.87	19.07	38.42	77.14	7777.9
N. of Settlments 1720	856	0.04	0.22	0	0	0	0	3
N. of Settlments 1770	856	0.18	0.5	0	0	0	0	4
N. of Settlments 1820	856	0.34	0.66	0	0	0	1	4
N. of Settlments 1870	856	1.06	1.24	0	0	1	1	12
N. of Settlments 1920	856	2.19	3.45	0	1	1	2	69
Gold Road Density	856	0.07	0.13	0	0	0	0.08	0.79
Mule Roads Density	856	0.31	0.27	0	0.06	0.26	0.49	1
Ruggedness	856	46.27	32.81	3.32	22.78	34.94	61.28	187.45
Elevation	856	490.74	307.27	5.79	204.59	510.65	726.05	1446.15
Precipitation	856	1237.32	342.15	428.93	999.57	1301.22	1467.3	2301.19
Temperature	856	222.84	28.17	151.31	200.68	224.13	244.09	277.83
Area	856	5643.09	37424.54	86.58	630.44	1417.2	3776.98	1056852.55
Distance to River	856	82358.33	63955.1	20	36321.91	69844.52	112033.45	455347.18
Distance to Coast	856	225861.84	214173.41	50	67859.43	171345.33	311199.14	1419954.19
Expected Mule Density	856	0.33	0.19	0	0.18	0.31	0.46	0.98

C Details: Historical pathways and the current population distribution

In this section, we present the main results in Section 3 using alternative specifications. Table C.1 refers to the gold roads sample, whereas Table C.2 refers to the mule roads sample. Both contain six columns. In column (1), the sample is expanded to include all municipalities except those in the state in the Amazon Basin (all Northern states, except Pará and Tocantins) and those where historical cities existed. In column (2), we exclude from the main sample municipalities in which the seat is within 100km of the coast to test if the results are driven by the dynamics of the population settlements on the coast. In column (3), we apply the inverse hyperbolic transformation to the measure of road density to deal with the right-skewness of the data in the presence of zero values. In column (4), we apply an indicator capturing whether road density is positive as the independent variable to alleviate concerns about measurement error in the road density variables. In column (5), we test whether the results hold within 1872 MCAs, and in column (6), we present spatially robust standard errors suggested by Conley (1999).

Table C.1: Gold roads and current agglomerations - Alternative Specifications

	No-Coast Sample	IHS	Dummy	MCA FE	Conley (160km)
	(1)	(2)	(3)	(4)	(5)
Panel A - Dep. Var.: Population Density:					
Gold Road Density	1.740***	2.357***	0.8887***	1.816***	2.222***
	(0.6655)	(0.6037)	(0.1825)	(0.6375)	(0.5870)
Observations	1,613	2,088	2,088	2,088	2,088
Cluster Groups	174	260	260	260	2,054
Kleibergen-Paap F:	63.082	101.19	180.51	55.134	76.572
Panel B - Dep. Var.: Nightlights:					
Gold Road Density	1.096**	1.518***	0.6169***	1.107**	1.429***
	(0.4741)	(0.4065)	(0.1563)	(0.4386)	(0.3941)
Observations	1,613	2,088	2,088	2,088	2,088
Cluster Groups	174	260	260	260	2,054
Kleibergen-Paap F:	63.082	101.19	180.51	55.134	76.572
Panel C - Dep. Var.: Urban Population Density					
Gold Road Density	1.957**	2.690***	1.007***	2.172***	2.536***
	(0.7571)	(0.6764)	(0.2088)	(0.7292)	(0.6766)
Observations	1,612	2,087	2,087	2,087	2,087
Cluster Groups	174	260	260	260	2,053
Kleibergen-Paap F:	62.501	100.69	182.17	54.751	76.004

Notes: All columns present 2SLS estimates using least-cost path density as an instrumental variable for gold road density. All columns include state fixed effects and include the following geography controls: the log-transformed median values of precipitation, temperature, elevation, terrain ruggedness, area, distance to rivers, and distance to the coast, along with a second-order latitude-longitude polynomial. Column 4 include MCA fixed effects. Standard errors, clustered at the level of 1872 Minimum Comparable Areas, are shown in parentheses, except in column 5 where Conley standard errors are used. The sample includes 2010 municipalities intersected by gold roads and their first-order neighbors, excluding those in states heavily influenced by the Amazon River basin (Amazonas, Pará, Roraima, Rondônia, Acre, and Amapá) and municipalities with settlements that existed prior to 1694. Column 1 also excludes municipalities within a 100 kilometers range from the coast. *Population Density*, *Nightlights*, and *Urban Population Density* are the log-transformed values of population over area, median nightlight incidence, and urban population over area, respectively. *Gold Road Density* is defined as the area within a five-kilometer buffer around gold roads within a municipality, relative to the municipality's total area. In column 2, the density is transformed by the inverse hyperbolic sine. In column 3, *Gold Road Density* represents a binary variable indicating if gold road density is positive. $^{*}p < 0.1, ^{**}p < 0.05, ^{***}p < 0.01$

Table C.2: Mule roads and current agglomerations - Alternative Specifications

	No-Coast Sample	IHS	Dummy	MCA FE	Conley (180km)
	(1)	(2)	(3)	(4)	(5)
Panel A - Dep. Var.: Population Density:					
Mule Road Density	0.2345**	0.2299**	0.1080***	0.1934**	0.2339**
	(0.1140)	(0.1025)	(0.0415)	(0.0803)	(0.1068)
Observations	2,413	3,343	3,343	3,343	3,343
Cluster Groups	233	354	354	354	3,308
Panel B - Dep. Var.: Nightlights:					
Mule Road Density	0.2550**	0.2493**	0.0542	0.1993***	0.2575***
	(0.1132)	(0.1014)	(0.0357)	(0.0730)	(0.0816)
Observations	2,413	3,343	3,343	3,343	3,343
Cluster Groups	233	354	354	354	3,308
Panel C - Dep. Var.: Urban Population Density					
Mule Road Density	0.3510***	0.2908**	0.1359***	0.2433**	0.2939**
	(0.1309)	(0.1249)	(0.0469)	(0.1016)	(0.1211)
Observations	2,412	3,342	3,342	3,342	3,342
Cluster Groups	233	354	354	354	3,307

Notes: All columns include state fixed effects and include the following geography controls: the log-transformed median values of precipitation, temperature, elevation, terrain ruggedness, area, distance to rivers, and distance to the coast, along with a second-order latitude-longitude polynomial and the expected mule road density computed as in Borusyak and Hull (2023). Column 4 include MCA fixed effects. Standard errors, clustered at the level of 1872 Minimum Comparable Areas, are shown in parentheses, except in column 5 where Conley standard errors are used. The sample includes 2010 municipalities intersected by gold roads and their first-order neighbors, excluding those in states heavily influenced by the Amazon River basin (Amazonas, Pará, Roraima, Rondônia, Acre, and Amapá) and municipalities with municipality seats that existed prior to 1872. Column 1 also excludes municipalities within a 100 kilometers range from the coast. *Population Density*, *Nightlights*, and *Urban Population Density* are the log-transformed values of population over area, median nightlight incidence, and urban population over area, respectively. *Mule Road Density* is defined as the area within a five-kilometer buffer around mule roads within a municipality, relative to the municipality's total area. In column 2, the density is transformed by the inverse hyperbolic sine. In column 3, *Mule Road Density* represents a binary variable indicating if gold road density is positive. $^{*}p < 0.1, ^{**}p < 0.05, ^{***}p < 0.01$

D Details: Historical pathways and the dynamics of agglomeration

This section presents detailed regression results analyzing the relationship between historical roads and population density across different decades using census data. While the main text provides a summary of these findings in the form of figures, the tables in this appendix offer a comprehensive account of the estimated coefficients, standard errors, and additional statistics, such as the number of observations and model fit measures. These tables provide the numerical foundation for the visual trends discussed in the main text, offering readers a more detailed view of the data and results. Additionally, Figure D.1 shows a strong positive correlation between population density and settlement density, which validates the settlement density analysis.

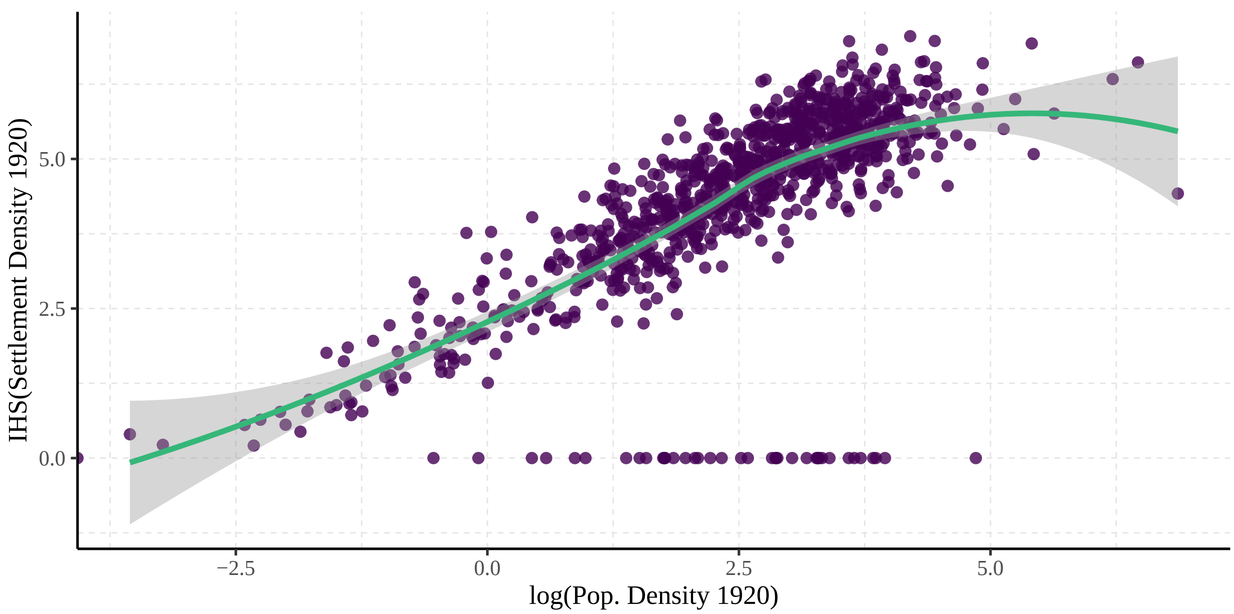


Figure D.1: **Correlation between population density and settlement density in 1920.**

Table D.1 presents the regression estimates evaluating the relationship between road density—distinguished by historical gold roads and mule roads—and population density across various decades from 1920 to 2010. The results are divided into four panels: Panels A and B focus on gold road density, while Panels C and D analyze mule road density. The sample is further split into two subsamples: the Full Sample, which excludes municipalities significantly influenced by the Amazon River basin and historical settlements, and the Neighbors Only sample, which includes municipalities traversed by historical roads and their neighbors. All models are estimated using two-stage least squares (2SLS) with instrumental variables to address potential endogeneity. Geography and state-level fixed effects, along with additional controls, are included to isolate the impact of road density.

The coefficients on Gold Road Density in Panels A and B demonstrate a consistently increasing positive association with population density over time. This relationship becomes statistically significant starting in 1950, with the magnitude of the coefficients stabilizing by 1980. These results suggest a long-term impact of gold roads on population density. In contrast, the coefficients for Mule Road Density in Panels C and D are generally smaller in magnitude but become significant in later decades, particularly after 1970. This suggests that while mule roads may have been less influential in earlier periods, their historical presence contributed to population density growth in the latter half of the 20th century. The robust Kleibergen-Paap F-statistics across all panels confirm the strength of the instrumental variable approach.

Table D.2 reports regression estimates using the 1872 MCAs to explore how gold road density relates to population density over time. Comparing these results to Panels A and B of Table D.1 highlights the advantages of using 1920 MCAs over 1872 MCAs. Across all columns, the standard errors in Table D.2 are significantly larger than those in Table D.1, resulting in fewer statistically significant coefficients. This difference suggests that the earlier administrative boundaries introduce additional noise or less precise spatial alignment, undermining the robustness of the estimates.

The Kleibergen-Paap F-statistics in Table D.2 are consistently lower than those in Table D.1, indicating weaker instrument relevance when using 1872 MCAs. Additionally, while the temporal dynamics of the coefficients follow a broadly similar pattern, with coefficients increasing over time and stabilizing toward the later decades, the magnitudes for the 1872 MCAs are generally smaller. For example, in the "Neighbors Only" sample (Panel B of Table D.2), gold road density coefficients are weaker and lack significance in earlier years compared to the corresponding results in Panel B of Table D.1. This disparity underscores the value of using the more updated 1920 MCAs, which provide more reliable and precise estimates while preserving similar trends.

Table D.1: Historical roads and population density over time

	Year								
	1920	1940	1950	1960	1970	1980	1991	2000	2010
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Panel A - Full Sample - Dependent Variable: Population Density									
Gold Road Density	0.110	0.266	0.657***	0.956***	1.20***	1.39***	1.46***	1.54***	1.55***
	(0.271)	(0.205)	(0.198)	(0.191)	(0.220)	(0.227)	(0.203)	(0.160)	(0.111)
Observations	856	856	856	856	856	856	856	856	856
Kleibergen-Paap F	81.564	81.564	81.564	81.564	81.564	81.564	81.564	81.564	81.564
Panel B - Neighbors Only - Dependent Variable: Population Density									
Gold Road Density	0.219	0.438	0.785***	1.06***	1.27***	1.47***	1.55***	1.61***	1.60***
	(0.351)	(0.269)	(0.208)	(0.189)	(0.165)	(0.162)	(0.184)	(0.185)	(0.173)
Observations	604	604	604	604	604	604	604	604	604
Kleibergen-Paap F	75.872	75.872	75.872	75.872	75.872	75.872	75.872	75.872	75.872
Panel C - Full Sample - Dependent Variable: Population Density									
Mule Road Density	0.065	-0.031	-0.014	0.100	0.208	0.353**	0.469***	0.525***	0.576***
	(0.166)	(0.141)	(0.128)	(0.113)	(0.128)	(0.140)	(0.147)	(0.174)	(0.195)
Observations	420	420	420	420	420	420	420	420	420
Panel D - Neighbors Only - Dependent Variable: Population Density									
Mule Road Density	0.062	0.0004	0.010	0.137	0.236**	0.371***	0.475***	0.531***	0.581***
	(0.169)	(0.140)	(0.122)	(0.104)	(0.119)	(0.138)	(0.150)	(0.180)	(0.202)
Observations	407	407	407	407	407	407	407	407	407

Notes: Spatially corrected standard errors are shown in parentheses. In Panels A and B, all columns report 2SLS estimates, using least-cost path density as an instrumental variable for gold road density. Each specification includes state fixed effects and geography controls, including the log-transformed median values of precipitation, temperature, elevation, terrain ruggedness, area, distance to rivers, and distance to the coast, as well as a second-order latitude-longitude polynomial. Panels C and D additionally include expected mule road density as a geography control. In Panel A, the *Full Sample* consists of 1920 MCAs, excluding those in states predominantly influenced by the Amazon River basin (Amazonas, Pará, Roraima, Rondônia, Acre, and Amapá) and MCAs with settlements predating 1694. Panel C excludes MCAs associated with 1872 municipalities rather than pre-gold settlements. The *Neighbors Only* sample includes only MCAs traversed by historical roads and their immediate neighbors. *Population Density* is calculated as the log-transformed population per unit area. *Gold (Mule) Road Density* is defined as the proportion of a municipality's area within a five-kilometer buffer surrounding gold (mule) roads. $^{*}p < 0.1,^{**}p < 0.05,^{***}p < 0.01$

Table D.2: Historical roads and population density over time (1872 MCAs)

	Year									
	1872	1920	1940	1950	1960	1970	1980	1991	2000	2010
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Panel A - Full Sample - Dependent Variable: Population Density										
Gold Road Density	0.746	-0.335	-0.212	0.278	0.717	0.999	1.14	1.08	1.02	0.948
	(0.507)	(0.431)	(0.544)	(0.557)	(0.581)	(0.643)	(0.694)	(0.717)	(0.716)	(0.723)
Observations	360	363	363	363	363	363	363	363	363	363
Kleibergen-Paap F	28.250	28.269	28.269	28.269	28.269	28.269	28.269	28.269	28.269	28.269
Panel B - Neighbors Only - Dependent Variable: Population Density										
Gold Road Density	0.589	-0.546	-0.411	0.080	0.540	0.851	1.01	0.984	0.945	0.900
	(0.502)	(0.463)	(0.540)	(0.539)	(0.540)	(0.615)	(0.673)	(0.703)	(0.718)	(0.739)
Observations	300	302	302	302	302	302	302	302	302	302
Kleibergen-Paap F	30.808	30.768	30.768	30.768	30.768	30.768	30.768	30.768	30.768	30.768

Notes: Spatially corrected standard errors are shown in parentheses. All columns report 2SLS estimates, using least-cost path density as an instrumental variable for gold road density. Each specification includes state fixed effects and geography controls, including the log-transformed median values of precipitation, temperature, elevation, terrain ruggedness, area, distance to rivers, and distance to the coast, as well as a second-order latitude-longitude polynomial. The *Full Sample* consists of 1872 MCAs, excluding those in states predominantly influenced by the Amazon River basin (Amazonas, Pará, Roraima, Rondônia, Acre, and Amapá) and MCAs with settlements predating 1694. The *Neighbors Only* sample includes only MCAs traversed by historical roads and their immediate neighbors. *Population Density* is calculated as the log-transformed population per unit area. *Gold Road Density* is defined as the proportion of a municipality's area within a five-kilometer buffer surrounding gold roads. $^{*}p < 0.1, ^{**}p < 0.05, ^{***}p < 0.01$

Table D.3 explores the relationship between gold road density and settlement density before the first national census in 1872. The table uses settlement density—calculated as the number of settlements per unit area—as the dependent variable, with variations that include weighting towns as ten times larger than other settlements (Panels C and D). By examining settlement density over time, this table provides insights into the historical role of gold roads in shaping pre-census agglomeration patterns.

The results indicate that gold roads significantly influenced settlement density during the peak of the gold rush period (1720). In Panels A and B, covering the full sample and the "Neighbors Only" sample, respectively, the coefficients on gold road density are consistently positive and significant during this period, with magnitudes peaking in the late 18th and early 19th centuries. These effects diminish in later years, becoming small and statistically insignificant by 1870 and 1920. A similar pattern is observed in Panels C and D, where settlements are weighted by size, further reinforcing the idea that gold roads were instrumental in shaping historical settlement clusters.

Table D.3: Historical roads and settlement density over time

	Year							
	1570	1620	1670	1720	1770	1820	1870	1920
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Panel A - Full Sample - Dependent Variable: Settlement Density								
Gold Road Density	0.579	0.743	2.59**	2.35***	2.43**	2.88**	0.240	0.004
	(0.497)	(0.453)	(1.29)	(0.753)	(1.23)	(1.42)	(0.414)	(0.358)
Observations	910	910	910	856	856	856	856	856
Kleibergen-Paap F	106.90	106.90	106.90	81.240	81.240	81.240	81.240	94.750
Panel B - Neighbors Only - Dependent Variable: Settlement Density								
Gold Road Density	0.531	0.669	2.54**	2.25**	1.93	2.54*	-0.355	0.114
	(0.534)	(0.455)	(1.27)	(0.887)	(1.20)	(1.39)	(0.558)	(0.106)
Observations	638	638	638	604	604	604	604	604
Kleibergen-Paap F	91.546	91.546	91.546	67.746	67.746	67.746	67.746	67.746
Panel C - Full Sample - Dependent Variable: Settlement Density (Towns $= 10\times$ *Settlements)*								
Gold Road Density	0.668	0.787*	2.55*	2.05***	2.10*	2.60**	0.765	-0.196
	(0.479)	(0.438)	(1.31)	(0.647)	(1.07)	(1.21)	(0.664)	(0.460)
Observations	910	910	910	856	856	856	856	856
Kleibergen-Paap F	106.90	106.90	106.90	81.240	81.240	81.240	81.240	81.240
Panel D - Neighbors Only - Dependent Variable: Settlement Density (Towns $= 10\times$ *Settlements)*								
Gold Road Density	0.632	0.731*	2.49*	1.98***	1.74	2.39**	-0.094	-0.127
	(0.495)	(0.435)	(1.28)	(0.760)	(1.08)	(1.21)	(0.778)	(0.506)
Observations	638	638	638	604	604	604	604	604
Kleibergen-Paap F	91.546	91.546	91.546	67.746	67.746	67.746	67.746	67.746

Notes: Spatially corrected standard errors are reported in parentheses. All columns present 2SLS estimates using least-cost path density as an instrumental variable for gold road density. Each specification includes state fixed effects and controls for geography, including the log-transformed median values of precipitation, temperature, elevation, terrain ruggedness, area, distance to rivers, and distance to the coast, as well as a second-order latitude-longitude polynomial. In Panel A, the *Full Sample* consists of 1920 MCAs, excluding those in states predominantly influenced by the Amazon River basin (Amazonas, Pará, Roraima, Rondônia, Acre, and Amapá) and MCAs with settlements predating 1694, except in columns 1 to 3, where MCAs with early settlements are retained. The *Neighbors Only* sample includes only MCAs traversed by historical roads and their immediate neighbors. *Settlement Density* is calculated as the inverse hyperbolic sine transformation of the number of settlements per unit area. In Panels C and D, towns and villages are weighted as 10 times larger than other settlements. *Gold Road Density* is defined as the proportion of a municipality's area within a five-kilometer buffer surrounding gold (or mule) roads. $^{*}p < 0.1, ^{**}p < 0.05, ^{***}p < 0.01$

Interestingly, the diminishing significance of gold road density post-1820 aligns with broader economic and social transitions, including the decline of the gold economy and shifts in transportation technology. The stronger coefficients during earlier periods suggest that gold roads played a pivotal role in fostering initial settlement density, particularly in municipalities and neighboring regions traversed by these roads. These findings emphasize the historical importance of infrastructure investments in driving agglomeration, even as their effects wane over time with evolving economic contexts.

E Details: Connections with modern transportation

Table E.1 examines the long-term impact of historical mule roads on population density in Brazil from 1940 to 2010 after controlling for MST distance. The negative coefficients for distance to the minimum spanning tree (MST) indicate that areas farther from key transportation networks tend to have lower population densities, though these effects are mostly insignificant in earlier years. Importantly, the effects of mule road density change only slightly when compared to Panels C and D in Table D.1. The results hold across both the full sample and a restricted sample of municipalities along historical roads and their immediate neighbors.

Table E.1: Mule roads, modern roads and agglomerations over time

	Year							
	1940 (1)	1950 (2)	1960 (3)	1970 (4)	1980 (5)	1991 (6)	2000 (7)	2010 (8)
Panel A - Full Sample - Dependent Variable: Population Density								
Mule Road Density	-0.070	-0.058	0.044	0.137	0.263**	0.373***	0.424***	0.473***
	(0.143)	(0.136)	(0.119)	(0.123)	(0.128)	(0.125)	(0.154)	(0.172)
Dist. to MST	-0.045	-0.051	-0.064	-0.081	-0.105	-0.111	-0.117	-0.120
	(0.034)	(0.037)	(0.047)	(0.055)	(0.064)	(0.069)	(0.072)	(0.074)
Observations	420	420	420	420	420	420	420	420
Panel B - Neighbors Only - Dependent Variable: Population Density								
Mule Road Density	-0.043	-0.040	0.074	0.158	0.273**	0.372***	0.423***	0.472***
	(0.143)	(0.130)	(0.110)	(0.111)	(0.121)	(0.121)	(0.153)	(0.174)
Dist. to MST	-0.048	-0.056	-0.070	-0.087	-0.109*	-0.116*	-0.121*	-0.123*
	(0.035)	(0.038)	(0.048)	(0.055)	(0.064)	(0.070)	(0.073)	(0.074)
Observations	407	407	407	407	407	407	407	407

Notes: Spatially corrected standard errors are shown in parentheses. Each specification includes state fixed effects and geography controls, including the log-transformed median values of precipitation, temperature, elevation, terrain ruggedness, area, distance to rivers, and distance to the coast, as well as a second-order latitude-longitude polynomial. The *Full Sample* consists of 1872 MCAs, excluding those in states predominantly influenced by the Amazon River basin (Amazonas, Pará, Roraima, Rondônia, Acre, and Amapá) and MCAs with municipality seats in 1872. The *Neighbors Only* sample includes only MCAs traversed by historical roads and their immediate neighbors. *Population Density* is calculated as the log-transformed population per unit area. *Mule Road Density* is defined as the proportion of a municipality's area within a five-kilometer buffer surrounding mule roads. *Dist. to MST* is the log-transformed distance from the MCA's centroid to the minimum spanning tree from Brasília computed by Morten and Oliveira (2024). $^{*}p < 0.1, ^{**}p < 0.05, ^{***}p < 0.01$

Table E.2 examines the long-term impact of historical roads on population density in Brazil from 1940 to 2010 after controlling for modern highway density.

Table E.2: Historical roads, modern roads and agglomerations over time

	Year							
	1940	1950	1960	1970	1980	1991	2000	2010
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Panel A - Full Sample - Dependent Variable: Population Density								
Gold Road Density	0.274	0.672***	0.764***	0.866***	0.973***	0.961***	1.09***	1.07***
	(0.197)	(0.194)	(0.159)	(0.223)	(0.219)	(0.210)	(0.165)	(0.135)
Highway Density	0.112	-0.572	0.561***	0.908***	1.21***	1.43***	1.51***	1.52***
	(0.412)	(0.386)	(0.203)	(0.159)	(0.157)	(0.165)	(0.144)	(0.137)
Observations	856	856	856	856	856	856	856	856
Kleibergen-Paap F	78.408	81.376	85.005	78.663	81.047	82.011	81.829	82.458
Panel B - Neighbors Only - Dependent Variable: Population Density								
Gold Road Density	0.464*	0.802***	0.855***	0.887***	1.01***	1.05***	1.15***	1.10***
	(0.245)	(0.207)	(0.141)	(0.163)	(0.138)	(0.182)	(0.202)	(0.195)
Highway Density	0.596*	-0.447	0.625***	0.963***	1.19***	1.38***	1.45***	1.48***
	(0.331)	(0.401)	(0.087)	(0.076)	(0.077)	(0.109)	(0.073)	(0.052)
Observations	604	604	604	604	604	604	604	604
Kleibergen-Paap F	72.341	76.366	76.829	76.478	79.552	78.751	79.086	80.980
Panel C - Full Sample - Dependent Variable: Population Density								
Mule Road Density	-0.024	0.026	0.023	0.258*	0.396***	0.569***	0.619***	0.666***
	(0.124)	(0.126)	(0.082)	(0.142)	(0.143)	(0.172)	(0.189)	(0.207)
Highway Density	-0.162	-0.580	0.941***	0.933***	1.26***	1.44***	1.56***	1.59***
	(0.511)	(0.538)	(0.362)	(0.200)	(0.225)	(0.243)	(0.256)	(0.259)
Observations	420	420	420	420	420	420	420	420
Panel D - Neighbors Only - Dependent Variable: Population Density								
Mule Road Density	0.006	0.051	0.061	0.288**	0.420***	0.588***	0.640***	0.687***
	(0.120)	(0.113)	(0.078)	(0.139)	(0.148)	(0.183)	(0.204)	(0.224)
Highway Density	-0.131	-0.579	0.939**	0.888***	1.22***	1.40***	1.52***	1.55***
	(0.501)	(0.537)	(0.382)	(0.202)	(0.227)	(0.254)	(0.270)	(0.272)
Observations	407	407	407	407	407	407	407	407

Notes: Spatially corrected standard errors are shown in parentheses. In Panels A and B, all columns report 2SLS estimates, using least-cost path density as an instrumental variable for gold road density. Each specification includes state fixed effects and geography controls, including the log-transformed median values of precipitation, temperature, elevation, terrain ruggedness, area, distance to rivers, and distance to the coast, as well as a second-order latitude-longitude polynomial. The *Full Sample* consists of 1872 MCAs, excluding those in states predominantly influenced by the Amazon River basin (Amazonas, Pará, Roraima, Rondônia, Acre, and Amapá) and MCAs with settlements predating 1694. In Panels C and D we exclude MCAs with municipality seats in 1872 instead of pre-gold settlements. The *Neighbors Only* sample includes only MCAs traversed by historical roads and their immediate neighbors. *Population Density* is calculated as the log-transformed population per unit area. *Gold Road Density* is defined as the proportion of a municipality's area within a five-kilometer buffer surrounding gold roads. *Highway Density* is defined as the proportion of a municipality's area within a five-kilometer buffer surrounding modern roads. $^{*}p < 0.1, ^{**}p < 0.05, ^{***}p < 0.01$

F Details: Road towns and the seeds of agglomeration

In this section, we present tables and extra results related to the characteristics of settlements associated with historical roads, their rate of population growth, and the stock of migrants.

Table F.1 examines the relationship between mule road density and the industrial composition of municipalities in 1920, focusing on agriculture, manufacturing, and services. The results indicate that mule road density has a positive and statistically significant effect on the share of workers in manufacturing, with coefficients of 0.020 in the full sample and 0.018 in the restricted sample (both significant at the 10% level). This suggests that mule roads contributed to the relative growth of manufacturing. In contrast, there are no significant effects of mule road density on the employment density or share of workers in agriculture or services.

The findings are robust across the full sample and the restricted sample, which includes only municipalities traversed by historical roads and their neighbors. Extensive geographic controls and state fixed effects ensure that the observed relationships are not confounded by environmental or regional factors. Overall, unlike the gold roads, the connection between mule roads and early industrialization is weak.

Table F.2 explores the relationship between historical road densities and population growth across decades. Panels A and B focus on the effect of gold road density, while Panels C and D assess the effect of mule road density with both full and restricted samples.

The results indicate that gold road density positively and significantly influenced population growth during the early decades (1920–1960). The coefficients in Panel A are significant at the 1% level for 1940–1960, with a diminishing impact in later decades, turning insignificant or negative by 2000. Similarly, Panel B (neighbors only) shows a robust positive effect for 1920-1960, but the influence diminishes afterward, becoming marginally negative by 2000.

For mule road density (Panels C and D), the effects are less pronounced in the early decades but become positive and significant from 1950 onward, particularly during 1960–1980, with coefficients significant at the 1% level. This suggests that mule roads contributed to sustained population growth later in the century, complementing the earlier impact of gold roads.

Table F.1: Mule roads and industrial composition in 1920

	Density			Share		
	Agriculture (1)	Manufacturing (2)	Services (3)	Agriculture (4)	Manufacturing (5)	Services (6)
Panel A - Full Sample						
Mule Road Density	0.089	0.252	0.054	-0.012	0.020*	-0.007
	(0.106)	(0.224)	(0.155)	(0.021)	(0.011)	(0.013)
Observations	420	420	420	420	420	420
Panel B - Neighbors Only						
Mule Road Density	0.087	0.244	0.029	-0.008	0.018*	-0.010
	(0.110)	(0.233)	(0.147)	(0.019)	(0.010)	(0.012)
Observations	407	407	407	407	407	407

Notes: Spatially corrected standard errors are shown in parentheses. Each specification includes state fixed effects and geography controls, including the log-transformed median values of precipitation, temperature, elevation, terrain ruggedness, area, distance to rivers, and distance to the coast, as well as a second-order latitude-longitude polynomial. The *Full Sample* consists of 1920 MCAs, excluding those in states predominantly influenced by the Amazon River basin (Amazonas, Pará, Roraima, Rondônia, Acre, and Amapá) and MCAs with settlements predating 1694. The *Neighbors Only* sample includes only MCAs traversed by historical roads and their immediate neighbors. The dependent is indicated in the column. *Density* refers to the log-transformed population working in a given industry per unit area. *Share* is defined as the population working in a given industry divided by the population working in all industries. *Mule Road Density* is defined as the proportion of a municipality's area within a five-kilometer buffer surrounding mule roads. $^{*}p < 0.1,^{**}p < 0.05,^{***}p < 0.01$

Table F.3 analyzes the relationship between historical road densities and migrant density across four panels. Gold road density is positively and significantly associated with higher migrant density from both other municipalities and states, with stronger effects observed in the neighbors-only sample. This suggests that proximity to gold roads facilitated migration. In contrast, the effects of mule road density are more varied. While significant positive effects are found for migration from other municipalities, the impact on migration from other states is more inconsistent, with some negative or insignificant coefficients. The temporal patterns indicate that the influence of gold roads on migration persists over time, although the effect slightly diminishes in later decades, while mule roads show more mixed results. Overall, historical road networks, particularly gold roads, had a lasting influence on migration, with stronger localized effects.

Table F.4 explores the relationship between historical road densities and urbanization rates over time. Panels A and B show that gold road density is significantly associated with higher urbanization rates across all years, with the strongest effects in the neighbors-only sample. This

Table F.2: Historical roads and population growth over time

	Decade							
	1920	1940	1950	1960	1970	1980	1990	2000
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Panel A - Full Sample - Dependent Variable: Population Growth								
Gold Road Density	0.009	0.040***	0.028***	0.021***	0.009*	0.0002	0.005	-0.002
	(0.007)	(0.011)	(0.007)	(0.005)	(0.005)	(0.003)	(0.005)	(0.003)
Observations	856	856	856	856	856	856	856	856
Kleibergen-Paap F	81.739	82.634	85.645	87.876	89.864	90.694	90.379	90.418
Panel B - Only Neighbors - Dependent Variable: Population Growth								
Gold Road Density	0.013***	0.036***	0.025***	0.016***	0.007	-0.0002	0.001	-0.006**
	(0.005)	(0.007)	(0.005)	(0.003)	(0.006)	(0.003)	(0.003)	(0.002)
Observations	604	604	604	604	604	604	604	604
Kleibergen-Paap F	76.919	78.869	81.789	84.087	86.018	86.037	85.715	84.982
Panel C - Full Sample - Dependent Variable: Population Growth								
Mule Road Density	-0.004	0.002	0.012***	0.010*	0.013***	0.009***	0.005*	0.004
	(0.005)	(0.003)	(0.004)	(0.005)	(0.004)	(0.003)	(0.003)	(0.003)
Observations	420	420	420	420	420	420	420	420
Panel D - Only Neighbors - Dependent Variable: Population Growth								
Mule Road Density	-0.002	0.001	0.013***	0.009*	0.012***	0.008***	0.005*	0.004
	(0.004)	(0.003)	(0.003)	(0.005)	(0.004)	(0.003)	(0.003)	(0.003)
Observations	407	407	407	407	407	407	407	407

Notes: Spatially corrected standard errors are shown in parentheses. In Panels A and B, all columns report 2SLS estimates, using least-cost path density as an instrumental variable for gold road density. Each specification includes state fixed effects and geography controls, including the log-transformed median values of precipitation, temperature, elevation, terrain ruggedness, area, distance to rivers, and distance to the coast, as well as a second-order latitude-longitude polynomial. Panels C and D additionally include expected mule road density as a geography control. In Panel A, the *Full Sample* consists of 1920 MCAs, excluding those in states predominantly influenced by the Amazon River basin (Amazonas, Pará, Roraima, Rondônia, Acre, and Amapá) and MCAs with settlements predating 1694. Panel C and D excludes MCAs associated with 1872 municipalities rather than pre-gold settlements. The *Neighbors Only* sample includes only MCAs traversed by historical roads and their immediate neighbors. *Population growth* is calculated as the average yearly growth of population in the period between the one indicated in the column and the one indicated in the next column. *Gold (Mule) Road Density* is defined as the proportion of a municipality's area within a five-kilometer buffer surrounding gold (mule) roads. $^{*}p < 0.1, ^{**}p < 0.05, ^{***}p < 0.01$

Table F.3: Historical roads and migrant density over time

	Born in another Municipality				Born in another State			
	1970	1980	2000	2010	1970	1980	2000	2010
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Panel A - Full Sample - Dependent Variable: Migrant Density								
Gold Road Density	1.64***	1.83***	1.34***	1.20***	1.60***	2.39***	1.72***	1.43***
	(0.457)	(0.320)	(0.193)	(0.161)	(0.463)	(0.410)	(0.340)	(0.315)
Observations	856	850	856	856	856	850	856	856
Kleibergen-Paap F	81.564	84.942	81.564	81.564	81.564	84.942	81.564	81.564
Panel B - Only Neighbors - Dependent Variable: Migrant Density								
Gold Road Density	1.91***	2.12***	1.57***	1.35***	1.88***	2.59***	1.91***	1.61***
	(0.270)	(0.290)	(0.273)	(0.274)	(0.277)	(0.378)	(0.368)	(0.382)
Observations	604	598	604	604	604	598	604	604
Kleibergen-Paap F	75.872	75.484	75.872	75.872	75.872	75.484	75.872	75.872
Panel C - Full Sample - Dependent Variable: Migrant Density								
Mule Road Density	0.070	0.370*	0.687***	0.580***	0.077	-0.427**	0.015	-0.035
	(0.256)	(0.216)	(0.120)	(0.204)	(0.259)	(0.207)	(0.226)	(0.327)
Observations	420	419	420	420	420	419	420	420
Panel D - Only Neighbors - Dependent Variable: Migrant Density								
Mule Road Density	0.122	0.406*	0.719***	0.596***	0.129	-0.471***	-0.022	-0.138
	(0.254)	(0.215)	(0.129)	(0.205)	(0.258)	(0.160)	(0.216)	(0.286)
Observations	407	406	407	407	407	406	407	407

Notes: Spatially corrected standard errors are shown in parentheses. In Panels A and B, all columns report 2SLS estimates, using least-cost path density as an instrumental variable for gold road density. Each specification includes state fixed effects and geography controls, including the log-transformed median values of precipitation, temperature, elevation, terrain ruggedness, area, distance to rivers, and distance to the coast, as well as a second-order latitude-longitude polynomial. Panels C and D additionally include expected mule road density as a geography control. In Panel A, the *Full Sample* consists of 1920 MCAs, excluding those in states predominantly influenced by the Amazon River basin (Amazonas, Pará, Roraima, Rondônia, Acre, and Amapá) and MCAs with settlements predating 1694. Panel C and D excludes MCAs associated with 1872 municipalities rather than pre-gold settlements. The *Neighbors Only* sample includes only MCAs traversed by historical roads and their immediate neighbors. *Migrant Density* is the log-transformed number of migrants from another municipality (or state) over the MCA's area. *Gold (Mule) Road Density* is defined as the proportion of a municipality's area within a five-kilometer buffer surrounding gold (mule) roads. $^{*}p < 0.1,^{**}p < 0.05,^{***}p < 0.01$

suggests that areas near gold roads experienced greater urbanization, with the influence remaining significant throughout the twentieth century. The coefficients for gold road density remain positive and statistically significant, though the magnitude decreases slightly over time. In contrast, the effect of mule road density, presented in Panels C and D, is less consistent: while some positive and statistically significant effects appear in the full sample for the later years, mule roads have a weaker and more fluctuating influence on urbanization, with only a few significant coefficients observed. This indicates that, although mule roads may have contributed to urbanization in certain periods, their overall impact was less pronounced compared to gold roads.

Table F.4: Historical roads and urbanization rate over time

	Year							
	1940	1950	1960	1970	1980	1990	2000	2010
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Panel A - Full Sample - Dependent Variable: Urbanization Rate								
Gold Road Density	0.277***	0.205**	0.003	0.239***	0.273***	0.281***	0.222***	0.173***
	(0.081)	(0.092)	(0.009)	(0.089)	(0.066)	(0.047)	(0.037)	(0.037)
Observations	856	856	856	856	856	856	856	856
Kleibergen-Paap F	81.564	81.564	81.564	81.564	81.564	81.564	81.564	81.564
Panel B - Only Neighbors - Dependent Variable: Urbanization Rate								
Gold Road Density	0.296***	0.229***	0.001	0.267***	0.290***	0.307***	0.260***	0.208***
	(0.035)	(0.072)	(0.013)	(0.080)	(0.079)	(0.063)	(0.055)	(0.052)
Observations	604	604	604	604	604	604	604	604
Kleibergen-Paap F	75.872	75.872	75.872	75.872	75.872	75.872	75.872	75.872
Panel C - Full Sample - Dependent Variable: Urbanization Rate								
Mule Road Density	0.006	0.007	-8.88e-6	0.024	0.064**	0.045	0.040	0.044
	(0.036)	(0.046)	(0.003)	(0.021)	(0.027)	(0.035)	(0.043)	(0.037)
Observations	420	420	420	420	420	420	420	420
Panel D - Only Neighbors - Dependent Variable: Urbanization Rate								
Mule Road Density	-0.0001	0.001	0.0001	0.015	0.055**	0.034	0.029	0.033
	(0.033)	(0.043)	(0.004)	(0.014)	(0.023)	(0.027)	(0.037)	(0.028)
Observations	407	407	407	407	407	407	407	407

Notes: Spatially corrected standard errors are shown in parentheses. In Panels A and B, all columns report 2SLS estimates, using least-cost path density as an instrumental variable for gold road density. Each specification includes state fixed effects and geography controls, including the log-transformed median values of precipitation, temperature, elevation, terrain ruggedness, area, distance to rivers, and distance to the coast, as well as a second-order latitude-longitude polynomial. Panels C and D additionally include expected mule road density as a geography control. In Panel A, the *Full Sample* consists of 1920 MCAs, excluding those in states predominantly influenced by the Amazon River basin (Amazonas, Pará, Roraima, Rondônia, Acre, and Amapá) and MCAs with settlements predating 1694. Panel C and D excludes MCAs associated with 1872 municipalities rather than pre-gold settlements. The *Neighbors Only* sample includes only MCAs traversed by historical roads and their immediate neighbors. *Urbanization Rate* is calculated the ratio of individuals living in urban areas to total population. *Gold (Mule) Road Density* is defined as the proportion of a municipality's area within a five-kilometer buffer surrounding gold (mule) roads. $^{*}p < 0.1, ^{**}p < 0.05, ^{***}p < 0.01$

Appendix References

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