Research article

Transportation infrastructure and University-Industry collaborations: regional-level evidence from Brazil ♦

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Abstract

It is widely known that universities have played a major role in fostering innovation at the firm level. A large body of literature has identified that knowledge spillovers are bound in space. Thus, an adequate transportation infrastructure may amplify potential knowledge spillovers by connecting places and promoting learning and knowledge diffusion. In this work, we examine the impact of an increase in roads provisioning on U-I linkages in Brazil using instrumental variables econometric models to account for possible endogeneity issues. Our results suggest that highways positively impact U-I interactions. These results remain stable under several specifications. We show that the effects of roads on local U-I collaborations are greater for small-sized firms and research groups, higher-quality research groups and leading micro-regions. Also, we find a negatively signed spatial effect of roads on U-I linkages, thus suggesting that the road network may be spatially concentrating knowledge flows in Brazil.

Keywords

Transportation infrastructure, U-I collaborations, Regional development, Brazil.

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Infraestrutura de transportes e colaborações Universidade-Empresa: evidência ao nível regional para o Brasil

Resumo

É amplamente conhecido que as universidades têm desempenhado um papel importante na promoção da inovação em nível empresarial. Uma grande parte da literatura identificou que as repercussões do conhecimento são limitadas no espaço. Assim, uma infraestrutura de transporte adequada pode ampliar as possíveis repercussões do conhecimento ao conectar locais e promover o aprendizado e a difusão do conhecimento. Neste trabalho, examinamos o impacto de um aumento no fornecimento de estradas sobre as ligações U-I no Brasil usando modelos econométricos de variáveis instrumentais para levar em conta possíveis questões de endogeneidade. Nossos resultados sugerem que as rodovias afetam positivamente as interações U-I. Esses resultados permanecem estáveis em várias especificações. Mostramos que os efeitos das rodovias sobre as colaborações locais de U-I são maiores para empresas e grupos de pesquisa de pequeno porte, grupos de pesquisa de maior qualidade e microrregiões líderes. Além disso, encontramos um efeito espacial negativo das rodovias sobre as ligações U-I, sugerindo, assim, que a rede rodoviária pode estar concentrando espacialmente os fluxos de conhecimento no Brasil.

Palavras-chave

Infraestrutura de transporte, Colaborações U-I, Desenvolvimento regional, Brasil.

Classificação JEL

O18; H54; O31; R40.

1. Introduction

Universities have been playing a central role in fostering technological progress in firms (Garcia et al., 2015; Xing et al., 2024). However, it is also known that knowledge spillover decreases with distance, thus imposing a limit to collaborative efforts between universities and firms (Bottazzi and Peri, 2003; Feldman and Audretsch, 1999; Jaffe et al., 1993). Aspects like face-to-face contact, the transit of researchers from universities to companies and the possibility of sharing labs and equipment favor the knowledge spillovers among closer locations. That is why spatial agglomeration generally stimulates the maintenance of frequent contacts between academic researchers and firms' research and development staff (Garcia et al., 2013). Consequently, innovative activity tends to be more concentrated than industrial activity (Carlino and Kerr, 2015).

Then efforts for shortening distance barriers among universities and firms enabling the transit of academic and industry researchers are expected to improve spatial diffusion of knowledge. This implies that pervasive knowledge building requires not only more investments in higher education and in academic R&D, but also more investments in the provisioning of adequate means to connect scientific and technological assets in different locations. In this way, the development of road network and efficient transportation systems in order to connect places can be taken as strategy for boosting learning and knowledge diffusion over space (Feldman and Kogler, 2010).

In Brazil, 24,646 out of 37,640 research groups in 2016 (around 68.4%) were concentrated in the South and Southeast regions, which are the regions hosting the main productive and innovative hubs in the country[1]. As a consequence, the U-I collaborations are highly concentrated in very few localities, thus exposing the marked spatial discontinuity of the Brazilian innovation system (Figure 1) (Gonçalves and Almeida, 2009; Santos, 2017).

The geographical distribution of the country's highway network also follows a similar pattern (Figure 2). Although the Brazilian transportation network comprises multiple modes, road infrastructure remains the predominant means of mobility for both goods and people. While the study primarily examines the role of roads in fostering university-industry (U-I) collaborations, this choice is justified by the extensive reliance on road transport for interregional travel, particularly in areas with limited access to alternative transportation modes. Unlike air transport, which is concentrated in major urban centers, roads provide greater connectivity between medium-sized and smaller cities, where many universities and innovative firms are located. Moreover, in regions where railway networks for passenger transport are underdeveloped, highways play a crucial role in facilitating face-to-face interactions, which are essential for knowledge exchange and collaboration. By enhancing mobility, road infrastructure reduces travel costs and time, ultimately fostering stronger linkages between academic and industrial actors.

Such an agglomeration process in terms of both roads, and productive and innovative activities, creates a vicious circle. If a region has poor road infrastructure and high transportation costs, firms might not be able to interact

[1] Figure A1 in the Appendix A shows the map of Brazil by region and state.

with more distant local partners; similarly, an undeveloped transportation infrastructure can discourage the displacement of researchers and workers within and between regions, hence disrupting the process of face-to-face contact, knowledge spillovers and innovation. Since innovation is considered one of the main drivers of economic growth and regions have different infrastructure endowments, investments in road infrastructure may be a key policy measure with the aim of promoting a sustained and regionally balanced economic growth.

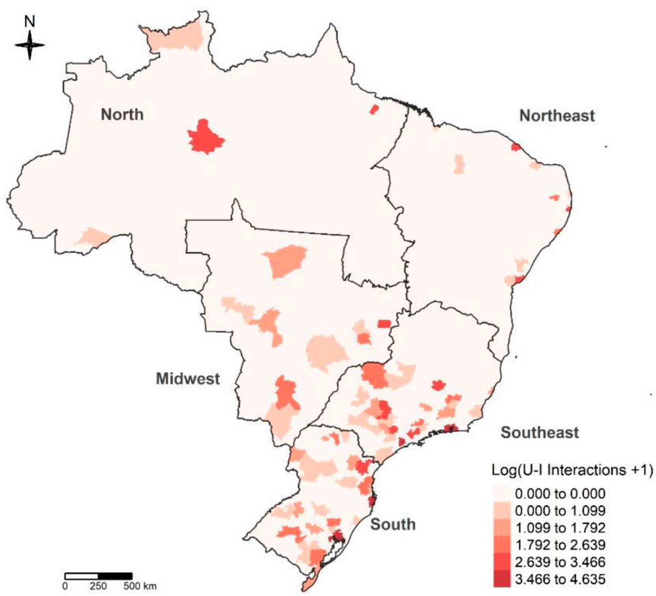

Figure 1 - Territorial distribution of local U-I collaborations in Brazil: 2016

Source: Authors' elaboration using data from the Brazilian Ministry of Science and Technology.

Several empirical studies have proven the role of infrastructure on economic growth, productivity, employment, trade and poverty (Arbués et al., 2015; Cosci and Mirra, 2017; Deng et al., 2014; Fingleton and Szumilo, 2019; Hong, Chu and Wang, 2011; Jiwattanakulpaisarn et al., 2010; Liu et al., 2020; Medeiros, Ribeiro and Amaral, 2020; Medeiros et al., 2025; Rioja, 2003; Wan and Zhang; 2018; Zhang and Ji, 2019; Zhou, Raza and Sui, 2021). However, few studies have investigated the role of transportation infrastructure in promoting innovation and expanding knowledge flows. Agrawal, Galasso and Oettl (2017) found that roads had a strong knowledge diffusion effect, which encouraged regional innovation in the United States. Similarly, Wang et al. (2018) showed that road development spurs innovation by enlarging market size and facilitating knowledge spillovers in China, whilst Cui and Tang (2022) found positive effects of transport infrastructure on regional innovation capability. Dong, Zheng and Kahn (2019) document a complementarity effect between knowledge production and the transportation network in China. Since high-speed railways reduce cross-city commute times, they reduce the cost of face-to-face interactions between skilled workers who work in different cities. Following these three studies, we examine the impact of road development on local U-I collaborations in Brazil, an issue that has been overlooked by both the innovation and the transportation infrastructure literature.

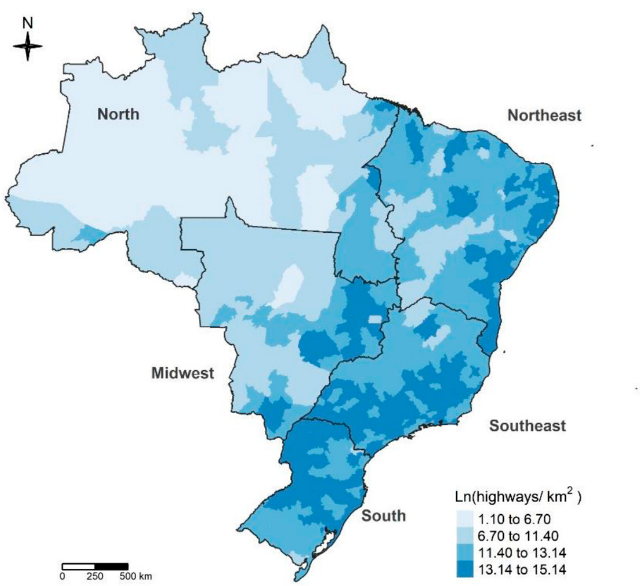

Figure 2 - Territorial distribution of highways in Brazil: highways density, 2010

Source: Authors' elaboration using data from the Ministry of Transport and the National Department of Transport Infrastructure.

The contribution of this paper to the literature is fourfold. Firstly, we examine the role of inter and intra state roads[2] on local U-I linkages in a developing country. Using Brazil's recent data on U-I collaborations, we document that increases in the highways stock effectively increases local U-I linkages with a lag of six years. We emphasize that the local within-region knowledge flows channel also works through the interaction among firms and universities (Agrawal, Galasso and Oettl, 2017). Better transportation infrastructure may increase the mobility of workers and researchers and consequently the diffusion of knowledge across space, thereby allowing ideas to cross-fertilize. This finding shed light on the "black box" of knowledge spillovers and provides solid evidence on the determinants of U-I collaborations. These results remain under several econometric specifications.

Secondly, in order to avoid possible endogeneity issues that may arise from mutual determination between U-I linkages and roads investment decisions, we employ an instrumental variables approach based on the bureaucratic and geographical costs associated with infrastructure projects. The choice of instruments follows the related literature (Duflo and Pande, 2007; Saiz, 2010; Wang et al., 2018) in light of the Brazilian case. This strategy seeks to solve the problem of endogeneity between infrastructure and development outcomes based on the identification of some of the main problems for the design and feasibility of infrastructure projects in developing countries, especially in those with large geographical areas and huge geographic heterogeneities. The first instrument is the share of legally protected areas[3] in a micro-region. The greater the proportion of protected areas, the higher the difficulty in constructing highways. The second instrument chosen is the slope of a micro-region, which measures the relative difficulty (cost) of constructing roads there. Similarly, we also try altitude and rain volume as instruments.

Thirdly, we also identify some heterogeneous effects of increased highways on local U-I interactions. The first one is related to firm and research group size heterogeneity. Larger firms tend to interact more with universities in order to obtain new knowledge, improving their innovative capacity.

[2] We study road transportation because of its importance in the Brazilian scenario. The sector has historically concentrated the most part of the country's cargo transportation, being more than 61% in 2019 (National Transport Confederation, 2019). Interstate roads may connect different states and are administrated by the Federal Government of Brazil, while intrastate roads connect different cities within the same state and are administrated by state-level governments.

[3] These are conservation units (sustainable use and integral protection), military areas and indigenous lands.

In general, larger firms have less financial and educational obstacles to innovate (Bishop et al., 2011). Our findings indicate a significant effect of highways stock for small-sized firms and research groups. Smaller firms and groups are more restricted to their local environment since long distance collaborations require a broader range of capabilities and incur in higher costs (Muscio, 2013). The second heterogeneity is related to the research group quality. High-quality groups tend to engage in collaborations at a larger geographical distance, suggesting that such research groups can attract more distant firms as collaboration partners (Garcia et al., 2015). We provide evidence that better highway connectivity encourages firms to search for higher quality research groups, probably by allowing these firms to interact with more distant local universities.

Lastly, our results provide insights on the role of roads on U-I linkages considering spatial issues. Infrastructure effects on growth and productivity might be greater in the initial stages of development, whilst in developed regions these impacts could be lower (Chen and Vickerman, 2016; Cosci and Mirra, 2018; Crescenzi and Rodríguez-Pose, 2012). Our findings show larger road effects on local U-I linkages in the leading region of the country – the South. Probably the highways are supporting innovative activities in those locations by facilitating the movement of researchers and workers to more distant locations and stepping up the interaction among them. In the laggard regions of the country, the undeveloped road infrastructure may be discouraging the flows of people through highways. Next, we test for spatial effects of the road stock. As argued by the New Economic Geography literature, infrastructure may affect the distribution of firms and workers between and within regions (Ottaviano, 2008), and it will shape the way which firms and universities interact. In order to capture these possible neighborhood effects, we include highways density in neighboring micro-regions in the regressions. Our findings provide evidence of a negatively signed and significant spatial effect of increased highways stock on U-I linkages, thereby indicating that the greater the roads stock in the neighboring regions, the lower the U-I collaborations in the micro-region. Nevertheless, the overall effects of transportation infrastructure on U-I collaborations are still positive.

The paper is organized as follows. Section 2 provides a brief literature review. Section 3 describes the data and methods. Section 4 reports the estimation results and the underlying heterogeneities. Section 5 concludes.

2. Related literature

Our paper is associated to the literature on the determinants of regional innovation and knowledge flows and the effects of transportation infrastructure on regional development. We focus on the role of roads network in stimulating local university-industry collaborations, especially in developing and more regionally unequal economies.

Universities are an essential source of knowledge and may boost innovative activities of firms. Knowledge produced by academic R&D generally serves as basis for relevant technological innovations (Mazzucato, 2013). In addition, universities contribute to the formation of new and skilled professionals and favor the rising of spin off companies (Trippl et al., 2015). In this way, higher education institutions are seen as agents for economic development in both regional and national levels. Furthermore, universities can play an important role as agents of social development (Arocena and Sutz, 2005), especially in laggard countries or regions at where the productive and innovative activities are weak and not based on high-technology industries compared to the leading economies.

However, evidence regarding the spatial distribution and the co-location of university-industry linkages is mixed. On the one hand, a number of works in the regional innovation literature has convincingly advocated the importance of spatial proximity in generating knowledge spillovers (Feldman, 1994; Feldman and Audretsch, 1999; Gonçalves and Almeida, 2009; Jaffe et al., 1993). Pecuniary knowledge externalities emerge from interactions among local agents, which tend to increase the knowledge sharing, technological learning, and its dissemination (Antonelli, 2008). Firm's R&D activities, skilled labor and academic research are examples of sources of local knowledge spillovers (Garcia et al., 2013). Many other studies have pointed out the importance of these knowledge spillovers bounded in space (Breschi and Lissoni, 2001; D'Este and Iammarino, 2010; Garcia et al., 2015; Laursen et al., 2011; Muscio, 2013; Rodríguez-Pose and Crescenzi, 2008; Varga, 2000). In general, those works found that the smaller the spatial distance between universities and firms, the greater the interactions among them. On the other hand, a number of studies have called into question the argument that the geographical proximity between universities and firms significantly increases the possibility of a firm achieving a successful pattern of innovation. Breschi and Lissoni (2009) show that the effect of spatial proximity on knowledge diffusion is not so strong. There are other factors that may influence innovation and knowledge flows rather than geographic proximity, including social and cognitive proximity, institutional and infrastructure aspects, and market opportunities (Xing et al., 2024). Recent studies have shown that firms often search for high quality, geographically distant universities that can solve their innovation problems (D'Este and Iammarino, 2010; De Fuentes and Dutrénit, 2014; Garcia et al., 2015; Laursen et al., 2011; Muscio, 2013).

Manifold studies have investigated the importance of infrastructure on economic growth, poverty, productivity, trade and innovation in a regional approach (Agrawal, Galasso and Oettl, 2017; Arbués et al., 2015; Cosci and Mirra, 2017; Fingleton and Szumilo, 2019; Hong, Chu and Wang, 2011; Jiwattanakulpaisarn et al., 2010; Medeiros, Ribeiro and Amaral, 2020; Wan and Zhang; 2018; Zhang and Ji, 2019). Our study sheds some light on the role of roads on local university-industry collaboration. We argue that an adequate transportation infrastructure amplifies knowledge spillovers by connecting places and promoting the exchange of ideas. By contrast, even if two places are geographically close, but lack the support of transportation infrastructure, knowledge spillovers will take place at a lower magnitude than expected (Feldman and Kogler, 2010). In this sense, highways might play a central role in stimulating knowledge creation and dissemination.

The literature on the role of infrastructure in regional development and innovation has emphasized the importance of physical and digital connectivity for knowledge dissemination and collaboration among economic agents (Feldman and Kogler, 2010; Crescenzi & Rodríguez-Pose, 2012). In the context of university-industry (U-I) interactions, transportation and telecommunications infrastructure play a fundamental role in reducing spatial barriers and enabling the exchange of information and knowledge (Agrawal, Galasso & Oettl, 2017; Wang et al., 2018).

Previous studies have shown that the expansion of road infrastructure can positively impact innovation by facilitating the mobility of skilled workers and researchers, thereby enhancing interactions between universities and firms (Gibbons et al., 2019; Holl, 2016). Reduced transportation costs can stimulate the movement of people between regions and foster collaborations that lead to technological advancements. However, the effect of infrastructure may vary according to regional development levels, potentially concentrating innovative activity in already developed hubs (Lee and Rodríguez-Pose, 2013).

Telecommunications infrastructure, particularly access to high-speed internet, has been identified as a critical factor in promoting innovation and remote collaboration (Na et al., 2020). Digitalization can act as a substitute for physical mobility, allowing interactions between researchers and firms regardless of geographical distance. However, there is an ongoing debate on whether digital communication technologies replace or complement face-to-face meetings (Agrawal, Galasso & Oettl, 2017). Some research suggests that while the internet facilitates information sharing, in-person interactions remain essential for building trust and developing joint innovative projects (Feldman & Kogler, 2010). In addition, airport infrastructure also plays a significant role in fostering academic and business collaborations. Studies indicate that the presence of airports can reduce geographical barriers by enabling rapid face-to-face interactions between researchers and industries located in distant regions (Laursen et al., 2011; Dong, Zheng & Kahn, 2019). This effect is particularly relevant for high-value collaborations that require frequent in-person meetings.

Some recent investigations have investigated the relationship between transportation infrastructure, innovation, and knowledge flows. Agrawal, Galasso and Oettl (2017) evaluated the impacts of the stock of interstate roads on regional innovation in the U.S. using patent data. The authors' main results show that in regions where the stock of highways is larger, innovators build on local knowledge that is geographically more distant, insofar as this infrastructure facilitates the circulation of local knowledge. Similarly, Wang et al. (2018) examined the effects of roads on innovation at the firm level in China. In addition to the circulation of local knowledge channels, they find that improved roads expand market size, which in turn leads to more innovation. Cui and Tang (2022) tested the impact of transportation infrastructure on innovation capabilities in Chinese provinces from 1996 to 2018 and found that the impact of transportation infrastructure on regional innovation capability is positive and significant. Dong, Zheng and Kahn (2019) evaluated the impacts of China's high-speed rail network on the interaction among high skilled teamwork and found that this type of transportation infrastructure increases the production of academic papers and facilitates flow of ideas between two high-speed rail connected cities.

Although the literature on transportation infrastructure and knowledge flows has advanced, there are still umpteen open points. We focus on the role of highways in encouraging U-I linkages, an issue that might be crucial in stimulating innovative activity in lagging countries and regions.

3. Data and empirical strategy

3.1. Data

In order to evaluate the role of transportation infrastructure on university-industry linkages, we used data from the Brazilian Ministry of Science and Technology[4] which provides a broad dataset covering the activities of academic research groups in Brazil at the regional level. We accessed the Directory of Research Groups (DGP) database, which is part of the Lattes Platform, a comprehensive system for managing information on research groups and their activities in Brazil. The DGP database provides detailed information on academic research groups, including their location, research areas, and collaborations with external entities, such as firms. Then, we merged this dataset with detailed information of firms' location and size collected from the Brazilian Ministry of Labor database. We obtained firm-level data, including the location and size of firms, from the Ministry of Labor's database. This dataset allowed us to identify firms that are potentially engaged in innovative activities and could be collaborating with academic research groups. From the DGP database, we extracted information on research groups, including their geographic location (micro-region) and their reported collaborations with industry partners. From the Ministry of Labor database, we identified firms located in the same micro-regions as the research groups. This way, we were able to combine information about the location of both firms and research groups. We matched research groups and firms based on their geographic location (micro-region). This allowed us to identify potential U-I collaborations within the same micro-region.

Next, we constructed local U-I measures at the micro-regional level, which can be associated with the European Union NUTS-3 (Garcia et al., 2015). The first measure is a count variable measuring the total number of U-I collaborations in the micro-region. The second measure is a binary outcome that equals 1 if there is at least one U-I collaboration in the micro-region and 0 otherwise. According to Santos (2017), there are several advantages in using the micro-regional scale compared to other aggregations in the Brazilian case. A state-level analysis tends to exhibit a high level of heterogeneity, not allowing us to capture local economic

[4] We exploit the Directory of Research Groups provided of the National Council for Scientific and Technological Development using the Lattes platform. These data were organized by the research group on Economics of Science and Technology of the Center for Development and Regional Planning of the Federal University of Minas Gerais.

dynamic. On the other hand, the municipal scale was not deemed the most appropriate one for this analysis either because the technological and economic structure of a municipality serves residents in neighboring municipalities as well. The highway data was obtained from the Ministry of Transport and the National Department of Transportation Infrastructure. Following the literature (Agrawal, Galasso and Oettl, 2017; Dong, Zheng and Kahn, 2018; Wang et al., 2018), we construct a proxy for the stock of roads. First, we used the length of paved roads (in km)[5] and multiplied it by the number of road lanes[6]. Next, we divided it by the micro-region area (km^2) and used the log form.

3.2. Empirical framework

Our baseline model focuses on the relationships between interstate and intrastate highways in micro-region *m* in 2010, $Highways_{m,2010}$, and local university-industry linkages in micro-region *m* in 2016, $Y_{m,2016}$. The idea of using the road variable with a lag of six years seeks to take into account that the realization of U-I connections at full potential may require some time until investments in the provision of transportation infrastructure reach maturity and specific new knowledge in both firms and universities is created. In other words, use of a six-year lag is justified since the provisioning of new roads will only come into productive use by both firms and universities in some future period[7]. Thus, our baseline model goes as follows:

$$Y_{m,2016} = \alpha + \beta Highways_{m,2010} + \theta X_m + \varepsilon_m \quad (1)$$

We use two measures for university-industry collaborations. The first is a dummy variable that equals one if a micro-region had at least one local U-I collaboration in 2016 and zero otherwise. The second variable is the total local U-I. In order to capture the local dynamic of the interactions among universities and firms, we consider only those interactions that occur between firms and research groups established in the same micro-region. In

[5] We tried three measures: total road length; road density (total road length divided by the micro-region area in km^2), and; road *per capita* (road length divided by the micro-region population). The results were quite similar regardless of the variable used.

[6] If the road has one lane, we multiplied its length by one. If the road is duplicated (two-lane), we multiplied its length by two.

[7] Infrastructure investments can be expected to take a long time to mature (Straub, 2011).

this sense, our dependent variables allowed us to evaluate the partial effects of highways on local U-I linkages. The term X_m is a vector of control variables, including the educational level, gross domestic product (GDP) *per capita*, population, demographic density, a dummy variable indicating the existence or not of a paved airport, the innovate dynamic of the micro-region measured by the number of patents and a dummy variable capturing regional heterogeneity. A more detailed description of the variables can be found at Table A1 in Appendix A.

We use Probit and Poisson[8] models to estimate the impacts of highways on U-I collaborations. These models are suitable[9] when using binary and count dependent variables, respectively (Cameron and Trivedi, 2005). The parameter of interest is β, which describes the impact of highways provision on U-I linkages. The main empirical challenge in estimating equation (1) is the possible bias coming from endogeneity issues. It is possible that the error term ε_m is correlated with the stock of highways. For instance, in areas with high growth potential, local governments may invest more in infrastructure there. At the same time, those micro-regions may have a greater fiscal capacity to improve its universities (Dong, Zheng and Kahn, 2019). If these situations exist, then the observed rise in micro-region innovative activity is likely driven by unobserved factors rather than road development. In this case, conventional Probit and Poisson would yield biased estimates of the causal effect of highways on U-I linkages.

3.3. Instrumental variables: a legal and geographical cost approach

To address potential endogeneity, we employ an instrumental variables approach, isolating exogenous variations in road infrastructure through natural constraints such as terrain slope and protected areas. While observable variables—such as public investment in education and infrastructure—can partially capture regional growth potential, they may not fully account for long-term structural and institutional factors driving development. Previous studies highlight the challenge of infrastructure endogeneity, as

[8] It could be argued that the Zero-Inflated model might be more appropriate in this case. However, studies (Naya *et al.*, 2008; Staub and Winkelmann, 2013) show that the Poisson and Zero-Inflated models generate, in most cases, similar estimates. In addition, the Zero-Inflated model does not yet offer reliable options for the application of an instrumental variables approach, an essential test in our work. On the other hand, the Poisson model has been widely used in models that account for endogeneity issues. In this sense, we have opted for the Poisson model.

[9] In these cases, linear models could generate biased and inconsistent estimates.

investments often follow rather than drive economic growth (Duranton & Turner, 2012; Wang et al., 2018). By using instruments that are correlated with road provision but exogenous to innovation dynamics, we mitigate omitted variable bias and strengthen causal inference.

We employ two types of instruments based on the transportation infrastructure literature in the light of the Brazilian reality. The first instrumental variable used is the proportion of legally protected areas[10] in a micro-region. The greater the proportion of protected areas, the more difficult it may be to construct highways. Building roads in these areas requires incurring in heavy bureaucratic costs including environmental licensing and long delays in permit issuance by local authorities. This instrument has a high negative correlation with the road stock. It seems to indicate the deep problems related to the Brazilian bureaucracy and its consequences for the elaboration and conclusion of infrastructure projects. National survey demonstrates excessive bureaucracy as one of the main problems in the construction and infrastructure sector - 30.5% of the country's entrepreneurs answered that they spent considerable time and resources in complying with legal requirements to set up, obtain licenses and authorizations).

The second set of instruments are related to geographical issues, which may directly affect the costs of constructing roads. The first instrument to be tested is the slope of a micro-region, following Duflo and Pande (2007), Saiz (2010) and Wang et al. (2018). Our slope variable measures the proportion of the micro-region area with slope above 20%, which corresponds to hilly areas. The greater the value of this variable, the higher the cost of building roads. In steeper areas, a stringent road design would lead to less winding construction. To conform to this type of project, it is essential to build several special artworks such as tunnels and bridges. Those roads have higher economic costs and higher environmental requirements, which in some cases may lead to the unfeasibility of their execution. Similarly, we use geographical features such as altitude and the rain volume as instrumental variables.

We argue that the instruments affect University-Industry interactions only through the infrastructure variable. The low correlation among measures of U-I interaction and the chosen instruments show that steep terrains or protected areas do not directly limit (or expand) local U-I linkages (Table

[10] These are conservation units (sustainable use and integral protection), military areas and indigenous lands.

A2 in Appendix A). On the other hand, these characteristics are crucial in determining the feasibility of an infrastructure project, which in turn will change the trade costs and travel times intra and inter cities.

We have also included several control variables in order to mitigate potential omitted variable problems. The validity of the instrumental variable estimation hinges on the orthogonality of the dependent variable and the instrument conditional on control variables, not on unconditional orthogonality (Duranton and Turner, 2012; Wang et al., 2018). The summary statistics are described in Table 1.

Table 1 - Summary statistics

Variable	Mean	Std. dev.	Min	Max
Highways	12.40	2.149	1.101	15.13
U-I interactions	1.473	7.543	0	102
Having at least one U-I interaction	0.142	0.349	0	1
GDP per capita	2.883	0.611	1.635	5.045
Population	12.19	0.954	7.983	16.50
Demographic Density	7.984	1.509	3.478	13.35
Airport	0.618	0.486	0	1
Patents	0.527	1.185	0	7.158
Instruments				
Slope	0.069	0.103	0.001	0.835
Protected areas	0.074	0.162	0.000	0.972
Altitude	382.1	276.9	2.75	1171
Rain	88.19	31.01	20.36	182.9

Source: authors' elaboration.

4. Results and discussion

4.1. Regional U-I collaborations: benchmark results

We begin our analysis by finding a positive and significant impact of intrastate and interstate highways stock on local U-I linkages in Brazil. Table 2 presents the econometric estimation results based on the specification in Equation (1). By using the full sample, it becomes difficult to disentangle two distinct transmission channels through which road networks affect innovation. The first one refers to the fact that highways might increase U-I interactions by facilitating the flow of researchers and workers between and within micro-regions. Better transportation infrastructure accelerates the mobility of people and the diffusion of knowledge across space, allowing ideas to cross-fertilize (Agrawal, Galasso and Oettl, 2017; Glaeser and Gottlieb, 2009). The second channel is related to the agglomeration economies (Duranton and Turner, 2012; Gibbons et al., 2018; Holl, 2016). Developed infrastructure may attract firms and researchers to a particular location, expanding local economies and its market potential. In this paper, we emphasize the first mechanism. To this end, our estimations refer to the impacts of interstate and intrastate highways stock in 2010 on local U-I linkages in 2016 between firms and research groups that already existed in 2010.

Table 2 - Highways stimulate University-Industry interactions: Poisson regressions. Dependent variable: University-Industry linkages

	1	2	3	4	5
Highways	0.926***	0.101*	0.183***	0.132**	0.157
	(0.20)	(0.05)	(0.07)	(0.06)	(0.12)
Higher Education		0.011	0.267	0.067	0.440
		(0.32)	(0.26)	(0.24)	(0.30)
GDP per capita		0.387**	0.488**	0.488**	0.336
		(0.17)	(0.21)	(0.21)	(0.25)
Patents		0.597***	0.326***	0.343***	0.310**
		(0.05)	(0.12)	(0.11)	(0.13)
Population			0.679***	0.467***	0.520***
			(0.12)	(0.10)	(0.16)
Population density			-0.280	-0.137	-0.123
			(0.18)	(0.16)	(0.19)
Airport				1.166**	1.097**
				(0.59)	(0.56)
Northeast					-0.034
					(0.49)
Southeast					-0.520
					(0.59)
South					0.152
					(0.61)
Midwest					-0.051
					(0.47)
Constant	-13.594***	-4.818***	-12.522***	-11.026***	-12.092***
	(2.77)	(0.91)	(2.13)	(1.90)	(1.99)
Observations	558	558	558	558	558
Pseudo R^2	0.14	0.39	0.42	0.43	0.44
Log likelihood	-338	-240	-230	-224	-220

Note: Values between square brackets are standard deviations. Clustered sandwich estimator option was used in order to allow for intragroup correlation (state-level). Significance: ***=1%; **=5%; *=10%.

In order to give robustness to our results, we include several control variables, beginning with no control variables, then including some control variables related to the micro-region development, demographic control variables, other modes of transportation and finally regional dummies. We find a positive and significant effect of roads on U-I collaborations based on conventional Poisson models[11]. However, in the most robust specification (Column 5), the highway coefficient is not significant. This insignificant effect may stem from endogeneity issues as we argue above. We expect unobservable factors to be correlated with both the levels of highways and the knowledge flows in a micro-region for a number of reasons (Agrawal, Galasso and Oettl, 2017; Wang et al., 2018).

In order to avoid this endogeneity, we turn to an instrumental variable estimation. The IV estimations using the protected area and slope instruments are described in Table 3[12]. These results can be interpreted as the causal impact of the 2010 level of interstate and intrastate highways in the micro-region on micro-region U-I linkages in 2016. We find that more roads in 2010 led to more U-I collaborations six years later. These estimation results are in line with the previous literature that has shed some light on the positive effect of the stock of highways on innovation (Dong, Zheng and Kahn, 2019; Wang et al., 2018). This result indicates that increases in the provision of highways might have accelerated the knowledge flows between firms and research groups that already existed in 2010, which goes beyond the expected agglomeration effects coming from better infrastructure. Our findings are in line with the results found by Agrawal, Galasso and Oettl (2017) using patent data.

In relation to the control variables, we have verified the expected signs. The higher the human capital the greater the U-I linkages in the micro-region. The same result holds for the GDP per capita, population and population density controls. The Southeast region's dummy has presented a negative and significative coefficient, indicating that the microregion has less local U-I interactions in comparison with the North region. This result suggests that the most developed region of the country had a lower number of local university-industry (U-I) interactions in 2016 compared to the less developed region. This finding is not entirely unexpected, as

[11] We have also tested Probit models using as dependent variable "Having at least one local U-I interaction" as robustness checks. The estimates are in Tables B1, B2 and B3 in Appendix B. Regarding the conventional Probit model, the results indicate a non-significant road effect on U-I interaction. When we move to the IV Probit regressions, the results indicate a positive and significant road effects in three of five specifications. This may suggest that our dependent dummy variable is not as suitable as the continuous U-I interaction variable. The results for the Wald test of exogeneity allow us to reject the null hypothesis of no endogeneity, which supports our choice of using models that control for endogeneity.

[12] In unreported estimates, we observed a high and significant correlation between the highways stock in 2010 and the instruments. The simple correlation among the variables can be seen in Table A2 in the Appendix A.

research groups in wealthier states may seek collaborations with firms located in more distant areas or even in other countries.

Table 3 - Highways stimulate University-Industry interactions: IV Poisson regressions. Dependent variable: University-Industry linkages

	1	2	3	4	5
Highways	0.290	0.767	1.125*	1.081*	1.054***
	(0.20)	(0.74)	(0.59)	(0.58)	(0.40)
Higher Education		0.383	1.042*	0.898	1.224***
		(0.47)	(0.56)	(0.56)	(0.45)
GDP per capita		0.148	0.177	0.177	0.616*
		(0.28)	(0.30)	(0.28)	(0.37)
Patents		0.416**	0.181	0.184	0.233*
		(0.18)	(0.15)	(0.15)	(0.13)
Population			0.852***	0.721***	0.674***
			(0.20)	(0.21)	(0.23)
Population density			-0.607***	-0.507***	-0.404**
			(0.18)	(0.19)	(0.19)
Airport				0.808	0.914
				(0.58)	(0.73)
Northeast					-0.712
					(0.73)
Southeast					-2.158**
					(0.97)
South					-1.422
					(0.94)
Midwest					-1.065
					(0.86)
Constant	-5.073*	-13.429	-24.876***	-23.889***	-22.155***
	(2.60)	(9.59)	(7.17)	(6.99)	(3.88)
Observations	558	558	558	558	558
Hansen's J statistic	0.28	0.20	0.05	0.10	1.39

Note: Values between square brackets are standard deviations. Clustered sandwich estimator option was used in order to allow for intragroup correlation (state-level). Instruments: 1- protected areas; 2- slope. Significance: ***=1%; **=5%; *=10%.

4.2. Robustness checks

4.2.1. Instruments

In order to test the validity of our estimations, we have tried several specifications varying the set of instruments used (Table 4). We run different models with different instruments such as protected area, slope, altitude and rain and report all in the results that satisfied the Hansen's J test of overidentifying restrictions. Independent of the model specification, we have obtained quite stable econometric parameters varying between 1.054 and 1.281, all suggesting a positive and significative relationship among the transportation infrastructure and the U-I interactions.

Table 4 - Highways stimulate University-Industry interactions: robustness check, instruments. Dependent variable: University-Industry linkages

	Protected areas	Protected areas and altitude	Protected areas and rain	Protected areas and slope	Protected areas, slope and altitude	Protected areas, slope and rain	Protected areas, altitude and rain	Protected areas, slope, altitude and rain
Highways	1.102***	1.271***	1.109***	1.054***	1.220***	1.054***	1.281***	1.224***
	(0.41)	(0.44)	(0.41)	(0.40)	(0.43)	(0.40)	(0.44)	(0.43)
Observations	558	558	558	558	558			
Hansen's J statistic	-	1.09	0.04	0.84	2.39	0.84	1.14	2.39

Note: Values between square brackets are standard deviations. Clustered sandwich estimator option was used in order to allow for intragroup correlation (state-level). Instruments: 1- proportion of area with slope above 20 degrees; 2- percentage of protected areas. Significance: ***=1%; **=5%; *=10%. All regressions control for the micro-region human capital, GDP per capita, population, population density, existence of an airport, regional dummies and level of patents.

4.2. The role of internet

Another issue that has been pointed out by Agrawal, Galasso and Oettl (2017) is the role of internet in shaping the U-I interactions. The access to Information and Communication Technology (ICT) may amplify or reduce the effect of roads depending on whether face-to-face interactions and ICT are complements or substitutes in knowledge production (Na *et al.*, 2020). Also, the road infrastructure variable might be just capturing the level of infrastructure development in a region, as infrastructure variables are likely to be highly correlated. In order to test this issue, we include the log of internet access[13] in each microregion as a proxy to the telecommunications infrastructure. Table 5 shows the econometric results.

[13] This variable was included as an exogenous covariate.

Table 5 - Highways stimulate University-Industry interactions: robustness check, the role of internet. Dependent variable: University-Industry linkages

	Protected areas	Protected areas and altitude	Protected areas and rain	Protected areas and slope	Protected areas, slope and altitude	Protected areas, slope and rain	Protected areas, altitude and rain	Protected areas, slope, altitude and rain
Highways	0.955**	1.069**	0.988**	0.851**	0.932**	0.851**	1.089**	0.949**
	(0.43)	(0.44)	(0.42)	(0.37)	(0.39)	(0.37)	(0.43)	(0.38)
Broadband infrastructure	1.114***	1.125***	1.132***	1.068***	1.035***	1.068***	1.133***	1.042***
	(0.36)	(0.38)	(0.36)	(0.33)	(0.34)	(0.33)	(0.38)	(0.35)
Observations	558	558	558	558	558			
Hansen's J statistic	-	1.24	0.12	1.72	3.78	1.72	1.28	3.77

Note: Values between square brackets are standard deviations. Clustered sandwich estimator option was used in order to allow for intragroup correlation (state-level). Instruments: 1- proportion of area with slope above 20 degrees; 2- percentage of protected areas. Significance: ***=1%; **=5%; *=10%. All regressions control for the micro-region human capital, GDP per capita, population, population density, existence of an airport, regional dummies and level of patents.

The positive and significant effect of road infrastructure remains. The inclusion of the internet variable slightly decreases the magnitude of the coefficient of the transport variable. In addition, the expected positive sign of the internet variable coefficient indicates its importance for the promotion of U-I interactions. Our findings are robust to the inclusion of an ICT variable as a control, thus reinforcing the key role played by road infrastructure on the U-I linkages at a more local level.

4.2.3. Infrastructure quality

Other issue that has been raised by the literature on infrastructure is the heterogeneous effect of the quality of infrastructure services (Medeiros and Ribeiro, 2020; Medeiros, Ribeiro and Amaral, 2020). Poor quality highways may increase the number of accidents and force individuals to adopt other modes of transportation, changing the expected effect of highways, for example. In order to control this effect, we include the log of the number of transit accidents[14] in each microregion as a proxy for road quality.

[14] This variable was included as an exogenous covariate.

Table 6 - Highways stimulate University-Industry interactions: robustness check, road quality. Dependent variable: University-Industry linkages

	Protected areas	Protected areas and altitude	Protected areas and rain	Protected areas and slope	Protected areas, slope and altitude	Protected areas, slope and rain	Protected areas, altitude and rain	Protected areas, slope, altitude and rain
Highways	0.838**	0.981**	0.929**	0.856**	0.913**	0.856**	1.066**	0.986**
	(0.41)	(0.43)	(0.41)	(0.38)	(0.41)	(0.38)	(0.44)	(0.41)
Traffic accidents	-0.137***	-0.118**	-0.134**	-0.141***	-0.132**	-0.141***	-0.117**	-0.126**
	(0.05)	(0.05)	(0.06)	(0.05)	(0.05)	(0.05)	(0.06)	(0.05)
Observations	558	558	558	558	558	558	558	558
Hansen's J statistic	-	1.04	0.52	1.34	2.67	1.34	1.41	2.87

Note: Values between square brackets are standard deviations. Clustered sandwich estimator option was used in order to allow for intragroup correlation (state-level). Instruments: 1- proportion of area with slope above 20 degrees; 2- percentage of protected areas. Significance: ***=1%; **=5%; *=10%. All regressions control for the micro-region human capital, GDP per capita, population, population density, existence of an airport, regional dummies and level of patents.

Even controlling for the road quality, the positive and significant road effect on U-I linkages remains. The inclusion of the road quality variable also slightly decreases the magnitude of the coefficient of the transport variable. Thus, the poorer the quality of the road network, the smaller the U-I interaction in a microregion.

4.2.4. Spatial autocorrelation

Classical econometrics does not consider the spatial dimension explicitly. If not taken into account, spatial dependence may cause bias in estimates or influencing the inference process, thus casting doubts on the results of regressions performed. This section re-estimates the IV regressions of Table 4 employing spatial econometric techniques in order to check the robustness of our main results.

In addition, the estimation results described so far have focused only on the direct impacts of increases in highways stock on U-I interactions. However, another key aspect that must be taken into account while assessing the economic impact of infrastructure provisioning at the local level is that regions may benefit disproportionally from road improvements elsewhere (Agrawal, Galasso and Oettl, 2017; Cui and Tang, 2022; Wang et al., 2018). As argued by the New Economic Geography literature, infrastructure may affect the distribution of firms and workers between and within locations (Ottaviano, 2008). A first possible effect ("straw effect") occurs when better connectivity between two regions causes less attractiveness to the poorer region. This effect occurs because economic activities are "sucked up" by the richer region due to better infrastructure conditions and establishment facilities for firms and families (Behrens et al., 2007). Another possible effect ("shadow effect") happens when improving infrastructure in a region does not make it more attractive. In this case, the expansion of transportation infrastructure in the poorest region would be mostly used as an additional economic support for the richest region, thus causing resources to shift from the poorest to the richest region. Apart from these unwanted effects, infrastructure may also reduce regional disparities, by promoting knowledge transmission from developed to less developed locations.

In order to capture those possible spatial effects, we include highways density in neighboring micro-regions in the regressions[15]. To create spatial lags, queen matrices of first-order were created. The spatial weight matrix was constructed by contiguity, wherein the micro-regions that have a common border were considered neighbors (LeSage and Pace, 2009). Before proceeding with the estimations, we tested for spatial autocorrelation using the Moran's I statistic. We observed a significant and positive spatial autocorrelation for the road stock in 2010, indicating that micro-regions with high (low) levels of road networks are surrounded by other micro-regions with high (low) road networks. Given that there are important local specificities in Brazil, we also tested for local clusters using the local Moran's I statistic. As expected, we note a great cluster of micro-regions with poor transportation infrastructure in the North and part of the Midwest region (see Figure B1 in Appendix B). On the other hand, there are "high-high" clusters in the Southeast and South regions.

Table 7 describes the estimation results. Even controlling for spatial autocorrelation, the positive direct effects of the highways stock on U-I interactions remained. The magnitude of the net effect (direct minus indirect effects) is quite similar to our estimates in Table 4. Our findings evidence

[15] This variable was included as an endogenous regressor.

a negative and significant indirect effect of highways stock in 2010 on U-I linkages in 2016, which indicates that the greater the roads stock in the neighboring regions, the lower the U-I collaborations in the micro-region.

Table 7 - Highways stimulate University-Industry interactions: robustness check, spatial autocorrelation. Dependent variable: University-Industry linkages

	Protected areas	Protected areas and altitude	Protected areas and rain	Protected areas and slope	Protected areas, slope and altitude	Protected areas, slope and rain	Protected areas, altitude and rain	Protected areas, slope, altitude and rain
Highways	2.513**	2.523**	2.454**	2.435**	2.502**	2.435**	2.456**	2.457**
	(1.21)	(1.21)	(1.15)	(1.16)	(1.22)	(1.16)	(1.13)	(1.16)
Highways, spatial lag	-1.478*	-1.487*	-1.448*	-1.452*	-1.499*	-1.452*	-1.450*	-1.471*
	(0.79)	(0.79)	(0.76)	(0.77)	(0.80)	(0.77)	(0.75)	(0.76)
Observations	558	558	558	558	558	558	558	558
Hansen's J statistic	-	0.44	1.03	1.55	1.05	1.55	1.02	1.56

Note: Values between square brackets are standard deviations. Clustered sandwich estimator option was used in order to allow for intragroup correlation (state-level). Instruments: 1- proportion of area with slope above 20 degrees; 2- percentage of protected areas. Significance: ***=1%; **=5%; *=10%. All regressions control for the micro-region human capital, GDP per capita, population, population density, existence of an airport, regional dummies and level of patents.

In the literature on roads and innovation using patent data, Wang et al. (2018) found a positive spatial spillover effect, while Agrawal, Galasso and Oettl (2017) obtained a not significant spatial feedback effect. However, our findings appear to indicate the existence of a negative spatial externality of roads stock on U-I linkages in Brazil. It is possible that more adequate transportation networks are intensifying the innovation dynamic of well establish micro-regions in terms of U-I interactions, which might exacerbate regional disparities through the occurrence of regionally unequal knowledge flows. This result is in line with the positive link between innovation and spatial inequality found by Lee and Rodríguez-Pose (2013) for European regions. Another explanation may be related to the immaturity of the Brazilian innovation system: because of the immense disparities in terms of urban, productive, and scientific and technological infrastructure, the spatial innovative agglomerations tend to be concentrated in historically more developed regions (Gonçalves and Almeida, 2009). In addition, we observe a huge discontinuity in the Brazilian territory, wherein great urban centers are surrounded by poor and small-population regions, which intensify the concentration of productive and innovative activities in few central places. A similar phenomenon is observed in the Chinese case (Crescenzi, Rodríguez-Pose and Storper, 2012). Our results suggest that laggard regions are not able to benefit from the knowledge spillovers stemming from the dynamism of surrounding regions due to their several economic and social constraints. This is entirely consistent with theories of economic development that suggest there is divergence in the earlier stages of development (Chen and Vickerman, 2016) and also corroborates the view that knowledge spillovers depend on a region's absorptive capabilities, which very poor areas may lack (Zhang and Ji, 2019). Finally, the negative effect of neighboring infrastructure on local U-I interactions may reflect a straw effect, where regions with stronger innovation ecosystems attract resources and collaborations from adjacent areas. This aligns with findings in the economic geography literature, which highlight the potential for infrastructure investments to reinforce spatial disparities. Consequently, policy prescriptions should be carefully designed to avoid exacerbating regional inequalities. While road connectivity remains essential, policymakers should consider alternative transportation modes and environmental concerns. Complementary strategies, such as investments in digital infrastructure and targeted innovation incentives for less-developed regions, may help mitigate unintended negative externalities.

It is important to emphasize that the total effects of transportation infrastructure on U-I collaborations are still positive, given that the magnitude of the direct effects exceeds the value of the indirect effects. Therefore, even with adverse spatial effects, larger road networks in 2010 caused an increase in U-I interactions in 2016.

4.2.5. Additional robustness checks

Given that the dependent variable in our main specifications is an interaction between the presence of firms and research groups, we conducted additional robustness checks to address potential concerns related to the distribution of these components across microregions. First, we verified the coverage of our sample. All 558 microregions included in the dataset presented some level of firm activity. However, 140 of them did not host any research group. To assess whether the inclusion of these microregions could bias our results, we re-estimated the main specification excluding the microregions without any research group. In unreported estimates, the results remained closely aligned with the baseline findings, both in the magnitude and statistical significance of the main variables. Other covariates—such as higher education, population, and patent activity—also retained their expected signs and significance levels.

4.3. Additional transmission channels and heterogeneities

4.3.1. Firms and research groups heterogeneities

Having investigated the impact of roads stock on total U-I collaborations, we further consider the impact on U-I linkages by firm's size and re-estimate eq. (1). Larger firms tend to seek such collaborations more often in order to obtain new information, enhance their professional recruitment, and facilitate the application of external knowledge in their innovation activities (Bishop et al., 2011). In Brazil, larger firms invest disproportionally more in innovative activities, have less obstacles to innovate, get more resources and incentives from government agencies to develop innovative activities, innovate more and have formal and informal methods that tend to be more effective in protecting new technologies and knowledge compared to their smaller competitors (Rapini, Chiarini and Santos, 2018). In order to test the existence of possible heterogeneities linked to the size of firms, we test the impact of increases in the highways stock on local U-I linkages for large, medium and small-sized firms[16].

The estimates by firm size are described in Table 8. This new set of estimations sheds some light on the presence of heterogeneities associated with firm and group size. Although we did not see significant effects of highways on local U-I interactions of larger and medium firms, column "Small" indicates a significant effect of increases in highways stock for small-sized firms. Small firms are more likely to engage in collaborative efforts with research groups located at a close distance to avoid incurring in substantial costs (Muscio, 2013). Small firms face worse conditions to

[16] We followed the IBGE classification based on the number of workers. We consider as small firms those with up to 99 employees; medium-sized firms those with 100 to 499 employees, and; large firms those with more than 500 employees.

innovate compared to big firms due to difficulties in attracting skilled workers, low access to credit and absorptive capacity, which might limit them to search for distant and high-quality universities. Due to their competitive disadvantage, small and medium-sized firms tend to become more dependent on local knowledge flows and hence interact with nearby universities and research groups. Our findings suggest that improving transportation infrastructure may stimulate local interactions between research groups and small and medium-sized firms, probably by cutting costs and expanding firms' access to more distant local knowledge.

Table8 - Highways stimulate University-Industry interactions: group and firm size heterogeneity. Dependent variable: University-Industry linkages

	Firms			Research groups	
	Large	Medium	Small	Large	Non-large
Highways	0.747	0.628	1.039**	0.833	1.127***
	(0.47)	(0.57)	(0.41)	(0.51)	(0.42)
Observations	558	558	558	558	558
Hansen's J statistic	0.00	0.63	0.02	3.47	0.11

Note: Values between square brackets are standard deviations. Clustered sandwich estimator option was used in order to allow for intragroup correlation (state-level). Instruments: 1- protected areas; 2- slope. Significance: ***=1%; **=5%; *=10%. All regressions control for the micro-region human capital, GDP per capita, population, population density, existence of an airport, regional dummies and level of patents.

We have also tested the effects of highways according to the size of the research group[17]. Research groups with more researchers have more accumulated capabilities, which overcome barriers to collaborating with industry partners (De Fuentes and Dutrénit, 2012). Similar to the previous result on firms, we have found that the road stock benefits the smaller research groups (column "Non-large").

Next, we estimated the effects of highways on U-I collaborations by research group quality. The lack of a high-quality local partner tends to be associated with more geographically distant collaborations (Laursen et al., 2011). The quality of academic research was measured as the number of published papers per researcher following Garcia et al. (2015). We created

[17] Following Garcia et al. (2015), we used the number of researchers as a proxy for research group size. We generated a dummy variable that assumed the value one if the research group was among the 75% higher groups in terms of researchers. Then, we divided the sample into "Large" group – local U-I linkages occurring between firms and large-sized research groups- and "Other" group – local U-I collaboration occurring between firms and not large-sized research groups.

a dummy variable that assumed the value one if the research group was among the 75% higher quality research groups. Then, we sliced the sample into "High" and "Other" quality interactions by micro-region. The results are described in Table 9.

Table 9 - Highways stimulate University-Industry interactions: research group quality heterogeneity. Dependent variable: University-Industry linkages

	High	Low
Highways	1.907**	1.015**
	(0.97)	(0.40)
Observations	558	558
Hansen's J statistic	0.00	0.00

Note: Values between square brackets are standard deviations. Clustered sandwich estimator option was used in order to allow for intragroup correlation (state-level). Instruments: 1- protected areas; 2- slope. Significance: ***=1%; **=5%; *=10%. All regressions control for the micro-region human capital, GDP per capita, population, population density, existence of an airport, regional dummies and level of patents.

The highways stock positively affects local U-I linkages for both high quality and non-high-quality research groups, being this impact quite higher for the U-I interactions of high-quality groups. This finding reinforces the important role of roads in stimulating local U-I collaborations and appears to indicate that better highway connectivity encourages firms to search for higher quality research groups, probably by allowing these firms to interact with more distant local universities. By the research group's side, it is likely that more developed transportation infrastructure facilitates the flows of researchers within the micro-region, facilitating face-to-face contact with firms. This closer contact may be leading to better meeting the firm's demands, making the U-I interaction more attractive.

4.3.2. Regional heterogeneity

Another important aspect of some developing economies – as the Brazilian case - is the marked regional heterogeneity in terms of economic and social conditions. On the one hand, we observe some regions with high levels of infrastructure coverage and technological dynamism. On the other hand, we also have a number of localities with poor transportation systems and weak or inexistent U-I linkages. As we have showed earlier, Brazil presents a high number of micro-regions without any U-I linkage. The U-I collaborations are extremely concentrated in the Southeast and South regions, which exhibits the incomplete and immature nature of the Brazilian system of innovation (Suzigan et al., 2009). In addition, the highways networks in sufficiently good conditions are most notably concentrated in high-income regions such as the South and Southeast states as well as in the coastal micro-regions.

In the literature on infrastructure and development, some findings point out different highways effects on development depending on the level of development of the country or region (Calderón and Serven, 2014; Chen and Vickerman, 2016; Deng et al., 2014; Hong, Chu and Wang, 2011). Some studies also argued that the benefits associated to the increased provision of highways are unevenly distributed across sectors and space (Cosci and Mirra, 2018; Holl, 2016; Qi *et al.*, 2020; Liu, Wan and Zhang, 2020). Infrastructure effects on growth and productivity might be greater in the initial stages of development, than in mature economies (Crescenzi and Rodríguez-Pose, 2012).

In the attempt to capture possible heterogeneous effects of U-I linkages by income level, we interact the road variable with a dummy variable that assumes the value 1 if the microregion are in the South, Southeast and Midwest (the Southern regions). While the Northern region consists of the low-income states, the Southern region is constituted by the high-income states of the country. Table 10 presents our estimates.

Table 10 - Highways stimulate University-Industry interactions: regional heterogeneity. Dependent variable: University-Industry linkages

	Protected areas	Protected areas and altitude	Protected areas and rain	Protected areas and slope	Protected areas, slope and altitude	Protected areas, slope and rain	Protected areas, altitude and rain	Protected areas, slope, altitude and rain
Highways	1.001**	1.071***	1.009**	1.003**	1.020***	1.004***	1.081**	1.024***
	(0.40)	(0.41)	(0.40)	(0.39)	(0.40)	(0.39)	(0.41)	(0.40)
Highways*South	0.443**	0.392**	0.522**	0.432**	0.468**	0.391**	0.499***	0.462**
	(0.18)	(0.17)	(0.21)	(0.17)	(0.20)	(0.17)	(0.19)	(0.19)
Observations	558	558	558	558	558	558	558	558
Hansen's J statistic	-	1.42	1.46	0.09	3.50	1.42	1.65	3.54

Note: Values between square brackets are standard deviations. Clustered sandwich estimator option was used in order to allow for intragroup correlation (state-level). Instruments: 1- protected areas; 2- slope. Significance: ***=1%; **=5%; *=10%. All regressions control for the micro-region human capital, GDP per capita, population, population density, existence of an airport, regional dummies and level of patents.

Our findings show a positively signed effect of the interaction variable, indicating that the more developed regions of the country are benefiting more from road development. One possible explanation is related to the more developed infrastructure in those regions, which may have been facilitating the knowledge flows between local universities and firms. Moreover, those leading regions are also characterized by higher levels of income and education compared to the laggard regions U-I interactions and by hosting more developed transportation infrastructure, which may place them in a better position to reap the benefits from local-specific policies. Conversely, in the laggard regions of the country, the poor condition of the roads networks may lead to increased transportation costs, thus substantially undermining the flow of people engaged in the innovation sector in those micro-regions. In some cases, it may be more cost effective for innovative firms based in low-income regions to use other modes of transportation such as air transportation in order to go after more distant and highly ranked universities and research groups located in high-income states.

5. Concluding remarks

Using a research group database merged with highways information both at the micro-regional scale, we estimate the causal effect of interstate and intrastate roads on local U-I collaborations. The empirical strategy is based on models for binary and count dependent variables that are robust to reverse causality. Our findings point out that better roads in a micro-region rise local U-I linkages over a six-year period, indicating that the “local within-region knowledge flows” channel found by Agrawal, Galasso and Oettl (2017) also works through the interaction among firms and universities. Better transportation infrastructure accelerates the mobility of workers and researchers and the diffusion of knowledge across space, allowing ideas to cross-fertilize. We tried several robustness checks in order to provide reliable results. The positive effects of road stock on U-I interactions seem to be robust to several instrument specifications and control variables, including broadband infrastructure, road quality, neighboring road stocks, regional heterogeneity, demographic and development variables.

We also investigate the possible existence of heterogeneous effects by firm and research group size and stages of regional development. Our additional estimates find larger collaborations effects for smaller research groups and firms and high-quality research groups. We also find a larger road effect on local U-I linkages in the high-income regions of the country. This result appears to indicate that roads are stimulating U-I connections only in more economically and socially developed states, thus possibly reinforcing a vicious circle of regional disparities across the country. Also, we find a negative spatial externality of roads stock on U-I linkages in Brazil. This result may be partially attributed to the huge discontinuity in the Brazilian innovation system, wherein great urban centers are surrounded by poor regions, concentrating productive and innovative activities in few central places. The neighboring less developed regions may not be endowed with the necessary economic and social conditions to effectively benefit from the knowledge spillovers stemming from more dynamic regions.

As stated by Wang et al. (2018), when designing innovation policy, the role of infrastructure should be included in the toolkit. It is shown here that transportation infrastructure endowments may shape the way that regions benefit from innovation spillovers. In addition, our estimates also suggest that road networks may increase regional gaps through U-I collaborations as firms and universities interact more in the developed regions than in the less developed regions. Given the existence of infrastructure's negative spatial effects on U-I linkages, coordinated policies might be needed in order to avoid competition among local governments using highway infrastructure investment to attract firms and workers. Road policies seem to be an important tool in promoting a more balanced economic development, since it benefited more small firms and research groups, who have less resources to seek distant partners. Also, complementary policies aimed at improving human capital and other absorptive capabilities may also be important to amplify knowledge diffusion (Zhang and Ji, 2019).

Our study has some limitations. The lack of longitudinal data at the micro-regional scale prevents us from studying time heterogeneity (Straub, 2011). The effects of roads on the different types and sectors of the U-I collaborations have not been studied as well. We leave those as future research topics.

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CONFLITO DE INTERESSE

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