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Evidence from Electrification and Highway Construction in Brazil

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Abstract

This paper uses four decades of data on Brazilian municipalities to study the separate and joint impacts of highway and electricity infrastructure access on local economic outcomes. The identification strategy employs difference-in-difference estimators with staggered adoption design. The results show strong contemporaneous effects of electrifying municipalities that already have access to a highway, whereas electrification or highway provision alone may, at best, have no effect. Infrastructure investments also facilitated long-lasting structural transformation effects, with both types of infrastructure access spurring growth of the industrial output share.

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Infrastructure Complementarities and Local Economic Growth: Evidence from Electrification and Highway Construction in Brazil*

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1 Introduction

It is well established in the economic literature that infrastructure investment is a major driver of economic development, particularly through its impact on structural transformation (Berg et al., 2017). Infrastructure investments can have sizeable multiplier effects on local economies by boosting productivity through better factor allocation (Vagliasindi and Gorgulu, 2021), facilitating trade through improved access to markets (Jedwab and Storeygard, 2021), or removing barriers to entry that prevent the development of local economic activities (Perez-Sebastian and Steinbuks, 2017). As various types of infrastructure may differently contribute to growth, it is important to disentangle their effects and how these effects may vary when provided in isolation or in combination. In particular, are different infrastructure types complements or substitutes in driving local economic effects? The answer to this question bears much policy relevance as policymakers need to optimize costly infrastructure investments and their distribution over localities. It is also important for policy makers to understand how these effects may be nuanced and vary according to location and sector.

In this paper, we study the joint impact of access to transportation (highways)[1] and electricity infrastructure on local gross value added (GVA) using panel data over four decades and more than 3,000 Brazilian municipalities. The study fills an important knowledge gap by focusing on infrastructure complementarities. It estimates the causal effect of infrastructure complementarities using the difference-in-differences model with potentially heterogeneous treatments (De Chaisemartin and d'Haultfoeuille, 2020), and an identification strategy that relies on the plausible exogeneity of the timing and common trends across municipalities in the absence of treatment. It then establishes a causal mechanism of infrastructure investment impacts, distinguishing between productivity and relative input use channels.

We find that neither the provision of highways nor electricity alone impacts GVA per capita (our main variable of interest) or, separately, GVA or population. At the same time, we find a strong complementarity associated with the joint provision of highways and electricity, which increases GVA per capita at the time the infrastructure investment is made. The effect, however, disappears after one

[1] We focus on highways because they are Brazil's main transportation mode for both people and freight/cargo. Brazil has the fourth largest highway system in the world. In 2014, road cargo transport accounted for over 60% of Brazil's transportation matrix (Sandoval, 2014).

or two periods. It percolates through increased output thanks to productivity gains, whereas reallocation of labor and capital has a small, if any, impact. We also find evidence of structural transformation associated with providing single and joint infrastructure types. Specifically, the provision of highways and electricity leads to a higher GVA share of industry in the local economy, and this effect persists over time. These results withstand robustness and sensitivity checks and are confirmed by an alternative identification strategy using two-way fixed effects with instrumental variables.

Our paper is closely related to several recent papers in the literature exploring the interactions between different types of infrastructure and economic development in low- and lower-middle-income countries. Moneke (2020) studies how big push infrastructure investments affect welfare through a positive TFP shock in Ethiopia in a spatial general equilibrium model. Pérez-Sebastián, Serrano Quintero, and Steinbuks (2023) endogenize the government's decisions to invest in the transport and electricity networks in a multi-sector quantitative spatial equilibrium model that incorporates the quality of the infrastructure networks, which determines sectoral productivities and trade costs. Using a reduced-form econometric approach, Vanden Eynde and Wren-Lewis (2021) and Abbasi et al. (2022) find evidence of strong economic complementarities for roads and electricity in the context of rural India and the Sub-Saharan Africa region, respectively. Our paper extends the approaches of the latter two studies using robust econometric approaches and focusing on the long-term effects in a middle-income country.

2 Background and Data

2.1 Policy Context

Brazil sporadically started building roads and hydropower plants in the late nineteenth century, with the first highways constructed in the 1920s. This trend slowly continued in the first half of the twentieth century and significantly accelerated in the 1960s and 1970s. The impetus came from President Kubitschek's prioritization of public infrastructure to support industrialization and fulfill his electoral platform of "fifty years of progress in five." During his presidency (1956–1961), Kubitschek launched a major national development plan (*Piano de Metas* or "Targets Plan") focusing on the transportation and energy sectors. This led to a major expansion of both electricity and transportation systems along with the creation of the new capital city, Brasília (Ayres et al., 2019). This impetus was continued under subsequent governments with a series of national development plans in 1967, 1973, and 1976 emphasizing the construction of hydroelectric dams and roads improvement and highway construction (Leturcq, 2018).[2]

The plans required a large public investment effort toward infrastructure. In the initial Targets Plan, 71 percent of public investments targeted energy, transportation, and communications (Ōbhara, 1974). These investments were sustained in the national development plans that followed. They were undertaken at a time when electricity demand increased due to population growth and urbanization. New investments then slowed down – starting with transport followed by electricity – during the "lost decade" of the 1980s and 1990s as Brazil's governments focused on addressing the macroeconomic crisis (Raiser et al., 2017). This led to a progressive deterioration of the transport network as investments did not cover maintenance needs (Correa and Ramos, 2010).

All in all, infrastructure investments resulted in a significant expansion of the electricity and highway networks. Lipscomb, Mobarak, and Barham (2013) report that the transmission network in Brazil grew at an average rate of 8.9 percent per year between 1950 and 2000, resulting in a 72-fold increase from 2,359 kilometers to 167,443 kilometers over the period. As a consequence, household access to electricity rose from 48% in 1970 to 93% in 2000. The total length of highways increased from 41,189 km in 1970 (of which 3,488 km of radial highways originating from Brasília) to 90,788 km in 2000 (of which 7,440 km were radial highways originating from Brasília–calculation by authors based on DNIT data).

2.2 Data

We start with creating a longitudinal dataset with four points in time (1970, 1980, 1996, and 2000) across 3,102 Brazilian municipalities for which economic data are available.[3] It covers more than 93 percent of the Brazilian population throughout the study period.[4] Our data comprise the municipal Gross Valued Added (GVA),

[2]The 1973 plan aimed to create 8 radial roads, 17 longitudinal highways, 24 transverse roads, 27 diagonal roads, and 62 connecting highways (Pereira and Lessa, 2011).

[3]Note that the data is unequally spaced in time, which will not affect the scope and magnitude of our results as shown in Section 4.4.

[4]We work with administrative boundaries at the municipality level from the Brazilian Institute of Geography and Statistics (*Instituto Brasileiro de Geografia e Estatística, IBGE*) using the 1970 data as a baseline reference. The 568 missing municipalities for which economic data are not available only represent 6 percent of the country's population in 1970 and 7 percent in 2000.

population, and labor and capital by sector of activity from Brazil's national accounts data disseminated by Brazil's Institute for Applied Economic Research (*Instituto de Pesquisa Econômica Aplicada, IPEA*).[5] Unfortunately, the data for labor and capital is available only for a subset of municipalities and years.

We use georeferenced data on roads for each decade from 1970 to 2000 obtained from Brazil's National Department of Transport Infrastructure (*Departamento Nacional de Infraestrutura de Transportes*, DNIT). From the road data, we subset the road segments that are paved, duplicated, or in the progress of duplication.[6] For the purpose of identification (see next section), we separate out radial roads extending from Brazilia towards the 25 state capitals[7] along with two coastal highways based on DNIT classification.[8] For each time period, we construct the start and end points of the DNIT radial and coastal highway road segments that existed at the time. Our road access measure is a dummy variable equal to 1 for municipalities that have a radial road within 50 km of its centroid and 0 otherwise.

Electricity access data over the period 1970 to 2000 come from various sources including the Geographic Information System of the Electric Sector (*Sistema de Informações Geográficas do Setor Elétrico, SIGEL*) of the Brazil National Electricity Regulatory Authority (*Agência Nacional de Energia Elétrica, ANEEL*), the Business Information System for the Electricity Sector (*Sistema de Informações Empresariais do Setor de Energia Elétrica, SIESE*) of a major Brazilian electric utility, *Eletrobras*, and Brazil's and Cadastral Geographic Information System of the National Interconnected System (*Sistema De Informações Geográficas Cadastrais Do Sistema Interligado Nacional, SINDAT*) of the Brazil's Operator of the National Electricity System (*Operador Nacional do Sistema Elétrico, ONS*). As in Lipscomb, Mobarak, and Barham (2013), we define electricity access in a given year as the share of municipality area located within 50 kilometers of a transmission line, distribution substation, or autonomous power plant.

Table 1 shows variable means for population, gross-valued added, and capital-labor ratio across municipalities, overall and for the industry sector, in the study's four periods.

[5] See `www.ipeadata.gov.br`.

[6] More precisely, the road segment is defined as one of the following: 'Pavimentada','Duplicada', and 'Em obra de Duplicação'.

[7] This includes the state of Tocantins and its capital, Palmas, even though Tocantins had not not yet been created in 1970.

[8] Radial highways include road segments with labels '010', '020', '030', '040', '050', '060', '070', '080', '090'. Coastal highways include segments with labels '101' and '116'.

Table 1: Variable Means (3,102 municipalities)

	1970	1980	1996	2000
Population	28.16	35.92	47.17	50.93
Gross Value Added (GVA)	93.59	230.59	287.65	307.75
GVA per capita	1.56	3.42	3.08	3.77
GVA, Industry	32.48	92.35	93.33	84.66
Capital-Labor Ratio	11,023	34,279	N/A	N/A
Capital-Labor Ratio, Industry	33,272	77,434	N/A	N/A

Note: Population and labor are in million people; GVA and capital are in million R$ (constant 2010 prices). The capital-labor ratio is available for 1231 municipalities.

2.3 Infrastructure Investments in the Data

Figure 1 shows the spatial evolution of radial and coastal highways and electricity access in Brazil by comparing infrastructure access for 1970 and 2000, which are the starting and end dates for our study. The maps show that electrification and radial and coastal highway expansion mostly occurred towards the Northeast and Center-West regions, whereas investments in other regions were modest. Figure 2 further details the number of municipalities by their degree of electrification in 1970 and 2000. We see that the bulk of electrification investment consisted of full electrification of formerly non-electrified municipalities. Only a small share of municipalities received partial electrification. As we construct a binary measure of electrification for the empirical analysis, we focus on the case of full electrification (i.e., municipalities with 100 percent of their population having electricity access).

Figure 3 shows the roll-out of both radial and coastal highway investment and full electrification. Consistent with the roll-out of the above investment plans, infrastructure access increased significantly. In 1970, 1,901 municipalities (i.e., 61 percent of all municipalities) did not have access to power or highway infrastructure, 975 municipalities only had electricity access, 117 municipalities only had highway access, and 109 municipalities had both infrastructure types.

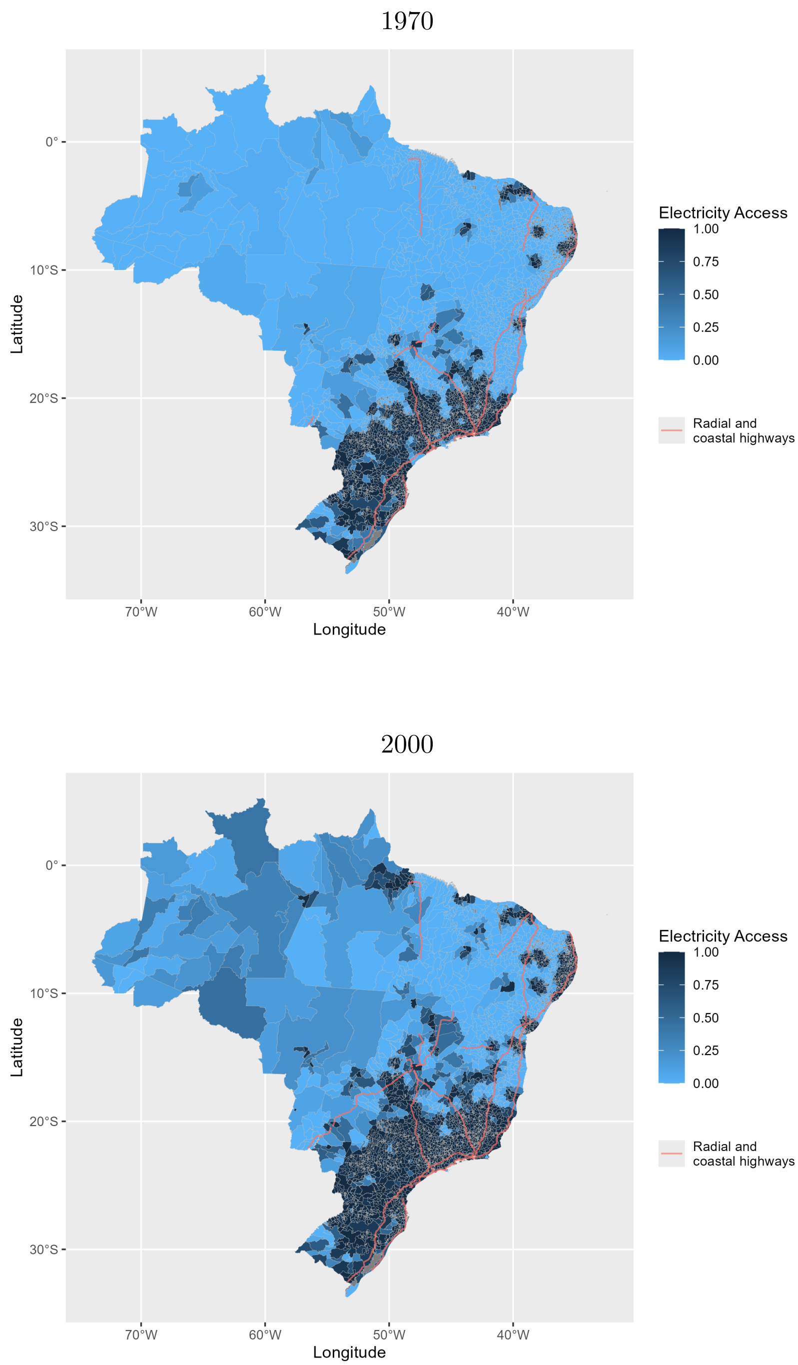


Figure 1: Changes in Infrastructure Access (1970-2000)

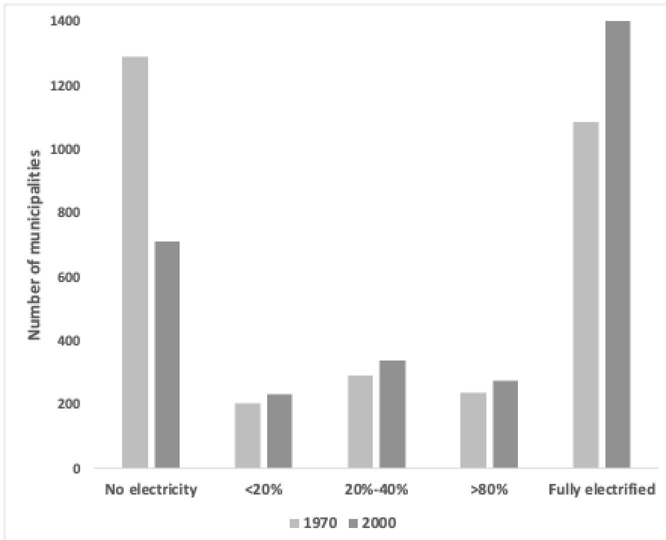


Figure 2: Electrification Rate across Municipalities in 1970 and 2000

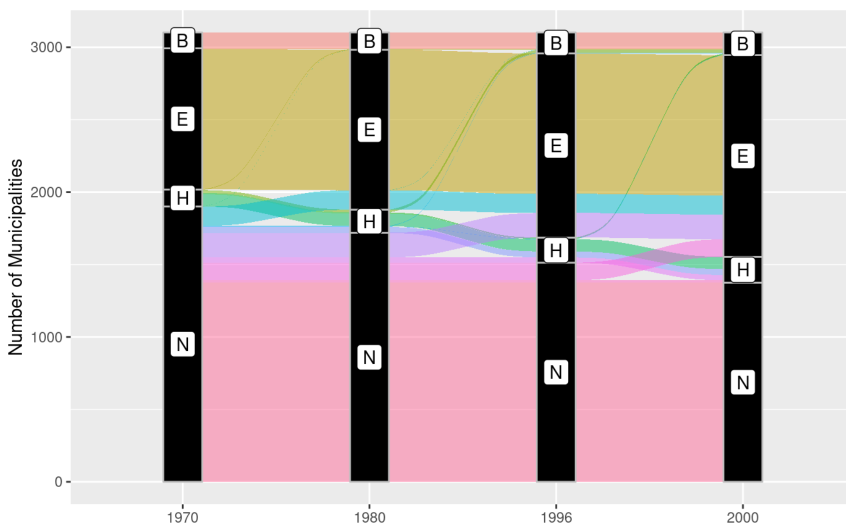


Figure 3: Sankey diagram of infrastructure investment flows, 1970-2000

Note. N: No infrastructure; H: Highway access; E: Electricity access; B: Both highway and electricity access.

The bulk of the investment between 1970 and 2000 was the electrification of

424 of the municipalities that lacked any infrastructure and of 32 municipalities that already had highway access. Highways were provided to 93 municipalities that had no infrastructure and to 6 municipalities that were already electrified.[9] Only 9 municipalities were simultaneously granted highway and electricity access.

3 Identification Strategy and Estimation Sample

We are interested in estimating the average causal effect of infrastructure provision on local economic outcomes at the municipality level (i.e., output per capita, output, input use, and productivity measures). As infrastructure is not necessarily placed independently of local economic outcomes, a potential reverse causality problem arises. Also, given that some variables correlated with both infrastructure and economic outcomes might not be observed, an omitted variable bias might also be present. We address both of these issues, leading to endogeneity problems, using two different approaches.

Our main approach estimates a difference-in-differences model with potentially heterogeneous treatments. Similar to Vanden Eynde and Wren-Lewis (2021), our identification strategy relies on the plausible exogeneity of the timing and common trends across municipalities in the absence of treatment. Following Bird and Straub (2020) and Morten and Oliveira (2023), we specifically focus on the radial network originating from Brasília, which was planned in the 1950s to become the new capital of Brazil. Because the creation of Brasília motivated the development of the current radial highway system linking it to other state capitals (Morten and Oliveira, 2023), we can obtain a sample of exogenously treated municipalities by removing these state capitals along with Brasília. To address the potential contamination effects of road placement, we restrict the analysis to “inconsequential areas”, excluding urban nodes that might have motivated highway construction. We also exclude municipalities that have received non-radial highways. Finally, to ensure the comparability of context, we only keep municipalities within 150 km of treated municipalities in the control group. This leaves us with 384 municipalities, either without any infrastructure or endowed with a radial highway in 1970.[10] Between 1970 and 2000, we observe

[9]This small number appears reasonable because electrification requires some means of transport. Moneke (2020) makes a similar observation for Ethiopia.

[10]Appendix Table A1 replicates the descriptive statistics from Table 1 for these 384 municipalities.

193 instances of infrastructure investments either by electrification or provision of a radial highway. In section 4.4, we explore the sensitivity of these sample construction criteria by expanding the control group to municipalities within 200 km of treated municipalities. To address the possibility of spatial spillovers (that could lead to potential contamination effects), we also perform a robustness check that excludes municipalities within 50 km of treated municipalities from the control group.

We denote with index i individual municipalities, and with index $s \in \{N, E, H, B\}$ the groups of municipalities with similar initial infrastructure endowment, where N stands for no infrastructure, E stands for electricity, H stands for highway, and B for both infrastructure types. We also use index t to refer to the periods defined in section 2.2. Adopting the notation of Freedman et al. (2023), we focus on treatment exposures that occur at the group $\times$ time level (with infrastructure staying in place once provided). In this perspective, we denote $A_{s,P}$ the period during which infrastructure type $P \in \{E, H, B\}$ is first provided to group s. We set $A_{s,P} = \infty$ for groups s that are not provided with infrastructure P during the study period. We can then define the binary treatment variable for group s with infrastructure P in period t as $D_{s,t} = \mathbb{I}(t \geq A_{s,P})$.

We are interested in estimating the average effect of treatment on the treated (ATT) in period $t \geq a$ for treatment P provided in period a, which can be written as

$$ATT(s, P, a, t) = E[\beta_{i,s,P,t}(a) | A_{s,P} = a] \tag{1}$$

where $\beta_{i,s,P,t}(a) = Y_{i,s,P,t}(a) - Y_{i,s,P,t}(0)$ is the causal effect at time t of provision in period a of infrastructure P to municipality i in group s on outcome variable Y compared to a hypothetical scenario in which group s would not have received the infrastructure by period t.

In our staggered adoption design, the average treatment effect on the treated in period $t = a + k$ (with $k \geq 0$) for treatment in period a is given by

$$\begin{aligned} ATT(s, P, a, a+k) &= E[Y_{i,s,P,a+k} - Y_{i,s,P,a-1} | A_s = a] \\ &\quad - E[Y_{i,s,P,a+k} - Y_{i.s,P,a-1} | A_s > a + k] \\ &= E[\beta_{i,s,P,a+k}(a) | A_{s,P} = a] \end{aligned} \tag{2}$$

To estimate equation (2) we use the difference-in-differences estimator (DID_M) robust to heterogeneous effects proposed by De Chaisemartin and d'Haultfoeuille (2020). As noted by De Chaisemartin and d'Haultfoeuille (2020), the DID_M estimator could fail if municipalities that received infrastructure investments experienced different trends than municipalities that did not receive any infrastructure. To test the parallel trends assumption, we use the placebo estimator proposed by De Chaisemartin and d'Haultfoeuille (2020) that compares the outcomes between periods $a-2$ and $a-1$ in municipalities that became treated in period a to those of the control group. If the parallel trends assumption is violated, the placebo estimator will be significantly different from 0.

4 Results, Robustness Checks, and Discussion

4.1 Aggregate Output and Population

In this section, we present the DID_M estimator (De Chaisemartin and D'Haultfoeuille, 2022b; De Chaisemartin and d'Haultfoeuille, 2020) of the effect of the separate and joint provision of electricity and highways on various municipality level outcomes. Our main focus is on gross value added per capita, which is a normalized measure of output (allowing comparisons of impact across municipalities of different sizes). It also provides a measure of the apparent productivity of municipalities. The DID_M estimator estimates the average treatment effect at the time when a municipality receives the infrastructure across all municipalities that become treated at some point. All outcomes are expressed in natural logarithms and have semi-elasticity interpretations.

We use binary measures of infrastructure access and consider whether a municipality has access to a highway or is fully electrified. We distinguish across three switching scenarios depending on whether a municipality without any infrastructure type receives electricity access only (denoted N2E), highway access only (denoted N2H), or whether a municipality with highway access becomes electrified (H2B). As we have seen in Figure 3, there are only a few transitions where an electrified municipality is provided with a highway (E2B), or a municipality is provided with both highway and electricity (N2B). We exclude those rare switching cases from the analysis as results for them would not have meaningful interpretations.[11]

[11] The standard errors cannot be accurately estimated when the number of switching municipalities is too small.

Tables 2-5 present the estimates of the impact of infrastructure provision on the logarithm of gross value added (GVA) per capita, the logarithm of GVA, the logarithm of population, and GVA shares. The first row presents the estimates for the entire period of the study (1970-2000), whereas the next three rows show estimates for the sub-periods 1970-1980, 1980-1996, and 1996-2000 respectively. The penultimate row presents the dynamic estimator of De Chaisemartin and D'Haultfoeuille (2022a), which measures effects one period after the infrastructure provision. The last row shows the placebo estimator (see section 3) of the effect of the separate and joint provision of electricity and highway access. To preserve space, we only report the number of observations and treated municipalities (switchers) in Table 2 as these numbers are the same for all tables.

Table 2 focuses on municipal gross value added per capita, our main variable of interest. We see from the first row that neither the provision of highways nor electricity alone has a statistically significant impact on value-added per capita. This contrasts with previous research on the impact of electricity and highway provision on output per capita and productivity (Bird and Straub, 2020; Fernald, 1999; Perez-Sebastian, Steinbuks, et al., 2020). These previous studies, however, did not consider whether municipalities receiving a type of infrastructure investment already had received the other type. At the same time, the electrification of municipalities already endowed with a highway increases the value added per capita by 29 percent.[12] This result highlights the strong impact of providing the two types of infrastructure. This is in line with the findings regarding the complementarity of roads and electricity provision by Moneke (2020) for Ethiopia and by Vanden Eynde and Wren-Lewis (2021) for rural India, but contrasts with the study of Lewis and Severnini (2020) for rural areas in the United States. We do not find statistically significant dynamic estimates (row 5), which suggests that the effect of infrastructure placement is temporary. Placebo estimates of the provision of electricity, whether alone or following highway provision, are much smaller and statistically insignificant. This indicates that the parallel trends assumption is unlikely to be violated for electricity provision. For highway provision, the placebo effect is positive and significant, preventing us from concluding whether the provision of highways alone impacted GVA per capita.

[12] As variables are measured in logs, the percentage change in the outcome is given by the formula exp(β)-1, where β is the reported regression coefficient.

Table 2: DID_M estimates of infrastructure provision (GVA per Capita)

		Dependent variable: Gross Value Added per Capita (log)		
		N2E	N2H	H2B
1970-2000 (E)	coef.	0.036	0.021	0.252**
	s.e.	(0.046)	(0.088)	(0.101)
	Obs./Switchers	390 / 102	338 / 55	274 / 36
1970-1980	coef.	-0.030	0.273	0.081
	s.e.	(0.057)	(0.174)	(0.175)
	Obs./Switchers	168 / 35	134 / 21	89 / 4
1980-1996	coef.	0.139**	-0.035	0.276**
	s.e.	(0.069)	(0.121)	(0.132)
	Obs./Switchers	133 / 44	113 / 22	104 / 23
1996-2000	coef.	-0.063	-0.319***	0.269**
	s.e.	(0.105)	(0.081)	(0.129)
	Obs./Switchers	89 / 23	91 / 12	81 / 9
1970-2000 (D)	coef.	0.074	0.170*	0.268
	s.e.	(0.061)	(0.100)	(0.170)
	Obs./Switchers	234 / 79	213 / 43	165 / 27
Placebo	coef.	-0.110	0.135	0.089
	s.e.	(0.067)	(0.080)	(0.087)
	Obs.	222	204	166

*Notes: Bootstrapped standard errors (200 replications) in parentheses. *p<0.1, **p<0.05, ***p<0.01. (E): estimated effect of the treatment at the time period of the infrastructure provision. (D): estimated effect one period after the infrastructure provision.*

The results by period (rows 2-4) show a more contrasted picture. There were positive, albeit marginally significant, impacts of highways on output per capita in the 1970-1980. The provision of electricity alone positively affected output per capita in 1980-1996. By contrast, the period 1996-2000 shows negative impacts on gross value added per capita of the separate provision of highways. This could be due to the sequencing of investments targeting lagging regions in the later period, as discussed in Section 2.1. We see suggestive complementarity effects for the last period, as the point estimate of the electrification effect for municipalities already endowed with a highway (column H2B) is greater than that for electrification only (column N2E).

Table 3: DID_{M} estimates of infrastructure provision (Gross Value Added)

		Dependent variable: Gross Value Added (log)		
		N2E	N2H	H2B
1970-2000 (E)	coef.	0.035	-0.004	0.325***
	s.e.	(0.047)	(0.081)	(0.125)
1970-1980	coef.	0.067	0.190	0.469
	s.e.	(0.071)	(0.184)	(0.309)
1980-1996	coef.	0.063	-0.018	0.284*
	s.e.	(0.071)	(0.112)	(0.167)
1996-2000	coef.	-0.069	-0.317***	0.367**
	s.e.	(0.103)	(0.103)	(0.156)
1970-2000 (D)	coef.	0.101	0.112	0.390*
	s.e.	(0.075)	(0.121)	(0.220)
Placebo	coef.	-0.183***	0.138	0.046
	s.e.	(0.070)	(0.094)	(0.109)

Notes: Bootstrapped standard errors (200 replications) in parentheses. $^{*}p<0.1$, $^{**}p<0.05$, $^{***}p<0.01$.
(E): estimated effect of the treatment at the time period of the infrastructure provision.
(D): estimated effect one period after the infrastructure provision.

Tables 3 and 4 decompose the previous findings by showing how municipality gross value added and population responded to infrastructure investment. The first row of Table 3 shows a strong complementarity effect as the gross value added in municipalities endowed with a highway that was subsequently electrified increases by 38 percent compared to untreated municipalities. The provision of electricity alone or highways alone did not have a statistically significant impact on GVA. The first row of Table 4 does not show any statistically significant impact on the population in municipalities due to any type of infrastructure provision. Taken together, these results suggest that the increase in gross value added per capita (Table 2) is solely driven by the effects of gross value added resulting from the electrification of municipalities already endowed with a highway. We do not find any significant dynamic effects except for a positive and marginally significant effect on GVA for the electrification of municipalities already endowed with a highway (row 5). The placebo estimates of highway provision and electrification in municipalities already endowed with highways are not statistically significant, lending credibility to the parallel trend assumption.

However, this is not the case for the provision of electricity alone, preventing us from concluding whether the provision of electricity alone had an impact on either GVA or population.

A closer examination by the period of the electrification of municipalities already endowed with a highway (rows 2, 3, and 4 of Tables 3 and 4) indicates that the complementarity effect mainly occurred in the 1996-2000 period. In that period, providing electricity in places already supplied with a highway positively increased gross value added by 44 percent and population by 10 percent.

Table 4: DID_M estimates of infrastructure provision (Population)

		Dependent variable: Population (log)		
		N2E	N2H	H2B
1970-2000 (E)	coef.	-0.001	-0.025	0.073
	s.e.	(0.025)	(0.033)	(0.066)
1970-1980	coef.	0.097**	-0.083	0.388
	s.e.	(0.041)	(0.063)	(0.342)
1980-1996	coef.	-0.076*	0.016	0.008
	s.e.	(0.041)	(0.044)	(0.073)
1996-2000	coef.	-0.006	0.002	0.098***
	s.e.	(0.023)	(0.031)	(0.022)
1970-2000 (D)	coef.	0.027	-0.058	0.121
	s.e.	(0.055)	(0.062)	(0.116)
Placebo	coef.	-0.073*	0.003	-0.044
	s.e.	(0.041)	(0.057)	(0.067)

Notes: Bootstrapped standard errors (200 replications) in parentheses. $^{*}p<0.1$, $^{**}p<0.05$, $^{***}p<0.01$.
(E): estimated effect of the treatment at the time period of the infrastructure provision.
(D): estimated effect one period after the infrastructure provision.

4.2 Structural Transformation

We now turn to the impact of infrastructure provision on the industry share in Gross Value Added. The findings (summarized in Table 5) point towards evidence of structural transformation. There are also noticeable heterogeneous effects associated with the separate and joint provision of electricity and highways.

Providing electricity (columns N2E) increases, on average, the share of industry by 5 percent as compared to municipalities that were not electrified.

The impact is consistently positive and significant only in the 1970-1980 period. The placebo test validates the impact of electrification. For electricity access, the size of dynamic effects is comparable to the average effect. This indicates that the impact of electrification on the industry GVA share persists over time, indicating a long-lasting effect on the economy's structure.

We find little average effect of highway connection (columns N2H) on the industry GVA share but a positive dynamic impact (6 percentage points), which is three times as large as the average effect and is statistically significant. Contrary to electricity provision, this indicates that highway provision has a long-lasting impact on the GVA share of the industry sector. The placebo test for highway provision does not reject this finding.

Both electricity and highway effects indicate structural transformation through an increase in the industry share. This is consistent with the previous literature on the impact of electrification and structural transformation (Gaggl et al., 2021; Perez-Sebastian, Steinbuks, et al., 2020) and previous studies that found that highways facilitate input use for industry and spur the development of industries trading heavier goods that can be transported by roads (Duranton, Morrow, and Turner, 2014; Jaimovich, 2019).

Finally, we look at the impact on the industry GVA share following the electrification of municipalities that were already connected to the highway network (columns H2B). We find no statistically significant effect. This suggests no complementarity in the sense that the share of industry does not change when both types of infrastructure are present. The placebo test does not reject the validity of these results.

Table 5: DID_M estimates of infrastructure provision (Industry GVA share)

		Dependent variable: Industry GVA share		
		N2E	N2H	H2B
1970-2000 (E)	coef.	0.049***	0.020	0.027
	s.e.	(0.016)	(0.020)	(0.029)
1970-1980	coef.	0.088***	0.030	0.042
	s.e.	(0.025)	(0.042)	(0.069)
1980-1996	coef.	0.027	0.026	-0.000
	s.e.	(0.023)	(0.028)	(0.040)
1996-2000	coef.	0.034	-0.009	0.090
	s.e.	(0.033)	(0.020)	(0.059)
1970-2000 (D)	coef.	0.051**	0.058**	0.025
	s.e.	(0.020)	(0.027)	(0.053)
Placebo	coef.	0.023	0.022	-0.009
	s.e.	(0.022)	(0.015)	(0.023)

Notes: Bootstrapped standard errors (200 replications) in parentheses. $^{*}p<0.1$, $^{**}p<0.05$, $^{***}p<0.01$.
(E): estimated effect of the treatment at the time period of the infrastructure provision.
(D): estimated effect one period after the infrastructure provision.

4.3 Causal Mechanisms

We now investigate in greater detail the possible mechanisms that can explain how infrastructure provision affects output and productivity. Assuming a Cobb-Douglas aggregate production technology at the municipal level, we focus specifically on the capital/labor ratio (capital intensity) and the total factor productivity (TFP), which captures technological improvements (see derivation and estimation procedure of TFP in Appendix 1). Capital and labor data are available only for the period 1970-1980, which, fortunately, is a period when significant investment was made. However, as we explain in section 2.2, the data are only available for some municipalities, leaving us with a smaller sample of municipalities during that period. Therefore, we first apply the DID_M estimator to this restricted subsample to make sure that the main results in the second row of Table 2 are unchanged. Appendix Table A2 shows that this is indeed the case. Because the subsample does not include municipalities with highway access that were subsequently electrified during the period, we cannot estimate complementarity effects. This said, our results for the provision of single infrastructure types indicate that the subsample does not seem to suffer from sample selection bias.

Table 6: DID_{M} estimates of infrastructure provision on TFP and capital-labor ratio: 1970-1980

		All Sectors		Industry	
		N2E	N2H	N2E	N2H
K/L	coef.	-0.128	-0.103	-0.361	-0.292
	s.e.	(0.137)	(0.180)	(0.255)	(0.492)
TFP	coef.	0.166*	0.367**	0.618***	0.100
	s.e.	(0.094)	(0.173)	(0.199)	(0.241)
	Obs./Switchers	87 / 25	89 / 19	87 / 25	89 / 19

Notes: Bootstrapped standard errors (200 replications) in parentheses.
**p<0.1, **p<0.05, ***p<0.01. Dependent variables are in natural logs.*

Table 6 shows the impact of electrification and highway provision on capital intensity and TFP, pooling all sectors together, and separately for the industry sector. We do not observe any statistically significant effects of the provision of electricity or highways on the capital/labor ratio at the aggregate level. On the contrary, the provision of either infrastructure type has strong positive effects on TFP. Electrification increases TFP by almost 18 percent, although this effect is only marginally significant.

When focusing on the industry sector, we see that electrification significantly increases TFP, which is 86 percent larger in electrified municipalities. This is consistent with the previous literature documenting positive total factor productivity effects in the industry sector following electrification (Kassem, 2021). These findings are also consistent with our estimated changes in industry GVA share following electrification (see Table 5), with TFP being the driver of this change (for a detailed explanation of this mechanism, see Perez-Sebastian, Steinbuks, et al., 2020).

Similar to electrification, we find a positive and significant effect (a 44 percent increase) of highway provision on aggregate TFP. The effect of highway provision on the industry sector TFP is positive but not statistically significant. This is consistent with the absence of significant effects of highway provision on the industry GVA share for the 1970-1980 period in Table 5.

Overall, the above results indicate that infrastructure-induced growth percolated through productivity and, thus, more efficient use of production inputs facilitated by better access to electricity, predominantly for the industry sector and by highways for the aggregated economy.

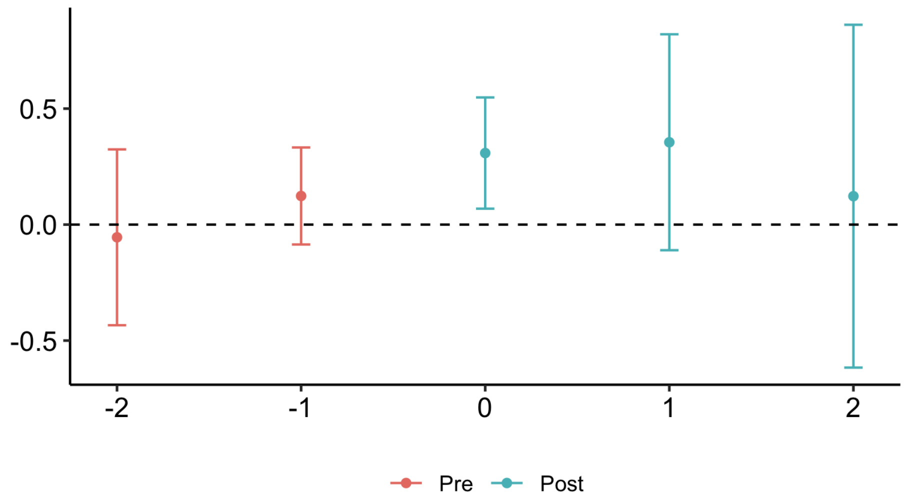
4.4 Robustness Tests

We find that there is no significant difference in the distribution of gross value-added and population across treatments and controls before treatment occurs, as shown in Appendix Figures A2 and A3. Consistent with Kahn-Lang and Lang (2020), this gives us further confidence that our difference-in-differences estimates are plausible.

Next, we re-estimate our specifications from Tables 2, 3 and 4 using the doubly robust difference-in-differences estimator proposed by Callaway and Sant'Anna (2021). Figures 4 and 5 show the corresponding event study graphs for our key results (the impact of electrification of municipalities previously endowed with highways on GVA per capita and the impact of electrification of municipalities without highways on the industry GVA share). Appendix Figure A4 and Table A3 show event study graphs and the estimated coefficients for all results. The event study graphs and estimation results confirm our earlier findings. First, only joint infrastructure placement has a significant though contemporaneous effect on GVA per capita (due to a temporary increase in GVA without effect on population, see Appendix Table A3). Second, the electrification of municipalities without highways has a longer-lasting effect on structural transformation, increasing the industrial GVA share. The estimated coefficients also carry the same significance as in our main specification (i.e., using De Chaisemartin and d'Haultfoeuille (2020)) for all types of infrastructure investments and outcome variables. If anything, all coefficients measuring complementarity effects (i.e., electrification in the presence of highways) are larger, indicating that our main estimates are likely to be conservative.

We also replicate our main results from Table 2 using a less stringent measure of electricity access, i.e., considering municipalities that are 80 percent electrified instead of fully electrified. The results presented in Appendix Table A4 are broadly of the same magnitude and significance as those presented in Table 2. One difference is that we lose the significance of the effect of electrification of municipalities already endowed with a highway for the 1996-2000 period (which was only marginally significant in Table 2). The only other difference is that

Figure 4: Event study graphs: GVA per Capita, H2B



Note. The event study graph is based on the estimator of Callaway and Sant'Anna (2021). H2B: electrification of municipalities already endowed with a highway.

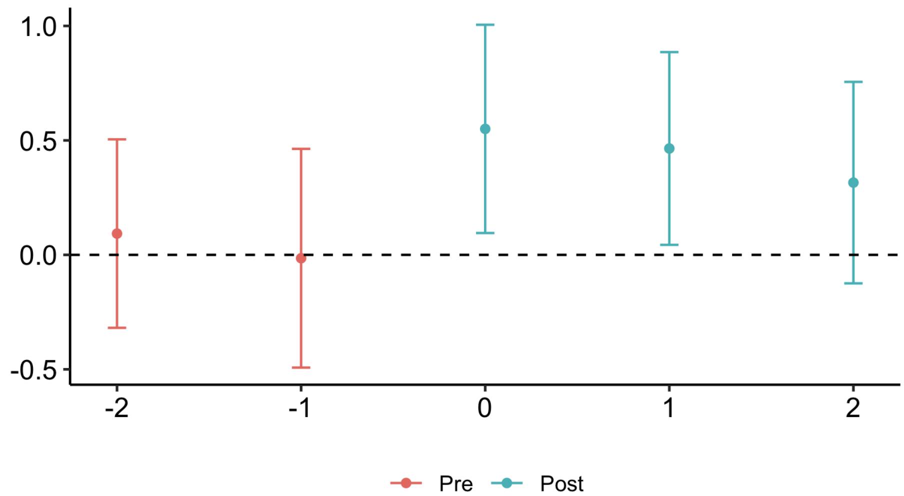
we find a positive dynamic effect for the provision of highways (N2H). However, this result is not robust to the placebo test. Importantly, the placebo test for complementarity (H2B) remains valid.

Additionally, in Table A5, we consider a larger sample of control municipalities located up to 200 km from a treated municipality. The results closely match those of Table 2 except that the positive complementarity effect for the period 1980-1996 becomes statistically significant, and the positive and significant dynamic effect emerges for the provision of highways. As for the previous robustness check, the placebo test for complementarity (H2B) also remains valid.

In Table A6, we exclude from the control group municipalities within 50 km of a treated municipality to reduce the possibility of local spillovers. Results are very similar to those of Table 2. We only lose the significance of the complementary effect for the period 1980-1996 (which was marginally significant in Table 2). Again, the placebo test remains valid for the electrification of municipalities already endowed with a highway.

Finally, we explore the implications of data unequally spaced in time. We follow recommendations from the Stata command `did_multiplegt` provided

Figure 5: Event study graphs: Industry GVA share: N2E



Note. The event study graph is based on the estimator of Callaway and Sant'Anna (2021). N2E: electrification of municipalities not endowed with any infrastructure.

by De Chaisemartin and d'Haultfoeuille (2020) and rerun the regression in two different ways: First, we remove the 1996 observations and append observations identical to 1980 but with the year equal to 1990, and consider 1990 treatments instead of 1996 treatments. This is a conservative approach as it assumes that the outcomes are delayed. Second, we keep the 1996 outcomes (which the command treats as if they were observed in 1990) but consider 1990 treatments. Appendix tables A7 and A8 show that the scope and magnitude of results for our main variable of interest, GVA per capita, are little changed. The impact on GVA per capita of electrification of municipalities endowed with highways (H2B) is only slightly diminished while significance remains. The same findings hold for other variables of interest.[13]

All in all, these results confirm the robustness of our main findings.[14]

[13]These results are available upon demand.

[14]We carried out the same robustness checks for Tables 3, 4 and 5 and also found comparable results.

4.5 Alternative Identification Strategy

Our quantitative placebo, balance, and sample sensitivity tests and the use of alternative DID estimators give us reasonable confidence that our identification approach using difference-in-differences estimation is justified. To strengthen our inference, we show in this section that our main results are also robust to an alternative identification strategy.

Specifically, we estimate an instrumental variable model for data with two-way fixed effects. As with the main specification, we exclude the state capitals, the areas covered by non-radial highways, and keep municipalities within 150 km of treated municipalities in the control group. We regress our outcomes of interest (log GVA, log population, and log GVA per capita) on a dummy variable indicating the presence of a radial highway in the municipality, a dummy variable indicating whether the municipality is electrified, and on the interaction between the two treatments (to assess complementarity effect). To address the endogeneity of electrification, we use the time-variant instrument developed by Lipscomb, Mobarak, and Barham (2013) and further refined in Szerman et al. (2022). To address road placement endogeneity, we use a time-variant instrument based on the natural least cost path between the urban nodes (see, e.g., Faber (2014), Donaldson (2018) or Bird and Straub (2020) who proposed time-invariant versions of the least-cost path instrument). Appendix A2 details the estimation and construction of our instruments.

Table 7 shows the estimation results of the instrumental variable model.[15] Consistent with our findings using our main identification strategy reported in section 4.1, we see no effect of highway provision alone on GVA per capita, GVA, or population. However, the estimated impact of electricity provision alone differs from the findings in section 4.1. Instead of finding no effect, we now see a negative and statistically significant effect of electrification on GVA and a positive and statistically significant effect on population. This translates into a negative and statistically significant effect of electricity provision on GVA per capita. We are not concerned about this difference since the placebo tests had failed for electricity provision in our main identification strategy. The new results imply that GVA is smaller in electrified places that lack highway access. This is consistent with the literature that documents how workers and activities leave unproductive peripheral areas when infrastructure is improved (Faber, 2014).

[15] See Appendix Table A11 for the first-stage estimation results.

Table 7: IV estimates of infrastructure provision (second-stage)

	Dependent variable:		
	GVA per capita (log)	GVA (log)	Population (log)
	(1)	(2)	(3)
Electricity Access	-2.341^{***}	-1.366^{***}	0.975^{***}
	(0.386)	(0.462)	(0.214)
Highway Access	-0.554	-0.406	0.148
	(0.496)	(0.576)	(0.276)
Electricity Access X Highway Access	3.372^{***}	2.898^{***}	-0.475
	(0.951)	(1.110)	(0.532)
Wald Test χ^2	3844.2^{***}	2577.3^{***}	2501.3^{***}
Observations	1,536	1,536	1,536

Note: Robust standard errors clustered at the state level in parentheses. $^{*}p<0.1$; $^{**}p<0.05$; $^{***}p<0.01$.

However, these negative effects associated with the provision of electricity alone are fully compensated when both types of infrastructure are present, confirming our main findings regarding infrastructure complementarity in section 4.1. The overall effect of joint infrastructure provision (given by the sum of the three coefficients on electricity access, highway access, and their interaction) is a twofold increase in GVA and an increase of GVA per capita by 61 percent.

5 Conclusions

This paper is among the few to investigate the effects of different types of infrastructure provision on local economic development and the first to investigate the issue over a long period (3 decades). Focusing on several decades is necessary not only because investments are staggered in time, but also because effects may take time to materialize. In our case, the study period allows us to capture the bulk of infrastructure investment in Brazil, which started in the 1970s, and to assess how these large investment programs affected targeted municipalities.

In contrast with previous results from the literature, we do not find strong evidence of single-type infrastructure provision on output and apparent labor productivity (which we measure with municipal GVA and GVA per capita). We do find, however, evidence of an impact of the joint provision of electricity and highway infrastructure, which we estimate to increase GVA by 38 to 100 percent and GVA per capita by 29 to 61 percent, depending on the econometric approach. Importantly, the impacts differ across decades, being highly significant in some and not significant in others. This arguably reconciles findings from the literature where short-term and long-term effects can significantly vary (Lee, Miguel, and Wolfram, 2020).

In addition, we find a positive effect of infrastructure provision (both highways and electricity separately) on TFP, though our data restricts the analysis of TFP impacts to a single decade.

Finally, we find evidence of infrastructure investment playing a role in facilitating structural transformation. The separate provision of highways and electricity increases the local GVA share of the industry by about 5 percent. These effects are found to persist over time.

These results have an important policy implication: the government should consider infrastructure provision as a package. If the objective is to promote local economic development, then failing to improve transport access along with electrification may not be effective.

References

Abbasi, Mansoureh et al. (2022). *Roads, Electricity, and Jobs: Evidence of Infrastructure Complementarity in Sub-Saharan Africa*. Policy Research Working Paper 9976. The World Bank.

Ali, Rubaba et al. (2015). *Highways to Success or Byways to Waste: Estimating the Economic Benefits of Roads in Africa*. The World Bank, Washington D.C.

Ayres, Joao, Marcio Garcia, Diogo A Guillén, and Patrick J Kehoe (2019). *The Monetary and Fiscal History of Brazil, 1960-2016*. Working Paper 25421. National Bureau of Economic Research.

Balestra, Pietro and Jayalakshmi Varadharajan-Krishnakumar (1987). "Full Information Estimations of a System of Simultaneous Equations with Error Component Structure". *Econometric Theory* 3.2, pp. 223–246.

Bensch, Gunther, Jörg Peters, and Colin Vance (2021). *Development Effects of Electrification in Brazil–A Comment on Lipscomb et al.(2013)*. USAEE Working Paper.

Berg, Claudia N, Uwe Deichmann, Yishen Liu, and Harris Selod (2017). "Transport Policies and Development". *The Journal of Development Studies* 53.4, pp. 465–480.

Bird, Julia and Stéphane Straub (2020). "The Brasilia Experiment: the Heterogeneous Impact of Road Access on Spatial Development in Brazil". *World Development* 127, p. 104739.

Bun, Maurice JG and Teresa D Harrison (2019). "OLS and IV Estimation of Regression Models Including Endogenous Interaction Terms". *Econometric Reviews* 38.7, pp. 814–827.

Callaway, Brantly and Pedro HC Sant'Anna (2021). "Difference-in-Differences with Multiple Time Periods". *Journal of Econometrics* 225.2, pp. 200–230.

Correa, Vivian Helena Capacle and Pedro Ramos (2010). "A Precariedade do Transporte Rodoviário Brasileiro para o Escoamento da Produção de Soja do Centro-Oeste: situação e perspectivas". *Brazilian Journal of Rural Economy and Sociology (Revista de Economia e Sociologia Rural-RESR)* 48.2, pp. 1–26.

Croissant, Yves and Giovanni Millo (2008). "Panel Data Econometrics in R: the plm Package". *Journal of Statistical Software* 27.2.

De Chaisemartin, Clément and Xavier D'Haultfoeuille (2022a). *Difference-in-differences Estimators of Intertemporal Treatment Effects*. Working Paper 29873. National Bureau of Economic Research.

— (2022b). *Two-way Fixed Effects and Differences-in-Differences Estimators with Several Treatments*. Working Paper 30564. National Bureau of Economic Research.

De Chaisemartin, Clément and Xavier d'Haultfoeuille (2020). "Two-way Fixed Effects Estimators with Heterogeneous Treatment Effects". *American Economic Review* 110, pp. 2964–96.

Donaldson, Dave (2018). "Railroads of the Raj: Estimating the impact of transportation infrastructure". *American Economic Review* 108.4-5, pp. 899–934.

Duranton, Gilles, Peter M Morrow, and Matthew A Turner (2014). "Roads and Trade: Evidence from the US". *Review of Economic Studies* 81.2, pp. 681–724.

Faber, Benjamin (2014). "Trade Integration, Market Size, and Industrialization: Evidence from China's National Trunk Highway System". *Review of Economic Studies* 81.3, pp. 1046–1070.

Fernald, John G (1999). “Roads to Prosperity? Assessing the Link between Public Capital and Productivity”. *American Economic Review* 89.3, pp. 619–638.

Freedman, Seth M et al. (2023). *Designing Difference in Difference Studies With Staggered Treatment Adoption: Key Concepts and Practical Guidelines*. Working Paper 31842. National Bureau of Economic Research.

Gaggl, Paul, Rowena Gray, Ioana Marinescu, and Miguel Morin (2021). “Does Electricity Drive Structural Transformation? Evidence from the United States”. *Labour Economics* 68, p. 101944.

Jaimovich, Esteban (2019). “Roadways, Input Sourcing, and Patterns of Specialization”. *European Economic Review* 120, p. 103319.

Jedwab, Remi and Adam Storeygard (2021). “The Average and Heterogeneous Effects of Transportation Investments: Evidence from sub-Saharan Africa 1960–2010”. *Journal of the European Economic Association* jvab027.

Kahn-Lang, Ariella and Kevin Lang (2020). “The Promise and Pitfalls of Differences-in-Differences: Reflections on 16 and Pregnant and Other Applications”. *Journal of Business & Economic Statistics* 38.3, pp. 613–620.

Kassem, Dana (2021). *Does Electrification Cause Industrial Development.* Working Paper.

Klein Goldewijk, Kees, Arthur Beusen, Gerard Van Drecht, and Martine De Vos (2011). “The HYDE 3.1 Spatially Explicit Database of Human-Induced Global Land-Use Change over the Past 12,000 Years”. *Global Ecology and Biogeography* 20.1, pp. 73–86.

Lee, Kenneth, Edward Miguel, and Catherine Wolfram (2020). “Does Household Electrification Supercharge Economic Development?” *Journal of Economic Perspectives* 34.1, pp. 122–44.

Leturcq, Guillaume (2018). *Dams in Brazil: Social and Demographical Impacts*. Springer.

Lewis, Joshua and Edson Severnini (2020). “Short-and Long-Run Impacts of Rural Electrification: Evidence from the Historical Rollout of the US Power Grid”. *Journal of Development Economics* 143, p. 102412.

Lipscomb, Molly, A Mushfiq Mobarak, and Tania Barham (2013). “Development Effects of Electrification: Evidence from the Topographic Placement of Hydropower Plants in Brazil”. *American Economic Journal: Applied Economics* 5.2, pp. 200–231.

Moneke, Niclas (2020). “Infrastructure and Structural Transformation: Evidence from Ethiopia”. PhD thesis. The London School of Economics and Political Science (LSE).

Morten, Melanie and Jaqueline Oliveira (2023). "The Effects of Roads on Trade and Migration: Evidence from a Planned Capital City". *American Economic Journal: Applied Economics* forthcoming.

Ōbhara, Yoshinori (1974). "Brazilian Economic Development Since 1956: A Study on Policies Reflecting the Stages of Growth". *The Developing Economies* 12.2, pp. 133–154.

Pereira, Luiz AG and Simone Narciso Lessa (2011). "O Processo de Planejamento e Desenvolvimento do Transporte Rodoviário no Brasil". *Caminhos de Geografia* 12.40, pp. 26–46.

Perez-Sebastian, Fidel and Jevgenijs Steinbuks (2017). *Public Infrastructure and Structural Transformation*. Policy Research Working Paper 8285. World Bank.

Perez-Sebastian, Fidel, Jevgenijs Steinbuks, José Féres, and Ian Trotter (2020). *Electricity Access and Structural Transformation: Evidence from Brazil's Electrification*. Policy Research Working Paper 9182. World Bank.

Pérez-Sebastián, Fidel, Rafael Serrano Quintero, and Jevgenijs Steinbuks (2023). *Spatial Misallocation of Complementary Infrastructure Investment: Evidence from Brazil*. Policy Research Working Paper 10650. The World Bank.

Raiser, Martin et al. (2017). *Back to Planning: How to Close Brazil's Infrastructure Gap in Times of Austerity*. Technical Report 117392-BR. World Bank.

Sandoval, Daylyne Maerla Gomes Lima (2014). "Análise das Implicações Logísticas, Conábeis e Financeiras da Escolha do Serviço de Transporte". PhD thesis. Universidade de Brasília, Faculdade de Tecnologia.

Stock, James H and Jonathan H Wright (2000). "GMM with Weak Identification". *Econometrica* 68.5, pp. 1055–1096.

Szerman, Dimitri, Juliano Assunçao, Molly Lipscomb, and Ahmed Mushfiq Mobarak (2022). *Agricultural Productivity and Deforestation: Evidence from Brazil*. Working Paper.

Tobler, Waldo (1993). *Three Presentations on Geographical Analysis and Modeling*. Technical Report.

Vagliasindi, Maria and Nisan Gorgulu (2021). *What Have We Learned about the Effectiveness of Infrastructure Investment as a Fiscal Stimulus? A Literature Review*. World Bank Policy Research Paper 9796. The World Bank.

Van Beveren, Ilke (2012). "Total Factor Productivity Estimation: A Practical Review". *Journal of Economic Surveys* 26.1, pp. 98–128.

Vanden Eynde, Oliver and Liam Wren-Lewis (2021). *Complementarities in Infrastructure: Evidence from Rural India*. CEPR Discussion Paper 16139.

Verdin, Kristine L et al. (2007). *Development of a Global Slope Dataset for Estimation of Landslide Occurrence Resulting from Earthquakes*. Technical Report.

Wooldridge, Jeffrey M (2010). *Econometric Analysis of Cross Section and Panel Data*. MIT press.

Appendix

A1 Estimation of Total Factor Productivity

We assume that municipal economies follow a Cobb-Douglas production of the form

$$Y_{it} = A_{it} K_{it}^{\alpha} L_{it}^{\beta} \tag{A1}$$

where Y_{it}, A_{it}, K_{it} and L_{it} are, respectively, the GVA, TFP, capital stock and total labor in municipality i at time t, α and β are the Cobb-Douglas elasticities. We estimate the production function by log-regressing municipal-level GVA on local capital and labor. We estimate both a pooled model, which assumes common production technology, and a fixed-effects model (our preferred specification), allowing for heterogeneous production technologies across municipalities (see Van Beveren, 2012). Tables A9 and A10 show the estimation results. Recovering the estimates for α and β, we then calculate TFP as $Y_{it}/K_{it}^{\alpha}L_{it}^{\beta}$. As a robustness check, we also estimate the production function parameters imposing homogeneity of degree 1 (i.e., assuming a constant return to scale), leading to similar effects of infrastructure access on TFP as in Table 6.

A2 Estimation Using Instrumental Variables

Empirical Specification

The first-stage regressions that we estimate are as follows:

$$\mathbf{X}_{it} = \alpha_i + \mathbf{B}_{it}\mathbf{Z}_{it} + \gamma_t + \varepsilon_{it} \tag{A2}$$

where i is the municipality index, t is the time index, $\mathbf{X}_{it}$ is the vector of variables of interest, i.e., the access to road indicator, the access to electricity indicator and their interaction term, $\mathbf{Z}_{it}$ is the vector of instrumental variables, $\mathbf{B}_{it}$ is a matrix of coefficients to be estimated, α_i and γ_t are vectors of municipality and year fixed effects, and ε_{it} is a vector of i.i.d. error terms.

Note that the functional form of the interaction model necessitates additional instrumental variables to satisfy the order condition for identification (Bun and Harrison, 2019; Wooldridge, 2010). That is, vector $\mathbf{Z}_{it}$ should include instruments for electricity access, road access, and the interaction of electricity access and road access. We instrument for the interaction term by the interaction of the instruments for each term separately. Doing so satisfies the rank identification condition as long as instrumental variables for electricity and road access terms are not perfectly colinear. However, owing to the nonlinear nature of the interaction term, weak identification problems may arise (Stock and Wright, 2000). We test for the possibility of weak identification using the Wald test for panel data (Wooldridge, 2010).

The second-stage regression that we estimate is as follows:

$$Y_{it} = \delta_i + \widehat{\mathbf{X_{it}}}'\lambda_{it} + \mu_t + \eta_{it} \tag{A3}$$

where Y_{it} is an outcome variable (such as municipality gross value added or total local employment), $\widehat{\mathbf{X_{it}}}$ is the vector of estimated variables of interest in the first stage, λ_{it} are our coefficients of interest, δ_i and μ_t are municipality and year fixed effects, and η_{it} is the error term.

The model is estimated using the instrumental variable transformation method of Balestra and Varadharajan-Krishnakumar (1987) with the *plm* package in R software (see Croissant and Millo, 2008).

Construction of the Instruments

As all the time-invariant exogenous spatial variation in infrastructure placement will be accounted for by municipality fixed effect, we must construct time-varying instruments for both electricity and road placements, as described below.

We use the access to electricity instrumental variable developed by Lipscomb, Mobarak, and Barham (2013) and further refined in Szerman et al. (2022).[16] The instrument takes advantage of the fact that hydropower accounts for the majority of electricity generation in Brazil, accounting for 88 to 92 percent of electricity generation in the country between 1980 and 2000, according to the US International Energy Statistics database.[17] The power potential of a hydropower plant depends on local topological and hydrological characteristics, such as e.g., slope, elevation, and the amount of water available. These characteristics are plausibly exogenous to the unobserved local conditions that may be correlated with economic growth. The construction of the instrument involves three key steps. The first step calculates the total spending budget for hydropower

[16] The original instrument of Lipscomb, Mobarak, and Barham (2013) was criticized for inconsistent demarcation of the Amazon region throughout the different steps of their instrument construction, see Bensch, Peters, and Vance (2021).

[17] See `https://www.eia.gov/international/overview/world`.

plants based on the actual construction of major dams across the entire country each decade. The second step calculates a cost factor that sorts potential locations by their geographic suitability. The final step applies the suitability predictions to the areas where hydropower plants were actually built. Using the predictions of the estimated construction site for each hydropower plant, a hypothetical transmission network that depends solely on topological and hydrological characteristics is constructed and used as an instrumental variable. Detailed description of constructing the instrument can be found in Lipscomb, Mobarak, and Barham (2013) and Szerman et al. (2022).

We construct the "natural path" instrumental variable for highways following Ali et al. (2015) based on the least amount of time between the 25 existing state capitals in the base period[18] and Brasília. It incorporates local terrain using slope derived from a Digital Elevation Model (NASA's Shuttle Radar Topography Mission) from Verdin et al. (2007) and a historical land cover dataset (circa 1900) from HYDE (Klein Goldewijk et al., 2011). We use the same walking velocity from Tobler (1993):

$$W = 6 * exp^{(-3.5|S+0.05|)} \tag{A4}$$

where W is the hiking velocity (kph) and S is the slope or gradient. We modify the walking speed by land cover classes from HYDE using the weights in Ali et al. (2015). We use the cost connectivity algorithm in ESRI ArcGIS to solve the least cost path.

We construct the natural path for each time period by taking the result of the intersection of the endpoints of a road segment for each radial corridor (in a time period) with the nearest point on the natural path line (see Figure A1).[19] That is, each time period, we only consider the least cost segments closest to existing roads in a given time period. The portion of the least cost path increases with time, along with the construction of the existing roads. This makes it possible to use it in a panel regression.

We define the instrumental variable for road access as the binary variable indicating the presence of a natural path road within 50 kilometers of the geographic center of a locality. We also consider other buffer sizes, leading to comparable results.

[18]Even though the state of Tocantins was only established in 1988, we conservatively treat it as an urban node motivating highway construction.

[19]We have a total of 8 radial corridors.

Table A11 describes the results of the first-stage regression (equation A2).

Appendix Tables and Figures

Table A1: Variable Means (384 selected municipalities)

	1970	1980	1996	2000
Population	19.22	24.69	34.09	37.34
Gross Value Added (GVA)	39.40	105.07	149.84	172.13
GVA per capita	1.49	3.36	3.14	3.88
GVA, Industry	9.01	34.13	39.17	43.19
Capital-Labor Ratio	11,410	43,409	N/A	N/A
Capital-Labor Ratio, Industry	31,773	73,795	N/A	N/A

Note: Population and labor are in million people; GVA and capital are in million R$ (constant 2010 prices).

Table A2: DID_{M} estimates of infrastructure provision on Gross Value Added per capita in 1970-1980 using a sample with available capital stock

	Dependent variable: Gross Value Added per Capita (log)	
	N2E	N2H
coef.	-0.030	0.288**
s.e.	(0.064)	(0.144)
Obs./Switchers	87 / 25	89 / 19

Notes: Bootstrapped standard errors (200 replications) in parentheses. $^{*}p<0.1$, $^{**}p<0.05$, $^{***}p<0.01$. *All*

Table A3: Doubly robust difference-in-differences estimator of infrastructure provision (Callaway and Sant'Anna, 2021)

		Period: 1970-2000		
		N2E	N2H	H2B
log(GVA/POP)	coef.	0.037	0.130	0.314^{**}
	s.e.	(0.050)	(0.094)	(0.133)
	Obs./Switchers	672 / 168	492 / 123	413 / 89
log(GVA)	coef.	0.067	0.047	0.457^{***}
	s.e.	(0.054)	(0.112)	(0.165)
	Obs./Switchers	672 / 168	492 / 123	413 / 89
log(POP)	coef.	0.030	-0.084	0.143
	s.e.	(0.045)	(0.057)	(0.123)
	Obs./Switchers	672 / 168	492 / 123	413 / 89

Notes: Bootstrapped standard errors (1000 replications) in parentheses. **p<0.1,* ***p<0.05,* ****p<0.01.*

Table A5: DID_M estimates of infrastructure provision on Gross Value Added per capita keeping controls within 200 km of treated municipalities

		Dependent variable: Gross Value Added per Capita (log)		
		N2E	N2H	H2B
1970-2000 (E)	coef.	0.023	0.043	0.228^{**}
	s.e.	(0.044)	(0.083)	(0.097)
	Obs./Switchers	450 / 102	401 / 55	310 / 36
1970-1980	coef.	-0.035	0.289	0.087
	s.e.	(0.062)	(0.175)	(0.184)
	Obs./Switchers	188 / 35	155 / 21	101 / 4
1980-1996	coef.	0.130^{**}	0.013	0.241^{*}
	s.e.	(0.055)	(0.114)	(0.133)
	Obs./Switchers	153 / 44	134 / 22	116 / 23
1996-2000	coef.	-0.094	-0.332^{***}	0.259^{*}
	s.e.	(0.103)	(0.075)	(0.149)
	Obs./Switchers	109 / 23	112 / 12	93 / 9
1970-2000 (D)	coef.	0.047	0.218^{**}	0.219
	s.e.	(0.059)	(0.100)	(0.169)
	Obs./Switchers	274 / 79	255 / 43	189 / 27
Placebo	coef.	-0.112^{*}	0.161^{**}	0.079
	s.e.	(0.065)	(0.073)	(0.085)
	Obs./Switchers	262	246	190

Notes: Bootstrapped standard errors (200 replications) in parentheses. **p<0.1,* ***p<0.05,* ****p<0.01. (E): estimated effect of the treatment at the time period of the infrastructure provision. (D): estimated effect one period after the infrastructure provision.*

Table A4: DID_M estimates of infrastructure provision
on Gross Value Added per capita
using 80% electrification rate proxy for electricity access

		Dependent variable: Gross Value Added per Capita (log)		
		N2E	N2H	H2B
1970-2000 (E)	coef.	0.016	0.073	0.220**
	s.e.	(0.050)	(0.091)	(0.092)
	Obs./Switchers	376 / 101	286 / 47	250 / 45
1970-1980	coef.	0.017	0.404**	0.131
	s.e.	(0.071)	(0.179)	(0.111)
	Obs./Switchers	160 / 31	113 / 17	82 / 4
1980-1996	coef.	0.069	0.014	0.274*
	s.e.	(0.089)	(0.141)	(0.149)
	Obs./Switchers	129 / 42	96 / 19	97 / 26
1996-2000	coef.	-0.063	-0.336***	0.150
	s.e.	(0.101)	(0.089)	(0.108)
	Obs./Switchers	87 / 28	77 / 11	71 / 15
1970-2000 (D)	coef.	-0.053	0.190*	0.292*
	s.e.	(0.084)	(0.099)	(0.166)
	Obs./Switchers	219 / 73	179 / 36	144 / 30
Placebo	coef.	-0.168**	0.155	-0.008
	s.e.	(0.078)	(0.082)	(0.092)
	Obs./Switchers	216	173	149

*Notes: Bootstrapped standard errors (200 replications) in parentheses. *p<0.1, **p<0.05, ***p<0.01. (E): estimated effect of the treatment at the time period of the infrastructure provision. (D): estimated effect one period after the infrastructure provision.*

Table A6: DID_M estimates of infrastructure provision
on Gross Value Added per capita
excluding controls within 50 km of treated municipalities

		Dependent variable: Gross Value Added per Capita (log)		
		N2E	N2H	H2B
1970-2000 (E)	coef.	0.037	0.023	0.230**
	s.e.	(0.044)	(0.086)	(0.102)
	Obs./Switchers	381 / 102	335 / 55	258 / 36
1970-1980	coef.	-0.033	0.283*	0.074
	s.e.	(0.070)	(0.168)	(0.171)
	Obs./Switchers	165 / 35	133 / 21	85 / 4
1980-1996	coef.	0.144*	-0.036	0.234*
	s.e.	(0.077)	(0.115)	(0.132)
	Obs./Switchers	130 / 44	112 / 22	98 / 23
1996-2000	coef.	-0.060	-0.325***	0.289*
	s.e.	(0.101)	(0.077)	(0.148)
	Obs./Switchers	86 / 23	90 / 12	75 / 9
1970-2000 (D)	coef.	0.079	0.172*	0.237
	s.e.	(0.060)	(0.098)	(0.185)
	Obs./Switchers	228 / 79	211 / 43	155 / 27
Placebo	coef.	-0.112	0.143	0.070
	s.e.	(0.069)	(0.078)	(0.099)
	Obs./Switchers	216	202	156

Notes: Bootstrapped standard errors (200 replications) in parentheses. *$^{*}p<0.1$, $^{**}p<0.05$, $^{***}p<0.01$. (E): estimated effect of the treatment at the time period of the infrastructure provision. (D): estimated effect one period after the infrastructure provision.*

Table A7: DID_M estimates of infrastructure provision on Gross Value Added per capita using treatment in 1990 and outcome copied from 1980 onto 1990

		Dependent variable: Gross Value Added per Capita (log)		
		N2E	N2H	H2B
1970-2000 (E)	coef.	0.016	0.058	0.209*
	s.e.	(0.043)	(0.070)	(0.116)
	Obs./Switchers	407 / 102	338 / 55	286 / 36
1970-1980	coef.	-0.030	0.273	0.081
	s.e.	(0.065)	(0.175)	(0.169)
	Obs./Switchers	168 / 35	134 / 21	89 / 4
1980-1990	coef.	0.000	0.000	0.000
	s.e.	(0.000)	(0.000)	(0.000)
	Obs./Switchers	133 / 27	113 / 22	104 / 11
1990-2000	coef.	0.068	-0.211*	0.343*
	s.e.	(0.090)	(0.118)	(0.175)
	Obs./Switchers	106 / 40	91 / 12	93 / 21
1970-2000 (D)	coef.	0.023	0.131	0.160
	s.e.	(0.055)	(0.118)	(0.192)
	Obs./Switchers	234 / 62	213 / 43	162 / 15
Placebo	coef.	-0.092***	0.097	0.028
	s.e.	(0.032)	(0.071)	(0.039)
	Obs./Switchers	239	204	178

Notes: Bootstrapped standard errors (200 replications) in parentheses. *$p<0.1$, **$p<0.05$, ***$p<0.01$. *(E): estimated effect of the treatment at the time period of the infrastructure provision. (D): estimated effect one period after the infrastructure provision.*

Table A8: DID_M estimates of infrastructure provision
on Gross Value Added per capita
using treatment in 1990 and outcome copied from 1996 onto 1990

	Dependent variable: Gross Value Added per Capita (log)			
		N2E	N2H	H2B
1970-2000 (E)	coef.	0.029	0.021	0.174**
	s.e.	(0.038)	(0.082)	(0.084)
	Obs./Switchers	407 / 102	338 / 55	286 / 36
1970-1980	coef.	-0.030	0.273*	0.081
	s.e.	(0.068)	(0.164)	(0.172)
	Obs./Switchers	168 / 35	134 / 21	89 / 4
1980-1990	coef.	0.139**	-0.035	0.206
	s.e.	(0.070)	(0.104)	(0.195)
	Obs./Switchers	133 / 27	113 / 22	104 / 11
1990-2000	coef.	0.006	-0.319***	0.175
	s.e.	(0.085)	(0.085)	(0.108)
	Obs./Switchers	106 / 40	91 / 12	93 / 21
1970-2000 (D)	coef.	0.032	0.170*	0.140
	s.e.	(0.057)	(0.102)	(0.194)
	Obs./Switchers	234 / 62	213 / 43	162 / 15
Placebo	coef.	-0.055	0.135*	0.142
	s.e.	(0.059)	(0.082)	(0.102)
	Obs./Switchers	239	204	178

Notes: Bootstrapped standard errors (200 replications) in parentheses. *$^{*}p<0.1$, $^{**}p<0.05$, $^{***}p<0.01$. (E): estimated effect of the treatment at the time period of the infrastructure provision. (D): estimated effect one period after the infrastructure provision.*

Table A9: Production function estimates

	Dependent variable:	
	Gross Value Added (log+1)	
	Pooled	FE
Capital (log)	0.70^{***}	0.23^{***}
	(0.01)	(0.03)
Labor (log)	0.28^{***}	0.34^{***}
	(0.02)	(0.03)
Constant	-2.70^{***}	
	(0.13)	
Municipality FE	No	Yes
Time FE	No	Yes
F Statistic	$3{,}777.56^{***}$	114.35^{***}
Observations	2,462	2,462

Note: Robust standard errors in parentheses.
$^{*}p<0.1$, $^{**}p<0.05$, $^{***}p<0.01$

Table A10: Production function estimates for the industry sector

	Dependent variable:	
	Gross Value Added (log+1)	
	Pooled	FE
Capital (log)	0.47***	0.27***
	(0.02)	(0.02)
Labor (log)	0.26***	0.18***
	(0.02)	(0.02)
Constant	$-$0.64***	
	(0.05)	
Municipality FE	No	Yes
Time FE	No	Yes
F Statistic	8,239.91***	351.93***
Observations	2,462	2,462

Note: Robust standard errors in parentheses.
**p<0.1,* ***p<0.05,* ****p<0.01.*

Table A11: IV estimates of infrastructure provision (first-stage)

	Dependent variable:		
	Electricity Access	Highway Access	Electricity X Highway Access
	(1)	(2)	(3)
Electricity Access IV	-0.323^{***}	0.474^{***}	-0.084^{***}
	(0.026)	(0.105)	(0.009)
Roads Access IV	0.052	0.830^{***}	0.247^{*}
	(0.129)	(0.065)	(0.141)
Electricity Access IV X Roads Access IV	0.058	-0.615^{***}	0.061
	(0.161)	(0.091)	(0.178)
Municipality FE	Yes	Yes	Yes
Time FE	Yes	Yes	Yes
Wald test χ^2	156.8^{***}	193.9^{***}	100.6^{***}
Observations	1,536	1,536	1,536

Note: Robust standard errors in parentheses. $^{*}p<0.1$, $^{**}p<0.05$, $^{***}p<0.01$.

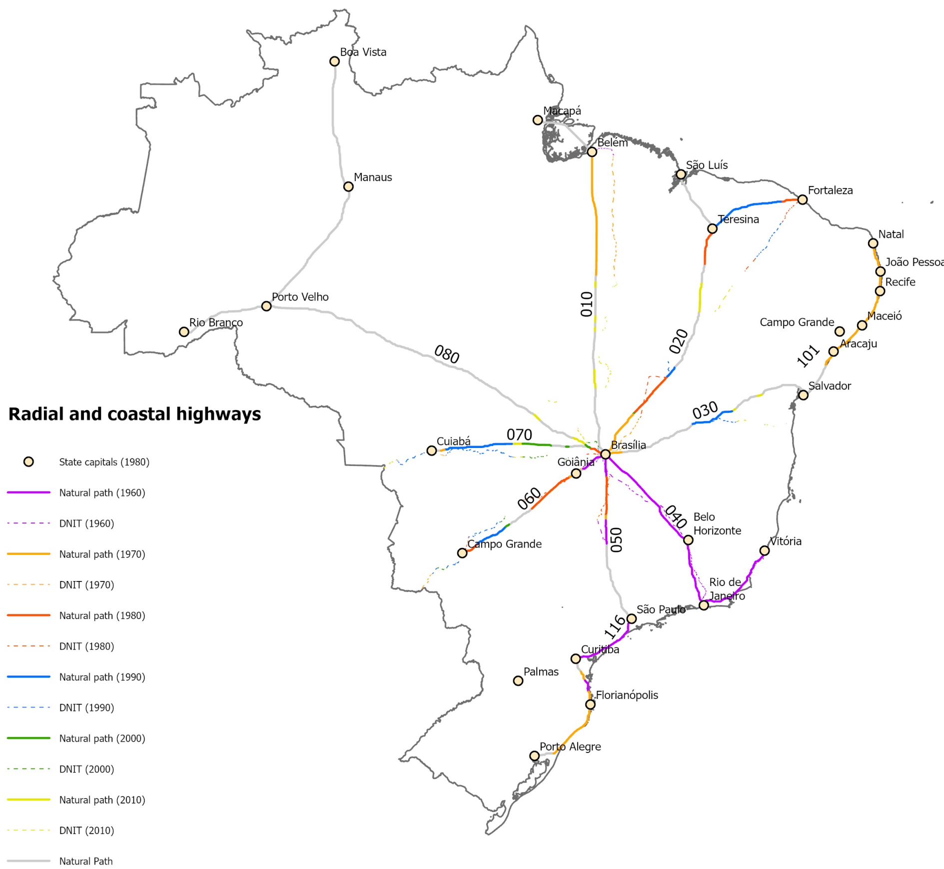
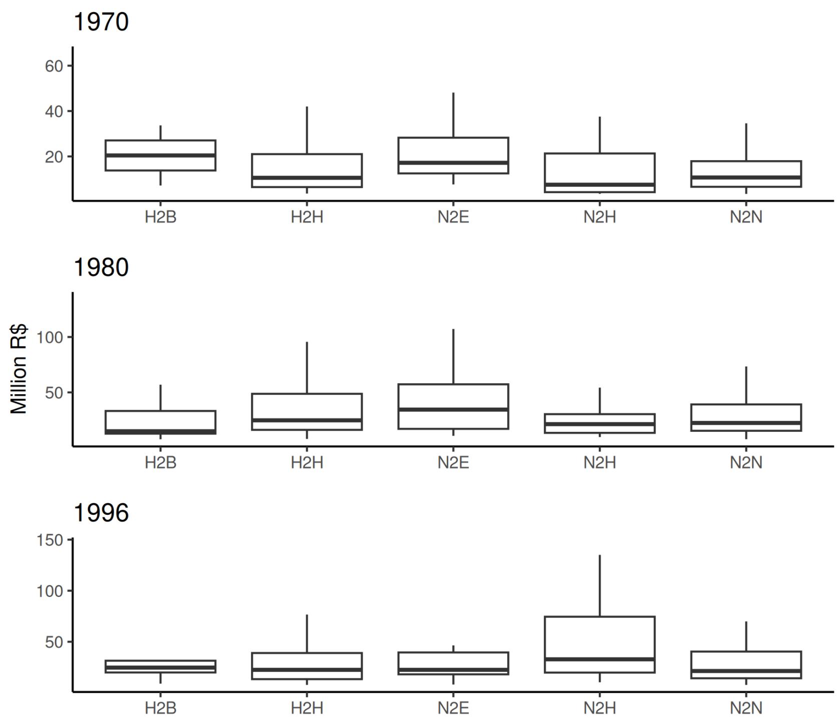


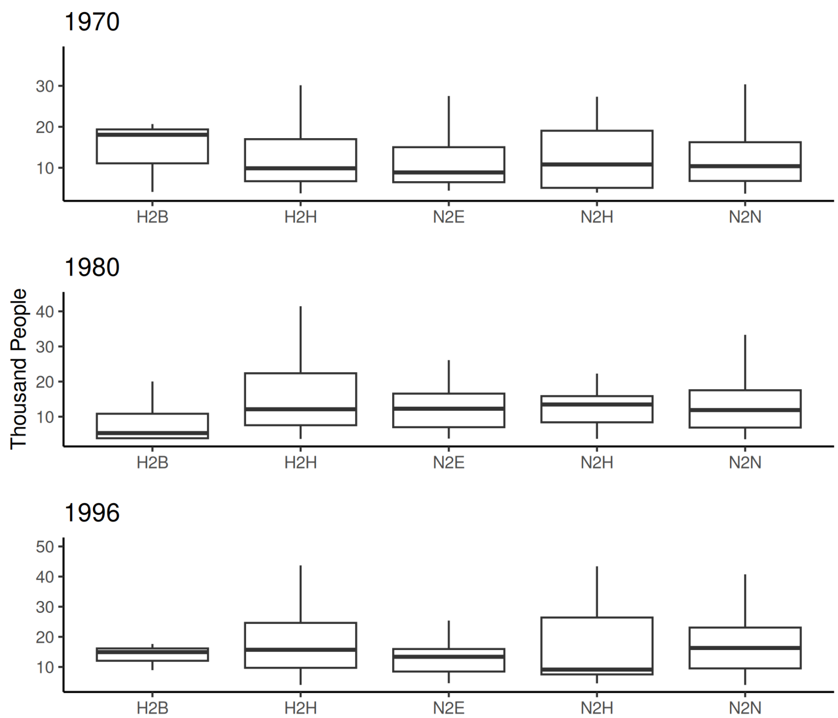
Figure A1: This map shows the time-variant natural path.

Figure A2: Box Plots of Municipal GVA by Investment Sequence



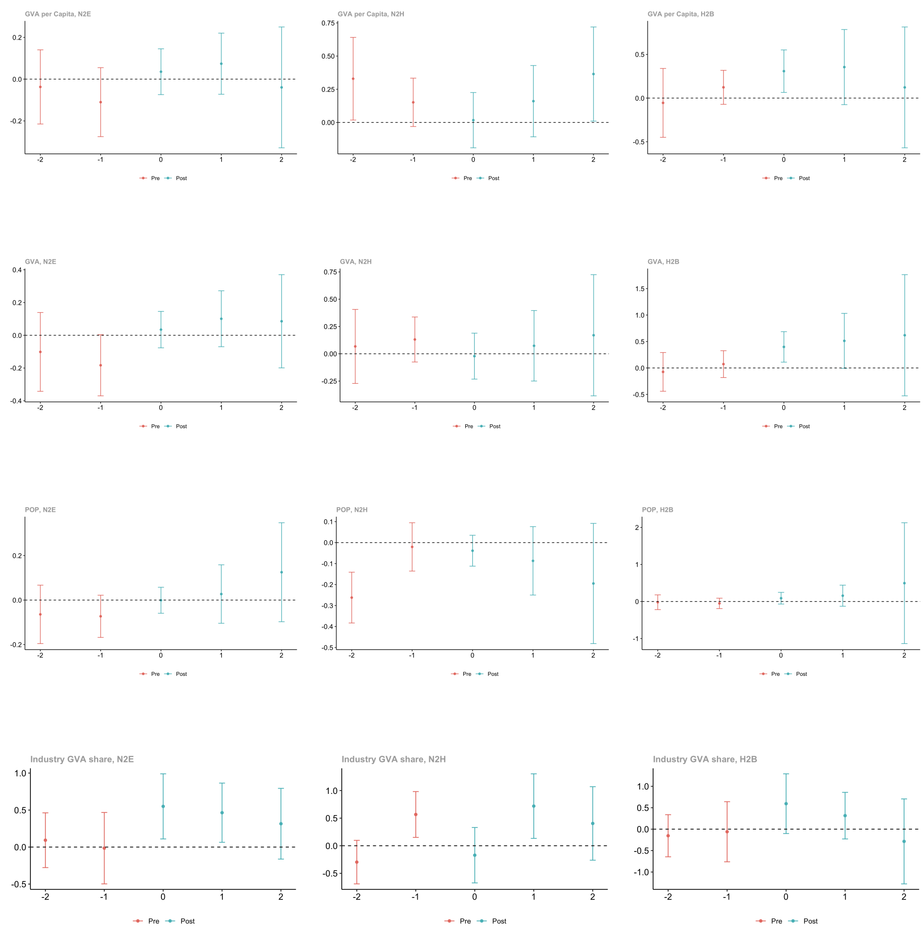
Note. The vertical axis measures gross value added or population at the beginning of the period. Box plots group municipalities by initial status and investment occurring during the period. H2B: highway access followed by electrification; H2H: highway access not followed by any investment; N2E: no access to infrastructure followed by electrification; N2H: no access to infrastructure followed by highway provision; N2N: no access to infrastructure throughout the period. Treatment groups are H2B, N2E and N2H. Control groups are H2H and N2N.

Figure A3: Box Plots of Municipal Population by Investment Sequence



Note. The vertical axis measures gross value added or population at the beginning of the period. Box plots group municipalities by initial status and investment occurring during the period. H2B: highway access followed by electrification; H2H: highway access not followed by any investment; N2E: no access to infrastructure followed by electrification; N2H: no access to infrastructure followed by highway provision; N2N: no access to infrastructure throughout the period. Treatment groups are H2B, N2E and N2H. Control groups are H2H and N2N.

Figure A4: Event study graphs



Note. The event study graphs are based on the estimator of Callaway and Sant'Anna (2021). H2B: highway access followed by electrification; N2E: no access to infrastructure followed by electrification; N2H: no access to infrastructure followed by highway provision.