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

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Abstract

The university-industry (U-I) linkages have become a subject of growing interest in studies on innovation. One of the key aspects discussed in this literature is that knowledge spillovers stemming from research activities tend to be bounded in space. Therefore, an adequate transportation infrastructure efficiently connecting universities and industries may be of paramount importance for a successful innovation strategy as it facilitates the exchange of ideas and knowledge diffusion between both interested parties. In this work, we examine the impact of an increase in roads provisioning on U-I linkages in Brazil using instrumental variables Probit and Tobit econometric models to account for possible endogeneity issues. Our results suggest that an increase in the provision of highways positively impact U-I interactions. We also show that the effect of a growing road network on local U-I collaborations are greater for small-sized firms, higher-quality research groups and high-income micro-regions. Also, we find a negatively signed effect of spatial spillover of roads on U-I linkages, thus suggesting that the highway system may be spatially concentrating knowledge flows in Brazil.

1. Introduction

Universities have been playing a central role in fostering technological progress in firms (Garcia et al., 2015). However, it is also known that knowledge spillover is bounded in space, thus imposing a limit to collaborative efforts between universities and firms (Jaffe et al., 1993; Feldman and Audretsch, 1999). This implies that pervasive knowledge building requires not only more investments in higher education, but also more investments in the provisioning of adequate road network and efficient transportation systems in order to connect places and boost learning and knowledge diffusion (Feldman and Kogler, 2010).

Firms and universities tend to be co-localized (Jaffe, 1989; Audretsch and Feldman, 1996). Spatial agglomeration may stimulate the maintenance of frequent contacts between academic researchers and firms' research and development staff (Garcia et al., 2013). Innovative activity tends to be more concentrated than industrial activity (Carlino and Kerr, 2015). 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] (Brazilian Ministry of Science and Technology, 2016). 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). The geographical distribution of the country's highway network also follows a similar pattern (Figure 2). Such an agglomeration process in terms of both roads, and productive and innovative activities, creates a vicious circle. If a micro-region has a poor road infrastructure and high transportation costs, firms might not be able to interact 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.

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[1] Figure A1 in the Appendix A shows the map of Brazil by region and state.
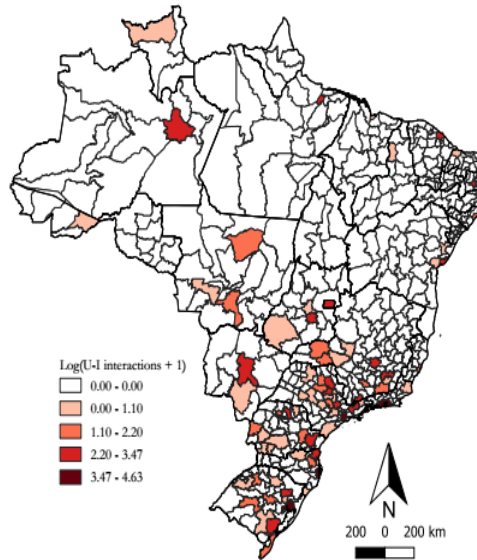
Figure 1. Territorial distribution of local U-I collaborations in Brazil: 2016
Source: Authors' elaboration using data from the Brazilian Ministry of Science and Technology.
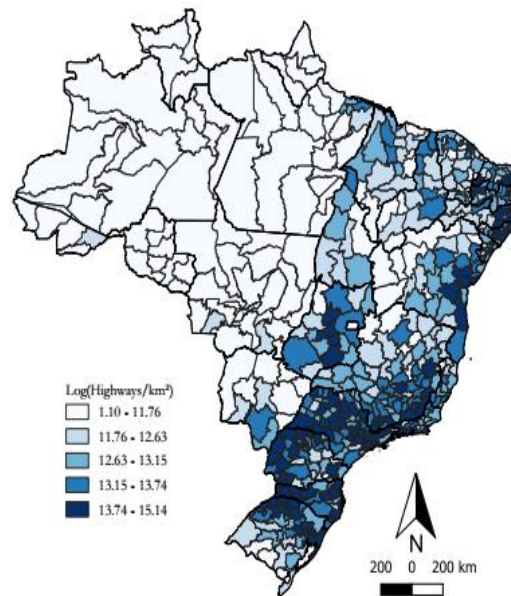

Figure 2. Territorial distribution of highways in Brazil: highways density, 2010
Source: Authors' elaboration using data from the Ministry of Transport and the National Department of Transport Infrastructure.

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. Dong, Zheng and Kahn (2019) document a complementarity effect between knowledge production and the transportation network in China. Since bullet trains reduce cross-city commute times, they reduce the cost of face-to-face interactions between skilled workers who work in different cities. Following those three papers, we examine the impact of road development on local U-I collaborations in Brazil, an issue that has been overlooked by the innovation and the transportation infrastructure literature.

The paper contributes to the literature in several dimensions. First, we examine the role of inter and intrastate roads[2] on local U-I linkages in a developing country. Using Brazil's recent data set on U-I collaborations, we document that increases in the highways stock effectively increases local U-I linkages with a lag of six years in average. 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 accelerates 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. In order to avoid possible endogeneity issue, we employ an instrumental variables approach. The choice of instruments follows the related literature (Duflo and Pande, 2007; Saiz, 2010; Wang et al., 2018). The first instrument chosen is the slope of a micro-region, which measures the relative difficulty (cost) of constructing roads there. The second one 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. We also include state-level dummies as instrumental variables.

In addition, we also identify some heterogeneous effects of increased highways on local U-I interactions. The first one is related to firm size heterogeneity. Larger firms tend to interact more with universities in order to obtain new knowledge, improving their innovative capacity. In general, larger firms have less financial and educational obstacles to innovate (Bishop et al., 2011). Our study indicates a significant effect of highways stock for medium and especially small-sized firms. Smaller firms 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

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[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.

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.

We also provide insights on the role of roads on U-I linkages taking into account spatial issues. In this case, we first test for spatial heterogeneity by dividing the sample into the developed (South) region and the undeveloped (North) region. Infrastructure effects on growth and productivity might be greater in the initial stages of development, whilst in developed regions these impacts could be lower (Cosci and Mirra, 2018; Chen and Vickerman, 2016; Crescenzi and Rodríguez-Pose, 2012). Our findings show significant road effects on local U-I linkages only 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 spillovers 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 spatial spillovers effects, we include highways density in neighboring micro-regions in the regressions. Our findings provide evidence of a negatively signed and significant spillover 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 contributes to the emerging literature examining the relationship between transportation infrastructure and innovation (Agrawal, Galasso and Oettl, 2017; Dong, Zheng and Kahn, 2019; Wang et al., 2018) by showing that roads also act by stimulating U-I collaborations. The work also contributes to the literature on the determinants of U-I linkages (Bishop et al., 2011; D'Este and Iammarino, 2010; Garcia et al., 2015; Laursen et al., 2011). We show that more roads are an important factor to establish local interactions. Finally, our article is related to the literature evaluating the impact of transportation infrastructure on various outcome variables in a regional approach (Cosci and Mirra, 2018; Crescenzi and Rodríguez-Pose, 2012; Holl, 2016). The study

emphasize the significant impact of transportation infrastructure on innovation in the context of a developing economy, specifically by fomenting U-I collaborations.

The paper is organized as follows. Section 2 depicts the related literature. 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. Some authors argue that radical innovations come from outside the firms. The interaction among agents of different areas - such as firms, universities and governments – is essential to allow the sharing of existing knowledge and the absorption of new information (Etzkowitz and Leyedesdorff, 2000; Etzkowitz, 2003). Universities contribute to the formation of new and skilled professionals (Lundvall et al., 2002) and by doing basic and applied research, thus benefiting firms and the society (Nelson, 1990). 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; and Jaffe et al., 1993). Pecuniary knowledge externalities emerge from interactions among local agents, which tends 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 others 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, 2009; 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 increase the possibility of a firm to achieve a successful pattern of innovation. Breschi and Lissoni (2009) shows that the effect of spatial proximity on knowledge diffusion is not so strong. There are other factors that may influence knowledge flows rather than geographic proximity, including social and cognitive proximity, institutional and infrastructure aspects. 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).

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. Some recent works 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 channel, they find that improved roads expand market size, which in turn leads to more innovation. 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. Then, we merged this dataset with detailed information of firms' location and size collected from the Brazilian Ministry of Labor database. This way, we were able to combine information about the location of both firms and research groups. 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). 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 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 (km²) 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

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[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.

[5] We tried three measures: total road length; road density (total road length divided by the micro-region area in km²), 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.

provisioning 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:

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

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 log of total local U-I collaborations, "log(U-I interactions + 1)" as proposed by Wang et al. (2018) and Agrawal, Galasso and Oettl (2017)[8]. 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 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 Tobit models to estimate the impacts of highways on U-I collaborations. These models are suitable[9] when using binary and censored 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 Tobit would yield biased estimates of the causal effect of highways on U-I linkages. In order to avoid the problem of omitted variables, we also employ an instrumental variables approach.

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

[8] In this case, the log form was applied to patent data.

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

3.3. Instrumental variables

We employ two instruments based on the transportation infrastructure literature. The first one is the slope of a micro-region, which measures the relative difficulty (cost) of constructing roads in the region (Duflo and Pande, 2007; Saiz, 2010; 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 a less winding construction. To conform 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. The second instrument 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 constructing highways. Building roads in these areas requires incurring in heavy bureaucratic costs including environmental licensing and long delays in permit issuance by local authorities. We also include state-level dummies as instrumental variables[11]. State governments control a substantial proportion of the highways in our dataset. The insertion of the state-level dummies allows us to control for possible heterogeneities in terms of infrastructure policy.

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.

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[10] These are conservation units (sustainable use and integral protection), military areas and indigenous lands.
[11] State governments may also influence innovation policies, which lays some doubt on the validity of these instruments. We estimated the same models without these instruments and the results remained quite similar.

Table 1. Summary statistics

Variable	Obs.	Mean	Std. dev.	Min	Max
Highways (density)	558	12.40	2.149	1.101	15.13
Log(U-I interactions + 1) - All	558	0.263	0.740	0	4.710
Log(U-I interactions + 1) - 2010	558	0.245	0.718	0	4.635
Having at least one U-I interaction - All	558	0.157	0.364	0	1
Having at least one U-I interaction - 2010	558	0.142	0.349	0	1
GDP per capita	558	2.883	0.611	1.635	5.045
Population	558	12.19	0.954	7.983	16.50
Demographic Density	558	7.984	1.509	3.478	13.35
Airport	558	0.618	0.486	0	1
South-Southeast	558	0.451	0.498	0	1
Patents	558	0.527	1.185	0	7.158
Instruments					
Slope	558	0.069	0.103	0.001	0.835
Protected areas	558	0.074	0.162	0.000	0.972

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). We note a positive but not significant effect of roads on U-I collaborations based on conventional Probit and Tobit models. 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). The results for the Wald test of exogeneity allow us to reject the null hypothesis of no endogeneity, which supports our choice of using Tobit/Probit models that control for endogeneity.

Table 2. Highways stimulate local University-Industry interactions

Variable	Probit-All	Probit-2010	IV-Probit-All	IV-Probit-2010	Tobit-All	Tobit-2010	IV-Tobit-All	IV-Tobit-2010
	Having at least one U-I interaction				Log(U-I interactions + 1)			
Highways	0.061	0.128	0.167*	0.297***	0.075	0.136	0.199*	0.332**
	(0.07)	(0.10)	(0.10)	(0.11)	(0.08)	(0.10)	(0.11)	(0.16)
Controls	√	√	√	√	√	√	√	√
Observations	558	558	558	558	558	558	558	558
Log likelihood	-143	-131	-924	-911	-250	-233	-1032	-1014
Left-Censored Observations					466	475	466	475
Wald test (p-value)			0.054	0.040			0.050	0.056

Obs: 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- existence of protected areas; 3- state dummies. Significance: ***=1%; **=5%; *=10%. All regressions control for the micro-region GDP per capita, population, demographic density, existence of an airport, South-Southeast regimes and level of patents.

In order to avoid this endogeneity, we turn to an instrumental variables estimation. The IV estimations are described in columns "IV-Probit" and "IV-Tobit" (Table 2)[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. In the first regression using "Having at least one U-I interaction" as dependent variable (IV-Probit-All), the coefficient of 0.167 implies that more roads in 2010 led to more U-I collaborations six years later. The same finding holds by using the "Log(U-I interactions + 1)" (IV-Tobit-All). These estimation results are based on all U-I interactions that occurred in 2016 and are in line with the previous literature that has shed some light on the positive effect of the stock of highways on innovation (Agrawal, Galasso and Oettl, 2018; Dong, Zheng and Kahn, 2019; Wang et al., 2018).

However, 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, we tested the

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[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.

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. Columns "IV-Probit-2010" and "IV-Tobit-2010" report the results focusing on the knowledge flows channel. Our estimates show a positive and strong effect of the highways stock in 2010 on U-I linkages in 2016. 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. Our estimates in the next sections are based on the sample of firms and research groups that already existed in 2010[13].

4.2. *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[14].

The estimates by firm size are described in Table 3. This new set of estimations sheds some light on the presence of heterogeneities associated with firm size. Although we did not see significant effects of highways on local U-I interactions of larger firms, columns "M&S" and "Small" indicate a significant effect of increases in highways stock for medium and especially small-sized firms. Small and medium-sized 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 and medium-sized firms face worse conditions to 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

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[13] We also tried the full sample, and the result remained quite similar.
[14] 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.

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.

Table 3. Highways stimulate local University-Industry interactions: firm size heterogeneity

Variable	Having at least one U-I interaction				Log(U-I interactions + 1)			
	Large	M&S	Medium	Small	Large	M&S	Medium	Small
Highways	0.154	0.164*	0.042	0.152**	0.133	0.198*	0.035	0.204**
	(0.09)	(0.10)	(0.07)	(0.07)	(0.12)	(0.10)	(0.08)	(0.09)
Controls	√	√	√	√	√	√	√	√
Observations	558	558	558	558	558	558	558	558
Log likelihood	-61	-919	-89	-906	-95	-1022	-131	-999
Left-Censored Observations					526	469	514	478
Wald test (p-value)		0.050		0.018		0.031		0.019

Obs: Dependent variable: log of the number of U-I interactions. M&S indicates sample of medium and small firms. 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- existence of protected areas; 3- state dummies. Significance: ***=1%; **=5%; *=10%. Columns "Large' and "Medium" were estimated by Tobit and Probit models without instrumental variables, since Wald test of exogeneity did not point to endogeneity problems. All regressions control for the micro-region GDP per capita, population, demographic density, existence of an airport, South-Southeast regimes and level of patents.

In unreported estimates, we also tested the effects of highways according to the size of the research group[15]. Research groups with more researchers have more accumulated capabilities, which overcome barriers to collaborating with industry partners (De Fuentes and Dutrénit, 2012). We found no difference between large groups and the other groups.

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 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 4.

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[15] 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.

Table 4. Highways stimulate the University-Industry interactions: research group quality

Variable	Having at least one U-I interaction		Log(U-I interactions + 1)	
	High	Other	High	Other
Highways	0.488***	0.239**	0.868**	0.212*
	(0.16)	(0.11)	(0.38)	(0.12)
Controls	√	√	√	√
Observations	558	558	558	558
Log likelihood	-851	-914	-905	-1012
Left-Censored Observations			518	471
Wald test (p-value)	0.060	0.053	0.040	0.099

Obs: Dependent variable: lof of the number of U-I interactions. M&S indicates sample of medium and small firms. 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- existence of protected areas; 3- state dummies. Significance: ***=1%; **=5%; *=10%. All regressions control for the micro-region GDP per capita, population, demographic density, existence of an airport, South-Southeast regimes 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. *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). 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). 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 split the sample in two regions, namely North and South, and re-estimate eq. (1) for both regions separately. While the Northern region consists of the low-income states, the Southern region is constituted by the high-income states of the country. Table 5 presents our estimates:

Table 5. Highways stimulate University-Industry interactions: regional heterogeneity

Variable	Having at least one U-I interaction		Log(U-I Interactions + 1)	
	Probit-South	Probit-North	Tobit-South	Tobit-North
Highways	1.212***	-0.097	2.007***	-0.046
	(0.16)	(0.08)	(0.52)	(0.08)
Controls	√	√	√	√
Observations	254	304	254	304
Log likelihood	-309	-30	-381	-58
Left-Censored Observations			196	279
Wald test of exogeneity (p-value)	0.001		0.001	

Obs: 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- existence of protected areas; 3- state dummies. Significance: ***=1%; **=5%; *=10%. Columns "Tobit-North' and "Probit-North" were estimated by Tobit models without instrumental variables, since Wald test of exogeneity did not point to endogeneity problems. All regressions control for the micro-region GDP per capita, population, demographic density, existence of an airport, South-Southeast regimes and level of patents.

Our findings show significant road effects on local U-I linkages only in the South region where the advanced states are located. 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 flows 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.

4.4. *Spatial spillover effects*

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; 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. A part 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 spillovers effects, we include highways density in neighboring micro-regions in the regressions. To create the 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 the Appendix B). On the other hand, there are "high-high" clusters in the Southeast and South regions.

Table 6 describes the estimation results. Even controlling for spatial autocorrelation, the positive direct effects of the highways stock on U-I interactions remained. Our findings evidence 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 6. Highways stimulate University-Industry interactions: spatial spillover effects

Variable	Having at least one U-I interaction	Log(U-I interactions + 1)
	SProbit	STobit
Highways	0.680***	0.774***
	(0.15)	(0.26)
Highways, spatial lag	-0.425***	-0.459***
	(0.10)	(0.14)
Controls	√	√
Observations	557	557
Log likelihood	-976	-1260
Left-Censored Observations		474
Wald test of exogeneity (p-value)	0.000	0.000

Obs: 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- existence of protected areas; 3- state dummies; 4 – spatial lags of control variables. Significance: ***=1%; **=5%; *=10%. Columns "STobit-North' and "SProbit-North" were estimated by Tobit models without instrumental variables, since Wald test of exogeneity did not point to endogeneity problems. All regressions control for the micro-region GDP per capita, population, demographic density, existence of an airport, South-Southeast regimes and level of patents. We missed an observation because it was an island.

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 tends 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).

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 spillover effects, larger road networks in 2010 caused an increase in U-I interactions in 2016.

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 censored 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 also investigate the possible existence of heterogeneous effects by firm size and stages of regional development. Our additional estimates find larger collaborations effects for smaller firms and high-quality research groups. We also find a significant road effect on local U-I linkages only 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. Next, 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. 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 road quality data at the micro-regional scale prevent us from studying this source of 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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APPENDIX A

Figure A1. Brazil's map: regions and states.

Table A1. Variables description and sources.

Variable	Description	Source
Highways (length)	Paved federal and state highways (km)	Elaborated by the authors using data from Ministry of Transport and the National Department of Transport Infrastructure
Highways (density)	Paved federal and state highways (kilometers) divided by micro-region area (km²)	Elaborated by the authors using data from Ministry of Transport, National Department of Transport Infrastructure and Institute of Geography and Statistics
Log(U-I interactions + 1) - All	Number of U-I linkages that occurred within the same micro-region plus one, log form	Elaborated by the authors using data from Brazilian Ministry of Science and Technology - CNPq Directory of Research Groups
Log(U-I interactions + 1) - 2010	Number of U-I calls that occurred between research groups and firms that already existed in 2010 within the same micro-region and plus one, log form	Elaborated by the authors using data from Brazilian Ministry of Science and Technology - CNPq Directory of Research Groups
Having at least one U-I interaction - All	This variable takes the value one 1 if there were U-I interactions within the micro-region and 0 otherwise	Elaborated by the authors using data from Brazilian Ministry of Science and Technology - CNPq Directory of Research Groups
Having at least one U-I interaction - 2010	This variable takes the value one 1 if there were U-I interactions between research groups and firms that already existed in 2010 within the micro-region and 0 otherwise	Elaborated by the authors using data from Brazilian Ministry of Science and Technology - CNPq Directory of Research Groups
Log(U-I interactions – Large Firms +1) - 2010	Number of U-I calls that occurred between research groups and large firms that already existed in 2010 within the same micro-region and plus one, log form	Elaborated by the authors using data from Brazilian Ministry of Science and Technology - CNPq Directory of Research Groups
Log(U-I interactions – Small and Medium Firms +1) - 2010	Number of U-I calls that occurred between research groups and medium and small firms that already existed in 2010 within the same micro-region and plus one, log form	Elaborated by the authors using data from Brazilian Ministry of Science and Technology - CNPq Directory of Research Groups
Log(U-I interactions – Medium Firms + 1) - 2010	Number of U-I calls that occurred between research groups and medium firms that already existed in 2010 within the same micro-region and plus one, log form	Elaborated by the authors using data from Brazilian Ministry of Science and Technology - CNPq Directory of Research Groups

| Log(U-I interactions – Small Firms + 1) - 2010	Number of U-I calls that occurred between research groups and small firms that already existed in 2010 within the same micro-region and plus one, log form	Elaborated by the authors using data from Brazilian Ministry of Science and Technology - CNPq Directory of Research Groups
Higher Education (% population)	Percentage of population with at least higher education	Atlas of Human Development in Brazil
GDP per capita	Gross Domestic Product (R$ million) divided by population, log form	Elaborated by the authors using data from Brazilian Institute of Geography and Statistics
Population	Population (number), log form	Brazilian Institute of Geography and Statistics
Demographic Density	Population (number) divided by area (km²)	Elaborated by the authors using data from Brazilian Institute of Geography and Statistics
Airport	This variable takes the value one 1 if there were a paved airport in the micro-region and 0 otherwise	Elaborated by the authors using data from Ministry of Transport, National Civil Aviation Agency and Brazilian Airport Infrastructure Company - INFRAERO
South-Southeast	This variable takes the value one if the micro-region is in the South or Southeast regions and 0 otherwise	Elaborated by the authors using data from Brazilian Institute of Geography and Statistics
Patents	Number of patent applications, log form	Elaborated by the authors using data from National Institute of Industrial Property
Slope	Proportion of area with slope above 20 degrees	Elaborated by the authors using data from Ministry of Mines and Energy - Geological Survey of Brazil
Protected areas	Percentage of protected areas (sustainable use and integral protection), military areas and indigenous lands	Elaborated by the authors using data from Ministry of the Environment
States	Dummies variables for each one of the 27 Brazilian states	Elaborated by the authors using data from Brazilian Institute of Geography and Statistics

Table A2. Correlation matrix.

	Highways density	Log(U-I interactions+1)	Having at least one U-I interaction	Slope	Protected areas
Highways density	1				
Log(U-I interactions+1)	0.201	1			
Having at least one U-I interaction	0.214	0.838	1		
Slope	0.159	0.046	0.024	1	
Protected areas	-0.638	-0.066	-0.087	-0.022	1

APPENDIX B

Figure B1. Moran's I Scatter Plot (left) and Local Moran's I (left): highways density, 2010
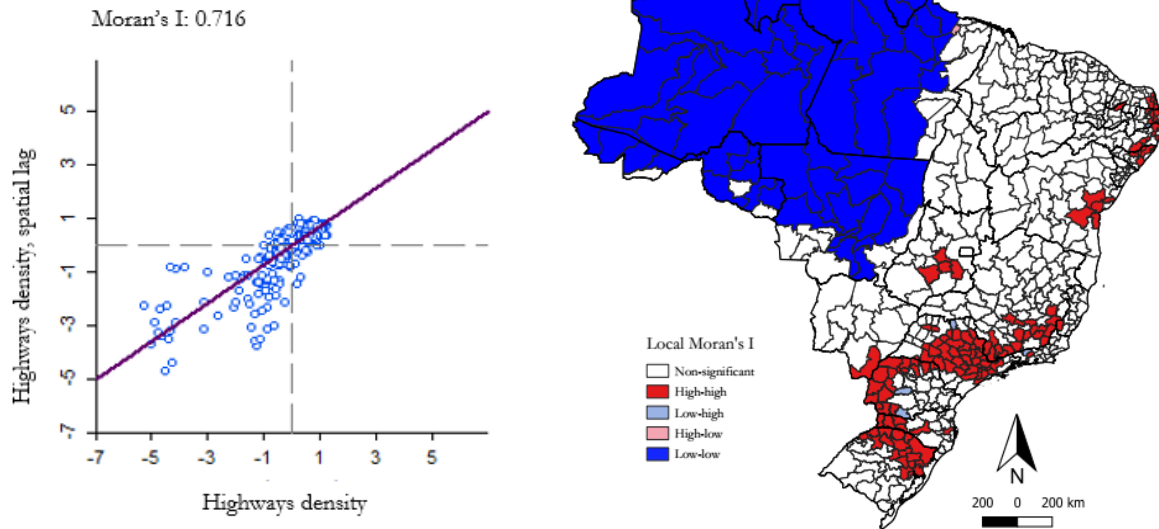
Source: Calculated by the authors based on data from the Ministry of Transport and the National Department of Transport Infrastructure.