Highway Infrastructure and Greenhouse Gas Emissions: evaluating environmental costs of road investments in Brazil

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Abstract

This study evaluates the highway infrastructure development impacts on greenhouse gas (GHG) emissions. To this end, we use detailed local-level data from Brazilian municipalities during the Growth Acceleration Program (PAC) period (2007-2018) and apply an instrumental variable identification approach to circumvent endogeneity concerns related to the non-random placement of roads. We find that an 1% increase in road investments raises CO2 emissions by 0.025%. Those damaging highways effects are sustained for the road, energy, and land use change sectors. In addition, findings point out heterogenous road impacts on CO2 emissions depending on agglomeration, population scale, deforestation, and technology. From the econometric estimates, we calculate an average CO2 Emissions Return Rate to Highway Investments (ERR) of 3.0%, implying a discount on the economic benefits of road investments proved in past studies.

Keywords: infrastructure; environmental costs; greenhouse gas emissions; regional development.

Resumo

Este estudo avalia os impactos do desenvolvimento da infraestrutura rodoviária nas emissões de gases de efeito estufa (GEE). Para isso, usamos dados detalhados em nível local de municípios brasileiros durante o período do Programa de Aceleração do Crescimento (PAC) (2007-2018) e aplicamos uma abordagem de identificação de variável instrumental para contornar preocupações de endogeneidade relacionadas à colocação não aleatória de estradas. Constatamos que um aumento de 1% nos investimentos em estradas aumenta as emissões de CO2 em 0,025%. Esses efeitos prejudiciais das rodovias são mantidos nos setores de estradas, energia e mudanças no uso da terra. Além disso, os resultados apontam para impactos heterogêneos das estradas sobre as emissões de CO2, dependendo da aglomeração, da escala populacional, do desmatamento e da tecnologia. Com base nas estimativas econométricas, calculamos uma taxa média de retorno de emissões de CO2 para investimentos em rodovias (ERR) de 3,0%, o que implica um desconto nos benefícios econômicos dos investimentos em rodovias comprovados em estudos anteriores.

Palavras-chave: infraestrutura; custos ambientais; emissões de gases de efeito estufa; desenvolvimento regional.

Área temática: 1. Economia.

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1. Introduction

A broad strand of literature has proven the positive role of transportation infrastructure on economic growth and productivity (Aschauer, 1989; Baum-Snow et al., 2020; Bird and Straub, 2020; Faber, 2014; Foster *et al*., 2023a, 2023b; Ghani *et al.,* 2014; Herzog, 2021; Jaworskiy and Kitchensz, 2019; Straub, 2011; Zhang e Ji, 2019). Some of those investigations has calculated economic return rates to highway investments as a measure of its profitability, which are used to guide cost-benefit analysis and transportation policies around the world (Fernald, 1999; Li *et al*., 2017; Medeiros *et al.,* 2021b; Medeiros *et al*., forthcomingb; Wang *et al.*,2020). Whilst those studies have provided important results, the environmental costs (or benefits) of highway investments are put aside.

In this paper, we evaluate the unclear relationship between highway infrastructure development and greenhouse gas (GHG) emissions. On the one hand, road construction and enhancement tend to increase GHG emissions in the construction and maintenance phases by the direct use of materials and equipment. Once the highway is built, the growth in the road network increases regional accessibility, population mobility and interregional traffic flows, boosting transportation demand and affecting the level of GHG emissions. On the other hand, road development might decrease GHG emissions by reducing the travel time and distance, which lowers GHG emissions during transportation, as well as by stimulating agglomeration economies, reducing energy consumption, and boosting energy efficiency. Empirical findings are mixed, pointing out increasing effects (Churchill *et al*., 2021; Emodi *et al*., 2022; Ghannouchi *et al*., 2023; Lin *et al*., 2017; Luo *et al*., 2018; Xiao *et al*., 2023; Xie *et al*., 2017; Yao *et al*., 2023) as well as null or reducing impacts (Georgatzi *et al*., 2020; Ghannouchi *et al*., 2023; Han *et al*., 2017; Li and Lu, 2022) of highway infrastructure on GHG emissions. In addition, there are heterogenous road impacts on GHG emissions depending on agglomeration, development level and economic growth, population scale, technology, among other moderating variables.

Whilst the literature on road infrastructure and GHG emissions has provided relevant findings and discussed critical transmission channels, some gaps remain. First, to the best of our knowledge, there are no studies that calculate a sustainable return rate to highways investments, i.e., adding (discounting) the environmental benefits (damages) from the broad evaluated economic returns of road investments, which would be relevant to infrastructure policy planning, design, financing, and evaluation. Second, investigations using detailed local level data are scarce, and the existing literature relates to China (Han *et al*., 2017; Li and Lu, 2022; Luo et al., 2018; Xiao et al., 2023; Xie et al., 2017; Yao et al., 2023). Using local data at the municipal (city) level might capture important heterogeneities across the space, providing new evidence to the specialized literature. Third, the most part of papers has studied European countries or China, wherein the energy and industry sectors are the most important sources of GHG emissions. Then, analyzing cases in which other sectors such as land use change and agriculture are more relevant to GHG emissions might shed some light on new transmission channels and heterogeneous impacts of road development on the environment. We seek to contribute to the literature in those directions.

We evaluate the highway investments impacts on GHG emissions growth in Brazilian municipalities during the Growth Acceleration Program (PAC) period (2007-2018). To this end, we use detailed local level data on national road investments and GHG emissions and apply an econometric approach dealing with the endogeneity coming from the non-random placement of roads, allowing us to identify causal road impacts on greenhouse gas emissions. From these estimates, we calculate carbon dioxide equivalent emissions return rates (ERR) and sustainable return rates (SRR) to highway investments to several Brazilian localities.

The Brazilian case study is interesting for several reasons. First, the PAC (divided into PAC 1 and 2) was the most important Brazilian infrastructure program in the last decades, doubling the level of investments in highway infrastructure compared to the previous ten years (Medeiros et al., 2021b). Second, Brazil presents deep regional heterogeneities in terms of infrastructure endowment, income

(Medeiros *et al.*, 2021a, 2022; Medeiros and Ribeiro, 2020), and GHG emissions. Third, differently from the most part of studies evaluating the Chinese and European cases wherein energy and industry sectors are the most important sources of GHG emissions, the Brazilian economy presents the land use change and agriculture sectors as the main contributors to GHG emissions. Then, our case study is ideal for evaluating the economic and environmental profitability of road investments in a developing country context with huge regional disparities, and to provide novel transmissions channels from roads to the environment in a unique environmental scenario.

Furthermore, the Brazilian Federal Government launched the third PAC in August 2023. To the best of our knowledge, that is the first time in the Brazilian history that an extensive national infrastructure program includes explicit environmental proposals. As one of the main mechanisms to foster environmental practices in the infrastructure sector, the Brazilian Government prioritizes and facilitates the availability of funds to projects with environmental devices fostering and accelerating the ecological transition. In the transportation sector specifically, the "new" PAC presents the "Efficient and Sustainable Transport" pillar, which deliberates investments of around R$ 349.1 billion in several transportation buildings, including the road sector. Additionally, the program provides several institutional initiatives related to environmentally suitable road infrastructure. For instance, the program incentives the ecological transition through issuing sustainable sovereign bonds, expanding the resources of the Climate Fund (*Fundo Clima*), promoting low-carbon transportation such as hybrid and electric vehicles, encouraging decarbonization and the use of sustainable materials in the construction sector.

Whilst those policy tools are critical to the Brazilian sustainable development, a clear regionalized measure indicating the environmental costs (or benefits) of highway investments is lacking. In this context, an evaluation of the "old" PAC – in which emphatic environmental initiatives related to the road sector were in most part absent–, is critical to provide evidence on the environmental costs of road investments, maximizing its economic returns whilst respecting environmental preservation and recovery. Then, a novel measure of sustainable return rate to highway investments might represent a key input to policymakers, technicians, financial institutions, and the civil society in planning, designing, financing, and evaluating current and future road policies.

In this context, we find three main results. First, we find that an 1% increase in road investments raises GHG emissions by 0.025%. This result is maintained under various specifications capturing heterogeneous road impacts, as well as under several robustness checks. Second, we calculate an average GHG emissions return rate to highway investment (ERR) of 3.0%, demonstrating a harmful environmental impact of roads. By subtracting our ERR from the economic return rate to highway investments (RR) from Medeiros *et al.* (forthcomingb), we find an average Sustainable Return Rate to Highway Investments (SRR) of around 17%, indicating a widespread need to develop the Brazilian transportation sector even considering its environmental costs. To reduce our average SRR of 17% to the threshold of 8.5%, Brazil would need 2 times more highways, which implies a road stock of 14% of national GDP, in line with Frischtak and Mourão (2017) and Medeiros et al. (2021b). Third, we find important regional heterogeneities in our ERR and SRR. In general, the environmental damages from roads are more pronounced in less populated and poorer localities, which coincides with some critical areas in the Brazilian Amazon.

Our main contributions to the specialized literature on infrastructure and regional development are fourfold. First, we propose two novel regional measures related to the environmental costs of highway investments: i) the CO2 Emissions Return (Discount) Rate to Highway Investments (ERR); and ii) the Sustainable Return Rate to Highway Investments (SRR). In doing so, we provide novel easy-to-interpret measures in the context of political decision-making. Second, we provide original evidence on the relationship between highway infrastructure development and GHG emissions in a context wherein land use change and agriculture sectors are the most important contributors to GHG emissions. Third, we advance in relation to past studies by evaluating new heterogenous road impacts on GHG emissions, mainly related to the environmental institutional weaknesses from deforestation and illegal land use. Fourth, we circumvent endogeneity issues coming from the non-random placement of roads by adapting an instrumental variable identification approach to the GHG emissions context.

This paper is structured as follows. Section 2 describes the related empirical literature. Section 3 presents the methods and data. Section 4 outlines the econometric results. Section 5 provides the results in terms of the sustainable return rate to highway investments. Section 6 concludes.

2. Related Literature

2.1. Transportation infrastructure and economic development

A massive strand of literature has investigated the relationship between transportation development and economic activity (Baum-Snow *et al.*, 2020; Bird and Straub, 2020; Duranton *et al.*, 2014; Faber, 2014; Fedderke and Bogetic, 2009; Foster *et al.*, 2023a, 2023b; Jaworski and Kitchens, 2019; Straub, 2011). Since the pioneering study by Aschauer (1989), several empirical studies have proved a positive role of highway investments on productivity and growth (Ghani *et al.*, 2014; Fahardi, 2015; Herzog, 2021; Holl, 2016; Li et al., 2017; Zhang and Ji, 2019).

Related papers calculated economic return rates (RR) to infrastructure investments to provide an easy-to-interpret measure for policymakers and the society. Fernald (1999) measured a RR of 6.0% using United States data, Li *et al.* (2017) and Wang *et al.* (2020) found return rates for China of around 11% and 23%, respectively, whilst Medeiros *et al.* (2021, *forthcomingb*) and Medeiros *et al.* (*forthcominga*) measured RRs around between 20% and 22.2% using Brazilian data. In general, findings confirms that road investments are profitable, especially in the developing world context.

Nonetheless, none of those articles include environmental costs (benefits) of road investments into the return rate. In other words, the measured return rates are based on the relationship between highway infrastructure investments and economic activity, mainly represented by Gross Domestic Product (GDP) or GDP *per capita*, neglecting any environmental impact from road investments such as increased GHG emissions (Churchill *et al.*, 2021; Xie *et al.*, 2017; Yao *et al.*, 2023), deforestation (Asher et al., 2020), energy efficiency (Lin and Chen, 2020), or ecological footprint (Awad et al., 2023). Disregarding environmental impacts of highway investments might bias the return rates, and directly impact road public policies. Next, we take into consideration the relationship between highway infrastructure development and the environment by focusing on GHG emissions, the most evaluated environment outcome in transportation studies.

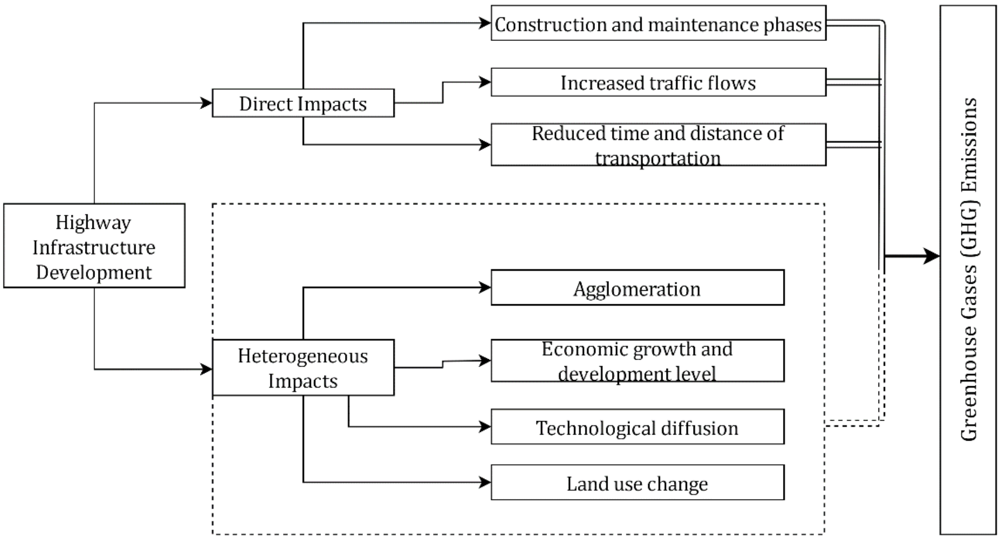
2.2. Highway infrastructure and sustainable development

A recent strand of literature has investigated the nexus between road investments and GHG emissions (Emodi *et al.*, 2022; Georgatzi *et al.*, 2020; Ghannouchi *et al.*, 2023; Luo *et al.*, 2018). This relationship is not clear, and there are two opposite views on the effect of highway infrastructure development on GHG emissions (Xu *et al.*, 2022). On the one hand, in the construction and maintenance phases, infrastructure development tends to increase GHG emissions directly by using materials and equipment, which tends to be characterized by heavy-duty fuel-intensive equipment and require the use of large quantities of concrete and asphalt (Han *et al.*, 2017; Lin *et al.*, 2017). Once the highway is built, the growth in the road network increases regional accessibility, population mobility and interregional traffic flows, boosting transportation demand and affecting the level of GHG emissions . On the other hand, some investigations suggest that developing highway infrastructure has a GHG reduction effect by lowering the travel time and distance, which decreases GHG emissions during transportation. In addition, transportation infrastructure development might promote agglomeration and technology diffusion, which might support the development of energy savings and emissions reduction.

Following this line of research, some investigations have provided evidence on the road impact heterogeneity on GHG emissions (Churchill *et al.*, 2021; Li and Lu, 2022; Lin *et al.*, 2017; Xiao *et al.*, 2023; Xie *et al.*, 2017; Yao *et al.*, 2023). Figure 1 summarizes the mechanisms.

The most evaluated heterogeneity is related to agglomeration economies. Developed highway infrastructure optimizes the flows of goods and services as well as the mobility of people within the region, increasing the spatial agglomeration of economic activity through economies of scale and scope. In turn, agglomeration and GHG emissions are strongly correlated. On the one hand, agglomeration tends to increase GHG emissions due to increased production scale and congestion effects. On the other hand, some positives externalities in terms of knowledge spillovers and technological advances might improve energy efficiency and lower energy consumption, decreasing GHG emissions. Then, studies have found that highway infrastructure expands GHG emissions in the early stages of urbanization and agglomeration, but after agglomeration exceeds a threshold, positive externalities from agglomeration are expected to offset the environmental damaging effects (Xu *et al.*, 2022).

Figure 1. The impacts of highway infrastructure on GHG emissions



Source: authors' elaboration.

Other researchers have examined different heterogeneity sources, as economic growth, technological innovation, tourism, among others (Churchill *et al*., 2021; Xiao *et al*., 2023; Xie *et al*., 2017). A huge number of studies has proven the positive role of highway investments on economic growth (Baum-Snow *et al.*, 2020; Bird and Straub, 2020; Faber, 2014; Ghani *et al.*, 2014). In turn, economic growth is an important determinant of GHG emissions, as investigations have shown a significant and non-linear relationship between those variables. In addition, transportation infrastructure development fosters the mobility of people, services, and goods, enhancing the spread of knowledge and technology. Technology diffusion impacts GHG emissions and intensity by stimulating human capital formation and higher R&D expenses. Then, the road impacts on GHG emissions are expected to vary according to local economic growth and technological innovation.

Besides those investigated moderating variables, other road impact heterogeneities might emerge depending on the local context of GHG emissions. For instance, land use change has been the most important contributor to GHG emissions in Brazil. The opening of roads might directly impact GHG emissions though increasing the number of vehicles on the roads, but also by expanding deforestation and illegal land use. Road construction in isolated areas might boost land supply, decreasing land prices and motivating a process of predatory agriculture production wherein landowners have incentives enough to buy new lands instead of improving the existing ones (Carrero *et al.*, 2022; Da Silva *et al.*, 2023; Ferrante *et al*, 2021; Lima *et al.*, 2022). In addition, the level of deforestation might capture institutional weaknesses related to the environment, which may be translated into a more harmful effect of road infrastructure development on GHG emissions. Then, road investments are expected to present heterogeneous impacts on GHG emissions depending on the level of deforestation and the efficacy of the environmental regulatory framework.

Findings are mixed. Some studies found that road investments increase GHG emissions (Churchill *et al.*, 2021; Emodi *et al.*, 2022; Ghannouchi *et al.*, 2023; Lin *et al.*, 2017; Luo *et al.*, 2018; Xiao *et al.*, 2023; Xie *et al.*, 2017; Yao *et al.*, 2023), whilst other investigations showed null or negative road impact on carbon emissions (Georgatzi *et al.*, 2020; Ghannouchi *et al.*, 2023; Han *et al.*, 2017; Li and Lu, 2022). In addition, there are heterogenous road impacts on GHG emissions depending on agglomeration, development level and economic growth, population scale, among other mediating variables.

Whilst this related literature has provided important evidence on the relationship between highway infrastructure and GHG emissions, some gaps remain. First, it is hard to interpret how much environmentally harmful (or beneficial) are the road investments. A way to overcome this issue is calculating a return rate to highway investments considering its effect on GHG emissions, which has not been made by past studies. Second, the most part of investigations has focused on China and European Countries, wherein GHG emissions are mainly generated by the energy and industry sectors. Evaluating the highway investment impact on the environment in different countries, in which GHG emissions depend more on other sectors such as land use change and agriculture might be an important contribution to literature. Third, studies on the nexus between road infrastructure and environmental outcomes at the regional or local levels are scarce, and the existing literature examines the Chinese case. Evaluating the road impacts on GHG emissions using detailed local level data might allow the identification of novel heterogeneities in this relationship. This paper seeks to contribute to the literature in those directions.

3. Methods

3.1. Baseline econometric specification

We intend to evaluate the highway investment impacts on municipal GHG emissions growth between 2007-2018. Our second-stage equation is specified as follows:

$$\Delta Y_{is} = \beta_0 + \alpha * HighwayInvestments_{is} + \beta' X_{is} + \theta_s + u_{is} \qquad (1)$$

Where Y_{is} is our dependent variable measured as CO2 equivalent emissions, i represents municipalities, s indicates the states, X_{is} is a vector of control variables, θ_s is a vector of state fixed effects and u_{is} is an idiosyncratic error term. We are interested in α, which measures the highway investment impact on CO2 emissions. As we take our variables in log form, α is the elasticity of CO2 emissions with respect to highway investments.

To estimate the causal impacts of highway investments on CO2 emissions, we adapt the third-step IV identification approach proposed by Medeiros et al. (forthcominga). To overcome measurement errors in the road investment variable – due to inefficiencies as corruption, harmful bureaucracy and poor infrastructure projects planning and execution – as well as reverse causality and omitted variable bias –policymakers might target more developed regions wherein the returns to infrastructure investments are higher, or focus on underdeveloped localities to foster regionally balanced economic growth – in the econometric estimates evaluating the road impacts on productivity in Brazilian municipalities, the authors built several instruments related to the propensity of municipalities to receive road interventions. In this paper, the same endogeneity issues may appear whether we have omitted variables affecting both environmental outcomes and road placement, which is highly expected (Asher *et al.*, 2020; Emodi *et al.*, 2022; Li and Luo, 2022).

Our preferred specification uses a Non-Random Allocation Index capturing the propensity of municipalities to receive highway investments as a source of quasi-random variation to road investments. To create the index, Medeiros et al. (forthcominga) used the Principal Component Analysis (PCA) method to reduce the data information of three original instruments. The first one is the distance from a hypothetical network constructed by using the Least Cost Path-Minimum Spanning Tree (LCP-MST) method following Faber (2014). This IV is a global minimization road network connecting the ending and starting points of those roads targeted by the PAC. The rationality behind the LCP-MST instrument is that this hypothetical highway network should affect city outcomes and the spatial allocation of industries

only through the actual highway network, conditional on controls. The second original IV follows the Bird and Straub (2020) Brasília experiment approach. The instrument is measured as the distance from targeted central cities to the capital Brasília, and its rationale is that the national Brazilian government in the 1950s and 1960s aimed to connect the whole country having the new capital Brasília as the central point of the network, and municipalities in the way among Brasília and the end points were incidentally connected. The third original IV is the distance from the municipality center to the nearest heavy traffic area, which Medeiros et al. (forthcominga) named "*potential road intervention areas"* IV. The rationality behind this instrument is that, conditional on controls, municipalities already connected by roads in the start period and nearer to "potential road intervention areas" are more likely to (inconsequentially) receive highway investments to reduce traffic levels and accidents in the critical areas and its surroundings. However, conditional on controls, this "luck" at receiving a federal road intervention would be unrelated to economic or political reasons, providing us a potentially suitable instrument. Finally, we rely on the inconsequential unit approach pioneered by Chandra and Thompson (2000) and exclude likely targeted and central cities. Then, our first-stage regression is specified as follows:

$$HighwayInvestments_{is} = \gamma_0 + \delta * NonRandomAllocationIndex_{is} + \gamma' X_{is} + \varepsilon_{is} \tag{2}$$

Where $NonRandomAllocationIndex_{is}$ is the instrument. Equations 1 and 2 are estimated using Two Stage Least Squares (2SLS) estimators. By using this econometric approach, we provide evidence on causal highway investment impacts on GHG emissions growth. To guarantee a full comparison with the Medeiros *et al.* (*forthcomingb*) economic return rates to highway investments, we also test models including an interaction term between the highway variable and an infrastructure reliance parameter (φ), as follows:

$$\Delta Y_{is} = \beta_0 + \alpha * \varphi * HighwayInvestments_{is} + \beta' X_{is} + \theta_s + u_{is} \tag{3}$$

If α is positive in Equation 3, municipalities more dependent on road infrastructure are more impacted in terms of GHG emissions growth.

3.2. Road heterogeneity econometric specification

A recent strand of literature has provided evidence on the heterogeneous impacts of road investments on environmental outcomes (Churchill *et al.*, 2021; Li and Lu, 2022; Lin *et al.*, 2017; Xiao *et al.*, 2023; Xie *et al.*, 2017; Xu *et al.*, 2022; Yao *et al.*, 2023). This is important as those heterogeneities might bias our baseline estimates and deeply influence our sustainable return rate to highway investments. Then, we adapt our baseline first and second stage equations to allow for road impact heterogeneity as follows:

$$\Delta Y_{is} = \beta_0 + \alpha * \varphi * HighwayInvestments_{is} + \lambda' * \varphi * (HighwayInvestments_{is} * Moderators_{is}) + \beta' X_{is} + \theta_s + u_{is} \qquad (4)$$

$$HighwayInvestments_{is} = \gamma_0 + \delta * NonRandomAllocationIndex_{is} + \tau' * (NonRandomAllocationIndex_{is} * Moderators_{is}) + \gamma' X_{is} + \varepsilon_{is} \qquad (5)$$

Where $Moderators_{is}$ is a vector of moderating variables related to agglomeration economies, technology, deforestation and so forth, which are all included in the vector of control variables as well, and λ' is its respective parameter vector to be estimated. The second stage equation (4) identify road impact heterogeneity by including an interaction term between the road variable and a moderating variable. To allow identification, we include an interaction term between the instrument and the mediator in the first stage equation (5), wherein τ' represents its parameters vector to be estimated. The other expressions are the same as Equations 1 and 2. From Equations 3 and 4, we can calculate road impact heterogeneity as follows:

$$\frac{\partial Y_{is}}{\partial HighwayInvestments_{is}} = (\alpha * \varphi) + (\lambda * \varphi) * (\overline{Moderators_{is}}) \qquad (6)$$

Equation 6 describes the marginal road impact on CO2 emissions. We estimate α and λ directly from Equations 3 and 4. Then, we assume values for $\overline{Moderators_{is}}$ by taking 10%, 25%, median, 75% and 90% sample values for each tested moderator. To estimate the point elasticities, we use tests of nonlinear combinations of parameter estimates following the “delta method” (Fieveson, 1999).

3.3. Data

3.3.1. GHG Emissions

Our main dependent variable is CO2 equivalent emissions (in tons), which we extract from the System for Estimating Greenhouse Gas Emissions (SEEG). All gases were converted to CO2 equivalent GWP-AR5. The SEEG platform is a 46-year long dataset of greenhouse gas emissions (GHG) in Brazil (1970–2015) providing more than 2 million data records for the Agriculture, Energy, Industry, Waste and Land Use Change Sectors at national and subnational levels. The SEEG dataset was developed by the Climate Observatory, a Brazilian civil society initiative, based on the Intergovernmental Panel on Climate Change (IPCC) guidelines and the Brazilian National Inventories embedded with country specific emission factors and processes, raw data from multiple official and non-official sources, and organized together with social and economic indicators. Due to the SEEG's highly disaggregated information, we can stratify municipal GHG emissions into road, energy, land use change and agriculture sectors and use them as additional dependent variables. A detailed description of the SEEG platform and methodologies can be found in Azevedo *et al.* (2018).

3.3.2. Highway infrastructure measures and instruments

Our interest variable is measured as the sum of federal highway investments between 2007 and 2018 by municipality. We get highway investments data from Medeiros et al. (forthcominga). The authors created a municipal level federal road investment dataset by combining the PAC highway investments data with the georeferenced National Highway System (SNV) from the National Highway

Infrastructure Department (DNIT). As robustness checks to measurement error in our road investment measure, we also try two additional road variables. The first one is a dummy variable assuming value one if the municipality received a road investment during the PAC period, and zero otherwise. The second one is the road length growth rate between 2006 and 2018. In this case, we use 2006 data from the 2007 National Transport Logistics Plan (PNLT) and 2018 data from DNIT[1]. To maintain comparability with the economic return rate calculated by Medeiros *et al.* (*forthcoming*b), we use their infrastructure reliance parameter (φ), measured as the share of the municipal intermediate consumption related to the land transportation sector. The φ data sources are the Annual Social Information Report (RAIS/Ministry of Labor) and the 2010 national Input-Output (I-0)(IBGE).

In addition, we also rely on Medeiros et al. (forthcominga) as the source of our instrumental variables. We get the Non-Random Allocation Index as our main IV, as well as their three original instruments as robustness checks. In addition, we also get some cost-related IVs (Cost Index 1 and 2) related to environmental, geographic, and human physical infrastructure project costs to run additional tests. The indexes also were created by using the PCA technic, reducing data information from original variables as the share of hilly areas in the total area, the share of urban infrastructure building in the total area, the share of legally protected environmental areas in the total area and the application of environmental embargoes.

3.3.3. Moderating variables

We include an extensive set of controls to avoid omitted variables bias following the specialized literature on road infrastructure and GHG emissions (Churchill *et al.*, 2021; Emodi *et al.*, 2022; Georgatzi *et al.*, 2020; Ghannouchi *et al.*, 2023; Han *et al.*, 2017; Li and Lu, 2022; Lin *et al.*, 2017; Luo *et al.*, 2018; Sharif and Tauqir, 2021; Xiao *et al.*, 2023; Xie *et al.*, 2017; Xu *et al.*, 2022; Yao *et al.*, 2023) and adapting for Brazilian features. First, we describe some variables that will be used as both controls and moderators. We include population to control and moderate for city scale and agglomeration effects. We also try population density and the share of road sector CO2 emissions in the total CO2 emissions as robustness checks. Second, we include GDP *per capita* to control for the municipal development level. Third, we include the ratio between residential capital and occupied population as a *proxy* for technological innovation. Finally, we include deforestation variation between 1996 and 2006 as a control for the municipal propensity to raise land use change CO2 emissions, the main source of CO2 emissions in the country.

3.3.4. Additional controls

As additional controls, we include the initial (2007) level of GHG emissions to control for level and convergence effects. We also include GDP per capita squared to control for a potential environmental Kuznets Curve. We include the share of the municipality exports in the national exports as a control for trade specialization. Gini Index controls for income inequality. Institutional Quality is inserted using the Index of Municipal Institutional Quality (IQIM). Human capital is included as the share of workers with graduate education. We control for complementary and substitute infrastructure by including the Euclidean distance from the municipality center to the nearest state road, port, and railroad. To guarantee the suitability of our instruments, we also include the distance to Brasilia and the number of railway stations in 1920 as controls, as Medeiros et al. (forthcominga) relied on

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[1] We can likely observe measurement error in the road length variable as well, as the PNLT and DNIT files are not fully comparable. In addition, there is methodological variations over the years in relation to road classifications as federal, state level and so forth. Then, this variable should be used with caution.

historical data to construct some of their IVs. A brief description of the variables used as well as their sources can be found in Table A1 and descriptive statistics can be seen in Table A2 in Appendix A.

4. Econometric results and discussion

4.1. Baseline estimates

Table 1 presents our baseline econometric results by estimating Equations 1 and 2[2]. In the first 5 columns, we use our highway investment measure as interest variable. In columns 6-10 we multiply our road variable by the road infrastructure reliance parameter (φ) following Fernald (1999). We estimate the road investments impact on CO2 emissions considering the full sample (columns "All"), and the road, energy, land use change and agriculture sectors separately. The Non-Random Allocation Index is a strong predictor of road investments as well as is a quite suitable IV as indicated by the high F Statistic values. Regarding the second stage regressions, we find a positive relationship between road investments and CO2 emissions for the full sample as well as for the road, energy, and land use sectors. We found no significant road effects on agriculture CO2 emissions.

We can interpret our findings in elasticity terms. More directly, an 1% increase in highway investments increases CO2 emissions by 0.025%. As expected, the elasticity is larger for the road and energy sectors, suggesting that an 1% increase in road investments raises road and energy CO2 emissions by 0.134% and 0.116%, respectively. These results corroborate several studies that found a damaging effect of highway construction and improvement on the environment, especially in the urban and road-related context (Churchill *et al*., 2021; Ghannouchi *et al*., 2023; Lin *et al*., 2017; Luo *et al.*, 2018; Xie *et al*., 2017; Yao *et al*., 2023).

Moreover, results point out a positive and significant indirect road effect on land use change CO2 emissions. These novel findings might be explained in some ways. The opening of new highways in isolated and previously environmentally protected areas might expands land supply. Therefore, land price drops because of the expanded land offer, and landowners might be more prone to buy new lands instead of investing in improving the productive efficiency in the existing ones. This might lead to a process of land abandonment, predatory agriculture and illegal extractivism, with consequent deforestation and destruction of fauna and flora (Carrero *et al.*, 2022; Da Silva *et al*., 2023; Ferrante *et al*, 2021; Lima *et al.*, 2022). As a result, we might expect an increase in CO2 emissions related to land use change from road investments.

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[2] Tables B1 and B2 in Appendix B presents OLS regressions results as comparison estimates.

Table 1. Federal Highway Investments and CO2 Emissions Growth (2007-2018): 2SLS IV Regressions

	1	2	3	4	5	6	7	8	9	10
Second stage	All	Roads	Energy	Land Use	Agriculture	All	Roads	Energy	Land Use	Agriculture
Log Highways Investments	0.0249***	0.1335***	0.1157***	0.0532***	-0.0030					
	(0.01)	(0.02)	(0.02)	(0.02)	(0.01)					
Log Highways Investments * φ						0.5770***	3.0916***	2.6802***	1.2362***	-0.0702
						(0.18)	(0.51)	(0.49)	(0.36)	(0.14)
First stage										
Non-Random Allocation Index	-0.4702***	-0.4808***	-0.4826***	-0.4759***	-0.4797***	-0.0203***	-0.0208***	-0.0208***	-0.0205***	-0.0207***
	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Observations	5142	5142	5142	5142	5142	5142	5142	5142	5142	5142
KP Wald F Statistic	349.317	359.100	360.198	356.129	360.001	332.469	343.528	344.349	338.341	340.560
R^2	0.23	0.51	0.52	0.22	0.15	0.23	0.50	0.52	0.21	0.15

All regressions include the following set of control variables: CO2 emissions in 2007; state fixed effects; population; GDP *per capita*; GDP *per capita*, square; capital-labor ratio; exports share; 1996-2006 deforestation; Gini index; institutional quality; human capital; distance to the nearest state road; distance to nearest railroad; distance to nearest port; railways stations in 1920; distance to Brasília. Robust standard errors reported in parentheses. * p<0.1, ** p<0.05, *** p<0.01.

4.2. Road impact heterogeneity

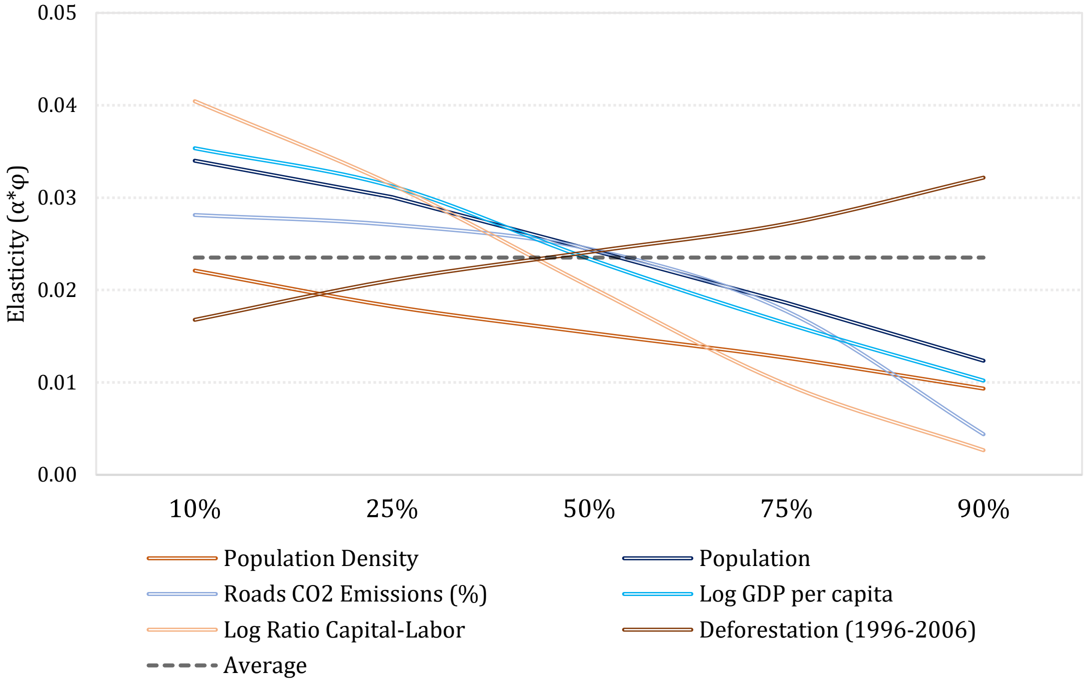
In this section, we evaluate potential heterogenous effects of road investments on CO2 emissions. To do this, we interact our road variable by some interest moderating variables following Equations 4 and 5. Then, we calculate point CO2 emissions elasticities with respect to highway investments applying Equation 6. Figure 2 exhibits the results. Full estimation results can be seen in Table C1 in Appendix C.

The first moderators we analyze are related to agglomeration economies and population scale effects (Lin *et al.*, 2017; Xiao *et al.*, 2023; Xie *et al.*, 2017; Xu *et al.*, 2022; Yao *et al.*, 2023). We test interactions between our road variable and population, also using population density as a robustness check. As an additional test, we use the share of the road sector CO2 emissions in relation to the total CO2 emissions to represent the importance of the road sector in the municipality economy and emissions as well as to identify places wherein high traffic congestion is expected. Findings point out that the positive impact of highway infrastructure improvement on CO2 emissions is higher for lower levels of our moderating variables. For instance, an 1% increase in road investments raises CO2 emissions by 0.034% in the bottom 10% of population, whilst the elasticity is 0.012% in the upper 10% of the same variable. The same rationality holds for population density and the share of road sector CO2 emissions. These results are in line with investigations reporting a significant moderating effect of agglomeration and population scale on the relationship between transportation development and carbon emissions. Agglomeration, as the most direct manifestation of the positive externality of highway infrastructure, is not only the core driver of rapid regional economic growth but also supports the development of energy savings and emission reductions in society. As municipalities reach a certain level of urbanization and agglomeration, the effects of roads on CO2 emissions become less harmful (Lin *et* al., 2017; Xie *et al.*, 2017; Xu *et al.*, 2022).

Next, we interact the road variable with GDP *per capita* and the capital-labor ratio to capture heterogeneities in terms of local development levels and technology innovation, respectively (Churchill *et al.*, 2021; Xie *et al.*, 2017). Like the agglomeration economies and population scale moderators, the road impact on CO2 emissions increases with the levels of GDP *per capita* and technology. The variation is more pronounced in the technology mediator, suggesting an α equal to 0.04% in the bottom 10%, 0.01% in the upper 25%, and a non-significant (nearly zero) effect in the upper 10%. These findings indicate that there is a greater polluting effect of roads in less developed locations, probably due to the construction of new roads and the expansion of new markets. As Medeiros et al. (*forthcomingb*) found, the highway effects on the local economy tend to be greater in poorer locations. Technology is positively correlated with economic development. In this sense, we expect roads to expand CO2 emissions through the economic growth and technological innovation channels in the initial stages of development.

Next, we include an interaction term between the road variable and the variation in deforestation in the ten previous years to the PAC. Results show that the damaging highway investments effects on the environment enlarge whilst deforestation in the recent past increases. A higher level of deforestation might represent national and local institutional weaknesses allowing the purchase of new lands at lower prices and its illegal use - such as land grabbing. By opening new roads, landowners may access new lands that were not available before, turning to a process of predatory agriculture production and widespread deforestation (Carrero *et al.*, 2022; Da Silva *et al.*, 2023; Ferrante *et al*, 2021; Lima *et al.*, 2022). This finding puts some caution on the role of road policies on sustainable development in Brazil, especially in the Brazilian Amazon municipalities, as the region has suffered from huge deforestation in the last decades.

Figure 2. Federal Highway Investments and CO2 Emissions Growth (2007-2018) - Elasticity (α*φ): Heterogeneous Impacts



Source: authors' elaboration.

4.3. Robustness checks

In this section, we present some robustness checks to increase confidence on our main results described so far. First, we used a highway investment flow measure as our preferred variable. However, several studies advocate against measuring infrastructure in monetary terms as inefficiencies in project planning and design, as well as corruption and flawed bureaucracy might turn investments ineffective in terms of building and implementing infrastructure, especially in developing economies. In other words, monetary variables might not represent effective infrastructure appropriately (Calderón and Servén, 2014; Kenny, 2009; Straub, 2011). This issue is alleviated as we used an IV identification approach dealing with endogeneity, but some bias may remain. As robustness checks, we use a dummy variable assuming value one if a municipality received a PAC highway intervention, and zero otherwise. In addition, we try road length growth between 2007 and 2018 as interest variable following a huge strand of literature[3] (Baum-Snow *et al.*, 2020; Duranton *et al.*, 2014; Foster *et al.*, 2023a, 2023b; Straub, 2011). Results can be seen in Table D1 in Appendix D. Findings corroborates our baseline estimates, suggesting a positive impact of road infrastructure on CO2 emissions. In

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[3] It is important to mention that this measure likely has measurement errors (perhaps more problematic than the monetary measure) due to changes in methodology and issues related to spatial disaggregation. Therefore, the results should be taken with caution.

addition, we find α equal to 0.10% using the road length variable, result that is quite in line with the elasticity of 0.08% estimated by Xie *et al.* (2017).

Second, we try additional IV combinations to validate our identification strategy. Table D2 in Appendix D presents the results. In Column 1, we include two infrastructure cost indexes following the three-step IV identification approach by Medeiros *et al.* (*forthcominga*). In Columns 2-4, we use the three original non-random allocation instruments instead of the Non-Random Allocation Index. In Columns 5-7, we include the two cost indexes jointly with the original non-random placement IVs. Results remain almost unchanged, presenting a stable elasticity.

Third, we run the same baseline models considering CO2 emissions in 2018 levels instead of growth rates as dependent variables. Results (Table D3 in Appendix D) are preserved. Next, we try additional robustness checks to alleviate concerns on CO2 emissions regional heterogeneity. First, we exclude all municipalities belonging to Amazon states. Those localities have suffered most from deforestation in the past decades, and very high amounts of CO2 emissions related to land use change might affect our baseline estimates. Second, we drop municipalities of the State of Pará. Pará received emblematic road buildings in environmental terms, some of them crossing extensive native people lands and generating huge environmental damages and land conflicts (Medeiros *et al.*, *forthcominga*). Third, we exclude municipalities of the state of São Paulo to alleviate issues related to high urbanization and development levels, which might impact our estimates due to a very large share of CO2 emissions related to the road and energy sectors. Finally, we estimate the road impacts on CO2 emissions growth related to the land use change sector by excluding municipalities of the Amazon states. If our baseline estimates are just capturing a regional road effect in the Brazilian Amazon, this robustness check should not present a significant parameter to road investments. Results can be seen in Table D4 in Appendix D. Findings remain, corroborating our baseline estimates. In unreported estimates, we also try the limited information maximum likelihood (LIML) and the generalized method of moments (GMM) estimators, and the results are unchanged.

5. Including Sustainability into the Return Rate to Highway Investments

5.1. The CO2 Emissions Return (Discount) Rate to Highway Investments (ERR) and the Sustainable (and Equitable) Return Rate to Highway Investments (SRR and SERR)

In this section, we provide a novel measure we call Sustainable Return Rate to Highway Investments (SRR). To do this, we take the (economic) Return Rates (RR) calculated by Medeiros *et al.* (*forthcomingb*) – which consider the road impact on productivity measured as GDP *per capita*, i.e., economic returns[4] – and discount from it our CO2 emissions Return Rate (ERR). To calculate the ERR, we adapt the return rate formula used by several studies (Fernald, 1999; Medeiros *et al.,* 2021; Medeiros *et al., forthcominga, forthcomingb;* Wang *et al.*, 2020) as follows:

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[4] The formula used by Medeiros *et al.* (*forthcominga*) to calculate the RR is: $RR_r = \alpha * GDP_r / RoadStock_r$, where α is the road elasticity in relation to GDP *per capita*, which multiplies the ratio between regional GDP and the road stock.

$$ERR_r = \alpha * \varphi_r * \frac{CO2Emissions_r^{SCC}}{HighwayStock_r} \quad (7)$$

Where $CO2Emissions_r^{SCC}$ is the total CO2 emissions in monetary terms, $HighwayStock_r$ is the stock of roads in monetary terms and r represents Brazilian Immediate Geographical Regions (RGI).

We follow Medeiros *et al.* (*forthcomingb*) in some steps to construct our ERR and to guarantee comparability with their RR. First, we alleviate issues with outliers by taking the decile average values of the ratio between CO2 emissions and the highway stock, then applying these averages to each municipality. Additionally, we exclude municipalities in the top and bottom 1% when calculating those averages to reduce measurement error bias from extremely high and low ratio values. Second, we also include the infrastructure reliance parameter (φ_{is}) to allow local road dependence heterogeneity to work. Third, we aggregate the municipality values at the RGI level by taking the average values of φ and the ratio between CO2 emissions and road stock, i.e., dividing those variables by the number of municipalities in each RGI. This third step is important to policy implications as we do not expect the Brazilian Federal Government targeting specific municipalities in allocating roads. The 510 RGIs are groups of municipalities in the urban network sharing a common local urban center as their basis, being constructed by the IBGE. Its design considers the connection of nearby cities through relationships of dependency and the movement of the population in search of goods, services, and employment opportunities. Then, the RGIs are closely related to transportation goals and can be seen as a reasonable spatial scale in terms of national highway public policies.

To construct the road stock variable, we follow Medeiros *et al.* (2021a) and Medeiros *et al.* (*fortchominga, fortchoming*b) by using the Frischtak and Mourão (2017) sectoral estimates for the Brazilian road stock. The authors found a road stock of around R$ 594 billion in 2023 values. Next, we use georeferenced road data from the 2007 National Transport Logistics Plan (PNLT) to calculate the road length by municipality. We multiply single lanes by 1 and duplicated lanes by 2 to control for road quality and scale in our stock measure. Then, we divide the total road stock in monetary terms by our physical measure of road length to generate the monetary value by kilometer of road. Finally, we multiply this value by the road length of each municipality, which gives us our local road stock variable.

To generate our ERR, we need to quantify CO2 emissions in monetary terms as well. To this end, we use the measure of Social Cost of Carbon (SCC). The SCC is an estimate of the cost, in dollars, of the damage done by each additional ton of carbon emission. SCC estimates mostly evaluate the carbon emissions impacts on health outcomes, agricultural production, and property values.

However, there is no consensus on the SCC value to be applied. Then, we use some benchmark SCCs around the world to provide consistency to our results. The first SCC we use is the Brazilian Government one (Ministry of Economy, 2022). The Brazilian Government SCC of around US$ 31 was mainly guided by a literature review considering several studies estimating the SCC worldwide (Nordhaus, 2016). The Brazilian Government SCC is in line with the Ricke *et al.* (2018) median SCC for Brazil of around U$$ 24.2 – the authors calculated country-level SCC values for several developed and developing economies –, which we also use as SCC in our ERR calculation. Recent studies have stablished substantially larger SCC values considering different studies and methodologies (Rennert *et al.*, 2022). For instance, the US Government SCC – one of the most relevant SCC guiding carbon pricing and environmental policies around the globe

– is around US$ 51. Even so, several academics consider the American SCC to be low, suggesting values above US$ 100. In this sense, we also consider the SCC of U$$ 113 proposed by the United Nations Environment Programme (UNEP, 2014), which is also the value identified in the UK Government's Stern report as the central, business-as-usual scenario value. Finally, we convert the SCCs to the Brazilian currency (R$) using an exchange rate of R$/US$ 5.17.

Importantly, we have demonstrated some significant heterogeneous road impacts on CO2 emissions. Whether Brazilian municipalities and regions present high variability in the values of the moderator variables, we can expect some bias in our ERR by taking a single average α value. To alleviate this issue, we adapt Equation 7 using the road heterogeneity impact results as follow:

$$ERR_r = ((\alpha * \varphi_{r)} + (\lambda * \varphi_r) * Moderator_r) * \frac{CO2Emissions_r^{SCC}}{HighwayStock_r} \qquad (8)$$

Where λ is the interaction term parameter allowing the road impact heterogeneities to exist, and $Moderator_{is}$ is the moderators values taken by the municipal average by RGI.

Finally, we calculate our Sustainable Return Rate to Highway Investments (SRR) as follows:

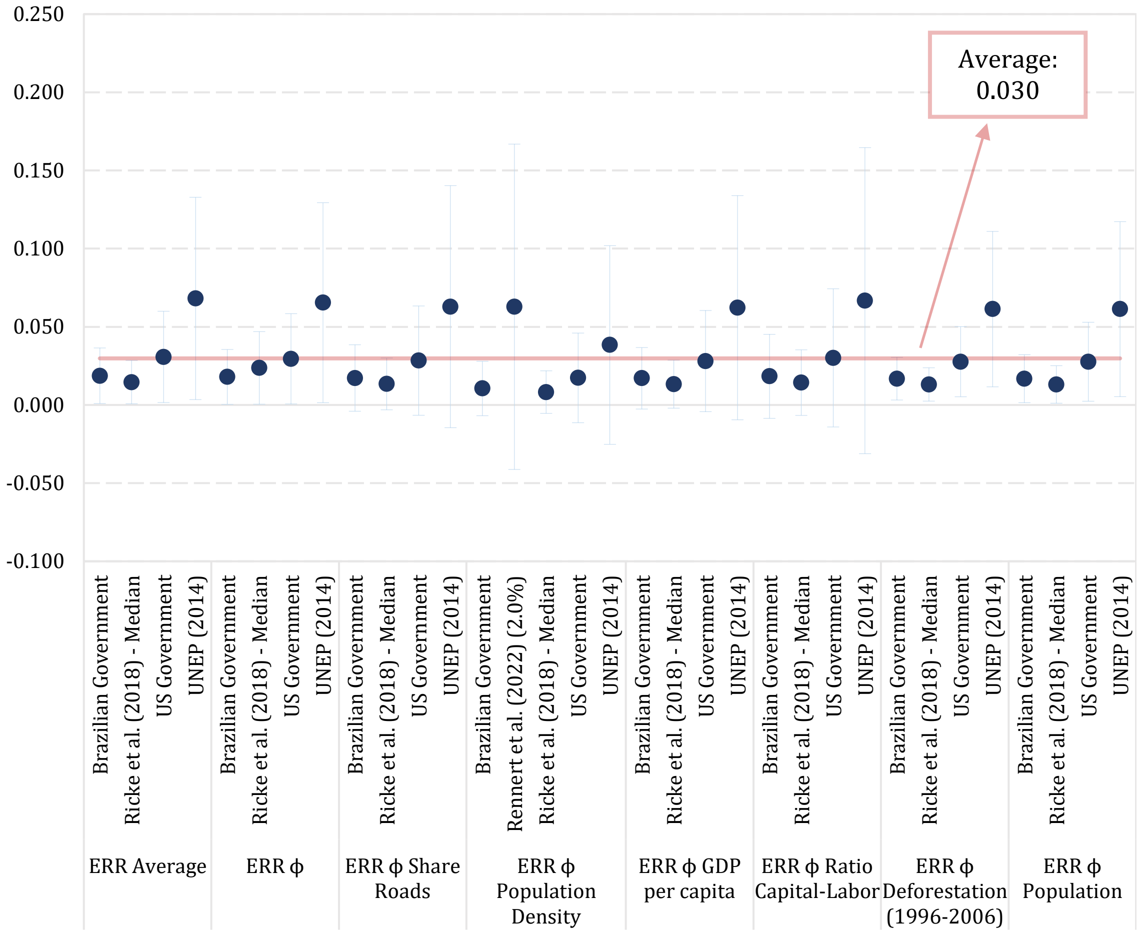
$$SRR_r = RR_r - ERR_r \qquad (9)$$

Equation 9 shows two opposite sides of road policies. In other words, the higher the ERR, the lower the positive economic and equitable returns of road investments to the society.

5.2. Results and policy implications

Figure 3 shows the ERR results. We calculate several ERRs trying different SCC values as well as varying our parameters following results in Sections 4.1 and 4.2. Our ERR ranges from 0.01 – using the Rick *et al.* (2018) SCC and the parameters following the population density moderator specification – to 0.07 – taking the UNEP (2014) SCC and the parameters from the average α specification. To stablish a benchmark for the ERR, we suggest taking the average value of all ERRs exhibited in Figure 3, indicating an average ERR of 0.03 (3.0%).

Figure 3. CO2 Emissions Return Rate to Highway Investments (ERR) under different Social Costs of Carbon (SCC) and road impact heterogeneities

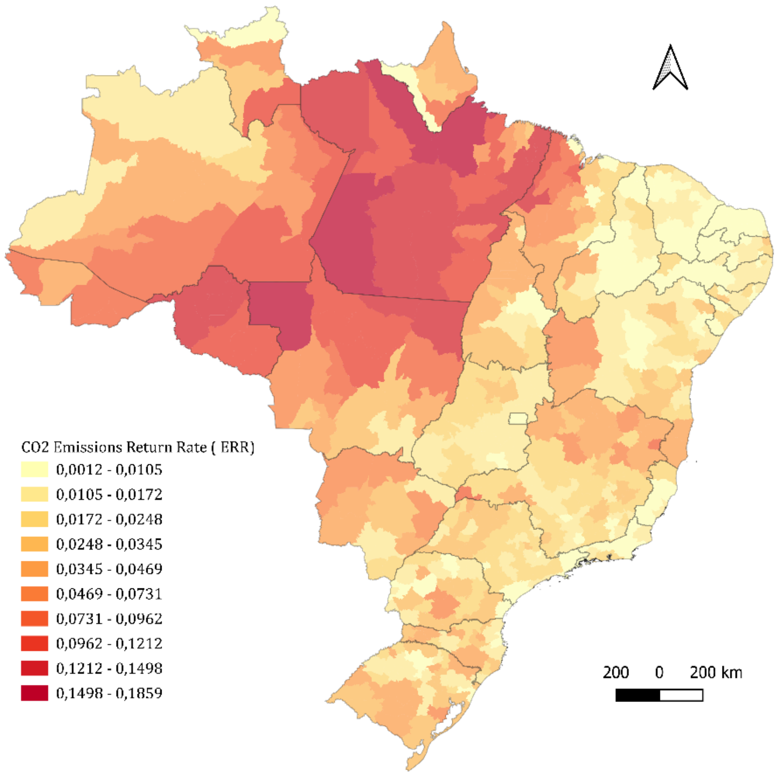


Source: authors' elaboration.

The average economic return rate (RR) by Medeiros *et al.* (*forthcominga, forthcomingb*) is around of 20%. Discounting our ERR from the average RR implies a SRR ranging from 13% to 19% in Brazil. At average, we find a high SRR of 17%. This result corroborates the consensus on the deep precarity of the Brazilian transportation infrastructure sector, even considering environmental damages.

Nonetheless, Brazil presents huge regional heterogeneities in terms of both CO2 emissions and road dependence, and looking at those features might reveal some spatial inequalities in the ERR and SRR. Figure 4 shows the ERR at the regional scale. We can observe a substantial geographic number of regions presenting low ERR values between approximately zero and 0.025. However, for an important part of RGIs in the north and part of the Mid-West regions – more specifically, in the Brazilian Amazon area –, our results indicate ERRs above 0.07, reaching peak values of around 0.19. For those very high ERR values, highway investments might constitute a quite environmentally damaging policy tool.

Figure 4. CO2 Emissions Return Rate to Highway Investments (ERR): Brazilian RGIs



Source: authors' elaboration.

To better elucidate how the environmental and economic issues of highways policies are operating, we display the SRR in Figure 5. In Figure 5 (a), we show the Sustainable Return Rate to Highway Investments (SRR) considering the average RR calculated by Medeiros *et al.* (*forthcomingb).* In the RR Average, the authors consider the road impact on productivity to be equal to all units. In Figure 5 (b), we show the Sustainable and Equitable Return Rate to Highway Investments (SERR), which considers the RR Efficient & Road Specialized & Redistributive & Equative measured by Medeiros *et al.* (*forthcomingb).* In this second return rate, the authors allowed the road impact on productivity to vary by units and found that the road investment profitability is higher for less developed and poorer infrastructure endowed places. Then, we evaluate the road return in terms of economic profitability (RR), weighting by social conditions considering equity features (RR Efficient & Road Specialized & Redistributive & Equative), and sustainability (ERR). The SERR is our preferred estimate as it deals with a broader range of road policy characteristics, going beyond the widely evaluated economic issue.

Whilst we observe a high average SRR, Figure 5 show us some important regional disparities in Brazil. First, we can observe positive SRRs for the most part of the country, as expected due to the Brazilian road sector historical bottlenecks. However, a considerable number of RGIs in the north and Mid-West regions present negative SRRs, implying that the environmental costs are higher than the economic benefits to construct and improve roads in those localities. When consider the SERR, the number of non-profitable RGIs drops, as the economic (and equitable) return is higher for the poorer places, especially in the North and Northeast regions. Evaluating the SERR, we have a larger number of RGIs presenting return rates above 8.5%, the cut-off rate following the

Social Discount Rate (TSD) calculated by the Brazilian Ministry of Economy (2021). Even so, some unprofitable and environmentally vulnerable RGIs remain.

Finally, we evaluate the sensitivity of our ERR and SERR measures to land use change CO2 emissions, the main source of CO2 emissions in Brazil. To this end, we provide some naïve counterfactuals exercises supposing drops of 25%, 50%, 75% and 100% in land use change CO2 emissions and recalculate our ERR and SERR. Results are described in Table E1 in Appendix E. Our ERR decreases from the average 3.0% to 2.54% and 1.42%, supposing a 25% and 100% reduction in land use CO2 emissions, respectively. Consequently, our SERR increases from the average 17% to 17.46% and 18.58%, taking the 25% and 100% reduction in land use CO2 emissions, respectively.

Additionally, we generate a new SERR considering the energy sector CO2 emissions[5] (Figure E1 in Appendix E). The aim of this exercise is to avoid the damaging road impacts coming from deforestation and agriculture, which might be in some extent out of control of the transport sector authorities as the Ministry of Transport and the DNIT. Then, we restrict the emissions more directly related to the highway improvements, as those strictly associated with increased traffic flows and urban activity. In this case, we consider the elasticity of the energy sector CO2 emissions growth with respect to highway investments equal to 0.12 following results in Table 1. The average ERR under the energy sector CO2 emissions analysis is around 1.3% (less than half of the ERR considering emissions from land use change and agriculture), whilst the average SERR is close to 18.7%. It is important to mention that several RGIs become economically and environmentally profitable when we evaluate only the energy sector CO2 emissions. This result indicates the critical role of complementary policies to prevent deforestation, preserve and restore the environment, especially in the Amazon region.

Our findings in terms of sustainable return rates to highway investments have some important policy implications. First, the average return rate to road investments is high even considering the environmental issue, indicating a widespread need to develop the Brazilian transportation sector. To reduce our average SRR of 17% to the threshold of 8.5%, Brazil would need 2 times more highways, which implies a road stock of 14% of national GDP, in line with Frischtak and Mourão (2017) and Medeiros *et al.* (2021). Second, the environmental damages from roads are more pronounced in less populated and poorer localities, which coincides with some critical areas in the Brazilian Amazon. For some of those RGIs, we can observe negative SRRs and SERRs, suggesting that the economic benefits are not offsetting the raising in environmental costs from road-related CO2 emissions. Then, road public policies must be implemented jointly with environmental tools ensuring environmental preservation and recovery. Third, even if moderate, we found a positive average road impact on CO2 emissions, implying a discount on the economic return rate to road investments. Additional public policies might be important to alleviate those harmful road impacts. For instance, taxes and subsidies for clean technologies such as electric vehicles and energy systems might make them more attractive. Once those technologies achieve a certain level of production scale, costs tend to fall, and the incentives to product and use clean technologies becomes high enough (Greene *et al.*, 2014; Santos, 2017). The same might holds for Research and Development (R&D) expenses in clean technology. Finally, improving the institutional and regulatory environmental framework is critical, especially those related to road projects design, execution, and evaluation in environmentally vulnerable areas. Improving the project

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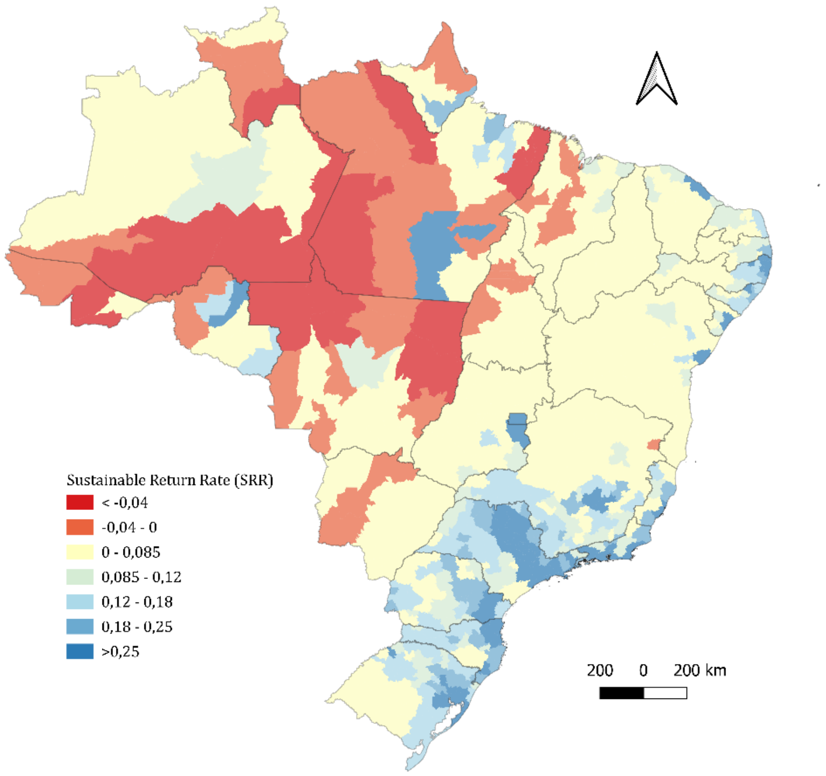
[5] We calculate the energy sector ERR following results in Columns 3 and 8 in Table 1. Then, we use the ERR Average and ERR φ specification as in Figure 3.

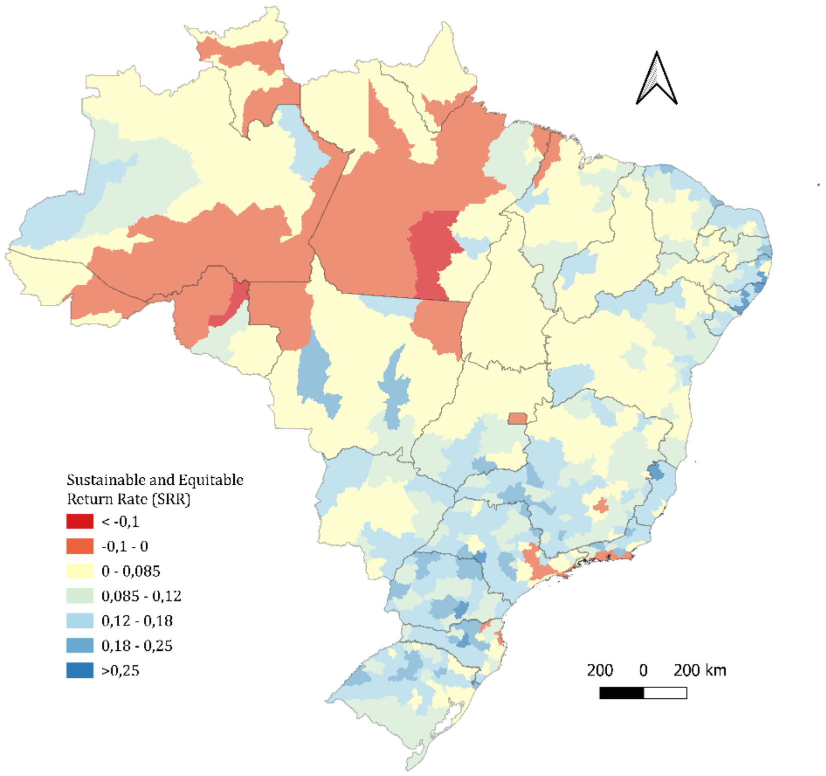
governance is a key issue, including the coordination between transportation and environmental institutions.

Figure 5. Sustainable Return Rates to Highway Investments: SRR (a) and SERR (b)

(a)



(b)



Source: authors' elaboration.

6. Concluding remarks

We evaluated the highway investments impacts on GHG emissions in Brazilian municipalities during the PAC period (2007-2018). Using an IV identification strategy dealing with the non-random allocation of roads, we find an increasing effect of roads on CO2 emissions, showing that an 1% raise in roads investments expands CO2 emissions by 0.025%. This damaging effect of road investments on the environment holds for the road, energy, and land use change sectors. We also found important heterogenous road impacts on CO2 emissions depending on agglomeration, population scale, deforestation, and technology. In short, less agglomerated and populated as well as poorer localities are more adversely affected by road investments. We detected a new transmission channel from road investment to CO2 emissions coming from deforestation, proving that municipalities with higher deforestation in the previous period to the PAC suffered more from the damaging effects of highways on the environment. Findings are robust to different specifications varying dependent and independent variables, instruments, excluding groups of municipalities and changing estimators.

From this, we calculated an average CO2 Emissions Return Rate to Highway Investments (ERR) of 3.0%, implying a discount on the economic benefits of road investments proved in past studies. Next, we measured a Sustainable Return Rate to Highway Investments (SRR) of around 17%, indicating a widespread need to develop the Brazilian transportation sector. It is important to note the existence of deep regional heterogeneities in Brazil, wherein we can observe negative SRRs and SERRs for some regions – especially in the Brazilian Amazon–, suggesting that the economic benefits are not offsetting the raising in environmental costs from road-related CO2 emissions in those places.

Whilst we contribute to the empirical literature on infrastructure and development in several ways, some gaps remain. First, we evaluated just one outcome in a wide range of environmental factors potentially impacted by roads. Future research might expand our study by focusing on deforestation, energy efficiency, water pollution, ecological footprint, among others. Second, a more detailed study on the moderating role of environment-related institutions on the nexus between highway investments and GHG emissions might provide important and novel evidence to the literature, especially to countries wherein land use change and agriculture are relevant contributors to GHG emissions. Third, differentiating the short run and the long run environmental impacts of road investments may provide important policy implications in terms of pollution from material and equipment in the construction phase versus the environmental damage caused by the increased traffic flows when the highway is already built.

7. References

Aschauer, D. A. (1989). Does public capital crowd out private capital?. *Journal of monetary economics*, 24(2), 171-188.

Asher, S., Garg, T., & Novosad, P. (2020). The ecological impact of transportation infrastructure. *The Economic Journal*, 130(629), 1173-1199.

Awad, A., Mallek, R. S., Ozturk, I., & Abdalla, Y. A. (2023). Infrastructure Development's role in environmental degradation in sub-Saharan Africa: Impacts and transmission channels. *Journal of Cleaner Production*, 137622.

Azevedo, T. R., Costa Junior, C., Brandão Junior, A., Cremer, M. D. S., Piatto, M., Tsai, D. S., ... & Kishinami, R. (2018). SEEG initiative estimates of Brazilian greenhouse gas emissions from 1970 to 2015. *Scientific data*, 5(1), 1-43.

Baum-Snow, N., Henderson, J. V., Turner, M. A., Zhang, Q., & Brandt, L. (2020). Does investment in national highways help or hurt hinterland city growth? *Journal of Urban Economics*, 115, 103124.

Bird, J., & Straub, S. (2020). The Brasilia experiment: the heterogeneous impact of road access on spatial development in Brazil. *World Development*, 127, 104739.

Calderón, C., & Servén, L. (2014). Infrastructure, growth, and inequality: An overview. World Bank Policy Research Working Paper, (7034).

Carrero, G. C., Walker, R. T., Simmons, C. S., & Fearnside, P. M. (2022). Land grabbing in the Brazilian Amazon: Stealing public land with government approval. *Land Use Policy*, 120, 106133.

Churchill, S. A., Inekwe, J., Ivanovski, K., & Smyth, R. (2021). Transport infrastructure and CO2 emissions in the OECD over the long run. *Transportation Research Part D: Transport and Environment*, 95, 102857.

da Silva, C. F. A., de Andrade, M. O., dos Santos, A. M., & de Melo, S. N. (2023). Road network and deforestation of indigenous lands in the Brazilian Amazon. *Transportation Research Part D: Transport and Environment*, 119, 103735.

Duranton, G., Morrow, P. M., & Turner, M. A. (2014). Roads and Trade: Evidence from the US. *Review of Economic Studies*, 81(2), 681-724.

Emodi, N. V., Inekwe, J. N., & Zakari, A. (2022). Transport infrastructure, CO2 emissions, mortality, and life expectancy in the Global South. *Transport Policy*, 128, 243-253.

Faber, B. (2014). Trade integration, market size, and industrialization: evidence from China's National Trunk Highway System. *Review of Economic Studies*, 81(3), 1046-1070.

Farhadi, M. (2015). Transport infrastructure and long-run economic growth in OECD countries. *Transportation Research Part A: Policy and Practice*, 74, 73-90.

Fedderke, J. W., & Bogetić, Ž. (2009). Infrastructure and growth in South Africa: Direct and indirect productivity impacts of 19 infrastructure measures. *World Development*, 37(9), 1522-1539.

Fernald, J. G. (1999). Roads to prosperity? Assessing the link between public capital and productivity. *American Economic Review*, 89(3), 619-638.

Ferrante, L., Andrade, M. B., & Fearnside, P. M. (2021). Land grabbing on Brazil's Highway BR-319 as a spearhead for Amazonian deforestation. *Land use policy*, 108, 105559.

Feiveson, A. H. (1999). FAQ: What is the delta method and how is it used to estimate the standard error of a transformed parameter.

Foster, V., Gorgulu, N., Straub, S., & Vagliasindi, M. (2023a). The Impact of Infrastructure on Development Outcomes: A Qualitative Review of Four Decades of Literature.

Foster, V., Gorgulu, N., Straub, S., & Vagliasindi, M. (2023b). The Impact of Infrastructure on Development Outcomes: A Meta-Analysis.

Frischtak, C. R., & Mourão, J. (2017). O Estoque de Capital de Infraestrutura no Brasil: uma abordagem setorial. *DESAFIOS DA NAÇÃO*, 133.

Georgatzi, V. V., Stamboulis, Y., & Vetsikas, A. (2020). Examining the determinants of CO2 emissions caused by the transport sector: Empirical evidence from 12 European countries. *Economic Analysis and Policy*, 65, 11-20.

Ghani, E., Goswami, A. G., & Kerr, W. R. (2016). Highway to success: The impact of the Golden Quadrilateral project for the location and performance of Indian manufacturing. *The Economic Journal*, 126(591), 317-357.

Ghannouchi, I., Ouni, F., & Aloulou, F. (2023). Investigating the impact of transportation system and economic growth on carbon emissions: application of GMM system for 33 European countries. *Environmental Science and Pollution Research*, 30(39), 90656-90674.

Greene, D.L., Park, S., Liu, C., 2014. Analyzing the transition to electric drive vehicles in the U.S. *Futures* 58, 34–52.

Han, J., Meng, X., Liu, J., & Zhang, Y. (2017). The impact of infrastructure stock density on CO2 emissions: Evidence from China provinces. *Sustainability*, 9(12), 2312.

Herzog, I. (2021). National transportation networks, market access, and regional economic growth. *Journal of Urban Economics*, 122, 103316.

Holl, A. (2016). Highways and productivity in manufacturing firms. *Journal of Urban Economics*, 93, 131-151.

Jaworski, T., & Kitchens, C. T. (2019). National policy for regional development: Historical evidence from Appalachian highways. *Review of Economics and Statistics*, 101(5), 777-790.

Kenny, C. (2009). Measuring corruption in infrastructure: Evidence from transition and developing countries. *The Journal of Development Studies*, 45(3), 314-332.

Li, H., & Luo, N. (2022). Will improvements in transportation infrastructure help reduce urban carbon emissions?——motor vehicles as transmission channels. *Environmental Science and Pollution Research*, 29(25), 38175-38185.

Li, Z., Wu, M., & Chen, B. R. (2017). Is road infrastructure investment in China excessive? Evidence from productivity of firms. *Regional Science and Urban Economics*, 65, 116-126.

Lima, M., Santana, D. C., Junior, I. C. M., Costa, P. M. C. D., Oliveira, P. P. G. D., Azevedo, R. P. D., ... & Silva Junior, C. A. D. (2022). The "New Transamazonian Highway": BR-319 and Its Current Environmental Degradation. *Sustainability*, 14(2), 823.

Lin, B., & Chen, Y. (2020). Transportation infrastructure and efficient energy services: A perspective of China's manufacturing industry. *Energy Economics*, 89, 104809.

Lin, C., Liu, G., & Müller, D. B. (2017). Characterizing the role of built environment stocks in human development and emission growth. *Resources, Conservation and Recycling*, 123, 67-72.

Luo, Z., Wan, G., Wang, C., & Zhang, X. (2018). Urban pollution and road infrastructure: A case study of China. *China Economic Review*, 49, 171-183.

Medeiros, V., & Ribeiro, R. S. M. (2020). Power infrastructure and income inequality: Evidence from Brazilian state-level data using dynamic panel data models. *Energy Policy*, 146, 111734.

Medeiros, V., Ribeiro, R. S. M., & do Amaral, P. V. M. (2021a). Infrastructure and household poverty in Brazil: A regional approach using multilevel models. *World Development*, 137, 105118.

Medeiros, V., Ribeiro, R. S., & AMARAL, P. (2021b). Productivity of transportation infrastructure in Brazil: a sectoral and regional approach using dynamic panel data models. Coletânea de Trabalhos–Prêmio ABDE-BID: edição.

Medeiros, V., Saulo Marques Ribeiro, R., & Vasconscelos Maia do Amaral, P. (2022). Infrastructure and income inequality: An application to the Brazilian case using hierarchical spatial autoregressive models. *Journal of Regional Science*, 62(5), 1467-1486.

Ministry of Economy. 2021. Social discount rate for evaluating infrastructure investments: update after public consultation. consultation. SEI Technical Note no. 19911/2020/ME.

Ministry of Economy (2022). General guide to socio-economic cost-benefit analysis of infrastructure investment projects. Brasília : SDI/ME.

Nordhaus, W. D. (2017). Revisiting the social cost of carbon. *Proceedings of the National Academy of Sciences*, 114(7), 1518-1523.

Rennert, K., Errickson, F., Prest, B. C., Rennels, L., Newell, R. G., Pizer, W., ... & Anthoff, D. (2022). Comprehensive evidence implies a higher social cost of CO2. *Nature*, 610(7933), 687-692.

Ricke, K., Drouet, L., Caldeira, K., & Tavoni, M. (2018). Country-level social cost of carbon. *Nature Climate Change*, 8(10), 895-900.

Santos, G. (2017). Road transport and CO2 emissions: What are the challenges?. *Transport Policy*, 59, 71-74.

Sharif, F., & Tauqir, A. (2021). The effects of infrastructure development and carbon emissions on economic growth. *Environmental Science and Pollution Research*, 28, 36259-36273.

Straub, S. (2011). Infrastructure and development: A critical appraisal of the macro-level literature. *The Journal of Development Studies*, 47(5), 683-708.

UNEP (2014) Valuing Plastics: The Business Case for Measuring, Managing and Disclosing Plastic Use in the Consumer Goods Industry.

Wang, Z., Wu, G. L., & Feng, Q. (2020). Productivity of core infrastructure investment in China: An input–output approach. *The World Economy*, 43(12), 3384-3406.

Xiao, F., Pang, Z., Yan, D., Kong, Y., & Yang, F. (2023). How does transportation infrastructure affect urban carbon emissions? an empirical study based on 286 cities in China. *Environmental Science and Pollution Research*, 30(4), 10624-10642.

Xie, R., Fang, J., & Liu, C. (2017). The effects of transportation infrastructure on urban carbon emissions. *Applied Energy*, 196, 199-207.

Xu, H., Cao, S., & Xu, X. (2022). The development of highway infrastructure and CO2 emissions: The mediating role of agglomeration. *Journal of Cleaner Production*, 337, 130501.

Yao, S., Zhang, X., & Zheng, W. (2023). On transportation, economic agglomeration, and CO2 emissions in China, 2003–2017. *Environmental Science and Pollution Research*, 30(14), 40987-41001.

Zhang, Y. F., & Ji, S. (2019). Infrastructure, externalities, and regional industrial productivity in China: A spatial econometric approach. *Regional Studies*, 53(8), 1112-1124.