UNIVERSIDADE FEDERAL DE VIÇOSA

Essays on Transport and Energy Transition

Carlos Eduardo Espinel Campos
Doctor Scientiae

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CARLOS EDUARDO ESPINEL CAMPOS

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Thesis submitted to the Applied Economics Graduate Program of the Universidade Federal de Viçosa in partial fulfillment of the requirements for the degree of *Doctor Scientiae*.

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Todos esses que aí estão
Atravancando meu caminho
Eles passarão...
Eu, *passarinho*!

Mário Quintana

ABSTRACT

CAMPOS, Carlos Eduardo Espinel, D.Sc., Universidade Federal de Viçosa, November, 2025. **Essays on Transport and Energy Transition**. Adviser: Ian Michael Trotter.

This thesis investigates the interplay between freight transport, economic growth, and the energy transition in Brazil through two complementary essays. The first essay employs Auto Regressive Distributed Lag (ARDL) models to project freight demand across road, rail, and air modes through 2099 under multiple Shared Socioeconomic Pathways (SSPs). GDP and population growth emerge as the main determinants of the expansion in freight demand. Road freight, responsible for 64.9% of cargo movement, is projected under SSP5 to increase by up to 653.3% by 2099, with rail and air freight growing by up to 472.9% and 770.8%, respectively, relative to 2019 levels. This highlights the structural dominance of road transport in Brazil, whose high carbon intensity raises environmental concerns. The historical road freight carbon intensity (RFCI) is estimated at 120.7 gCO_2/TKU, which establishes a demanding mitigation baseline. The second essay assesses the economic implications of mitigation by projecting the evolution of logistics costs as a share of GDP and estimating the costs required to meet Brazil's climate targets. Freight logistics costs could reach 2.2% of Brazil's GDP by 2099 under the projected scenarios, up from approximately 1.8% in 2019, highlighting the growing economic weight of the activity. Diesel demand is inelastic (-0.610), implying that pricebased interventions alone are likely insufficient. Simulated Marginal Abatement Costs (MACs) to meet Brazil's 2035 NDC targets range from BRL 1,349.77 to 1,532.79 per ton of CO_2, which underscores the need for coordinated policy interventions. By integrating demand projections, carbon intensity, and economic feasibility, this thesis develops a scenario-based framework for policymaking, suggesting that a credible energy transition in Brazilian freight may depend on structural, regulatory, and technological measures.

Keywords: freight transport demand; energy transition; marginal abatement costs

RESUMO

CAMPOS, Carlos Eduardo Espinel, D.Sc., Universidade Federal de Viçosa, novembro de 2025. **Ensaios em Transporte e Transição Energética**. Orientador: Ian Michael Trotter.

Esta tese investiga a interação entre transporte de cargas, crescimento econômico e transição energética no Brasil, integrando dois ensaios complementares. O primeiro ensaio utiliza modelos Autorregressivos de Defasagem Distribuída (ARDL) para projetar a demanda de transporte rodoviário, ferroviário e aéreo até 2099 sob diferentes Trajetórias Socioeconômicas Compartilhadas (SSPs). PIB e crescimento populacional são os principais determinantes da expansão da demanda por transporte. O transporte rodoviário, responsável por 64,9% do movimento de cargas, pode crescer em até 653,3% no cenário SSP5, com projeção para 2099, com transporte ferroviário e aéreo aumentando em até 472,9% e 770,8%, respectivamente, em relação a 2019, evidenciando o domínio estrutural do rodoviário e sua alta intensidade de carbono. A intensidade histórica de carbono do transporte rodoviário (RFCI) é estimada em 120,7 gCO_2/TKU, estabelecendo uma linha de base desafiadora para mitigação. O segundo ensaio avalia as implicações econômicas da mitigação, projetando a evolução dos custos logísticos como parcela do PIB e estimando os custos necessários para cumprir as metas climáticas do Brasil. Os custos logísticos de transporte podem alcançar 2,2% do PIB do Brasil até 2099 nos cenários projetados, contra aproximadamente 1,8% em 2019, evidenciando o crescente peso econômico da atividade. A demanda por diesel é inelástica (-0,610), indicando que intervenções via preços são insuficientes. Os Custos Marginais de Abatimento (CMAs) simulados para alcançar as metas da NDC brasileira de 2035 variam de R$ 1.349,77 a R$ 1.532,79 por tonelada de CO_2, sinalizando a necessidade de intervenções políticas coordenadas. Ao integrar projeções de demanda, intensidade de carbono e viabilidade econômica, esta tese desenvolve uma estrutura de cenários para a formulação de políticas, sugerindo que uma transição energética crível no transporte de cargas no Brasil dependerá de medidas estruturais, regulatórias e tecnológicas.

Palavras-chave: demanda por transporte de cargas; transição energética; custos marginais de abatimento

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1 INTRODUCTION

In the early 1950s, development became synonymous with economic growth, asserting that progress could only be achieved through economic expansion. However, in the 1970s, it became evident that rapid economic growth failed to equate to genuine development, negatively impacting both human well-being and the environment. Thus, the concept of sustainable development emerged, emphasizing the need to address issues such as resource depletion, environmental degradation, the energy crisis, and poverty through alternative approaches. Economic growth has historically driven emissions. Increased economic activity necessitates greater energy consumption, and fossil fuels still constitute 80.0% of global energy production. To mitigate severe climate repercussions and limit global warming, the global economy must urgently reduce greenhouse gas emissions, aiming for climate neutrality by 2050. However, rapid climate action magnifies macroeconomic implications, requiring substantial initial investments in green infrastructure such as solar panels, wind farms, storage facilities, and modern heating systems, which may require greater capital outlay compared to the existing fossil fuel-based system. Furthermore, accelerating the transition to a climate-neutral economy requires significant macroeconomic policy interventions (Claeys et al., 2024).

The contemporary world faces the significant environmental challenge of climate breakdown, largely driven by its reliance on fossil fuels, which account for over eighty percent of total energy use and are the main source of carbon dioxide emissions. The increasing awareness of climate change has spurred global attention towards transitioning to renewable energy sources, known as the Renewable Energy Transition (RET), aiming to shift from conventional fossil fuels to zero-emission energy within fifty years. This transition aligns with the 7th Sustainable Development Goal (SDG)[1] of ensuring access to clean and sustainable energy, this initiative reinforces the commitments made at the COP29, held in Baku, Azerbaijan, in 2024[2]. During the conference, countries pledged to deploy 1,500 gigawatts (GW) of global energy storage capacity by 2030 and to expand renewable energy corridors connecting clean energy sources to the communities most in need. These efforts are essential to achieving a just and inclu-

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[1] The Sustainable Development Goals (SDGs) are a set of 17 global objectives established by the United Nations in 2015 to address the world's most pressing challenges by 2030. These goals aim to end poverty, protect the environment, promote prosperity, and ensure peace and justice for all people. The SDGs cover a wide range of issues, including health, education, equality, clean energy, climate action, and sustainable economic growth, fostering an integrated approach to global sustainable development (UN, 2015).

[2] The Conference of the Parties (COP) is the supreme decision-making body of the United Nations Framework Convention on Climate Change (UNFCCC). All States that are Parties to the Convention are represented at the COP, at which they review the implementation of the Convention and any other legal instruments that the COP adopts and take decisions necessary to promote the effective implementation of the Convention, including institutional and administrative arrangements (UNFCCC, 2025).

sive energy transition and to keeping the global temperature rise below $1.5\,^{\circ}\mathrm{C}$. Meeting this target, however, requires a substantial increase in the share of renewable energy in the global energy supply, from 14.0% in 2018 to 74.0% by 2050, as highlighted by the IRENA (2018).

As stated by Carley and Konisky (2020) an energy transition denotes the transformation from one primary energy source or group of sources to another, as observed historically in shifts such as the replacement of whale oil by kerosene in the late 19th Century and the transition from wood to coal during the Industrial Revolution. In contemporary times, the energy transition signifies a diminishing reliance on fossil fuels, in favor of lower-carbon alternatives like wind and solar. While complete replacements of energy resources are rare occurrences, transitions typically involve the gradual ascent of a particular resource from a minor to a dominant position within the energy mix, often defined as a shift from 5.0% to 80.0% of energy consumption for a specific resource or technology. The discourse surrounding energy transition has expanded significantly, progressing from earlier examinations of transition pace to encompass discussions on diverse transition pathways and the impacts on households. This evolution underscores the acknowledgment that transitions inherently create both beneficiaries and those disadvantaged, emphasizing the critical importance of promoting equitable participation and distributional equity throughout the transition process.

Scientific evidence, as summarized by IPCC (2023), shows that human activities have already warmed the climate system. Global surface temperature rose by 1.1 ℃ between 2011 and 2020 relative to 1850–1900, with warming of 1.59 ℃ over land and 0.88 ℃ over oceans. Atmospheric concentrations of CO_2 reached 410 parts per million (ppm)[3] in 2019, the highest level in at least two million years, while methane and nitrous oxide also reached record levels in the past 800,000 years. Net anthropogenic GHG emissions were 54.0% higher in 2019 than in 1990. These emissions have already driven widespread changes in the atmosphere, ocean, and biosphere, including more frequent extreme events, sea-level rise of 0.20 m since 1901, and adverse impacts on ecosystems, health, food security, and water availability. If current trends persist, climate change is set to worsen sharply, with consequences reaching far and wide. To limit warming and avoid the most severe risks, the global economy must rapidly curtail GHG emissions to achieve net-zero CO_2 by mid-century. Key transformations include full decarbonization of electricity, widespread electrification of end-use sectors, and major efficiency gains, each with substantial economic repercussions still insufficiently understood (Claeys et al., 2024).

Werner and Lazaro (2023) point out that from the perspective of socio-technical transition and policy mobility, the drivers behind the energy transition involve reducing

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[3] Parts per million (ppm) expresses the number of molecules of a substance per one million molecules of air.

carbon emissions in the energy sector and decreasing reliance on fossil fuels. In the Brazilian context, new challenges have emerged. These include the necessity to: *i)* decrease reliance on hydroelectric power plants, owing to environmental concerns related to projects near the Amazon forest region, and the impacts of water scarcity and droughts exacerbated by climate change, especially considering the effects on hydrological patterns and Brazil's dependence on hydroelectricity, which could lead to electrical vulnerabilities; *ii)* diversify the energy mix by embracing renewable energy sources, restructuring production and social systems, achieving technological autonomy, and altering both domestic and international labor divisions; and *iii)* address historical environmental injustices by ensuring that electricity provision aligns with the needs of communities and territories affected by past projects.

As noted in Pereira Jr et al. (2013), the Brazilian electricity sector operates under a hydrothermal system dominated by large hydroelectric reservoirs across multiple basins, often distant from industrial and urban centers. Extensive transmission lines connect these facilities, while thermal, nuclear, bioelectricity, wind, and solar generation complement hydropower capacity. Despite the growing share of renewables in electricity generation, other sectors such as transport remain dependent on fossil fuels, contributing to national greenhouse gas emissions. Since the mid-2000s, when oil was discovered in the pre-salt layer, energy policy has focused on expanding oil production and its by-products, delaying investments and incentives for cleaner fuels and hindering the renewable energy agenda, despite early expectations that oil revenues would support it. Also, the authorization for Petrobras to operate in the pre-salt and in the Equatorial Margin[4] reinforces the fossil fuel lock-in in the Brazilian economy. Political debates over this agenda, shaped by conflicting interests among stakeholders, have often led to outcomes different from initial expectations regarding the use of oil revenues for the energy transition and environmental protection. Dependence on fossil fuels in the transport sector generates uncertainty about the future, making it important to quantify how freight demand may evolve under different pathways, which is the focus of the first essay of this thesis.

One of the primary mechanisms for implementing the international response to climate change under the Paris Agreement of the UNFCCC, established in December 2015, is the adoption of voluntary commitments by countries to reduce GHG emissions and undertake other actions, known as Nationally Determined Contributions (NDCs) (Mills-Novoa and Liverman, 2019). NDCs outline the measures a country is taking to mitigate emissions at a national level, with the option to address adaptation measures as well. Also, as highlighted in Den Elzen et al. (2019), NDCs are dynamic and not one-

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[4] According to Petrobras (2025), the Equatorial Margin, located between the states of Amapá and Rio Grande do Norte, has petroleum potential and ongoing development, with more than 700 wells drilled. Petrobras emphasizes that its strategy combines technological investment with safety and environmental standards.

time commitments. Countries are obligated to regularly enhance their commitments, informed by progress assessments conducted every five years under the Paris Agreement. In addition, achieving the goals outlined in an NDC does not necessarily imply that a country is implementing more rigorous mitigation measures compared to others. Furthermore, countries employ diverse approaches to policy-making; some view their pledges or targets as a catalyst for ambitious policies, whereas others primarily formalize the anticipated impact of existing measures.

Brazil's most recent update to its NDC, submitted in 2024, raises the country's climate ambition in line with the objectives of the Paris Agreement. The new NDC commits Brazil to reducing its net greenhouse gas emissions by 59.0% to 67.0% by 2035, compared to 2005 levels (equivalent to reaching between 850 million and 1.05 billion tonnes of CO_2 equivalent by that year). This updated commitment strengthens the trajectory set by the country's first and second NDCs, expanding the reduction target from 9.0% between 2025 and 2030 to 13.0–29.0% between 2030 and 2035.[5] Brazil also maintains its long-term objective of achieving climate neutrality by 2050. The submission reaffirms the principles of the UNFCCC, particularly the *"common but differentiated responsibilities and respective capabilities, in light of different national circumstances"*, acknowledging Brazil's role as a developing country with historically low contributions to global emissions[6] (Brasil, 2024).

Total anthropogenic CO_2 emissions from the Brazilian energy mix reached approximately 431 $MtCO_2$e in 2024., a 0.6% increase over 2023, highlighting the challenge Brazil faces in meeting its updated NDC targets. Although the power sector typically accounts for 75.8% of net GHG emissions worldwide, Brazil presents a distinct emissions profile due to the high share of renewables in its energy mix (EPE, 2025)[7]. Within this context, the transport sector, one of the largest energy consumers in Brazil, has been the primary contributor to recent emissions growth. Figure 1 presents transport

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[5] The target range accounts for uncertainties in future scenarios and recognizes that implementation will depend on both national and global factors through 2035. Brazil is committed to reaching the upper end of its target, aiming for a 67.0% emissions reduction by 2035. Achieving this depends on mobilizing financial resources, technology transfer, and capacity building, particularly through international cooperation under the Paris Agreement. The new NDC applies to all economic sectors and adopts an absolute emissions cut. It aligns with Brazil's goal of climate neutrality by 2050 and the Paris Agreement's $1.5\,^{\circ}\mathrm{C}$ target, as reaffirmed in the Global Stocktake adopted at COP28, held in Dubai in 2023 (Brasil, 2024).

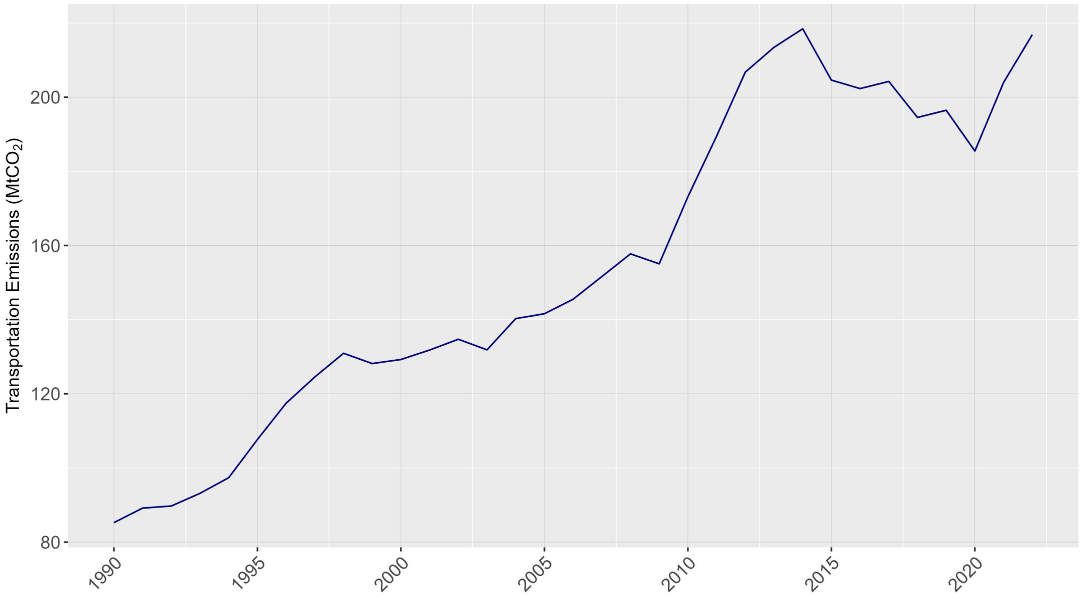
[6] According to IEA (2022), Brazil's carbon intensity was 33.0% of China's, 62.0% of the United States (US), and similar to that of OECD Europe. Per tonne of oil equivalent (toe) supplied, Brazil emitted 71.0% of OECD Europe's emissions, 66.0% of the US, and 50.0% of China. The standard unit of measurement for converting the different forms of energy used is the (toe). The conversion factors are determined taking into account the higher calorific value of each type of energy compared to that of oil, which is 10,800 kcal/kg (Brasil, 2022a).

[7] The Empresa de Pesquisa Energética (EPE) develops and publishes the *Balanço Energético Nacional* (BEN) Synthesis Report annually, following the tradition established by the Ministério de Minas e Energia (MME). The BEN provides a comprehensive account of Brazil's energy supply and demand, covering all stages from the extraction of primary energy resources to their transformation into secondary forms, as well as imports, exports, distribution, and final energy consumption (EPE, 2025).

sector emissions from 1990 to 2023, showing both long-term trends and recent increases. According to EPE (2025), transport remained the main driver of emissions growth in 2024, with energy consumption increasing by 2.3%, supported by substantial rises in hydrated ethanol (30.1%) and biodiesel (19.3%)[8], raising the renewable share of the transport energy mix to 25.7%.

As a result, transport emissions reached 214.3 $MtCO_2$e, accounting for 49.7% of total anthropogenic emissions from Brazil's energy mix. These emissions would have been higher without the additional contribution of renewables compared to 2023 (Observatório do Clima, 2024a). The transport sector's large share of national emissions underlines the importance of understanding the associated economic costs. The second essay of this thesis estimates abatement costs and assesses the feasibility of carbon pricing instruments. This analysis sheds light on how Brazil can align transport sector growth with its climate commitments while accounting for the economic implications of emissions reduction and the promotion of low-carbon alternatives.

Figure 1: GHG emissions ($MtCO_2$e) from Brazil's transport sector (1990-2023)



Source: Own elaboration based on SEEG data.

Henderson and Sen (2021) argue that unlike previous transitions, which were based on competition between fuel efficiency such as coal, petrol, and gas, the current transition is driven by a different motive: mitigating global climate change. However, the high costs of the transition, at least initially, highlight one of the main underlying barriers to the transition, which is the current failure of markets to price environmental externali-

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[8] The increase in hydrated ethanol consumption was driven by its greater competitiveness relative to Gasoline C and by expanded corn ethanol production. Biodiesel use rose due to higher diesel demand and the implementation of a 14.0 % blending ratio in mineral diesel (B14) in March 2024 (EPE, 2025).

ties. The introduction of new energy sources has and will require changes not only in the regulation of energy markets but also in the prevailing linear paradigm of production and consumption, in which resources are extracted, transformed into goods, used, and then discarded. In this context, the energy transition requires systematic changes not only in energy technologies but also in the broader political, social, environmental, and economic systems built around energy production and consumption (Lazaro et al., 2022).

Losekann and Hallack (2018) emphasize Brazil's unique position in the energy transition, citing the significant success of renewable sources in national energy generation, with a remarkable 47.3% compared to the world average of 11.0% in 2019. However, challenges such as increasing costs, technical limitations, and environmental restrictions hinder the further expansion of renewable energy sources, requiring the country to address structural barriers associated with integrating new renewables to maintain a clean energy mix. Delgado (2022) extend this discussion by highlighting that the energy transition encompasses not only the transformation of the energy sector but also spillover effects on fossil fuel–intensive sectors such as transport. Efforts toward a low-carbon economy have therefore combined bioenergy, electrification, and hydrogen strategies with broader industrial and regulatory instruments. In addition to RenovaBio (Law No. 13.576/2017) and the National Hydrogen Program (PNH$_2$), recent initiatives such as the Fuel of the Future Law (Law No. 14.993/2024), which established the Sustainable Aviation Fuel Program (ProBioQAV), the National Green Diesel Program (PNDV), and the National Decarbonization and Biomethane Incentive Program, as well as mobility and industrial modernization policies including InovarAuto (2012), Rota 2030 (2018), the Mover Program (Law No. 14.902/2024), the Renovar Program (Law No. 14.440/2022), and the Brazilian Sustainable Taxonomy (Decree No. 12.705/2025), reinforce Brazil's institutional commitment to aligning energy, transport, and industrial policy with long-term decarbonization objectives.

Brazil, the world's second-largest ethanol and third-largest biodiesel producer, aims to increase the share of these renewable sources in its energy mix to approximately 18.0% by 2030. The RenovaBio program seeks to expand the use of sustainable biofuels, including biomass in energy cogeneration, and to increase the consumption of advanced second-generation ethanol as well as biodiesel, green diesel, and renewable coprocessed diesel in the diesel mix. The Fuel for the Future program will establish a regulatory framework for CO_2 capture and storage technology (ProBioCCS) to reduce carbon emissions from the oil and gas sector, promote the production of sustainable aviation kerosene through the ProBioQAV program, and support investments in research, development, and innovation of low-carbon technologies through programs such as the PNH$_2$ (Brasil, 2022b).

In general, the studies[9] point to Brazil's need to accelerate the implementation of policies to comply with its NDCs. Analyses[10] emphasize that the main challenge for Brazilian climate action lies in achieving net zero deforestation by 2050, given that land-use change remains the primary driver of national greenhouse gas emissions.[11] Eliminating illegal deforestation would require that agricultural expansion occur through sustainable intensification practices, particularly in cattle ranching. Recovering degraded pastures and adopting integrated crop-livestock-forest (ICLF) systems would make it possible to meet growing demand for agricultural products using less land, while reducing emissions relative to current practices (Strassburg et al., 2014; Brasil, 2021). Studies in the energy sector indicate that mitigation measures involve increasing the use of low-carbon energy sources across all sectors, promoting fuel substitution in transport, improving energy efficiency in industry and transport, and expanding electricity generation from biomass, wind, and solar sources with low GHG emissions (IEA, 2021; IRENA, 2024).

Studying the energy transition in Brazil, particularly within the transport sector, plays an important role in the global effort to mitigate climate change and achieve sustainable development. As evidenced by a large body of research (Udemba and Tosun, 2022; Claeys et al., 2024; Liu et al., 2023; Carley and Konisky, 2020), the urgency to transition from fossil fuels to renewable energy sources is clear. Brazil, a country highly dependent on hydroelectric power and biofuels, faces unique challenges such as environmental concerns regarding deforestation and the impacts of water scarcity on hydropower. Additionally, the transport sector remains a significant contributor to GHG emissions due to its heavy dependence on fossil fuels. By studying the transition in this sector, policymakers and stakeholders can identify key areas for intervention and innovation, such as promoting electric vehicles[12], investing in public transport infrastructure, and incentivizing the use of renewable fuels. Furthermore, understanding the socioeconomic implications of this transition is central for ensuring equitable distribution of benefits and addressing historical environmental injustices, as highlighted by Werner and Lazaro (2023). Thus, studying the energy transition in Brazil's transport sector not only contributes to global efforts to mitigate climate change but also has the potential to support inclusive and sustainable development within the country.

Brazil's commitment to reducing GHG emissions, as outlined in its NDC under the

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[9] Bustamante et al. (2019); Den Elzen et al. (2019); Carvalho et al. (2020) and Köberle et al. (2020).

[10] Bustamante et al. (2019); Gallo and Albrecht (2019); Kissinger et al. (2019); Köberle et al. (2020).

[11] According to Observatório do Clima (2024b), despite recent declines in deforestation rates, land-use change continues to position Brazil among the largest global emitters. Gross emissions from deforestation alone exceed the total emissions of major oil-producing countries such as Saudi Arabia (793 $MtCO_2e$) and Canada (760 $MtCO_2e$).

[12] While the deployment of Battery Electric Vehicles (BEVs) is a key global decarbonization strategy, its rapid adoption in Brazil's heavy-duty truck segment faces major structural constraints. These challenges include the high initial capital cost of BEV technology, severe driving range limitations for the long-haul routes prevalent across the country, and the scarcity of adequate high-power charging infrastructure.

Paris Agreement, highlights the need to evaluate the energy transition in specific sectors, including transport (Brasil, 2024). While implementing climate policies remains challenging, Brazil has considerable renewable resources that can be integrated into the energy system (Bustamante et al., 2019; Carvalho et al., 2020). Policies such as RenovaBio and measures to increase the share of renewables in the energy mix directly affect the transport sector. This thesis provides a quantitative, scenario-based analysis of Brazil's freight transport system, focusing on projected demand growth and the economic implications of decarbonization.

The analysis is structured into two essays. The first essay employs Auto Regressive Distributed Lag (ARDL) models to project freight demand across road, rail, and air modes through 2099 under multiple Shared Socioeconomic Pathways (*SSPs*[13], identifying GDP and population growth as the main drivers. Road transport, which accounts for the majority of cargo movement, is projected to expand, reflecting its structural dominance and high carbon intensity, establishing a reference mitigation baseline. The second essay examines the economic implications of reducing transport emissions, estimating logistics costs as a share of GDP, the price elasticity of diesel demand, and the Marginal Abatement Costs (MACs) required to meet Brazil's 2035 NDC targets. The findings indicate that diesel demand is inelastic, suggesting that price-based interventions alone are likely insufficient. By integrating demand projections, carbon intensity, and economic feasibility, the thesis develops a scenario-based framework for policymaking, showing that an energy transition in Brazilian freight requires coordinated structural, regulatory, and technological measures. Together, the two essays provide evidence to support policy design and inform Brazil's path toward a lower-carbon and more sustainable transport system.

1.1 Objectives

To investigate the interplay between freight transport, economic growth, and the energy transition in Brazil, developing a quantitative, scenario-based framework to inform policymaking.

1.1.1 Specific Objectives

The specific objectives are: *i)* project freight demand across road, rail, and air modes through 2099 under multiple *Shared Socioeconomic Pathways* (SSPs); *ii)* estimating the historical Road Freight Carbon Intensity (RFCI) for the dominant mode,

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[13] The *Shared Socioeconomic Pathways* (SSPs) are alternative socioeconomic development scenarios combining qualitative narratives and quantitative projections of population, GDP, and urbanization. They provide a consistent framework for analyzing future energy use, land use, and greenhouse gas emissions in climate modeling (Riahi et al., 2017). Further details on the SSP framework are presented in Section 2.4.2.

establishing a mitigation baseline; *iii)* assessing the economic scale of freight transport by projecting logistics costs as a share of Brazil’s GDP; and *iv)* estimating the long-run price elasticity of diesel demand and calculating the Marginal Abatement Costs (MACs) implied to meet Brazil’s 2035 Nationally Determined Contribution (NDC) targets.

2 FREIGHT TRANSPORT DEMAND IN BRAZIL: SOCIO-ECONOMIC DRIVERS AND PROJECTIONS (2020–2099)

Abstract

The energy transition in Brazil faces a central challenge in the transport sector, which accounts for almost 15.0% share of GHG emissions and is highly dependent on fossil fuels. Understanding the future evolution of freight demand is therefore essential for planning effective decarbonization policies. This article analyzes the factors influencing freight transport demand in Brazil and presents projections for the period 2020–2099. Using historical socioeconomic data from 2000 to 2019, ARDL models were estimated to forecast demand across road, rail, and air transport. The results indicate that GDP and population are the primary drivers of freight demand, and that the models explain a substantial portion of historical variations in sector activity. Projections under the *Shared Socioeconomic Pathways* (*SSPs*) reveal significant growth in freight demand across all modes. Under the *SSP5* scenario, characterized by fossil-fuel-driven economic expansion and high consumption, annual transport demand in 2099 is projected to rise relative to 2019 levels by 653.3% for road, 472.9% for rail, and 770.8% for air, reflecting the intensification of logistical activity in a resource-intensive development pathway. The *SSP1* scenario, emphasizing sustainability and renewable energy adoption, exhibits the second-highest demand, while *SSP2*, representing a continuation of historical trends, shows moderate growth, highlighting the variability introduced by differing socioeconomic trajectories. The emissions analysis focuses exclusively on road transport due to its dominant share of both freight activity and sectoral CO_2 emissions. Historical data from 2000 to 2019 show an average Road Freight Carbon Intensity (RFCI) of 120.7 gCO2/TKU. Future emissions were projected by applying this constant RFCI to road freight demand under *SSP1*, *SSP2*, and *SSP5*. The *SSP5* scenario produces the highest emissions, exceeding 600 $MtCO_2$ annually by 2099, whereas *SSP2* reaches just over 300 $MtCO_2$, and *SSP1* approximately 400 $MtCO_2$. These forecasts highlight how socioeconomic trajectories critically influence the sector's long-term carbon emissions and the need for structural measures, such as fleet renewal, deployment of low-carbon fuels, and enhancements in operational efficiency. By combining demand modeling with a targeted assessment of road freight emissions, this research offers a framework for transport planning and climate policy, enabling evidence-based strategies that reconcile economic growth with emission reduction objectives and advance Brazil's shift toward a sustainable and efficient freight transport system.

Key-words: Transport Demand; Energy Transition, Emissions

2.1 Introduction

This study examines the determinants of freight transport demand in Brazil and presents scenarios for future demand based on projections from the *Shared Socioeconomic Pathways* (*SSPs*) (Van Vuuren et al. (2017); Riahi et al. (2017); O'Neill et al. (2017)). The Brazilian transport sector plays an important role in the national energy transition, as its final energy demand has grown faster than that of any other sector. In 2024, the sector accounted for 33.2% of Brazil's total energy consumption and emitted 214.3 $MtCO_2e$, representing approximately 14.4% of the country's total net greenhouse gas emissions (EPE, 2025). If current trends continue, the sector's share of emissions is expected to increase to 40.0% by 2030 and 60.0% by 2050 (Arioli et al., 2020). Reducing emissions from the transport sector will therefore play an important role in any integrated carbon reduction strategy. Achieving these reductions will require measures such as improving vehicle fleet efficiency, lowering the carbon intensity of fuels, and/or reducing demand for vehicle kilometers traveled (Yeh et al., 2017). In addition, emission mitigation will require investments in the production of alternative fuels, the expansion of refueling infrastructure for freight transport, and improvements in the quality and capacity of existing transport infrastructure.

The energy transition in the transport sector is an ongoing global process in the face of climate change. Sustainable solutions are envisioned for the future, but many societies are still stuck with high carbon energy regimes and high GHG pollution. Projecting future energy transitions in the transport sector has raised global concerns. It is now understood that replacing the current energy system requires integrating new energy technologies with environmental science, economics, and management. Therefore, understanding the specificities of the Brazilian transport sector and how its energy transition will unfold is essential for developing appropriate decarbonization and climate policies (Chen et al., 2019).

As for Brazil, the government committed to strengthening low-carbon development by 2030 as part of the 2015 Paris Agreement. Key measures included the expansion of biofuels at the expense of petroleum-based fuels and energy efficiency gains in the transport sector, which currently accounts for almost half of total energy-related CO_2 emissions (Lefèvre et al., 2018). Furthermore, Köberle et al. (2020) identify transport as one of the main candidates for deep decarbonization in Brazil, taking advantage of low-carbon electricity generation and its high bioenergy production. They found that the most important mitigation measures are the electrification of the light-duty vehicle fleet and the production of biodiesel and biokerosene. However, the authors point out that the electrification of transport in Brazil (and globally) could reduce the demand for biofuels and increase the demand for electricity, with implications for the electricity sector.

Brazil holds a prominent position in the biofuel industry and has made substantial progress in developing biodiesel. Understanding the drivers behind this trajectory is essential for designing future sustainability strategies that require structural changes in energy production and consumption. Since the 1990s, Brazil has improved energy efficiency and reduced the carbon intensity of its transport energy mix, even though total CO_2 emissions from the transport sector have increased over the same period, as shown in Figure 1. This increase occurs despite the growing use of biofuels, due to the expansion of the vehicle fleet, rising transport demand, and continued reliance on fossil fuels in certain transport modes. This pattern reflects the impact of biofuels, targeted policies, and technological innovations, and suggests significant potential to further enhance sectoral efficiency, expand the share of biofuels in the transport energy mix, and support the formulation of long-term pathways toward sustainable energy development (Nikas et al., 2022).

The projection of the Deep Decarbonization Pathways Project (DDPP)[14] for Brazil's transport sector showed that reliance on renewable energy, especially ethanol, will increase. An ambitious biofuels program will increase the production of sugarcane ethanol, biodiesel and biokerosene, and allow renewable ethanol to replace a significant amount of gasoline, as it will fuel most of the light vehicle fleet. Thus, through these combined measures, more than half of the total energy used in transport would be renewable. In addition, the carbon intensity of transport fuels per unit of energy is expected to be reduced by nearly half. Furthermore, the projection also expressed that higher national energy efficiency standards will be used to increase the fuel economy of all vehicles (cars, buses, and trucks), and the current tax incentives for cars with smaller engines and lower fuel consumption will be strengthened and expanded (La Rovere et al., 2015).

Freight transport is a fundamental component of the global economy. As there is growing concern about the externalities of projected future growth in transport demand, policymakers are looking for ways to steer its progress in a more sustainable direction. The quantity and composition of freight transport demand is determined by a series of decisions made by a variety of decision makers (Van de Riet et al., 2016). The demand for transport is derived and not an end in itself, as freight movements occur to satisfy needs. Moreover, a good transport system expands the opportunities to satisfy these needs, while a system that is too congested or poorly connected limits opportunities and limits economic and social development, as well as generating negative externalities. In this sense, it is essential to understand the determinants that influence the demand for freight transport in order to identify the opportunities for energy transition in this sector (de Dios Ortúzar and Willumsen, 2011).

The factors that determine the demand for transport services and influence the decisions of policy makers can be categorized into five groups, as highlighted by de Dios Ortúzar and Willumsen (2011): Gross Domestic Product (GDP), consumer demand, economic structure, logistics system, and mode characteristics. These factors play interrelated and complex roles in the analysis of transport demand, providing

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[14] The *DDPP*, an initiative of the *Sustainable Development Solutions Network* (SDSN) and the *Institute for Sustainable Development and International Relations* (IDDRI), aims to demonstrate how countries can transform their energy systems by 2050 to achieve a low-carbon economy and significantly reduce the global risk of catastrophic climate change (La Rovere et al., 2015).

a comprehensive view of the forces that drive mobility-related decisions. The relationship between GDP and freight transport demand is particularly important, as GDP has traditionally been considered one of the main indicators of changes in freight transport demand, with a significant relationship between the volume transported in tonne-kilometres (TKM). This relationship is based on the premise that GDP growth is associated with increased production and consumption, which in turn drives demand for transport services. However, it is important to note that the relationship between GDP and transport demand can be affected by a number of other factors, such as changes in technology, environmental policies, international trade trends, and consumer preferences.

Understanding the demand for transport is important for analyzing issues related to the transport system (Winston, 1983). To provide future scenarios of freight demand in Brazil that can support the energy transition, this study employs autoregressive models with distributed lags (ARDL) for road, rail, and air freight, capturing both long- and short-term dynamics and validated using the *bounds testing* procedure developed by Pesaran et al. (2001). The estimated models are combined with GDP and population projections based on the *SSPs*, incorporating economic and demographic drivers to explore potential future trends in freight transport until the end of the 21st century. Building on these demand projections, the study also analyzes emissions from road transport, given its significant share of both freight activity and sectoral CO_2 emissions. By considering different pathways under *SSP1*, *SSP2*, and *SSP5*, the analysis shows how future development trajectories can affect the sector's long-term carbon footprint. This integrated approach provides insights into the factors shaping freight transport in Brazil and supports evidence-based planning and policy strategies aligned with sustainable development goals.

This introduction is followed by an overview of the Brazilian freight transport sector. Section 2.3 provides details on the methodology used to construct transport demand scenarios for Brazil, section 2.4 discusses the data sources and pre-processing. Section 2.5 discusses the results, while section 2.6 presents the final remarks.

2.2 Freight transport in Brazil

Road transport accounts for 64.9% of total freight transport in Brazil (CNT, 2025b). This structural imbalance is primarily the legacy of a historical development model that, since the mid-20th century, prioritized massive public investment in road infrastructure over rail and waterway networks, particularly during the country's industrialization and interiorization strategies in the 1960s and 1970s. Thus, the dominance of road transport is associated much more with historical and structural economic choices than with inherent technological superiority. This historical trajectory, rather than inherent superiority, established strong path dependency effects that reinforced road transport's market position. Nonetheless, several factors currently sustain its market share, notably its inherent door-to-door flexibility, which ensures widespread logistical access, and its simplified documentation process compared to rail. Moreover, road transport is recognized for its speed in delivering products, making it essential for operations between cities, states, producers, and distribution centers, and for supplying the end market, which generates significant economic impact (Soliani, 2021).

The state of Brazil's freight transport system has been the subject of much debate. The country's continued reliance on an unbalanced modal structure, dominated by road transport, which is responsible for the largest share of emissions, remains a major challenge. The infrastructure related to this activity has significant shortcomings, reflected in the poor quality of roads, railways, ports and airports, which hampers the movement of goods and contributes to increased emissions. Another obstacle to the development of a cleaner and more sustainable freight transport system is the lack of coordination between public authorities. The Brazilian system is highly fragmented, involving multiple institutions across different government levels, including the Ministry of Transport, federal agencies responsible for infrastructure planning and regulation, state and municipal authorities, and sectoral bodies involved in logistics and freight management. Although communication exists among these entities, coordination remains limited and fragmented, hindering the implementation of integrated policies aimed at improving freight transport efficiency and infrastructure quality (Fleury, 2012).

Novo (2016) points out that rail stands out for its high capacity and ability to move heavy loads over long distances, making it a key component of a sustainable freight transport system. Its low energy intensity contributes to reduced carbon emissions per tonne-kilometer, but realizing its full potential requires significant investment in infrastructure, modernization of existing lines, and expansion of the rail network to underserved regions. Rail transport is particularly suitable for bulk commodities, such as grains, minerals, and industrial raw materials, where economies of scale can be fully exploited. Meanwhile, air transport serves specific demands for high value-added goods, small volumes, and urgent deliveries, offering unmatched speed and reliability. Despite having the highest energy consumption per revenue tonne-kilometer (RTK)[15] transported, air transport represents less than 1.0% of the overall modality mix, resulting in considerably lower total emissions of pollutants compared to road transport. The complementary roles of rail and air highlight the need for an integrated multimodal strategy, where each mode is leveraged according to its strengths, to improve effi-

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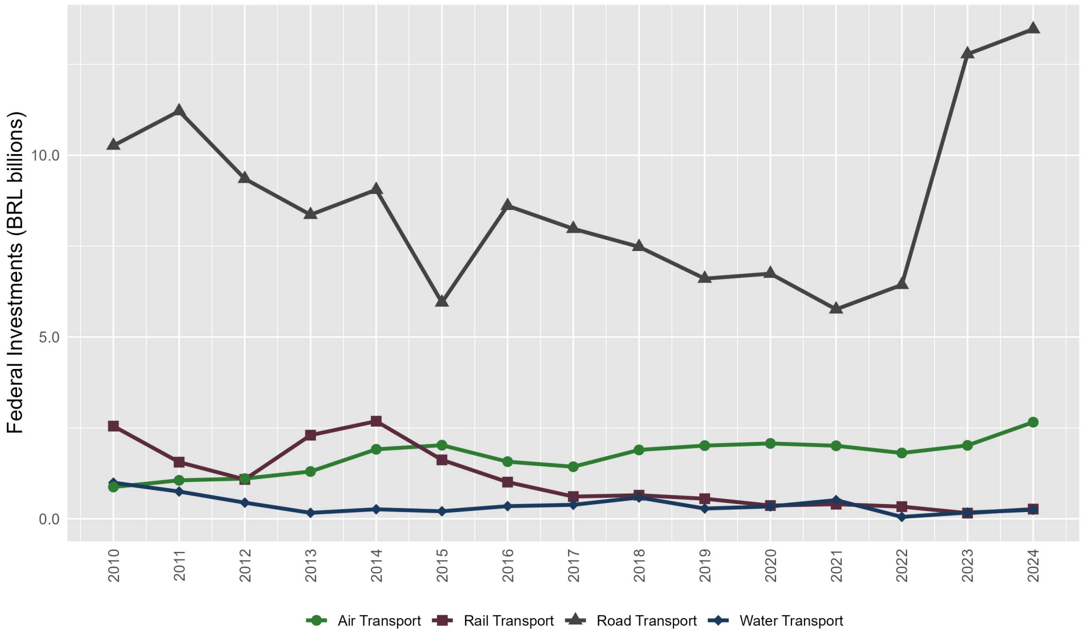
[15] RTK, short for "revenue tonne kilometers," is a physical unit of measurement that quantifies the effort required to transport freight. It represents the effective tonnes, taking into account only the weight of the cargo being transported, without taking into account the weight of the equipment or vehicles used in the transport. It is an important metric for evaluating the efficiency and amount of work required to move goods over a given distance.

ciency, reduce environmental impact, and meet the diverse demands of Brazil's freight sector.

Figure 2 presents federal investment in transport infrastructure in Brazil, broken down by mode (road, rail, air, and water), covering the period from 2010 to 2024 (in BRL billions, deflated by the *Índice Nacional de Preços ao Consumidor Amplo* (IPCA) as of December 2024). The figure shows that road transport has consistently received the largest share of investment, reflecting both its extensive existing network and the structural importance of road freight in Brazil. Rail investments declined after 2015, indicating a reduction in relative allocation, even though railway expansion and modernization projects continue to progress, albeit at a gradual pace. Air transport investment exhibits a steady, moderate increase, whereas water transport continues to represent a small share of total investment. These patterns are consistent with a context of relatively constrained fiscal capacity for transport infrastructure investment in Brazil, which may contribute to the concentration of resources in the most widely used freight transportation mode. Overall, these patterns suggest that infrastructure investment decisions are influenced by budgetary constraints, historical network structure, and the operational centrality of road transport in the Brazilian freight system, rather than necessarily indicating explicit policy prioritization of any specific transport mode. It is also important to note that infrastructure investment in Brazil has been partly complemented by concession-based programs implemented over the past few decades across highways, railways, airports, and ports.

Figure 2: Transport infrastructure investment, by mode (BRL billions), in Brazil (2010-2024)



Source: Own elaboration, based on SIGA Brasil data.
Deflated by the IPCA as of December 2024.

The Brazilian freight transport modality mix remains heavily reliant on road transport, as highlighted by CNT (2025b). In 2017, the base year for the National Logistics Plan, 66.2% of road ton-kilometers (RTK) and 83.2% of the value per useful kilometer (VPUK) were concentrated in the road mode, indicating that road freight transports both the largest volumes and higher-value goods across most origin-destination flows. Public investment in transport infrastructure has historically remained relatively low. According to CNT (2025a), federal investment peaked at 0.26% and 0.25% of GDP in 2010 and 2011, respectively, remaining below 0.5% even during high expenditure periods. This persistent underinvestment contributes to infrastructure bottlenecks, including pavement deterioration, poor signage, and geometric design deficiencies, increasing accident risks and operational costs. Federal investment further declined to 0.14% of GDP in 2016, limiting maintenance and expansion capacity and reinforcing the structural vulnerability of a transport network that supports the majority of freight and passenger movements in Brazil.[16]

However, it is important to note that this activity also poses challenges in terms of environmental sustainability. The large number of trucks in circulation and the loading and unloading operations have an impact on urban areas and roads. In addition, road freight transport is highly dependent on fossil fuels, which contributes to an increase in man-made GHG emissions. While road freight is essential to the country's economic development, its dynamics also highlight the need for more sustainable alternatives to mitigate the sector's environmental impact. In this sense, the current transport modality mix has shown its inadequacy, since the high dependence on road transport aggravates the challenges of urban mobility, exacerbates environmental problems and has a negative impact on the quality of life of the population. It is therefore clear that the improvement of the country's economic and environmental results is directly linked to changes in the transport sector (Soliani, 2021).

2.3 Methodology

This study develops scenarios for freight transport demand in Brazil between 2020 and 2099, taking into account different socioeconomic pathways. The scenarios are based on GDP and population projections prepared by the International Institute for Applied Systems Analysis (IIASA) (Riahi et al., 2017). First, econometric models were estimated using historical data for the volume of freight transport demand, GDP, and population in Brazil. The annual seasonality of transport demand was taken into account, and both short-term dynamics and long-term relationships were determined. In

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[16] International comparison shows that infrastructure investment in Brazil is substantially below levels observed in many developing economies and also lower than in countries such as China (5.1%), Georgia (2.9%), and Belarus (2.8%). Although high-income countries such as the United Kingdom (0.8%), Germany (0.7%), and the United States (0.6%) tend to exhibit lower investment ratios after reaching mature infrastructure stocks (CNT, 2025d).

addition, the coefficients of the estimated models and the socioeconomic projections of the *IIASA* were used to draw up scenarios for the demand for freight transport in Brazil until year 2099.

2.3.1 Determinants of freight transport demand

The determinants of freight transport demand are diverse and can be grouped into several categories, as noted by de Dios Ortúzar and Willumsen (2011). These include GDP, consumer demand, economic structure, the logistics system, and characteristics of the transport mode. Among these, GDP is widely recognized as the primary determinant of changes in freight demand, with growth generally leading to a proportional increase[17]. While other factors such as consumption patterns, economic structure, and logistics efficiency also play important roles, GDP provides the most direct and measurable link to freight activity. For this reason, the present study focuses primarily on GDP (income) and population as the key drivers of freight transport demand. These two determinants together account for more than 90.0% of the observed variation, as will be shown later, they benefit from the availability of consistent long-term projections, and they display significant year-to-year variation compared to other explanatory factors[18].

Although GDP is the main driver of freight transport demand, its role is largely indirect. Economic growth stimulates freight demand by influencing consumer spending and shaping the sectoral structure of the economy. In other words, rising GDP increases the demand for goods and services, which in turn drives the need to transport them. This effect is compounded by the concentration of population and economic activity in specific regions, which not only determines the distance and volume of freight movements but also affects the choice of transport mode, the frequency of shipments, and the allocation of resources across the logistics system (de Dios Ortúzar and Willumsen, 2011).

The selection of GDP and population as the principal explanatory variables is supported both by economic theory, which identifies them as key indicators of economic activity and consumption needs, and by recent empirical studies. For instance, Tjandra et al. (2024) systematically evaluated ten socioeconomic variables, including infrastructure investment, consumer spending, and vehicle stock, to determine the main drivers of global transport demand. Their regression analysis showed that income in-

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[17] The relationship between freight transport demand and GDP is often expressed as GDP elasticity, i.e., the ratio between a percentage change in freight transport demand (measured in tonne-kilometers or tonnes) and a percentage change in GDP. A GDP elasticity greater than 1 indicates that a 1.0% increase in GDP results in a greater than 1.0% increase in freight demand (Van de Riet et al., 2016).

[18] A recognized limitation of this approach is the exclusion of the specific economic structure (e.g., the shifting ratio of manufacturing to services, or the composition of commodity production), which influences the freight intensity of economic growth. However, incorporating such granular changes into the long-term *SSP* scenarios is constrained by data availability

dicators (GDP per capita) and demographic indicators (urban population) not only had the highest statistical significance, but were also the only variables with consistent and publicly available projections for most countries. Scenarios of the future often provide projections for a limited set of variables, but GDP and population are almost always included. This combination of statistical relevance, data availability, and practical coverage provides empirical support for the methodological approach adopted in this study for Brazil, justifying the use of these variables in projecting future demand scenarios.

Taken together, these considerations justify the selection of GDP and population as the core explanatory variables for projecting future freight demand in Brazil. By capturing both the scale of economic activity and the demographic drivers of transport needs, this approach provides a systematic and literature-supported basis for scenario analysis and long-term planning[19].

2.3.2 Models of freight transport demand

Various methods are available for classifying models of freight demand, and according to Winston (1983), it proves beneficial to categorize these models into two distinct types: aggregate and disaggregate. In aggregate models, the primary unit of observation involves the collective share of a specific freight mode at the regional or national level. On the other hand, disaggregate models focus on the unique choices made by individual decision-makers regarding a specific freight mode for a given shipment. These freight demand models have significant practical applications, such as forecasting regional or national freight flows and anticipating demand for new transport modes. The integration of realistic freight demand models into forecasting systems holds the promise of significantly improving the accuracy and foundation of specific forecasts.

Abdelwahab and Sargious (1992) points out that econometric modeling plays an essential role in dissecting freight transport systems by leveraging time series and/or cross-sectional data to reveal and estimate structural relationships that illuminate the intricacies of specific segments or the entire system. The substantial body of research within the field of econometric modeling for freight transport can be neatly classified into three primary categories: supply-side models, demand-side models, and integrated models, which consider both supply and demand behaviors in a comprehensive manner.

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[19] Other factors, including economic structure, international trade, and characteristics of each transport mode, also influence freight demand, both directly and indirectly. Van de Riet et al. (2016) highlight the role of new communication technologies, mainly through changes in logistics systems or trade patterns. Characteristics of each transport mode additionally affect demand through infrastructure capacity, availability of transport modes, service characteristics, vehicle capacity, and travel time. These factors were not included in the present analysis due to insufficient data availability for consistent projection across the study period.

De Jong et al. (2004) argues that many modeling principles utilized in predicting passenger transport have found application in freight transport forecasting. The four-step transport modeling framework from passenger transport can be beneficial for freight transport[20]. However, variations arise within each step, as freight models diverge significantly from their passenger transport counterparts. Noteworthy distinctions between the two markets encompass the diverse range of decision-makers in freight (shippers, carriers, intermediaries, drivers, operators), the variability of transported items (ranging from parcel deliveries with multiple stops to single bulk shipments of considerable tonnage), and the restricted availability of data, particularly disaggregate data, partly attributed to confidentiality concerns.

In the early phase of modeling for freight transport, four distinct model types have been practically utilized. System dynamics models are applied to analyze and forecast patterns in freight transport using overall data. Zonal trip rate models, also relying on overall data, concentrate on determining trip rates within specific zones. Another category involves Input-Output (IO) and associated models, which explore IO relationships in freight transport based on overall data, and trend and time series models, where historical trends are extended into the future, varying from basic growth factor models to intricate autoregressive moving average models. These models exclusively depend on overall data, and currently, there are no identified instances of production and attraction models in freight transport estimated on disaggregate data. Furthermore, time series models incorporating explanatory variables like GDP have been developed within this framework (De Jong et al., 2004).

According to Pendyala et al. (2000), the analysis of trends and time series in freight activity involves projecting historical trends into the future. Models in this category range from simple growth factor models to more complex autoregressive integrated moving average models, which are well-suited for analyzing time series data. Furthermore, De Jong et al. (2004) emphasize that these modeling techniques are easy to implement, require minimal data, and rely on historical trends for predicting future outcomes. However, it is essential to acknowledge the inherent limitations of these models, particularly their limited ability to provide deep insights into causality or to assess the potential impacts of policy interventions.

In light of the approaches reviewed in this section, the present study follows the econometric tradition of demand-side models that incorporate explanatory variables such as GDP and population. This type of model is particularly suitable for freight

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[20] In a freight transport model system, the process comprises four main steps: production and attraction, where quantities of goods moving between origin and destination zones are determined; distribution, calculating goods transport flows between zones; modal split, allocating commodity flows to transport modes; and assignment, converting flows into vehicle-units and assigning them to transport networks. This encompasses both truck and passenger car flows on road networks, depending on the model's specifications. (De Jong et al., 2004).

transport analysis because it can account for both short and long-run dynamics, can be estimated with relatively limited datasets, and allows for the examination of relationships between macroeconomic determinants and transport demand. While the model allows analysis of how macroeconomic factors relate to transport demand, the results should be interpreted as indicative rather than definitive evidence of causal effects. By focusing on explanatory variables identified as the main drivers of freight activity, the modeling strategy ensures policy relevance while offering a practical balance between analytical rigor and empirical applicability. The next section presents the model specification adopted in this study.

2.3.3 Autoregressive Distributed Lag Model (ARDL)

An Autoregressive Distributed Lag (ARDL) model was estimated to analyze the demand dynamics for freight transport across different modes (road, rail, and air), considering key determinants, lag structures, and potential cointegration. The empirical specification of the model is presented in equation (1). A key advantage of the ARDL framework is its ability to capture both short-run adjustments and long-run equilibrium relationships within a single specification, making it well-suited for analyzing long-term transport demand. This choice is further justified by three considerations. First, ARDL models allow the explicit inclusion of explanatory variables to assess their effects on freight demand, rather than relying solely on descriptive analysis of historical time series. This feature enables the model to capture both short-run adjustments and long-run relationships, providing a more informative approach than methods that only extrapolate past trends. Second, they can handle variables with mixed integration orders, a frequent issue in freight transport studies. Third, estimation is computationally straightforward and feasible even with relatively small datasets. By also accounting for lagged effects and cointegration, the ARDL framework provides a transparent and policy-relevant tool for understanding the evolution of freight demand.

$$dmc_t = \beta_0+\beta_1 t+\sum_{i=1}^{p}\beta_i^{dmc}\, dmc_{t-i}+\sum_{i=0}^{q_1}\beta_i^{gdp}\, GDP_{t-i}+\sum_{i=0}^{q_2}\beta_i^{pop}\, Pop_{t-i}+\sum_{m=2}^{12}\alpha_m\, MTH_{m,t}+\varepsilon_t \tag{1}$$

The variables in equation (1) have the following meanings:

- dmc_t represents the demand for freight transport, by mode, in period t;
- GDP_t is the Gross Domestic Product in period t;
- Pop_t is the population in period t;
- $p \in \mathbb{N}$, $q_1, q_2 \in \mathbb{N}_0$ denote the number of lags of each variable;

- β_0 is a constant, β_1 is the trend, and $\{\beta_1^{dmc}, \ldots, \beta_p^{dmc}\}$, $\{\beta_0^{GDP}, \ldots, \beta_{q1}^{GDP}\}$, $\{\beta_0^{pop}, \ldots, \beta_{q2}^{pop}\}$ are the coefficients to be estimated;
- $MTH_{m,t}$ is a dummy variable equal to one if the month in period t is m and zero otherwise. January is omitted because it serves as the base month;
- ε_t represents the error term.

First, the stationarity of the variables was tested to ensure the validity of the estimation results. Table I shows the results of three different stationarity tests: the *Augmented Dickey-Fuller* (ADF)[21], Phillips-Perron (PP)[22], and Kwiatkowski-Phillips-Schmidt-Shin (KPSS)[23]. Also in Table I, the number of lagged terms selected by the Bayesian Information Criterion (BIC) is given in parentheses after the p-value. For example, the tests indicated that the demand for road freight (dmc_t), GDP (gdp_t), and population (pop_t) are I(1). All three variables, dmc_t, gdp_t, and pop_t, are found to be non-stationary in levels but stationary in first differences, indicating that they are integrated of order one, I(1). Therefore, the *bounds testing* procedure of Pesaran et al. (2001) will be employed to ensure the validity of the model.

Table I: p-values of the stationarity tests for the variables included in the analysis

	ADF			**PP**	**KPSS**		**Conclusion**
	Random-Walk	*Drift*	*Trend*		*Level*	*Trend*	
dmc_{t-1}	0.93 (14)	0.30 (14)	0.72 (14)	$<$0.01	$<$0.01	$<$0.01	I(1)
Δdmc_{t-1}	0.00 (13)	0.01 (13)	0.05 (13)	$<$0.01	$>$0.1	$>$0.1	I(0)
gdp_{t-1}	0.96 (12)	0.80 (12)	0.80 (13)	0.24	$<$0.01	$<$0.01	I(1)
Δgdp_{t-1}	0.00 (12)	0.00 (11)	0.00 (11)	$<$0.01	$>$0.1	$>$0.1	I(0)
pop_{t-1}	0.97 (1)	0.51 (1)	0.97 (1)	0.97	$<$0.01	$<$0.01	I(1)
Δpop_{t-1}	0.00 (0)	0.01 (0)	0.05 (0)	$<$0.01	$>$0.1	$>$0.1	I(0)

Source: Own elaboration.

Therefore, we estimated an autoregressive distributed lag (ARDL) model for freight demand in each mode (road, rail, and air), using Brazil's GDP and population as explanatory variables, between 2000 and 2019. The method used was able to capture long-term relationships and short-term dynamics in a single equation model. The model was then validated using the *bounds testing* procedure developed by Pesaran et al. (2001). The ARDL model can incorporate seasonality using *dummy* variables, which are not easily implemented in alternative cointegration techniques, and the inclusion of lagged terms is important to capture the dynamics of transport demand in Brazil and to incorporate autocorrelation properties into the modeling. As pointed out by Rodriguez and Trotter (2019), the ARDL approach with *bounds testing* is also known

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[21] Dickey and Fuller (1979)

[22] Phillips and Perron (1988).

[23] Kwiatkowski et al. (1992).

to have better properties in small samples compared to alternative cointegration techniques.

Following the procedure of Pesaran et al. (2001), an error correction model (ECM) was first estimated using ordinary least squares (OLS).

$$\begin{aligned}\Delta dmc_t = \mu_0 + \sum_{i=1}^{p} \mu_i^{\text{dmc}}\, dmc_{t-i} + \sum_{i=0}^{q_1} \mu_i^{\text{gdp}}\, GDP_{t-i} + \sum_{i=0}^{q_2} \mu_i^{\text{pop}}\, pop_{t-i} \\ + \theta_0 dmc_{t-i} + \theta_1 gdp_{t-i} + \theta_2 pop_{t-i} + \sum_{m=2}^{12} \alpha_m MTH_{m,t} + \varepsilon_t\end{aligned} \tag{2}$$

The lag structure of this model, represented by p, q_1, q_2, was determined by the BIC, considering up to 12 lagged terms of each variable. The *bounds testing* of Pesaran et al. (2001) determines whether there is a long run relationship between the variables, in which case it is possible to infer both their short run dynamics and their long run relationship. By projecting the exogenous variables into the future, it is then possible to generate scenarios for freight demand that reflect both the adjustment dynamics and the equilibrium relationship. Furthermore, the model in equation (2) is technically interchangeable with equation (1), although the coefficients are different.[24]

2.3.4 Road freight carbon intensity (RFCI)

Following a projection of freight demand for road, rail, and air transport, this study focuses on road freight transport for the emissions analysis. Road transport dominates Brazil's freight modality mix, accounting for 64.9% of total freight movement, making it the primary source of sectoral emissions. Furthermore, any decarbonization strategy in Brazil requires a profound transformation of this mode, rendering its analysis a priority. Finally, the Greenhouse Gas Emissions and Removals Estimation System (SEEG) provides disaggregated emissions data specifically for trucks, enabling a direct and empirical calculation, a level of granularity not available for other freight modes.

To estimate future emissions consistent with national conditions, the *Road Freight Carbon Intensity (RFCI)* was calculated, capturing the historical carbon intensity of road freight transport. This indicator is defined as the ratio of total GHG emissions to total freight transport demand over a given period. The RFCI was calculated annually using historical series of emissions and transport demand. Emissions and demand were expressed in consistent units to allow computation of grams of CO_2 per TKU.[25]

$$\text{RFCI (gCO}_2\text{/TKU)} = \frac{\text{Annual emissions in MtCO}_2 \times 10^{12}}{\text{Annual demand in billions of TKU} \times 10^{9}}$$

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[24] For details on the transformation of coefficients between models, see Hassler and Wolters (2006).

[25] Emissions, originally reported in Megatonnes of CO_2 ($MtCO_2$), and demand, in billions of Ton-Kilometers (billions of TKU), were converted to grams per TKU.

By simplifying the exponents ($10^{12}/10^{9} = 10^{3}$), the applied formula becomes:

$$\text{RFCI (gCO}_2\text{/TKU)} = \left(\frac{\text{Emissions in MtCO}_2}{\text{Demand in billions of TKU}} \right) \times 1000$$

The simple arithmetic mean of the annual RFCI values over the period provides a representative measure of the carbon intensity of road freight transport in Brazil. This average RFCI was subsequently adopted as a constant coefficient to estimate future emissions across the various Shared Socioeconomic Pathway (*SSP*) scenarios.

The final methodological step consists of projecting future annual emissions (E) for the road freight sector in each socioeconomic scenario (s) over time (t). This projection is obtained by multiplying the projected road freight demand ($D_{s,t}$), as presented in Section 2.5.1, by the calculated average *RFCI*, as expressed in the following equation:

$$E_{s,t} = D_{s,t} \times RFCI$$

Through this formulation, the *RFCI* links demand projections with emissions estimates, allowing for scenario-based analysis.

2.4 Data sources and preprocessing

This section details the diverse dataset constructed for the analysis, which is organized into three main components. Section 2.4.1 presents the historical data used for the econometric estimation of the demand models, covering monthly time series (2000–2019) for freight demand across road, rail, and air modes, as well as for key socioeconomic variables such as GDP and population, sourced from various Brazilian national agencies. Section 2.4.2 outlines the long-term socioeconomic scenarios used to project future demand, detailing the GDP and population projections for Brazil until 2100 from the IIASA's Shared Socioeconomic Pathways (*SSPs*). Finally, Section 2.4.3 describes the specific data compiled for the RFCI calculation, which integrates historical emissions data from the SEEG with the road freight demand series.

2.4.1 Historical data

Monthly data on road freight in Brazil from 2000 to 2019, expressed in TKU, were compiled by integrating historical vehicle flow records from the Associação Brasileira de Concessionárias de Rodovias (ABCR)[26] with information from the Plano Nacional de

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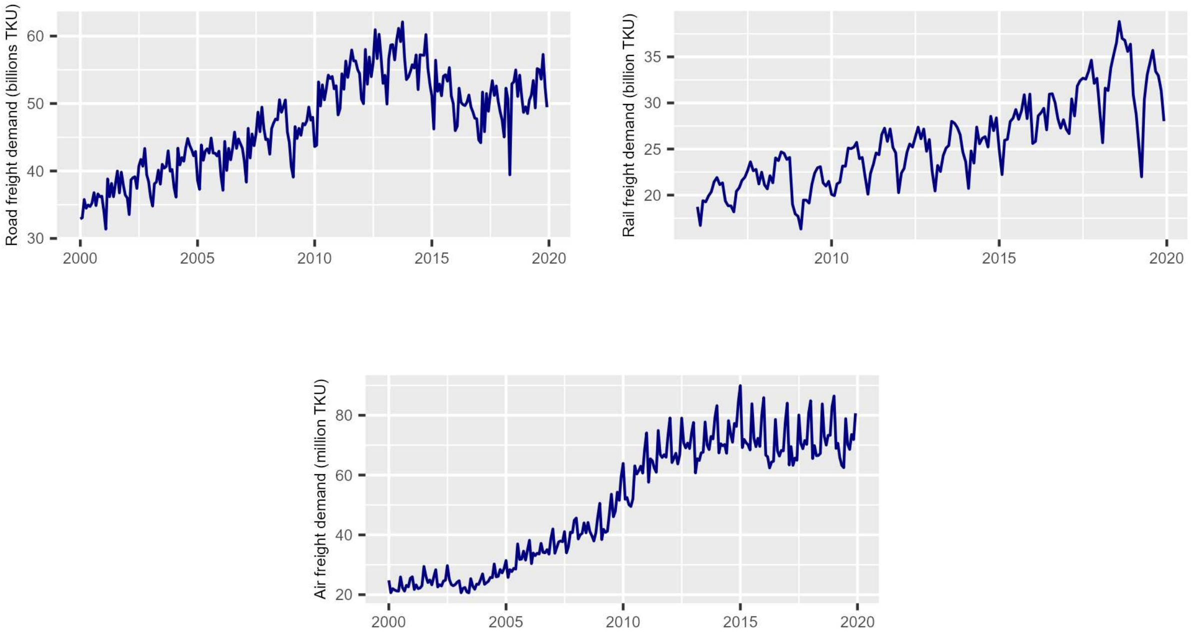
[26] ABCR calculates an index based on the total flow of vehicles passing through the country's toll plazas. In 2012, the Instituto Brasileiro de Geografia e Estatística (IBGE) included the index in the

Logística e Transportes (PNLT)[27]. Data on rail transport from January 2006 to December 2019, on a monthly basis, were obtained from the Agência Nacional de Transportes Terrestres (ANTT). Air transport data from January 2000 to December 2019, also on a monthly basis, were obtained from the Agência Nacional de Aviação Civil (ANAC)[28].

Figure 3: Freight demand by transport mode in TKU, monthly data from 2000 to 2019



Source: Own elaboration, based on data from PNLT, ANTT, ANAC and ABCR.

Socioeconomic data on Brazil's Gross Domestic Product (GDP)[29] and population size from 2000 to 2019, on an annual basis, were collected from the Banco Central do Brasil (BCB) and IBGE, as shown in Figure 4. It is important to note that from 2011, the population series were chained by the rate of population change, using data from the National Accounts. In order to make the databases compatible, the values were interpolated using linear interpolation, which allowed a monthly frequency. This approach made it possible to integrate data on GDP, population and freight demand by estimating the econometric model, allowing a more aligned analysis of the interactions

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calculation of GDP, highlighting its importance as an economic indicator (ABCR, 2023). For further methodological details on the construction and treatment of the ABCR Index, see Appendix A.

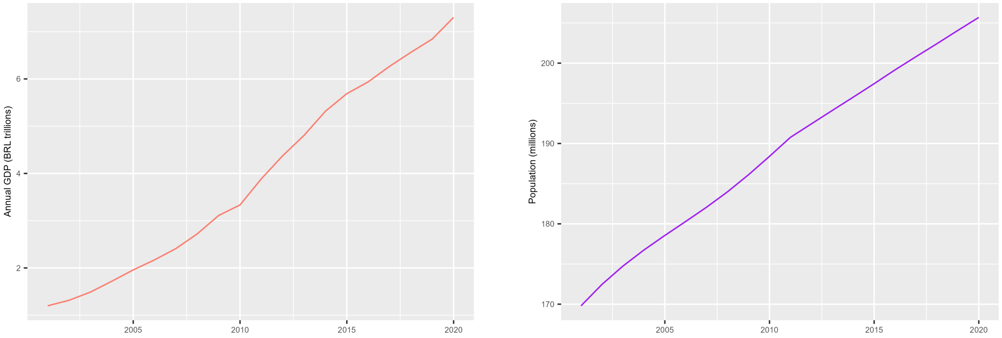
[27] PNLT is Brazil's national transport and logistics plan, originally launched in 2007 and subsequently updated. It marked the resumption of strategic planning in the sector, providing a structured database on supply and demand conditions and serving as an important source of historical information for policy analysis and long-term projections (Brasil, 2023f).

[28] Water transport is not considered in this study due to limitations in the availability of sufficiently long official data from Agência Nacional de Transportes Aquaviários (ANTAQ). Additionally, existing datasets are not reported in a consistent unit that would allow comparability with road, rail, and air transport data. Finally, water transport represents a relatively small share of Brazil's overall transport modality mix, further justifying its exclusion from the present analysis.

[29] Gross Domestic Product (GDP). Deflated by IGP-DI, 2023.06=1.00.

between these variables over time.

Figure 4: Brazil’s GDP and population historical growth (2000-2019)



Source: Own elaboration, based on BCB and IBGE data.

2.4.2 Socioeconomic scenarios (2020-2099)

The transport demand scenarios constructed in this article are based on the socioeconomic projections of the *Shared Socioeconomic Pathways* (*SSPs*). These projections are part of a scenario framework developed as a collaborative effort by the international scientific community and describe internally consistent alternative pathways of global socioeconomic development, which in turn imply different mitigation and adaptation challenges. The *SSPs* consist of narratives describing alternative developments, including a sustainable future, fossil fuel development, and intermediate development. The long-term demographic and economic projections of the *SSPs* present a wide range of alternative developments, with global energy consumption ranging from 400 to 1200 EJ[30] and changes in land use showing very different dynamics, ranging from a possible reduction in cultivated area to a massive expansion of more than 700 million hectares by 2100 (Riahi et al., 2017).

The *SSPs* set of scenarios consists of a set of baselines, which describe future developments in the absence of new climate policies, and mitigation scenarios, which explore the impact of policies. The development of the *SSPs* scenarios went through several key stages. First, narratives were developed, which were then translated into quantitative projections of key socioeconomic factors such as population, economic activity, and urbanization. In order to obtain quantitative projections of energy, land use and emissions related to the *SSPs*, both the narratives and the projections of socioeconomic factors were developed using a set of integrated assessment models (*IAM*). These models made it possible to explore different interpretations and scenarios for each *SSPs*, and among the various interpretations, so-called *SSPs* “markers” were

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[30] *Joule* is the unit traditionally used to measure mechanical energy (work) and is also used to measure thermal energy. One exajoule (EJ) is equal to 10^{18} *joules*.

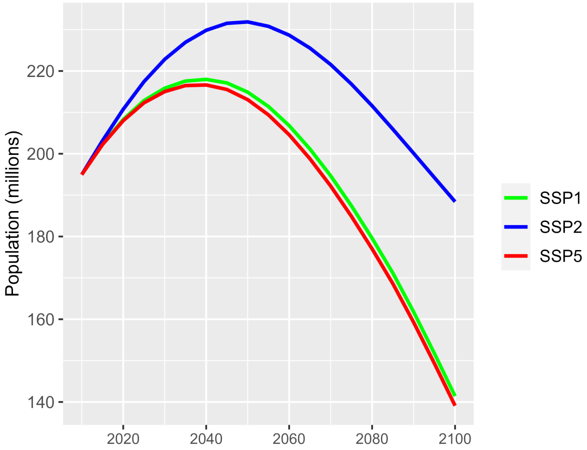
selected to represent the broader developments of each *SSP*. On the other hand, the "non-marker" scenarios are relevant because they offer *insights* into possible alternative interpretations of the basic elements and storylines of the *SSPs* (Riahi et al., 2017).

The *SSPs* narratives, according to (O'Neill et al., 2017), consist of textual descriptions of how the future might unfold in terms of overarching social trends and aim to establish a coherent logic of their key causal relationships. In this way, the narratives of the *SSPs* play an important role in complementing the quantitative projections of the model. By describing key socioeconomic, demographic, technological, lifestyle, political, institutional, and other trends, these narratives provide an essential context for better understanding the basis and meaning of the *SSPs*' quantitative projections. This study focuses on exploring future possibilities using narratives *1*, *2*, and *5* from the *SSPs*. This selection provides an examination of potential scenarios, ranging from optimistic outcomes with successful climate action to more challenging situations requiring global efforts. In addition, it allows for a thorough analysis of different levels of adaptation and mitigation challenges and their associated policy implications because, as noted by Riahi et al. (2017), *SSP1* depicts a future with low adaptation and mitigation challenges, *SSP5* combines high mitigation challenges with low adaptation challenges, and *SSP2* describes a world with intermediate challenges for both adaptation and mitigation.

The *SSPs* demographic projections use a multidimensional demographic model to estimate national populations based on different assumptions about fertility, mortality, migration, and educational transitions in the future. The different assumptions about fertility, mortality, and migration are partly derived from the narratives and also reflect different educational compositions of the population. The results for total population size vary considerably across the *SSPs*. As described in the narratives, *SSP1* and *SSP5* assume relatively lower population growth, while the intermediate scenario (*SSP2*) reaches a higher population. The results in terms of educational composition, which have important implications for economic growth and vulnerability to the impacts of climate change, also vary considerably between the *SSPs* (Samir and Lutz, 2017).

The *IIASA* population projections for Brazil were made, according to Samir and Lutz (2017), using multidimensional mathematical demographic methods based on alternative assumptions about the future, fertility, mortality, migration, and educational transitions. In terms of Brazil's total population, the projections for the *SSPs* are very close to each other until around 2030, as shown in Figure 5. This is due to the dynamics of population growth and the fact that the differences in the assumed trajectories of the components become more pronounced only gradually. The *SSP1*, *SSP2* and *SSP5* peak around the year 2040 and then decline. The projection for the *SSP2* scenario is 231 million inhabitants in 2050 and 188 million in 2099, making it the scenario with the highest population projection. In addition, *SSP1* and *SSP5* have very different assumptions but similar trajectories, with *SSP1* being slightly higher than *SSP5*.

Figure 5: *SSPs:* Monthly population projections of Brazil (2020–2099)



Source: Own elaboration based on *IIASA* data.

Riahi et al. (2017) point out that there are three sets of economic projections.[31] However, the three economic projections differ in their focus on different drivers of economic development, such as technological progress, efficiency improvements in energy use, income convergence dynamics, or human capital accumulation, in terms of the GDP for each *SSP*, which was developed together with the demographic projections to keep the assumptions regarding education and aging consistent. The projections developed by Dellink et al. (2017) were used as *SSPs* markers to ensure consistency in the projection of all scenarios. The (*SSP5*) had the highest level of GDP, showing very rapid development and convergence between countries. However, in all *SSPs*, economic growth is projected to decline over time and there are also large differences in inequality between countries.

Figure 6 shows the stylized long-term projections of Brazil's GDP between 2020 and 2099, derived from the ENV-Growth model developed by IIASA. This model relies on a gradual process of conditional convergence towards a balanced growth path. Using the model's outputs, we constructed illustrative paths of GDP levels for each of the *SSP* scenarios. The projections vary significantly between the different *SSPs*, reflecting the challenges each scenario presents in terms of mitigating and adapting to climate change. *SSP5* presents significant mitigation challenges due to its fossil-energy-intensive economic activity. However, Dellink et al. (2017) note that a more in-depth analysis is needed to identify the specific adaptation and mitigation challenges arising from income projections.

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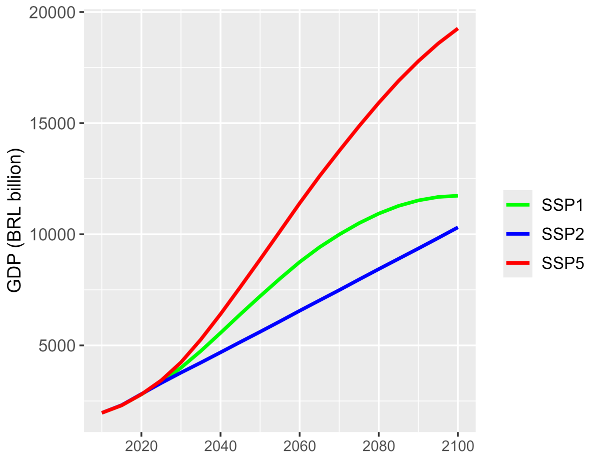
[31] GDP marker projections by the Organization for Economic Cooperation and Development (Dellink et al., 2017); GDP projections by the International Institute for Applied Systems Analysis (Cuaresma, 2017) and GDP projections by the Potsdam Institute for Climate Impact Research (Leimbach et al., 2017).

Figure 6: *SSPs*: Monthly GDP projections of Brazil (2020–2099)



Source: Own elaboration based on *IIASA* data.

This study only used the driving forces behind the *SSPs*, such as the time series of GDP and population size, and assumed that their relationship with freight transport demand will remain stable in the future, based on the historical relationships obtained by econometric analysis of data from 2000 to 2019. Other aspects of future trajectories, such as efficiency gains resulting from technological development, changes in consumption patterns (such as the spread of electric vehicles), etc., were not directly incorporated into the model. It was assumed that the observed historical relationships between the variables would be maintained in the future.

2.4.3 Data for the RFCI calculation

The calculation of the empirical emission factor for road freight transport, as detailed in the methodology section, was performed using a combination of two historical annual data series, covering the period from 2000 to 2019. The first series, obtained from SEEG, reports GHG emissions. Specifically, the emissions series for the category “trucks” was used, expressed in Megatonnes of CO_2 equivalent ($MtCO_2$e). The second series represents historical demand for road freight transport, expressed in billions of Ton-Kilometers (billions of TKU). This series was compiled from data provided by the Agência Nacional de Transportes Terrestres (ANTT) and the Associação Brasileira de Concessionárias de Rodovias (ABCR), as described earlier in this section.

Both time series were aligned for the period 2000–2019, forming the dataset used to apply the emission factor calculation formula. The result of this preprocessing is an annual historical series of the carbon intensity of the mode, which serves as the foundation for projecting future emissions.

2.5 Results and discussion

This section presents the results derived from the econometric modeling of freight transport demand in Brazil. The analysis is organized into two main parts. The first part details the demand projections for each of the three transport modes considered in this study: road, rail, and air. For each mode, the validated ARDL model is presented, followed by scenarios of future demand up to the year 2099, based on the three selected Shared Socioeconomic Pathways (*SSPs*). The analysis then addresses the environmental implications, with particular attention to carbon emissions from road freight transport. This emphasis is justified by the predominance of this mode in Brazil's modality mix and its significant contribution to the sector's GHG emissions. The historical carbon intensity is first calculated, followed by projections of future emissions, which serve as a starting point for the subsequent discussion on decarbonization policies.

2.5.1 Demand for road freight transport

The ARDL models were validated using the *"bounds testing"* procedure of Pesaran et al. (2001). The F-statistic of the equation (2) model for road freight transport is 10.64, exceeding the upper bound critical value at the 1.0% significance level with unrestricted intercept, no trend, and two regressors (6.36) as tabulated by Pesaran et al. (2001). Therefore, the null hypothesis of no long-run relationship can be rejected, and the corresponding ARDL specification is considered statistically valid. Residual diagnostics indicate only negligible serial correlation, approximate normality, and dynamic stability of the model. The regression results are presented in Table II, from which both long-run relationships and short-run dynamics were derived. The R^2 statistic indicates that the model explains approximately 95.5% of the observed variation in road freight demand. However, this high explanatory power should not be interpreted as guaranteeing structural stability of the estimated relationships over long forecasting horizons. Thus, the model is used to generate future demand scenarios under the assumption that the underlying economic mechanisms captured by the historical data remain broadly relevant, without implying deterministic persistence of past relationships.

The estimated model was then linked to the *IIASA* scenarios (for GDP and population size) and used to project the three *SSPs* reflecting the demand for road freight transport in Brazil between 2020 and 2099, as shown in Figure[32] 7. The *SSP5* showed the highest projected volume of demand for road transport: about 5,031.75 billion TKU in 2099. With regard to the intermediate scenario, the estimated demand for road trans-

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[32] Annual values are calculated as the sum of the projected monthly demand values for each year. The analysis presented here covers the period 2020–2099. Although IIASA projections extend to January 2100, annual totals for 2100 cannot be reported due to unavailable population and GDP projections beyond that date; only the January 2100 monthly value is available. See **Appendix B** for detailed annual projections.

Table II: Regression results from the estimation of the ARDL model (road transport)

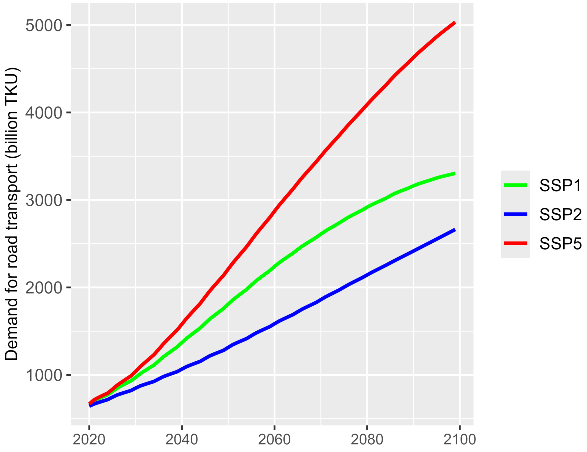
Variable	***Estimate***	***Std. Error***	***t value***	***Pr***$(> \|t\|)$	
Intercept	16.3000	5.5300	2.9410	0.0036	**
dmc_{t-1}	0.5930	0.0573	10.3470	$<$ 2e-16	***
dmc_{t-2}	0.2300	0.0538	4.2780	0.0000	***
ΔGDP	0.0000	0.0000	10.3370	$<$ 0.0000	***
gdp_{t-1}	-0.0000	0.0000	-8.4310	0.0000	***
Δpop	-0.0000	0.0000	-2.4500	0.01507	*
pop_{t-1}	0.0000	0.0000	2.445	0.0152	*
$MTH_{02,t}$	-1.4600	0.5090	-2.8610	0.0046	**
$MTH_{03,t}$	2.5100	0.7080	3.5410	0.000	***
$MTH_{04,t}$	-0.1380	0.7010	-0.1970	0.8438	
$MTH_{05,t}$	-0.3040	0.5920	-0.5130	0.6081	
$MTH_{06,t}$	-1.2200	0.6100	-2.0050	0.0461	*
$MTH_{07,t}$	0.3910	0.6180	0.6320	0.5281	
$MTH_{08,t}$	2.1400	0.5880	3.6350	0.0003	***
$MTH_{09,t}$	0.6680	0.5270	1.2670	0.2064	
$MTH_{10,t}$	-0.6570	0.6940	-0.9460	0.3452	
$MTH_{11,t}$	-2.2600	0.6180	-3.6530	0.0003	***
$MTH_{12,t}$	-2.1900	0.5490	-3.9890	0.0000	***
Observations	240	R^2	0.9550	Adjsted-R^2	0.9518

***0.1%; **1.0%; *5.0%; .10.0%

Source: Own elaboration.

port in *SSP2* is 2,662.28 billion TKU in 2099. In *SSP1*, characterized by high energy efficiency and a high share of renewable energies, projected road transport demand in 2099 is 3,303.45 billion TKU, falling between the highest and lowest scenarios.

Figure 7: *SSPs*: Annual demand for road freight transport (2020–2099)



Source: Own elaboration.

Table III presents the annual demand for road freight transport (in TKU) under the three *SSPs* considered in this study. The table allows an analysis of the evolution of

Table III: Annual road freight demand (in billion TKU) for different *SSPs*

Year	***SSP1***	***SSP2***	***SSP5***
2020	663.99	642.94	668.00
2030	971.61	848.76	1,039.15
2040	1,369.61	1,066.91	1,580.29
2050	1,809.29	1,314.60	2,209.81
2060	2,239.69	1,584.71	2,871.63
2070	2,609.62	1,860.34	3,500.66
2080	2,917.44	2,143.10	4,090.75
2090	3,161.41	2,416.12	4,629.14
2099	3,303.45	2,662.28	5,031.75

Source: Own elaboration

road freight demand in Brazil between 2020 and 2099 across different future scenarios. Focusing on the medium-term horizon, demand growth by 2050 is particularly pronounced, highlighting the urgency of policy intervention. Under the high-growth *SSP5* scenario, demand is projected to reach 2,209.81 billion TKU, an increase of 230.7% relative to the 2019 baseline of 668.00 billion TKU. Even the *SSP1* “Sustainability” scenario anticipates substantial demand of 1,809.29 billion TKU by 2050. This rapid front-loading of demand, with the sector more than tripling its activity within three decades, underscores that structural dependence on road transport will be entrenched well before the national 2050 net-zero target, necessitating immediate and large-scale structural interventions rather than incremental adjustments.

Table III also highlights projections under *SSP5*, labeled *“Fossil Fuel Driven Development”*. This scenario is characterized by high economic growth, resource-intensive production and consumption patterns, and heavy reliance on abundant fossil fuel resources, creating high mitigation challenges but relatively low adaptation challenges. As noted by Kriegler et al. (2017), the assumption of abundant fossil fuel resources in *SSP5* implies that fossil fuels continue to dominate the rapidly growing primary energy supply. Low public acceptance and limited political support for renewable energy result in slower cost reductions and a smaller share of renewable technologies compared with *SSP2*, and especially *SSP1*.

An in-depth analysis of the projections reveals an important dynamic for transport policy in Brazil: the *SSP1* scenario projects the second-highest demand for road transport, surpassing the *SSP2* scenario. This indicates that economic growth and social development, even when guided by sustainability principles, are such powerful drivers of logistics demand that, in the absence of direct policies promoting efficiency and modal shift, pressure on road infrastructure is projected to increase substantially over the coming decades. In contrast, the *SSP5* projection reaches 5,031.75 billion TKU in 2099, representing an increase of more than 653.3% compared to 2019. This scenario illustrates the potential for logistical and environmental strain, emphasizing the challenges and limitations of a fossil fuel-based development path and underscoring the need for proactive measures to ensure sustainable transport growth.

The high demand for road transport projected under the *SSP1* scenario reflects several underlying factors. Although oriented toward clean energy and sustainable development, the scenario assumes an inclusive GDP growth, higher than *SSP2*. It also incorporates high energy efficiency and a large share of renewable energy in the supply mix, resulting in a sharp decline in total fossil fuel consumption, with the use of oil practically eliminated (Van Vuuren et al., 2017). In the absence of alternative infrastructure, such as railways and waterways capable of handling additional transport demand, most traffic continues to rely on the dominant mode: road freight. Moreover, the projections indicate that road freight becomes increasingly dominant over time, as its growth outpaces that of other modalities relative to GDP and population expansion. This continued reliance reinforces pressures on road networks, raising operational costs and environmental impacts, and underscores the importance of coordinated policies to encourage modal shifts and enhance infrastructure efficiency.

A possible structural explanation helps clarify why road freight demand remains high in *SSP1* despite the scenario's sustainable orientation. The resilience of road transport reflects the strong structural inertia, or path dependency[33], of Brazil's freight system. This structural inertia is a direct result of decades of historical underinvestment in competitive rail and waterway alternatives, effectively locking the national economy into reliance on the diesel-intensive road network. Anchored in agricultural and mineral commodity production, the economy relies on long-distance corridors connecting inland production areas to ports and consumption centers. Since a dense and integrated multimodal network has not materialized, road transport remains the default option for a large share of flows. In this sense, even with a greener energy mix, economic expansion will continue to generate transport demand that relies on the existing infrastructure, maintaining heavy pressure on the road system[34].

The sharp increase in freight demand projected for Brazil across all scenarios aligns with global trends identified in recent literature. Global projections indicate a 200.0% increase in freight demand between 2020 and 2050, reaching a total of 395.00 trillion TKU, with the expansion disproportionately driven by developing and less-developed

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[33] The concept of *path dependency* was popularized in economic history and institutional economics to explain why certain technological or institutional trajectories persist even in the presence of more efficient alternatives. A seminal reference is David (1985), who analyzed the persistence of the QWERTY keyboard layout as an outcome of historical lock-in. Later, Arthur (1994) extended the framework to technology adoption processes under increasing returns and network effects.

[34] It is important to note that the long-term freight projections presented here are based on socioeconomic drivers (GDP and population) and inherit the historical structure of the transport sector. Consequently, the ARDL model implicitly assumes that the current modal mix will persist and does not account for a significant redistribution of cargo to lower-carbon modes (modal shift) that might result from aggressive future infrastructure policies.

countries, where current demand is relatively low but growth potential is high due to socioeconomic development (Tjandra et al., 2024). The projections presented in this study indicate an increase of up to 511.4% in road freight demand in Brazil by 2099 under the highest growth scenario (*SSP5*), reflecting this dynamic at the national level and positioning the country as a central player in the global expansion of freight activity. Such growth will directly translate into high energy demand in the transport sector and, consequently, increased GHG emissions.

Building on this structural perspective, the analysis of projected freight demand also highlights a key implication for transport decarbonization: even with increased use of biofuels, road transport is likely to remain dominant, and total emissions may continue to grow unless structural changes are implemented. Acknowledging this path dependency reinforces the conclusion that decarbonization of the sector cannot rely solely on fuel substitution. Without territorial planning policies and investments in multimodal infrastructure, the freight modality mix will remain locked into its current configuration, undermining the effectiveness of energy transition policies. Only by addressing both dimensions, energy and infrastructure, can Brazil achieve a genuine transformation of its transport system.

The pathway to a low-carbon economy, as outlined in studies such as La Rovere et al. (2015), relies on efficiency gains and a higher share of biofuels in the energy mix. Yet, an increase in demand of up to 511.4% suggests that these measures alone would be insufficient to curb emissions. This reinforces the conclusions of Köberle et al. (2020), highlighting the need for a deep and structural decarbonization of the transport sector if Brazil is to meet its climate commitments. The results underscore that achieving emission reductions will require not only technological improvements and fuel substitution but also policy frameworks that address the scale and structural characteristics of the sector.

2.5.2 Demand for rail freight transport

The estimation results of the ARDL model for the rail sector is detailed in Table IV, which provides an analysis of the long-term relationships and short-term dynamics discerned from the coefficients obtained. The coefficient of determination R^2 indicates that the model is able to explain approximately 91.5% of the variation in rail freight demand, demonstrating a good fit.

Table IV: Regression results from the estimation of the ARDL model (rail transport)

Variable	***Estimate***	***Std. Error***	***t value***	***Pr***$(>\|t\|)$	
Intercept	-2.6800	1.0400	-2.5750	0.0109	*
dmc_{t-1}	0.7600	0.0817	9.3080	0.0000	***
dmc_{t-2}	0.1370	0.0812	1.6830	0.0945	.
ΔGDP	0.0000	0.0000	2.1670	0.0318	*
$MTH_{02,t}$	0.7220	0.6080	1.1870	0.2371	
$MTH_{03,t}$	4.2300	0.5810	7.2850	0.0000	***
$MTH_{04,t}$	2.2800	0.5800	3.9280	0.0001	***
$MTH_{05,t}$	4.3000	0.5600	7.6800	0.0000	***
$MTH_{06,t}$	2.9600	0.5700	5.1900	0.0000	***
$MTH_{07,t}$	3.6600	0.5540	6.6030	0.0000	***
$MTH_{08,t}$	3.3300	0.5560	5.9860	0.0000	***
$MTH_{09,t}$	2.1000	0.5560	3.7740	0.0002	***
$MTH_{10,t}$	2.7600	0.5610	4.9160	0.0000	***
$MTH_{11,t}$	0.6660	0.5540	1.2040	0.2306	
$MTH_{12,t}$	2.1800	0.5850	3.7340	0.0003	***
Observations	168	R^2	0.9149	Adjusted-R^2	0.907

***0.1%; **1.0%; *5.0%; .10.0%

Source: Own elaboration.

This high explanatory power strengthens the confidence in using the model to create scenarios for future demand in this sector. The analysis revealed insignificant serial correlation in the residuals, reinforcing the premise of normality and dynamic stability of the proposed model, which are fundamental to its predictive applicability. These findings support the validity and reliability of the model in projecting future scenarios, as long as the estimated historical relationships remain consistent over time and take into account possible changes or evolutions in the context of rail freight transport.

The estimated model was then applied to *IIASA*'s projection of Brazil's GDP up to the year 2099, in order to obtain a varied perspective of the demand for rail freight transport in Brazil over a longer period of time, as shown in Figure 8. The *SSP5* scenario stood out with the highest projection of the volume of demand for rail transport: about 1,995.06 billion TKU for the year 2099. Meanwhile, in the intermediate scenario of *SSP2*, the estimated demand for rail transport at the end of the 21st century was around 1,471.19 billion TKU. For its part, the *SSP1*, recognized for its emphasis on energy efficiency and the high use of renewable energy, presented the second highest demand forecast for rail transport among the scenarios analyzed, projecting approximately 1,562.28 billion TKU for the year 2099.

Table V presents the projected annual demand for rail freight transport in Brazil (in TKU) from 2020 to 2099 under the three *SSP* scenarios considered in this study[35]. Focusing on the medium-term horizon, rail freight demand is projected to grow substan-

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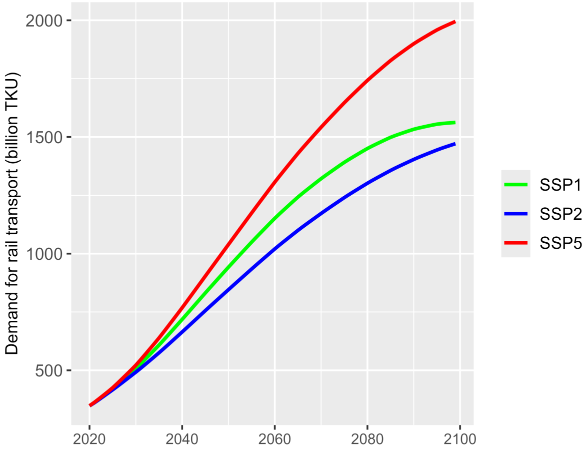
[35] See **Appendix C** for detailed annual projections.

Figure 8: *SSPs*: Annual demand for rail freight transport (2020–2099)



Source: Own elaboration.

tially toward 2050. Under the *SSP5* scenario, demand reaches 1,039.27 billion TKU by 2050, while under *SSP1* it reaches 942.13 billion TKU, representing an increase of about 198,4% compared with 2019 levels (348.00 billion TKU in *SSP1*). The comparison among scenarios shows that *SSP1* ("Sustainability"), despite its emphasis on energy efficiency and renewable sources, projects higher demand by 2050 than the intermediate *SSP2* (845.68 billion TKU), reflecting the influence of stronger economic activity on freight volumes. Although rail transport is expected to triple its activity within three decades, its structural disadvantage relative to road transport remains evident, indicating the need for timely and large-scale infrastructure investments to enable this expansion and support a meaningful modal shift.

Table V: Annual rail freight demand (in billion TKU) for the different *SSPs*

Year	***SSP1***	***SSP2***	***SSP5***
2020	348.00	347.79	348.23
2030	507.51	492.41	522.10
2040	718.25	664.38	768.13
2050	942.13	845.68	1,039.27
2060	1,151.44	1,020.32	1,306.52
2070	1,321.29	1,172.18	1,541.68
2080	1,450.61	1,301.77	1,742.37
2090	1,532.93	1,403.70	1,899.43
2099	1,562.28	1,471.19	1,995.06

Source: Own elaboration.

The resulting projections, detailed in Figure 8 and Table V, show an increase in rail demand across all scenarios, reaching 1,995.06 billion TKU under the *SSP5* scenario by 2099. This represents an increase of 472.9% relative to 2019, highlighting the sector's significant potential for expansion. However, when contextualizing rail growth within the overall land transport modality mix, a structural challenge becomes evident: the projected increase for the road mode over the same period is even higher, reaching 653.3%. This means that, although rail transport expands substantially in absolute terms, its relative share in the land freight modality mix is likely to decline in the absence of aggressive mode shift policies, signaling a continued reliance on road transport even in high-growth rail scenarios. This conclusion aligns with European experience, where studies such as Islam et al. (2015) show that without ambitious policy interventions, rail's share tends to stagnate despite overall economic growth, and only targeted strategies and investments result in significant modal shifts.

The realization of this growth potential in Brazil faces the historical challenge of underinvestment in the rail sector. As shown in Figure 2 of this thesis, federal investment in railways has historically been both lower and more volatile than that directed to the road sector. Moreover, to accommodate, at least, the projected 323.1% growth under *SSP2*, the business-as-usual scenario, and to effectively compete with road transport, the Brazilian rail sector must expand beyond its traditional focus on agricultural and mineral commodities. Capturing market share will require the capacity to transport higher-value goods, such as manufactured products and consumer items. This, in turn, necessitates investments not only in rail infrastructure but also in intermodal terminals, tracking and logistics technology, and improvements in service reliability and speed.

The demand projections presented here should therefore not be interpreted as an inevitable outcome, but rather as an indication of an economic opportunity contingent upon long-term strategic planning and targeted policy interventions. To both accommodate this growing demand and leverage it to rebalance Brazil's transport modality mix while reducing carbon emissions, it will be essential to overcome the historical investment deficit and implement public policies prioritizing the expansion and modernization of the national railway network.

2.5.3 Demand for air freight transport

The ARDL regression method was also used to analyze air freight transport. Table VI presents the results, highlighting both long-term relationships and short-term dynamics inferred from the estimated coefficients. With an R^2 of approximately 98.7%, indicating a good fit. Residual analysis further confirmed the absence of significant serial correlation and adherence to a normal distribution. These findings support the validity of the model for projecting future scenarios, assuming that the historical relationships estimated remain stable over time. The application of the ARDL framework to air transport provides an approach to analyzing sectoral dynamics, offering insights to support strategic decision-making.

Table VI: Regression results from estimating the ARDL model (air transport)

Variable	***Estimate***	***Std. Error***	***t value***	***Pr***$(>\|t\|)$	
Intercept	-27.2000	9.1700	-2.9650	0.0034	**
dmc_{t-1}	0.5290	0.0568	9.3140	$<$ 0.0000	***
ΔGDP	0.0000	0.0000	3.3210	0.0011	**
gdp_{t-1}	0.0000	0.0000	2.5760	0.0107	*
gdp_{t-2}	-0.0000	0.0000	-2.5920	0.0102	*
gdp_{t-3}	0.0000	0.0000	1.8050	0.0724	.
Δpop	-0.0000	0.0000	-2.9670	0.0033	**
pop_{t-1}	0.0000	0.0000	2.9830	0.0032	**
$MTH_{02,t}$	-12.3000	0.9920	-12.3760	0.0000	***
$MTH_{03,t}$	-5.6500	1.2600	-4.4950	0.0000	***
$MTH_{04,t}$	-8.8600	1.0200	-8.7030	0.0000	***
$MTH_{05,t}$	-6.6900	1.1400	-5.8690	0.0000	***
$MTH_{06,t}$	-8.3400	1.0300	-8.1040	0.0000	***
$MTH_{07,t}$	0.6710	1.1300	0.5930	0.5540	
$MTH_{08,t}$	-11.0000	0.9430	-11.6880	0.0000	***
$MTH_{09,t}$	-7.1000	0.8930	-7.9450	0.0000	***
$MTH_{10,t}$	-4.9800	1.1600	-4.2800	0.0000	***
$MTH_{11,t}$	-9.2900	1.0500	-8.8300	0.0000	***
$MTH_{12,t}$	-1.3100	1.0800	-1.2130	0.2263	
Observations	240	R^2	0.9866	Adjusted-R^2	0.9855

***0.1%; **1.0%; *5.0%; .10.0%

Source: Own elaboration.

Using the *IIASA* projections for GDP and population, the estimated model was used to forecast the three *SSPs* representing the demand for air freight in Brazil from 2020 to 2099, as shown in Figure 9. The *SSP5* showed the highest estimated demand for air transport: about 8,396.40 million TKU in 2099. The *SSP1*, known for its energy efficiency and considerable use of renewable energy, had the second highest demand for air transport among the scenarios studied: about 5,040 million TKU in 2099. The intermediate scenario, *SSP2*, has an estimated demand of 4,398.73 million TKU by the end of the 21st century.

Table VII presents the projected annual demand for air freight transport in Brazil (in TKU) from 2020 to 2099 under the three *SSP* scenarios considered in this study[36]. In the medium term, demand is expected to rise steadily toward 2050, reflecting the increasing complexity and international integration of the Brazilian economy. By 2050, demand reaches 3,883.36 million TKU under *SSP5* and 3,110.49 million TKU under *SSP1*, representing an increase of about 302.7% compared with the 2019 baseline of 964.32 million TKU. This growth is likely to create additional pressure on airport cargo infrastructure and ground logistics before mid-century, indicating the need for more efficient investments in cargo terminals and process optimization. The *SSP5* ("Fossil-

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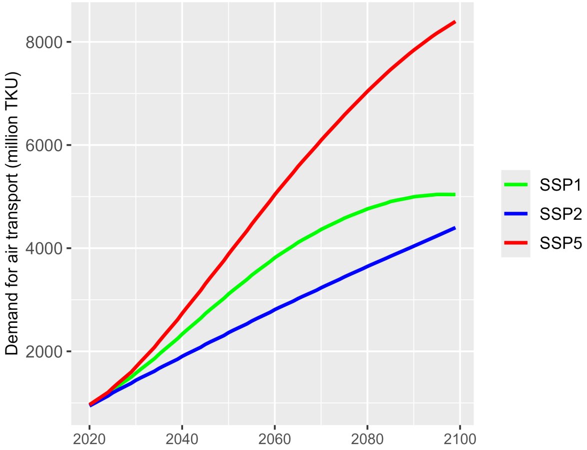
[36] See **Appendix D** for detailed annual projections.

Figure 9: *SSPs*: Annual demand for air freight transport (2020–2099)



Source: Own elaboration.

Fueled Development”) scenario assumes rapid population growth, robust global economic expansion, and accelerated technological progress, but with limited emphasis on environmental sustainability. In the aviation sector, this configuration leads to higher aircraft activity and air travel, resulting in greater GHG emissions and contributing to an overall increase in total emissions.

Figure 9 and Table VII show that air transport records the highest relative growth among modes, with demand expanding by 770.8% under *SSP5* between 2020 and 2099. This pattern reflects the characteristics of air freight, which primarily serves high-value goods such as electronics, pharmaceuticals, and components for just-in-time production chains. It is further driven by foreign direct investment (FDI) and the expansion of e-commerce. Consequently, the projected increase suggests not only a rise in freight volume but also greater economic diversification, with Brazil becoming more integrated into global value chains that depend on speed and logistical reliability. This trend is consistent with global evidence, as Tjandra et al. (2024) report that, despite its relatively small base, air transport exhibits high income elasticities, particularly in developing regions. As the Brazilian economy grows and urbanizes, demand for fast and efficient logistics services is expected to rise more than proportionally, making air freight a sensitive indicator of technological progress and economic modernization.

However, an increase of over 770.8% in demand poses a significant challenge to the country’s airport infrastructure. Historically, overall investments in the Brazilian air sector, as shown in Figure 2, have been limited. Although recent years have seen some improvements through airport concessions and private investments (CNT, 2025c), most resources have still been directed primarily toward passenger terminals rather than cargo infrastructure. Satisfying the demand from these projections will therefore require a strategic reallocation of investments toward the construction and

Table VII: Annual air freight demand (in million TKU) for the different *SSPs*

Year	*SSP1*	*SSP2*	*SSP5*
2020	966.91	942.96	964.32
2030	1,576.70	1,438.94	1,695.82
2040	2,333.90	1,902.86	2,735.19
2050	3,110.49	2,362.08	3,883.36
2060	3,814.97	2,809.16	5,038.76
2070	4,362.75	3,232.25	6,092.87
2080	4,761.70	3,646.76	7,040.64
2090	4,996.80	4,039.45	7,838.94
2099	5,040.00	4,398.73	8,396.40

Source: Own elaboration.

modernization of cargo terminals, apron areas for freighter aircraft, and the optimization of customs and ground logistics processes. Proactive planning is essential, as highlighted in the literature; for example, Suryani et al. (2012) demonstrate how demand projections can inform the timing and scale of capacity expansions, effectively transforming growth forecasts into actionable investment strategies. Without a national policy prioritizing air cargo capacity, Brazilian airports risk becoming bottlenecks, constraining the growth potential of high-value economic sectors and limiting the country's competitiveness in international trade.

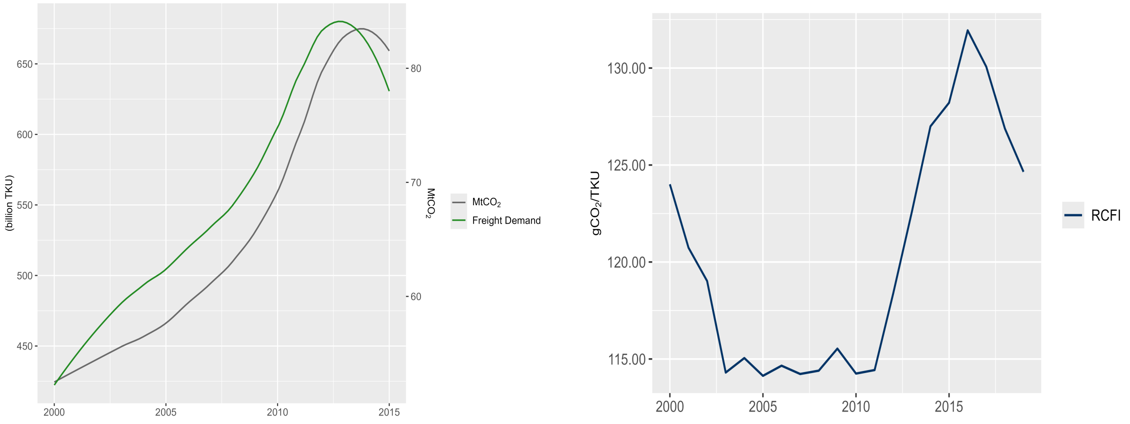
Taken together, these projections for road, rail, and air transport provide an integrated view of the potential evolution of the Brazilian freight sector under different *SSP* scenarios. While each mode exhibits distinct growth trajectories and challenges, the subsequent analysis narrows its focus to road transport. This choice reflects not only its dominant share in national freight activity but also its disproportionate contribution to sectoral CO_2 emissions. Concentrating on road freight enables a detailed assessment of historical emission trends, carbon intensity, and the projected evolution of emissions under varying socioeconomic pathways, laying the groundwork for an evaluation of mitigation strategies.

2.5.4 Road freight emissions and carbon intensity

Figure 10a presents the historical evolution of road freight demand alongside the associated CO_2 emissions in Brazil (2000–2019). By concentrating on this mode, the analysis highlights periods in which changes in carbon intensity caused deviations between demand and emissions trends, providing a clearer picture of the drivers behind sectoral emissions. This approach allows policymakers and researchers to evaluate the potential effectiveness of mitigation strategies within the road freight sector, and to identify opportunities for reducing the carbon intensity of future freight activity.

The calculated RFCI, shown in Figure 10b, offers a more precise measure of the

Figure 10: Road freight demand, CO_2 emissions, and RCFI (2000–2019)



(a) Road Freight and CO_2 Emissions

(b) RFCI

Source: Own elaboration based on ABCR and SEEG data

environmental efficiency of the sector. Analysis of historical data from 2000 to 2019 indicates an average RFCI of 120.7 gCO_2/TKU, approximately 53.0% higher than the 79.0 gCO_2/TKU estimated by Fleury (2012). This discrepancy suggests that the carbon intensity of road freight in Brazil has been underestimated, highlighting the scale of the decarbonization challenge[37]. This starting point, being less efficient than previously assumed, underscores the urgency of implementing mitigation strategies, as proposed by Yeh et al. (2017). The high carbon intensity indicates significant potential for reductions through fleet efficiency improvements, one of the key measures identified by the Deep Decarbonization Pathways Project for Brazil (La Rovere et al., 2015). At the same time, it reveals that the effort required to achieve such improvements will be considerably greater.

Several structural factors may contribute to the elevated RFCI observed in Brazil. The quality of the road infrastructure is uneven, with poorly maintained sections increasing fuel consumption per TKU and directly affecting carbon intensity. According to CNT (2024), 56.9% of evaluated pavements exhibit some form of deterioration, with inadequate surfaces raising diesel consumption by an estimated 5.0%. These conditions result in an annual waste of approximately 1.184 billion liters of diesel, corresponding to 3.13 million tons of unnecessary GHG emissions, and elevate operational costs by an average of 32.5%. Logistical inefficiencies further exacerbate emissions. Although CNT (2024) does not directly quantify empty return trips, it identifies 2,446

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[37] A possible explanation for this discrepancy lies in the data sources and methodology employed in this study, which integrate more recent and granular information from SEEG, ABCR, and other sources. This approach captures operational inefficiencies and sectoral realities that earlier models may have overlooked, providing an accurate representation of real-world performance. Regional differences in road infrastructure, fleet characteristics, and logistical conditions mean that the national average RFCI may conceal substantial variation in carbon intensity across Brazil's territory.

critical points, including landslides, erosion, and collapsed bridges, that hinder route planning and travel predictability. This challenging environment increases the likelihood of underloaded returns, raising emissions per unit of freight transported. Fleet composition also contributes to high carbon intensity. In 2023, the average age of registered trucks was 16.4 years, limiting the sector's capacity to realize efficiency gains from Proconve[38] standards (P7 and P8). Adoption of newer P8 vehicles remains low, comprising only 4.9% of the national truck fleet by mid-2024. Complete replacement with P8 models could reduce NO_X emissions by 97.8% and particulate matter by 98.3%, revealing substantial potential for technological improvements.

The historical evolution of RFCI, shown in Figure 10b, does not display a consistent trend of efficiency gains. Following an initial period of decline, the indicator rose from 2012, peaking in 2016, which may reflect the combined effects of deteriorating infrastructure, logistical inefficiencies, and slow fleet renewal. Collectively, these observations suggest that reducing carbon intensity in Brazilian road freight will require not only technological upgrades but also targeted interventions in infrastructure and logistics management, addressing the structural factors encompassed by the so-called "Custo Brasil".[39]

Future CO_2 emissions from road freight transport were estimated by combining projections of freight demand with the historical average RCFI of 120.7 gCO_2/TKU. For this simplified exercise, it is assumed that the emissions intensity remains constant, without considering potential technological improvements or regulatory changes. By applying this constant factor to the demand trajectories of *SSP1*, *SSP2*, and *SSP5*, the analysis shows how different socioeconomic development pathways may affect the evolution of emissions. Under this assumption, differences across scenarios result only from variations in the scale and intensity of projected freight activity, providing a reference baseline.

As shown in Figure 11, the projected trajectories follow the expansion of freight activity under each socioeconomic pathway. The *SSP5* scenario, associated with rapid economic growth based on fossil energy and higher consumption levels, results in

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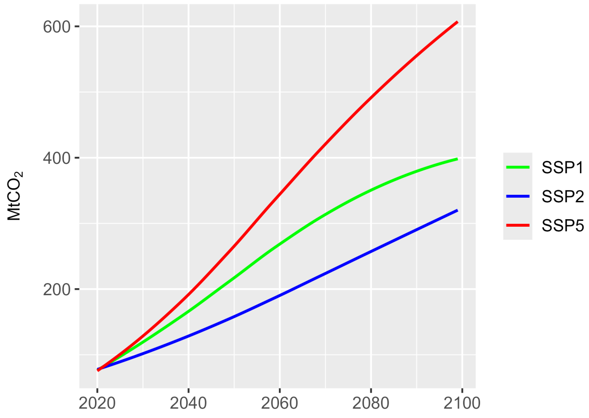
[38] The Vehicle Emission Control Program (Proconve) was established under CONAMA Resolution No. 18 on May 6, 1986, with the aim of reducing air pollution from motor vehicles in Brazil. Its objectives include: reducing pollutant emissions to meet air quality standards, particularly in urban areas; promoting national technological development in automotive engineering and emissions testing methods; implementing vehicle inspection and maintenance programs; raising public awareness about vehicular air pollution; improving the technical characteristics of fuels used by the national vehicle fleet to reduce emissions; and establishing procedures to evaluate the program's outcomes. Recent phases, such as Proconve P7 and P8, introduced in 2022, represent significant advances in emission control Brasil (2022c).

[39] The term "Custo Brasil" refers to the combination of structural, institutional, and operational inefficiencies that increase the cost of doing business in Brazil. Key factors include inadequate infrastructure, bureaucratic complexity, high financing costs, regulatory uncertainty, and operational inefficiencies such as an aging vehicle fleet and low adoption of logistics technologies. In the context of road freight, these elements contribute directly to higher fuel consumption, carbon intensity, and overall transport costs.

Figure 11: Projected CO_2 emissions from road freight transport (2020–2099)



Source: Own elaboration.

emissions of 604.93 $MtCO_2$ by 2099. The *SSP1* (“Sustainability”) pathway, emphasizing resource efficiency and cleaner technologies, reaches 397.15 $MtCO_2$ by 2099. *The SSP2 (“Middle of the Road”) scenario*, assuming moderate progress and partial policy implementation, reaches 320.07 $MtCO_2$ by 2099. This trajectory is relatively close to the historical pattern of gradual change observed in road freight emissions, suggesting a continuation of the long-term structural dynamics of the sector.

Table VIII presents the projected emissions values for key years between 2020 and 2099. By 2050, annual road freight emissions are estimated at 265.67 $MtCO_2$ under *SSP5*, 217.52 $MtCO_2$ under *SSP1*, and 158.04 $MtCO_2$ under *SSP2*. Under the constant-intensity assumption, higher emissions are associated with greater road freight transport demand. Even in more sustainable socioeconomic contexts, the sector would continue to represent a substantial share of Brazil’s total CO_2 output, underscoring the importance of mitigation strategies such as modal shifts, logistics optimization, and low-carbon fuel adoption.

Table VIII: Projected CO_2 emissions from road freight transport (2020–2099)

Year	***SSP1***	***SSP2***	***SSP5***
2020	79.83	77.30	80.31
2030	116.81	102.04	124.93
2040	164.66	128.27	189.99
2050	217.52	158.04	265.67
2060	269.26	190.52	345.24
2070	313.74	223.66	420.86
2080	350.74	257.65	491.80
2090	380.07	290.47	556.53
2099	397.15	320.07	604.93

Source: Own elaboration.

These results highlight that socioeconomic pathways influence the long-term carbon footprint of the freight transport sector. By the end of the century, emissions under *SSP5* are projected to be roughly twice those under *SSP2*, indicating that development trajectories shape sectoral environmental outcomes even in the absence of technological or policy changes. Although the transport sector represents a smaller share of Brazil's total greenhouse gas emissions compared to land-use change and agriculture, accounting for approximately 15.0% of national emissions, it remains an important component of mitigation strategies due to its dependence on fossil fuels and expected growth in energy demand. The projections are consistent with Arioli et al. (2020), suggesting that the transport sector's contribution to total Brazilian emissions may increase under current development patterns. Consequently, integrating sustainable transport policies with broader economic strategies is relevant for improving mitigation outcomes. Without structural changes in the sector, Brazil's ability to meet its Paris Agreement commitments, as analyzed by Lefèvre et al. (2018), may face additional challenges, reinforcing the importance of incorporating socioeconomic foresight into transport planning and climate policy to support long-term emission reductions.

2.6 Conclusions

This study developed long-term scenarios for freight transport demand in Brazil up to 2099 by employing ARDL models for road, rail, and air transport, which allowed for an analysis of how GDP and population, together with seasonal and cyclical factors, influence freight demand across different modalities. These models provide a foundation for future projections, as they not only capture the link between economic expansion and freight activity, reflected in the identification of *GDP* as the main driver of sector growth, but also account for the complementary role of *population* in shaping demand patterns. Furthermore, the incorporation of seasonal effects enhances the precision of the projections by capturing fluctuations that may be critical for both logistics planning and infrastructure investment, ensuring that the anticipated dynamics of the transport sector are represented in a realistic and policy-relevant manner.

The projections based on the *SSP* scenarios indicate a continuous expansion of freight demand across all cases, with distinct trajectories for each pathway. By 2050, road freight demand is projected to more than triple under high-growth scenarios, contributing to CO_2 emissions of approximately 267 $MtCO_2$ in *SSP5*, prior to the national net-zero target. Over the longer term, the *SSP5* scenario ("Fossil Fuel Driven Development") exhibits the highest overall growth, with annual demand reaching 5,031.8 billion TKU for road transport, 1,995.1 billion TKU for rail transport, and 8,396.4 million TKU for air transport by 2099. This scenario represents a pathway of resource-intensive economic development. The projections highlight the relevance of mitigation strategies, including the adoption of low-carbon technologies and the expansion of sustainable transport networks, in the context of steadily increasing freight demand and associated emissions.

The *SSP1* scenario, characterized by a transition toward renewable energy sources and improvements in overall energy efficiency, exhibited the second-highest freight demand by the end of the century. This result indicates that even under a sustainability-oriented socioeconomic pathway, freight activity may continue to expand as a consequence of economic development. These dynamics highlight that progress toward a cleaner energy mix does not automatically translate into lower transport emissions if freight demand remains strong. Therefore, emission mitigation in the transport sector requires complementary strategies that enhance operational efficiency and promote shifts toward lower-carbon transportation solutions. More broadly, the findings underscore the importance of integrated energy, economic, and transport policy planning to support sustainability objectives while maintaining long-term development prospects.

The analysis of emissions, centered on road transport, showed that the historical average RFCI from 2000 to 2019 was 120.7 gCO_2/TKU, 53.0% higher than previously estimated. This indicates that decarbonization is more challenging than earlier assessments suggested. Structural factors such as an aging fleet, deteriorating logistics infrastructure, and adverse macroeconomic conditions further increase this difficulty. National energy policies that continue to promote fossil fuel production through subsidies and favorable exploration conditions (e.g., pre-salt, Equatorial Margin) also weaken carbon pricing mechanisms and reinforce the sector's current trajectory. Examining historical RFCI trends alongside the current policy framework provides essential context for evaluating emission reduction targets and emphasizes the importance of fleet renewal and operational efficiency.

Future emissions projections, assuming a constant RFCI, highlighted the decisive role of socioeconomic pathways in shaping the long-term evolution of freight-related CO_2 emissions. The *SSP5* scenario produced the highest trajectory, exceeding 600 $MtCO_2$ annually by 2099, reflecting a pathway of rapid economic growth with high energy and transport demand. In contrast, *SSP2 "Middle of the Road"*, characterized by moderate economic growth, yielded the lowest emissions, just over 300 $MtCO_2$. *SSP1* reached approximately 400 $MtCO_2$, showing that even development pathways with strong sustainability ambitions can result in substantial emissions if no additional measures are implemented. These projections highlight that structural interventions and policy measures may be relevant to influence future emissions trajectories, particularly in scenarios of high economic and transport expansion.

These findings have implications for public policy and energy transition planning, showing that socioeconomic trajectories strongly shape Brazil's freight transport carbon footprint. Demand projections under alternative *SSPs* scenarios provide a quantitative basis for assessing strategies such as infrastructure investments or efficiency regulations affecting modal choice. The results indicate that policies in transport, energy, and environmental sectors are interdependent and should be designed jointly, as actions in one area affect others. Even in sustainable development pathways, freight emissions remain significant, underscoring the need to align climate and energy goals with transport and economic planning.

Future work could extend the current analysis by incorporating evolving fleet efficiency and low-carbon technologies to reflect changes in carbon intensity over time; evaluating the effects of policies such as regulations or incentives for modal shifts; increasing spatial detail to capture regional differences and major corridors; and linking demand projections dynamically to emissions, allowing for feedbacks from fuel prices or policy measures. Such extensions would yield a more detailed and policy-relevant picture, complementing the insights of the present model.

3 FREIGHT TRANSPORT, CARBON PRICING, AND THE ENERGY TRANSITION IN BRAZIL

Abstract

This study examines the long-term evolution of Brazil's freight transport demand and its implications for the economic feasibility of reducing CO_2 emissions under alternative socioeconomic pathways (*SSPs*). Projected freight demand, measured in Ton-Kilometers (TKU), is converted into an aggregate economic cost indicator expressed as a share of GDP. Three scenarios are considered: *SSP2 ("Middle-of-the-Road")*, which represents a continuation of historical trends and serves as a reference case; *SSP1 ("Sustainability")*, emphasizing sustainable development and lower resource intensity; and *SSP5 "(Fossil-Fueled Development")*, characterized by rapid, resource-intensive economic growth. This range of scenarios provides a baseline for assessing the potential economic and emissions outcomes arising from projected transport activity in Brazil. The second stage involves a policy simulation focused on road freight, which estimates the long-run price elasticity of demand using an Autoregressive Distributed Lag (ARDL) model and subsequently calculates the Marginal Abatement Cost (MAC) implied by Brazil's Nationally Determined Contribution (NDC) target for 2035. The results indicate that the share of GDP allocated to freight transport increases across all scenarios, consistent with the structural relationship between economic activity and freight demand embedded in the model, and that demand for road transport is highly inelastic to diesel prices ($\eta \approx -0.610$). Consequently, the estimated MAC is economically prohibitive, exceeding BRL 1,532 per ton of CO_2. This suggests that a decarbonization policy relying solely on carbon pricing is unlikely to be feasible and highlights the need for a policy portfolio that combines price signals with non-tariff interventions, including modal shifts and efficiency mandates, to achieve a successful energy transition. By linking demand projections with an assessment of mitigation costs, this study enhances the understanding of transport planning and climate policy in Brazil, highlighting the interactions between socioeconomic development, freight activity, and sectoral emissions under different future pathways.

Key-words: Energy Transition; Freight Transport; Marginal Abatement Costs.

3.1 Introduction

This study evaluates Brazil's freight transport sector by combining demand projections, emissions modeling, and carbon pricing analysis to quantify the economic implications of current transport trends and policy interventions for achieving national climate targets. The Brazilian freight system is highly dependent on road transport, a structural feature that generates significant environmental and economic challenges and contributes to the accelerated growth of emissions in the country. This pattern is corroborated by studies showing that developing regions have been experiencing faster increases in transport emissions than Europe or North America, and this trend is expected to continue (IPCC, 2022). Addressing this sector requires more than incremental efficiency improvements. It involves replacing entrenched infrastructures and carbon-intensive technologies with low-carbon alternatives while balancing environmental sustainability, energy security, and economic feasibility. The structural reliance on road transport amplifies the difficulty of transitioning to a low-carbon system, as it underpins the economy's long-distance corridors connecting production hubs to consumption centers. Consequently, even with improvements in fuel efficiency or cleaner energy sources, existing infrastructure and logistical patterns sustain high transport demand and emissions. As Banister (2008) emphasizes, the transition to a low-carbon transport system is not merely a technical challenge but also a social and political process that requires new governance approaches, broad stakeholder engagement, and collective responsibility.

The Brazilian freight sector is highly dependent on trucks, which account for 64.9% of domestic cargo transport. This structural imbalance generates substantial environmental and economic consequences. On the environmental side, road freight leads to high carbon intensity, with the transport sector responsible for 49.7% of Brazil's total CO_2 emissions from the energy mix (EPE, 2025). Economically, dependence on fossil fuels exposes the sector to oil price volatility, creating cost instability and undermining competitiveness. Hamilton (2009) shows that oil price spikes reduce disposable income and can render existing capital and product portfolios obsolete, particularly in transport-related industries. Diesel is the most consumed fuel, with the road sector as its largest consumer (CNT, 2025b). These dynamics underline the critical role of freight transport in facilitating goods movement, integrating regions, and sustaining supply chains essential for economic activity.

Brazil's Nationally Determined Contribution (NDC) under the Paris Agreement sets a strengthened target for 2035, aiming to reduce net GHG emissions by 59.0% to 67.0% below 2005 levels. This commitment represents a marked increase in ambition relative to previous pledges and is aligned with the country's goal of achieving climate neutrality by 2050 and limiting global warming to $1.5\ ^\circ\mathrm{C}$. To achieve this objective, Brazil is implementing a series of economy-wide initiatives, including the Ecological Transformation Plan[40] and the National Climate Plan[41]. In the transport and energy sectors, these measures are operationalized through targeted programs such

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[40] The Ecological Transformation Plan promotes low-carbon development across sectors, with emphasis on sustainable production, ecological preservation, and energy transition. It seeks to align fiscal and industrial policies with long-term decarbonization goals (Brasil, 2023a).

[41] The National Climate Plan consolidates mitigation and adaptation targets, setting sectoral policies to reduce greenhouse gas emissions by mid-century. It integrates climate action with national development and energy security priorities (Brasil, 2023e).

as the Fuel for the Future Program[42], the National Hydrogen Program (PNH_2)[43], and the Green Mobility-Mover initiative[44]. Beyond transport, the national strategy also encompasses low-carbon agriculture, deforestation control, and industrial transition, supported by investment platforms such as the Climate Fund[45] and Eco Invest Brazil[46], alongside regulatory frameworks like tax reform. These interactions underscore that transport decarbonization must be understood not in isolation but as part of a broader sustainable transformation across the national economic and energy system (Brasil, 2024).

Economic theory, as highlighted by Baumol and Oates (1988), distinguishes between command-and-control regulations, such as fuel efficiency standards exemplified by the Euro VI emission standards for trucks in the European Union, and market-based instruments, including carbon taxes, as in Sweden, or tradable emission permits, such as the European Union Emissions Trading System (EU ETS). In the context of freight transport decarbonization, these instruments are tools to internalize the negative externalities of greenhouse gas emissions. While command-and-control measures can achieve emission reductions, empirical evidence indicates that they often generate higher societal costs because firms differ in their abatement opportunities and face heterogeneous compliance expenses (Goulder and Schein, 2013)[47]. Older or less efficient fleets, for example, may incur disproportionately high costs to comply with uniform standards. Market-based instruments, by contrast, assign a price to emissions, creating incentives for firms to reduce pollution where it is cheapest, thereby improving overall efficiency. The concept of the Marginal Abatement Cost (MAC) formalizes this logic, representing the cost of reducing the final unit of emissions necessary to achieve a given reduction target.

Practical applications of market-based instruments illustrate their relevance for freight decarbonization. Montgomery (1972) demonstrates that tradable permit systems, such

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[42] This program aims to expand the use of advanced biofuels, improve fuel efficiency, and support the deployment of cleaner energy sources for transport, thereby reducing reliance on fossil fuels (Brasil, 2023c).

[43] The PNH_2 seeks to build a domestic hydrogen economy by supporting production, infrastructure, and technological adoption, particularly in energy and transport (Brasil, 2023b).

[44] The Green Mobility–Mover initiative promotes sustainable urban mobility, incentivizing electrification, public transport expansion, and low-carbon innovation in the automotive sector (Brasil, 2023d).

[45] Managed by the BNDES, the Climate Fund finances projects that contribute to both mitigation and adaptation, including renewable energy, sustainable mobility, and resilience-building initiatives (BNDES, 2023).

[46] Eco Invest Brazil is designed to attract and mobilize private capital for sustainable and low-carbon projects, complementing public financing and strengthening the country's green investment ecosystem (Brasil, 2023g).

[47] Prior studies cited in Goulder and Schein (2013) indicate that under direct regulation, marginal abatement costs (MAC) differ substantially among firms, so market-based instruments such as carbon taxes or cap-and-trade can reduce the costs of achieving the same aggregate emissions reductions by substantial margins (e.g., 46.0% savings in the RECLAIM program in Los Angeles; \$700–\$800 million/year savings in SO_2 trading under the U.S. Clean Air Act).

as Brazil's Sistema Brasileiro de Comércio de Emissões (SBCE)[48], can achieve environmental targets efficiently by allowing flexible allocation of rights. The Pigouvian principle suggests that taxing emissions equal to their social cost aligns private incentives with societal goals (Pigou, 1920). Estimating the MAC in freight is challenging because alternatives such as electrification or biofuels are costly and demand may respond weakly due to the sector's reliance on road transport. Also, according to Goulder and Parry (2008), effective decarbonization often requires hybrid approaches combining carbon pricing with complementary measures such as infrastructure investment, efficiency mandates, and technology promotion.

Freight transport provides a particularly relevant case study for understanding the challenges of aligning economic development with climate policy in emerging economies. In Brazil, the sector embodies structural tensions: it is indispensable for economic integration and growth yet heavily dependent on fossil fuels, making it carbon-intensive and economically vulnerable to oil price volatility. These characteristics highlight the need for carefully designed policy packages that reconcile development objectives with climate commitments while maintaining economic feasibility.

This study contributes by combining long-term demand projections, emissions modeling, and MAC analysis to evaluate feasible pathways for decarbonizing Brazil's freight sector. It quantifies the share of GDP associated with freight activity under alternative socioeconomic pathways, estimates road freight demand responsiveness to diesel prices, and derives the MAC implied by Brazil's 2035 NDC target. By linking transport demand trajectories with mitigation cost assessments, the study provides evidence on the economic and policy trade-offs of freight decarbonization, highlighting when carbon pricing alone may be prohibitive and where complementary measures such as modal shifts, efficiency improvements, and technology adoption are necessary.

The remainder of the chapter is organized as follows. The next section presents the theoretical framework, contrasting command-and-control regulations with market-based instruments and elaborating on the concept of the MAC. This is followed by the methodological approach, including the analytical tools employed. Subsequent sections describe the data sources and preprocessing procedures, present and analyze the results, and conclude by discussing the main implications for transport decarbonization in Brazil, with emphasis on policy-relevant insights and actionable strategies.

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[48] The SBCE, established by Law No. 15.042 of December 11, 2024, regulates GHG emissions in Brazil through tradable carbon credits and promotes cost-effective reductions (Brasil, 2024).

3.2 Economic instruments and regulatory frameworks for transport decarbonization

Decarbonizing Brazil's road freight sector, a system defined by its structural dependence on highways and inelastic demand for fossil fuels, requires a combination of economic instruments and regulatory frameworks to address market failures and technological adoption constraints. This section presents the theoretical framework used in this study to analyze the economic feasibility of decarbonizing freight transport, focusing on how different policy tools can address the sector's specific structural characteristics. This study specifically applies this framework by estimating the Marginal Abatement Cost (MAC) for Brazil's road freight transport sector, thereby quantifying the economic challenge of decarbonization and assessing the feasibility of price-based instruments in a system characterized by structural rigidity. Market-based instruments guide behavior through economic incentives rather than prescriptive mandates on pollution levels or control technologies. Examples include tradable permits and pollution taxes, which, when properly implemented, motivate firms to undertake emissions reduction measures that are both privately beneficial and collectively aligned with policy objectives (Stavins, 2003). In the Brazilian road freight sector, these instruments must consider the dominance of diesel trucks and the scarcity of low-carbon modal alternatives.

A central principle underpinning the design of market-based instruments is the Pigouvian approach, which holds that government intervention is warranted when the marginal private net benefit of an activity differs from its marginal social net benefit. Corrective taxes internalize the external costs of unpriced societal harms, such as pollution, thereby promoting overall economic welfare (Pigou, 1920). In the context of climate change, operationalizing this principle requires quantifying the cost of reducing emissions. This cost is captured by the MAC, defined as the expense of abating the last and most costly unit of emissions needed to achieve a specific reduction target. This concept is central to this thesis, as estimating the MAC for Brazil's road freight sector reveals the economic challenges of decarbonization. Structural factors such as the lack of modal alternatives and the low price elasticity of diesel demand result in a steep MAC curve, suggesting that a purely price-based instrument may be economically prohibitive.

In practice, uncertainty, firm heterogeneity, and informational limitations may prevent a Pigouvian tax from perfectly matching the MAC for every individual firm, but it still provides a guiding signal for efficient abatement. Individual abatement costs can be aggregated into a MAC curve, which ranks interventions from the lowest to highest cost, plotting the marginal cost of achieving cumulative emissions reductions (Gillingham and Stock, 2018). This curve helps policymakers identify which measures provide the greatest reductions at the lowest cost and informs the design of complementary incentives and regulatory measures suitable for the freight sector.

Formally, if E denotes emissions and $C(E)$ the social cost associated with them, the efficient Pigouvian tax τ^* is defined as:

$$\tau^* = \frac{\partial C(E)}{\partial E}, \tag{3}$$

ensuring that firms internalize the external costs of emissions. In a standard partial equilibrium framework, a firm producing emissions E faces private marginal costs $MC(E)$ and contributes to social damages $C(E)$. The socially optimal output occurs where

$$MC(E) + \frac{\partial C(E)}{\partial E} = MB(Q), \tag{4}$$

with $MB(Q)$ representing the marginal benefit of output Q. Imposing a Pigouvian tax τ^* aligns the firm's private decision-making with the social optimum, so that production and abatement are balanced to achieve the socially efficient level of emissions.

Extensions of Pigouvian theory recognize heterogeneity in abatement costs across firms, uncertainty in the social cost of emissions, and interactions with existing regulatory frameworks, emphasizing that efficiency gains are maximized when instruments are harmonized (Baumol and Oates, 1988). Firms with lower abatement costs will reduce emissions more, while those with higher costs respond to price signals or permit markets to meet regulatory targets efficiently. In the Brazilian road freight sector, this is particularly relevant because large carriers and smaller operators face very different costs and constraints, influencing the effectiveness of any single instrument. Theoretical analyses also highlight potential limitations, such as imperfect markets, nonlinear behavioral responses, threshold effects in environmental damages, and distributional impacts (Fullerton and West, 2002).

Carbon pricing can be implemented through market-based instruments such as emissions trading systems (cap-and-trade). In a cap-and-trade system, the regulator establishes an aggregate emissions limit (cap) and allocates or auctions tradable permits to firms. Each permit entitles the holder to emit a specific quantity of pollutants, and the market determines the permit price through supply and demand. Firms with low abatement costs can sell surplus permits, while firms facing higher costs can purchase additional permits to comply. Even when permits are allocated freely, they create an opportunity cost for emissions, since using a permit precludes selling it in the market. This mechanism ensures that emissions reductions are achieved cost-effectively across all firms, equalizing MACs and minimizing total mitigation costs (Goulder and

Schein, 2013).

Command-and-control instruments, by contrast, impose direct mandates on technologies or performance standards. Examples include fleet fuel efficiency requirements, per-vehicle emission limits, and biofuel blending obligations. Formally, a CAC policy can be represented as:

$$\text{Minimize } C(Q) \text{ subject to } E(Q) \leq \bar{E}, \tag{5}$$

where $C(Q)$ is the cost of providing transport services Q, $E(Q)$ the resulting emissions, and $\bar{E}$ the regulatory cap. CAC instruments provide regulatory certainty, ensure compliance with minimum standards, and are particularly effective in sectors where technological adoption requires regulatory compulsion. Compared with market-based instruments, CAC policies are generally less cost-effective because they impose uniform standards or technology mandates rather than allowing firms to abate emissions according to their individual cost structures. In Brazil, the Proconve program illustrates this approach, progressively tightening emission standards and driving the adoption of cleaner vehicle technologies (Brasil, 2025).

Empirical studies indicate that combining market-based and command-and-control instruments can achieve better outcomes than relying on a single policy (Goulder and Schein, 2013; Baumol and Oates, 1988). MAC analysis is particularly important in this context, as it quantifies the additional cost of reducing one unit of emissions and helps identify the least-cost abatement options (Fullerton and West, 2002). Conceptually, the MAC is represented by an ascending curve, ranking abatement measures from the cheapest to the most expensive. This framework allows policymakers and firms to compare technological alternatives such as vehicle electrification, biofuel adoption, and modal shifts, and to understand the interaction between price signals, regulatory mandates, and permit markets. In cap-and-trade systems, the MAC curve determines the equilibrium permit price: firms with lower abatement costs reduce emissions and sell permits, while firms facing higher costs purchase permits, ensuring that the marginal cost of abatement is equalized across participants. The efficiency of cap-and-trade derives from the fixed aggregate cap (Goulder and Schein, 2013). Additional policies, such as efficiency mandates or biofuel blending requirements, may not yield further reductions under a rigid cap but can redistribute abatement responsibilities and influence permit prices.

Under a Pigouvian tax, supplementary policies can generate additional reductions beyond those achieved by the price signal alone (Baumol and Oates, 1988). A carbon tax sets a price for emissions rather than a fixed quantity, leaving firms flexibility in how much to abate. Complementary instruments, such as technology mandates or efficiency standards, can target areas where the price signal alone is insufficient due to market failures, behavioral frictions, or high upfront investment costs. By combining Pigouvian taxes with carefully designed regulatory measures, policymakers can encourage deeper and faster emissions reductions while allowing firms to respond to economic signals. Analyzing MAC curves alongside policy interactions enables decision-makers to identify the least-cost abatement options across heterogeneous firms, optimize the allocation of mitigation effort, and balance environmental effectiveness, economic efficiency, and social acceptability.

Policy integration is particularly relevant in Brazil, where the road freight sector faces structural constraints that can limit the effectiveness of individual instruments. Command-and-control measures, such as Proconve, establish baseline compliance and drive the adoption of cleaner vehicle technologies. Market-based instruments, including cap-and-trade systems like SBCE, introduce flexibility and cost efficiency, while Pigouvian taxes provide continuous price signals that influence fuel use and emissions. Together, these instruments create a framework in which transport firms' operational and investment decisions respond to a combination of regulatory requirements and economic incentives. This integrated approach supports the adoption of low-carbon technologies, encourages the efficient allocation of abatement effort, and gradually decouples transport activity from fossil fuel use, contributing to the decarbonization of Brazil's road freight sector in a cost-effective and economically sustainable manner.

3.3 Methodology

This study adopts a two-stage methodological framework to estimate the carbon price necessary to reduce freight transport demand in order to achieve Brazil's NDC targets. The framework covers both diagnostic evaluation and policy simulation. The first stage quantifies baseline freight transport costs by projecting their share of GDP through 2099 under different Shared Socioeconomic Pathways (*SSPs*) (Riahi et al., 2017), which provide standardized scenarios of population, economic growth, and technological development. Specifically, the calculation multiplies projected transport demand (in Ton-Kilometers, TKU) by unit costs for each transport mode, yielding an estimate of total annual freight transport costs. This allows for the comparison of costs across scenarios and over time.

The second stage focuses on the road freight sector, which is the largest contributor to emissions and accounts for 64.9% of freight transport in Brazil. The analysis begins by estimating the long-run price elasticity of demand using an Autoregressive Distributed Lag (ARDL) model. This elasticity is then used as a key parameter to simulate the MAC, representing the implicit carbon price necessary to reduce freight transport demand in line with Brazil's official NDC target for 2035. The following subsections detail each step of the methodology, from the determination of cost factors to the final MAC calculation.

3.3.1 Freight transport costs as a share of GDP

The first stage calculates the total economic cost of freight transport by multiplying projected physical demand, measured in Ton-Kilometers (TKU), by corresponding unit costs. The resulting cost is then expressed as a share of GDP, providing a clear and objective measure of its economic significance. Freight demand projections are based on the Shared Socioeconomic Pathways (*SSPs*) (Riahi et al., 2017). The *SSPs* are a set of standardized socioeconomic scenarios widely used in climate and transport research. This analysis considers three key scenarios: the *SSP2 "Middle-of-the-Road"* scenario, serving as a reference case reflecting the continuation of historical trends; the *SSP1 "Sustainability"* scenario, representing a future with greater emphasis on sustainable development and lower resource intensity; and the *SSP5 "Fossil-Fueled Development"* scenario, characterized by rapid, resource-intensive economic growth. By comparing these divergent pathways, this stage establishes a baseline for assessing the magnitude and variation of transport costs under alternative future scenarios.

The total annual economic cost for scenario s in year t ($CT_{s,t}$) is then calculated as:

$$CT_{s,t} = (\text{TKU}_{\text{road},s,t} \times \bar{F}_{\text{road}}) + (\text{TKU}_{\text{rail},s,t} \times \bar{F}_{\text{rail}}) + \left(\frac{\text{TKU}_{\text{air},s,t} \times \bar{F}_{\text{air}}}{1000} \right) \tag{6}$$

This equation aggregates costs across transport modes, normalizing air transport demand, which is measured in millions of TKU, relative to road and rail, which are measured in billions. It provides an estimate of total freight transport costs relative to GDP. Here, $\bar{F}_{\text{road}}$, $\bar{F}_{\text{rail}}$, and $\bar{F}_{\text{air}}$ represent the average unit freight costs per TKU for each mode. These cost factors are held constant in real terms across all projections, ensuring that differences in total transport costs are driven solely by changes in projected freight demand.

The indicator is then calculated as:

$$I_{s,t}(\% \text{ of GDP}) = \left(\frac{CT_{s,t}}{GDP_{s,t}} \right) \times 100 \tag{7}$$

where $CT_{s,t}$ represents total annual transport costs for scenario s and year t, and $GDP_{s,t}$ is the GDP in constant 2005 BRL after conversion. This formulation allows for comparison of transport costs across scenarios and over time, providing a measure of their relative share of GDP and enabling the exploration of the potential effects of a specific policy intervention on total costs.

3.3.2 Marginal Abatement Cost (MAC)

The second phase of the methodology focuses on the road transport mode to estimate the carbon price necessary to reduce freight transport demand in line with Brazil's NDC targets. This focus is justified because road freight accounts for the largest share of CO_2 emissions in the Brazilian freight sector, making it the most relevant target for carbon pricing policies. Furthermore, the greater availability and granularity of historical data for road transport (including long-term series on freight volumes, fuel prices, and modality-specific emissions) allow for a more detailed econometric analysis compared to other modes. Specifically, the analysis estimates the MAC for the road freight sector, which is considered a hard-to-abate sector, and represents the carbon price necessary to reduce the last and most expensive ton of CO_2 by lowering freight transport demand to meet a specific target. The MAC corresponds to the level at which a Pigouvian carbon tax should be set to achieve the target efficiently (Pigou, 1920; Nordhaus, 2017).

3.3.3 Autoregressive Distributed Lag Model (ARDL)

To measure the sensitivity of road freight demand to cost variations, the central step is the estimation of the price elasticity of demand. An ARDL model was used, which can handle variables with mixed orders of integration and estimate long-run cointegration relationships Pesaran et al. (2001). All variables were transformed into natural logarithms, allowing the long-run coefficients to be interpreted directly as elasticities.

The selection of explanatory variables, Gross Domestic Product (GDP_t) and the real diesel price ($Dprice_t$), is based on derived demand theory, which posits that the demand for transport services depends on the demand for the goods being transported (Winston, 1983). The long-run price elasticity of demand (η), a key parameter for this study, is estimated from the cointegration relationship derived from the ARDL model. Unlike in the first essay of this thesis, where diesel price elasticity was not considered due to the low responsiveness of demand, applying the ARDL model here allows for the estimation of the long-run elasticity specific to road freight. This elasticity is essential for the strategy employed in this study, providing a basis for evaluating the economic implications of carbon pricing and informing the assessment of the MAC under different policy scenarios[49]. The model is specified as follows:

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[49] Alternative approaches for deriving a MAC do not necessarily rely on long-run price elasticity and may instead use engineering-based estimates of abatement costs or optimization models that minimize total system costs under emissions constraints.

$$\begin{aligned}\ln(dmc_t) = \beta_0 &+ \sum_{i=1}^{p} \beta_i^{dmc} \ln(dmc_{t-i}) + \sum_{i=0}^{q_1} \beta_i^{gdp} \ln(GDP_{t-i}) \\ &+ \sum_{i=0}^{q_2} \beta_i^{dprice} \ln(Dprice_{t-i}) \\ &+ \sum_{m=2}^{12} \alpha_m \, MTH_{m,t} + \varepsilon_t \end{aligned} \tag{8}$$

The variables in equation (8) have the following meanings:

- $\ln(dmc_t)$ denotes the natural logarithm of road freight demand in period t;
- $\ln(GDP_t)$ is the logarithm of Gross Domestic Product in period t;
- $\ln(Dprice_t)$ is the logarithm of the real diesel price in period t;
- $p \in \mathbb{N}$, $q_1, q_2 \in \mathbb{N}_0$ represent the number of lags selected for each explanatory variable;
- $\{\beta_i^{dmc}\}$, $\{\beta_i^{gdp}\}$, and $\{\beta_i^{dprice}\}$ are the coefficients to be estimated;
- $MTH_{m,t}$ is a monthly dummy variable, equal to one if the month in period t corresponds to m, and zero otherwise. January is omitted and serves as the base category;
- ε_t is the error term.

Lag lengths p, q_1, and q_2 are determined using the Bayesian Information Criterion (BIC). By incorporating real diesel prices into the ARDL model, it becomes possible to estimate the long-term responsiveness of diesel demand to price changes, a key input for calculating the MAC in this framework.

First, the stationarity of the real diesel price (*Dprice*) was assessed to ensure the validity of the estimation results. Three widely used stationarity tests were applied: the *Augmented Dickey-Fuller* (ADF)[50], Phillips-Perron (PP)[51], and Kwiatkowski-Phillips-Schmidt-Shin (KPSS)[52]. Different specifications were considered, including random-walk and trend for the ADF, and level and trend for the KPSS. The number of lagged terms selected according to the Akaike Information Criterion (AIC) is indicated in parentheses after each p-value in Table IX. The results indicate that *Dprice* is non-stationary in levels, as suggested by the ADF (Random-Walk and Trend), PP, and KPSS (Trend) tests. However, after taking the first difference (Δ*Dprice*), all tests confirm that the series is stationary, indicating that *Dprice* is integrated of order one, I(1).

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[50] Dickey and Fuller (1979)

[51] Phillips and Perron (1988)

[52] Kwiatkowski et al. (1992)

Table IX: p-values of stationarity tests for the real diesel price (*Dprice*)

	ADF		**PP**	**KPSS**		**Conclusion**
	Random-Walk	Trend		Level	Trend	
$Dprice_t$	0.03 (5)	0.03 (5)	0.03	0.09 (4)	0.01 (4)	I(1)
$\Delta Dprice_t$	0.01 (5)	0.00 (5)	<0.01	0.1 (4)	0.1 (4)	I(0)

Source: Own elaboration.

An ARDL model for road freight demand was then estimated using GDP and the real diesel price as explanatory variables, covering the period 2000–2019. This approach allows for the simultaneous modeling of short-run dynamics and long-run relationships within a single-equation framework. Seasonality was captured through monthly dummy variables, and lagged terms were included to account for autocorrelation and the dynamic adjustment of freight demand. The model was validated using the *bounds testing* procedure developed by Pesaran et al. (2001), which is widely used for assessing cointegration relationships in both small and large samples (Rodriguez and Trotter, 2019).

Following Pesaran et al. (2001), the ARDL model was expressed in its error correction form (ECM) and estimated via ordinary least squares (OLS):

$$\begin{aligned}\Delta \ln(DMC_t) = \mu_0 &+ \sum_{i=1}^{p-1} \mu_i^{\text{dmc}}\, \Delta \ln(DMC_{t-i}) + \sum_{i=0}^{q_1} \mu_i^{\text{gdp}}\, \Delta \ln(GDP_{t-i}) \\ &+ \sum_{i=0}^{q_2} \mu_i^{\text{price}}\, \Delta \ln(Dprice_{t-i}) \\ &+ \theta\Big(\ln(DMC_{t-1}) - \lambda^{\text{gdp}} \ln(GDP_{t-1}) - \lambda^{\text{price}} \ln(Dprice_{t-1}) \Big) \\ &+ \sum_{m=2}^{12} \alpha_m MTH_{m,t} + \varepsilon_t \end{aligned} \tag{9}$$

The *bounds testing* procedure, following Pesaran et al. (2001) and described in Section 2.3.3, identifies whether a long-run relationship exists between the variables, enabling inference on both short-run dynamics and long-run equilibrium. Projecting the exogenous variables forward allows for the generation of road freight demand scenarios that reflect both adjustment dynamics and equilibrium relationships. The long-run coefficient λ_{price} provides the long-run price elasticity of diesel demand (η), which is a key input for the subsequent MAC estimation (Hassler and Wolters, 2006).

3.3.4 Elasticity and MAC simulation

To assess the implications of different policy ambitions for 2035, a range of emission reduction targets is considered. For each target, the corresponding percentage reduction in diesel demand ($\%\Delta Q$) is calculated by comparing projected emissions under the business-as-usual baseline with the target path. This calculation provides a first-order approximation of the required reduction in fossil fuel consumption and the associated price increase necessary to achieve the target, linking policy objectives to changes in fuel use in the road freight sector.

Based on the estimated long-run price elasticity of diesel demand (η), the fuel price increase necessary to achieve each reduction in road freight demand ($\%\Delta Q$) is calculated as:

$$\%\Delta P = \frac{\%\Delta Q}{\eta} \tag{10}$$

This calculation translates the emission reduction target into a concrete economic signal, representing the proportional change in fuel prices needed to induce the required decrease in road freight demand. The estimated elasticity captures the responsiveness of road freight demand to price changes and is assumed to remain constant for the purposes of this exercise, reflecting a simplifying assumption rather than an expectation of how the sector will actually evolve. By relying on estimated long-run elasticities, the framework ensures that the simulated policy interventions are consistent with observed demand responses.

The corresponding implicit fuel tax is then defined as:

$$T_{BRL/L} = P_{base} \times \%\Delta P \tag{11}$$

This step converts the required price increase into a monetary value applicable at the pump, which can be interpreted as a policy instrument such as a fuel tax or surcharge. The tax reflects the policy lever needed to achieve the targeted reduction in road freight demand, linking the price increase directly to the corresponding demand reduction.

Finally, the MAC, expressed in BRL[53] per ton of CO_2, is computed as:

$$MAC = \frac{T_{BRL/L}}{FE_{CO_2/L}} \tag{12}$$

where $FE_{CO_2/L}$ denotes the diesel emission factor. The MAC provides a standardized measure of the cost associated with reducing one ton of CO_2, allowing for comparisons across policy scenarios, transport modes, and time periods. This metric is particularly useful for policymakers and analysts, as it quantifies the marginal cost of mitigation

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[53] All monetary values are expressed in Brazilian reais (BRL) to maintain consistency with the domestic context analyzed in this study. Since the focus of the thesis is the Brazilian transport sector, presenting results in local currency avoids exchange-rate distortions and better reflects the economic interpretation of domestic fuel pricing and taxation effects.

measures and facilitates the prioritization of interventions within the freight transport sector.

Overall, this methodological framework links observed demand elasticity, projected road freight demand, and emission reduction targets into a single policy analysis structure. It provides a simulation that translates abstract environmental goals into the implied diesel price increase required to achieve a given reduction in road freight demand, while remaining consistent with empirical estimates and long-run equilibrium relationships in the transport sector.

3.4 Data sources and preprocessing

This section details the data sources and preprocessing steps for the two stages of the analysis. Section 3.4.1 presents the data used to compute the "cost of transport as a share of GDP", combining long-term freight demand projections with modal cost factors and macroeconomic scenarios from the *SSPs*. Section 3.4.2 describes the data for the MAC simulation, which relies on a historical monthly database (2002–2019) integrating road freight demand from national transport agencies, GDP from the Instituto Brasileiro de Geografia e Estatística (IBGE), and real diesel prices from Agência Nacional do Petróleo, Gás Natural e Biocombustíveis (ANP) data.

3.4.1 Data for the cost of transport as a share of GDP

Projected freight demand for the period 2020–2099, covering road, rail, and air transport and expressed in TKU, was provided from the projections developed in the first essay of this thesis. These projections are based on econometric models conditioned on the *Shared Socioeconomic Pathways* (*SSPs*). Brazil's GDP projections for the same period were obtained from the IIASA *SSP* Database and are reported in billions of Purchasing Power Parity (PPP)[54] US dollars at constant 2005 prices.

An average cost factor (in BRL per TKU) was calculated for each transport mode by combining energy efficiency parameters (E, in MJ/TKU)[55] from Deutsche Bahn AG (2022)[56] with national fuel price data (P_m, in BRL/liter, denoting the fuel price for mode

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[54] Purchasing Power Parity (PPP) is a theory which relates changes in the nominal exchange rate between two countries' currencies to changes in the countries' price levels. The purchasing power parity theory predicts that an increase in a currency's domestic purchasing power will be associated with a proportional currency appreciation, while a decrease will be associated with a proportional currency depreciation (IMF, 2025).

[55] E denotes the energy efficiency of a given transport mode, expressed in megajoules per tonne-kilometer (MJ/TKU). It represents the amount of energy required to transport one tonne of freight over one kilometer and is used to estimate fuel consumption and transport costs.

[56] Data sourced from Deutsche Bahn AG (2022) *Integrated Report 2022*. While differences exist between German and Brazilian transport systems, these data provide the most comprehensive publicly available information on transport modes' energy efficiency and were adapted to the Brazilian context due to gaps in national data. To ensure plausibility, these values were compared with alternative sources for Brazil. For example, World Bank (2009) reports a transport cost of 3.5 US cents per TKU in Brazil

m) provided by ANP for the pre-pandemic period (2017–2019). The resulting representative average cost factor ($\bar{F}_m$) is held constant in real terms across all projections. This ensures that differences in total transport costs across scenarios are solely driven by changes in projected freight demand, rather than by variations in fuel prices or energy efficiency. Cost coefficients for each transport mode, along with the PPP conversion factor, are summarized in Table X.

Table X: Key parameters for the economic analysis

Parameter	Value	Source
Road Cost Factor ($\bar{F}_{\text{road}}$)	0.074 BRL/TKU	Own elaboration
Rail Cost Factor ($\bar{F}_{\text{rail}}$)	0.017 BRL/TKU	Own elaboration
Air Cost Factor ($\bar{F}_{\text{air}}$)	0.531 BRL/TKU	Own elaboration
PPP Conversion Factor (2005)	1.61 BRL per Intl. $	World Bank (2024)

Source: Own elaboration.

The total annual cost ($CT_{s,t}$) for the year 2020 was computed by first aggregating the monthly projected demand series for each transport mode into annual totals, and then multiplying the annual demand of each mode by its respective constant cost factor ($\bar{F}_m$). For air freight, an unit conversion adjustment was applied to express the results in the same units as the other modes (TKU). This calculation yields the total annual cost of freight transport in constant 2005 BRL. The key parameters used in this analysis are summarized in Table X.

The cost of transport as a share of GDP indicator is calculated by dividing the total annual freight transport cost ($CT_{s,t}$) by the annual GDP series, converted to constant 2005 BRL using Brazil's 2005 PPP conversion factor of 1.61 BRL per PPP US Dollar (World Bank, 2024). This indicator represents the proportion of economic resources allocated to freight transport, providing a standardized measure to compare the relative weight of transport costs across time and between modes. By maintaining a constant cost factor in real terms, the indicator primarily reflects variations in freight demand and policy scenarios, supporting the evaluation of trends and the assessment of policy scenarios in the transport sector.

3.4.2 Data for the MAC simulation

The ARDL model was estimated with data from January 2002 to December 2019. The dataset includes historical road freight demand, GDP, and diesel prices. Road freight demand, expressed in TKU, was obtained from the Agência Nacional de Transportes Terrestres (ANTT) and the Associação Brasileira de Concessionárias de Rodovias

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(2007 data). Considering the average exchange rate in 2007 of 1.948 BRL/USD, this corresponds to approximately 0.068 BRL/TKU, consistent with the values used in this study.

(ABCR)[57]. Monthly GDP and population series were constructed by linearly interpolating the corresponding annual IBGE data, so that the frequency of all variables matches the freight demand series for the model estimation.

The real diesel price series was constructed using a two-step procedure. First, the nominal monthly average retail prices of diesel (2002–2019) were collected at the national level from the ANP[58]. Second, the nominal series was adjusted for inflation by deflating it using the IPCA from IBGE, with December 2019 chosen as the reference period. This procedure allows the analysis to focus on real price dynamics.

To anchor the policy simulations within Brazil's official climate commitments, historical road freight emissions for 2005 were retrieved from the SEEG, providing a baseline consistent with Brazil's NDC. The dataset also incorporates the diesel emission factor ($FE_{CO_2/L}$), representing the amount of CO_2 emitted per liter of diesel combusted. Following the IPCC (2006) benchmark, a standard value of 2.68 $kgCO_2/L$ (0.00268 tCO_2/L) was adopted, enabling subsequent calculation of the marginal abatement cost (MAC).

The *SSP2 "Middle-of-the-Road"* scenario serves as the baseline for the policy simulations, representing a business-as-usual trajectory. To assess the economic implications of climate policy, a range of emission reduction targets for 2035 is considered, including the lower (59.0%) and upper (67.0%) bounds of Brazil's official Nationally Determined Contribution (NDC), alongside alternative levels of 10.0%, 20.0%, 30.0%, and 40.0% to examine the sensitivity of the results. A key methodological assumption links these national targets to the sectoral analysis: the MACs are simulated under a proportional effort-sharing framework, meaning the national percentage reduction targets are applied directly to the road freight sector's projected diesel consumption. While this simplifying assumption enables estimation of the required carbon price, it is acknowledged that a real-world policy might allocate abatement responsibilities differently across sectors.

For each reduction target, the corresponding diesel price increase needed to reduce road freight demand is calculated, providing an economic signal for the sector. These adjustments are then used to derive the MAC associated with each scenario, allowing assessment of the economic trade-offs and relative costs of achieving different decarbonization levels, while maintaining consistency with observed demand elasticities and projected freight activity. This framework links economy-wide targets to sector-specific

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[57] ABCR calculates freight indices based on vehicle flows through toll plazas. The IBGE incorporated these indices into GDP calculations in 2012, highlighting their economic significance (ABCR, 2023). For further methodological details on the construction and treatment of the road freight demand, see Appendix A.

[58] Until October 30, 2004, all average prices were calculated using a simple arithmetic mean. After this date, the average resale and distribution prices of fuels, at the state, regional, and national levels, have been weighted based on sales information reported by distributors to the ANP. Currently, only the average price at the municipal level is obtained using a simple arithmetic mean (ANP, 2025).

price changes, supporting an analysis of policy implications in the road freight sector.

By integrating historical data on road freight demand, GDP, and diesel prices with long-term projections from the *Shared Socioeconomic Pathways* (*SSPs*), the dataset forms the basis for the analysis. The historical series cover 2002–2019 and provide information on freight demand, GDP, and diesel price dynamics, while the *SSP* projections extend these patterns up to 2099. This combination preserves temporal continuity between observed and projected values, allowing the ARDL model to capture both short-term fluctuations and long-run relationships among GDP, diesel prices, and freight demand. The dataset is used to calculate two key indicators for the policy analysis: the long-run price elasticity of road freight demand, quantifying responsiveness to diesel price changes, and the MAC, representing the cost of reducing one ton of CO_2 emissions.

3.5 Results and Discussion

This section presents the results of the analysis, organized into two parts corresponding to the methodological framework. The first part quantifies the projected cost of transport as a share of GDP, providing a reference for the economic role of the sector. By projecting direct logistics costs through 2099 under three Shared Socioeconomic Pathways (*SSP1, SSP2, and SSP5*), the analysis illustrates the relationship between economic growth and transport demand and the difficulty of decoupling the two, even under scenarios oriented toward sustainability.

The second part estimates mitigation costs for the road freight sector. It begins by presenting the long-run price elasticity of diesel demand, estimated via an ARDL model. The results indicate that demand is inelastic, reflecting the sector's structural characteristics. This elasticity is then used to calculate the MACs, representing the carbon price required to reduce road freight demand in order to achieve Brazil's 2035 emission reduction targets. The results suggest that relying solely on a carbon pricing policy would entail high costs, indicating the limitations of single-instrument approaches and the potential value of a diversified policy portfolio.

3.5.1 Projected cost of transport as a share of GDP (2020–2099)

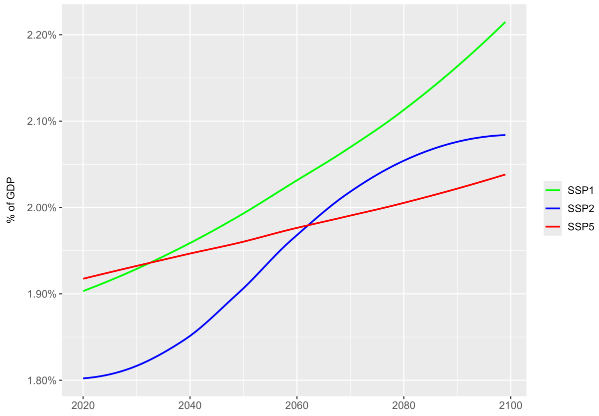
This subsection analyzes the evolution of freight transport costs as a share of Brazil's GDP across the three long-term development scenarios defined by the Shared Socioeconomic Pathways (*SSPs*). The indicator provides a direct measure of the relative weight of freight expenditures within the national economy, linking the projections of demand by mode to the broader trajectories of economic growth.

Over the short term, from 2020 to 2035, the share of GDP devoted to freight transport remains relatively stable. In *SSP1* and *SSP5*, it moves from 1.89% in 2020 to

1.94% by 2035, while in *SSP2* the share stays almost unchanged, at around 1.82%. This stability may reflect the inertia of freight demand in the first decades of the projection.

From the mid-century onward, the upward trajectory becomes clearer. Figure 12 shows the overall evolution, with *SSP1* gradually surpassing the other scenarios after 2060, while *SSP2* and *SSP5* remain closer to each other. The divergence after mid-century indicates the different patterns of freight expenditures under alternative socioeconomic and technological pathways.

Figure 12: Projected cost of transport as a share of GDP under *SSP1*, *SSP2*, and *SSP5* (2020–2099)



Source: Own elaboration.

The long-term results indicate that by the end of the century, *SSP1* reaches the highest share, at 2.22%, while *SSP2* stabilizes around 2.08% and *SSP5* at 2.04%. These values show the persistence of transport expenditures relative to GDP and the limited scope for decoupling under the scenarios considered. Table XI summarizes selected benchmark years for ease of comparison[59].

Table XI: Projected cost of transport as a share of GDP (%) under *SSP1*, *SSP2*, and *SSP5*

Year	*SSP1*	*SSP2*	*SSP5*
2020	1.89	1.82	1.89
2035	1.94	1.82	1.94
2070	2.07	2.02	1.99
2099	2.22	2.08	2.04

Source: Own elaboration.

Taken together, the Figure 12 and the Table XI indicate that the evolution of freight transport costs as a share of GDP is gradual across all scenarios. Although the abso-

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[59] See **Appendix E** for complete annual data.

lute differences between *SSP1*, *SSP2*, and *SSP5* are relatively modest, the long-term divergence highlights how variations in economic growth and freight demand projections influence the relative burden of transport costs over time.

The results indicate that the cost of transport as a share of GDP is projected to remain persistently high, and even increase, across all scenarios through 2099. This persistence, even in high-growth pathways such as *SSP5*, suggests that economic growth alone is insufficient to dilute the relative economic weight of logistics in Brazil. A plausible explanation, though not a direct output of the model, lies in the country's well-documented structural challenges, particularly its heavy reliance on road transport and historical underinvestment in more efficient infrastructure. The model, trained on historical data reflecting these inefficiencies, projects their continuation, implicitly assuming that past patterns and structural constraints will persist.

The distinct trajectory of each scenario warrants further discussion. The *"S-shaped curve"* in *SSP2* is consistent with a development pathway in which transport costs rise as demand pressures meet infrastructure limitations, before stabilizing as economic growth slows in the long term. In contrast, the more moderate increase in *SSP5* suggests that when GDP growth is exceptionally rapid, the relative impact of rising logistics costs may be partially offset by scale economies and productivity gains in transport and distribution activities. The outcome for *SSP1*, which has the highest long-term share, is driven by its unique trajectory where freight demand growth, although part of a sustainable pathway, outpaces the corresponding GDP growth more significantly than in other scenarios over the long run. This suggests that even sustainable economic development can increase the relative economic weight of logistics if demand for physical goods transport remains high.

From a policy perspective, these projections emphasize the need for strategic interventions to modify baseline trajectories. IBGE data indicate that the transport sector accounts for 3.1% of Brazil's GDP (IBGE, 2025), while this study estimates that freight transport alone represents roughly 2.0% of GDP, suggesting that freight may account for approximately two-thirds of the sector's total economic weight. This substantial economic footprint highlights the importance of targeted policies promoting modal diversification and operational efficiency, as the Brazilian economy is likely to continue bearing a significant relative cost for freight transport, potentially limiting competitiveness. In line with this perspective, the CNT (2024) estimates that BRL 99.7 billion will be required for pavement reconstruction, restoration, and maintenance, underscoring the scale of investment needed to reduce these long-term costs.

Overall, this baseline analysis quantifies the persistent economic cost of Brazil's current freight transport structure, emphasizes the magnitude of the challenge, and sets the stage for the following section, which assesses the direct costs of using a carbon price to reduce road freight demand in order to achieve national climate targets.

3.5.2 Carbon pricing in road freight

This phase of the study focuses on the road transport sector to analyze the responsiveness of freight volumes to diesel prices and economic activity, acknowledging that the model is a simplification and does not capture all possible determinants of demand. The long-run price elasticity of diesel demand is estimated using a simplified ARDL model that includes only GDP and diesel prices as explanatory variables. Table XII presents the complete estimation results in error correction form (ECM), detailing short-run dynamics, the speed of adjustment to equilibrium, and seasonal effects. The model demonstrates a good overall fit, with an adjusted R^2 of 0.948 and a highly significant F-statistic (228.0, $p < 0.001$), indicating that the specification explains most of the variation in monthly freight volumes conditional on the included variables. Key explanatory variables, GDP, diesel prices, and lagged freight volumes, are statistically significant, confirming their importance in shaping short and long-term demand within the scope of the model.

Table XII: ARDL/ECM model estimation results for road freight demand

Variable	**Estimate**	**Std. Error**	**t value**	**P-value**	
Short-run Dynamics					
$\Delta \ln(GDP)$	1.018	0.117	8.670	<0.001	***
$\Delta \ln(Dprice)$	-0.101	0.029	-3.425	0.001	**
$\Delta \ln(dmc_{t-1})$	-0.406	0.066	-6.110	<0.001	***
$\Delta \ln(dmc_{t-2})$	-0.251	0.057	-4.402	<0.001	***
Error Correction Term					
ECT_{t-1}	-0.165	0.045	-3.642	<0.001	***
Seasonal Effects					
MTH_{Feb}	-0.028	0.011	-2.521	0.012	*
MTH_{Mar}	0.056	0.017	3.345	0.001	**
MTH_{Apr}	0.030	0.018	1.715	0.088	.
MTH_{May}	0.040	0.018	2.213	0.028	*
MTH_{Jun}	-0.014	0.014	-0.973	0.332	
MTH_{Jul}	0.032	0.016	2.028	0.044	*
MTH_{Aug}	0.066	0.014	4.677	<0.001	***
MTH_{Sep}	0.050	0.014	3.585	<0.001	**
MTH_{Oct}	0.006	0.017	0.361	0.719	
MTH_{Nov}	-0.028	0.015	-1.941	0.054	.
MTH_{Dec}	-0.025	0.013	-1.842	0.067	.
Intercept	-0.348	0.228	-1.523	0.129	
Adjusted R^2	0.948				
F-statistic (Bounds Test)	228.0				<0.001 ***

***0.1%; **1.0%; *5.0%; .10%

Source: Own elaboration.

The negative and significant Error Correction Term (ECT$_{t-1} = -0.165$, $p < 0.001$) indicates that approximately 16.5% of any deviation from the long-run equilibrium is corrected each month. Although this adjustment is relatively fast for the road freight sector, deviations may persist over several months due to structural inertia, regulatory constraints, and periodic macroeconomic or climatic shocks typical of Brazil's transport industry. Seasonal effects further reveal predictable monthly fluctuations in freight activity. Overall, these results offer a focused, data-driven view of the influence of GDP and diesel prices on road freight volumes, with the caveat that they reflect the relationships captured by the simplified model rather than the full complexity of the market.

In the short run, road freight demand responds to changes in economic activity and fuel prices in a quantitatively moderate way. The estimated short-run income elasticity, given by the coefficient on GDP, is 1.018, indicating that a 1.0% increase in monthly GDP leads to an approximately 1.018% increase in freight volumes, all else being equal. Diesel prices have a negative effect on demand, with a short-run price elasticity of -0.101, meaning that a 1.0% increase in diesel prices reduces freight volumes by roughly 0.1%. This relatively limited response may reflect operational constraints, including fixed transport routes, pre-existing contracts, limited fleet flexibility, and a scarcity of viable alternative transport modes. Seasonal effects further modulate demand, capturing variations associated with production cycles, harvest periods, and consumer consumption patterns, which influence the timing and intensity of freight movements.

Table XIII presents the long-run elasticities derived from the ARDL model. The results indicate a diesel price elasticity of $\eta = -0.610$, implying that a 1.0% increase in the real price of diesel could reduce freight demand by approximately 0.6% over the long run. This relatively inelastic response, which is broadly consistent with the empirical estimates reported in Table XIV, reflects the structural rigidity of the Brazilian road freight system, which relies on road transport for 64.9% of cargo movements. This rigidity is partly a consequence of decades of public policy prioritizing road infrastructure over alternative modes such as railways and waterways. The observed inelasticity suggests that long-standing policy choices have constrained the sector's responsiveness to fuel price changes.

Table XIII: Long-run elasticities derived from the ARDL model

Variable	**Long-run Elasticity**
GDP	0.489
Dprice	-0.610

Source: Own elaboration.

In contrast, the long-run income elasticity ($\eta = 0.489$) indicates that freight demand responds positively but inelastically to economic growth in the long run, with a 1.0% increase in GDP leading to an approximate 0.5% increase in cargo transport. A comparison of the two elasticities reveals that, in the long run, road freight demand is more

Table XIV: Selected estimates of diesel price elasticity in Brazil

Study	Method	Estimated Elasticity
Uchôa et al. (2020)	Panel data with IV	Short run: -1.36
Cardoso and Jesus (2018)	Partial adjustment model	Short run: -0.16; Long run: -0.46
Reis (2016)	Multiple linear regression	Short run: -0.27
Luz (2015)	Error correction model	Short run: -0.30; Long run: -0.40
Iootty et al. (2009)	LA-AIDS model	Short run: -0.63

Source: Own elaboration.

sensitive to diesel price changes than to variations in income. These results may underline the structural characteristics of the sector: although demand grows with the economy, reducing diesel consumption without substantial changes to infrastructure and modal options remains challenging.

Taken together, the long-run elasticities highlight the limited responsiveness of road freight demand to changes in GDP and diesel prices. Assuming a constant long-run price elasticity, this inelasticity implies that substantial adjustments in diesel prices are required to achieve meaningful reductions in fuel consumption associated with freight transport. Building on these insights, Table XV presents the simulated MAC values for diesel consumption in Brazil in 2035, calculated based on the estimated responsiveness of road freight demand across different CO_2 reduction targets. The results indicate an inelastic response: even relatively modest reductions in diesel use require substantial price increases. For instance, achieving a 10.0% reduction implies a 16.39% increase in diesel prices, corresponding to a MAC of BRL 228.77 per tCO_2. As reduction targets rise, the required price increases grow more than proportionally, reflecting the nonlinear response of road freight demand to diesel prices. Meeting the lower target of the Brazilian NDC (59.0% reduction vs. 2005) would necessitate a diesel price increase of 96.72%, resulting in a MAC of BRL 1,349.77/tCO_2, while the upper target (67.0%) pushes this value to 109.84%, with a MAC of BRL 1,532.79/tCO_2.

The elevated MAC values obtained in this chapter should not be interpreted as the universal economic cost of all decarbonization options, but rather as the expense associated with relying exclusively on price-based measures in a system with limited modal alternatives. These results highlight the necessity of complementary, non-price interventions. Strategic investments in rail and waterway infrastructure, along with stricter vehicle efficiency standards, would offer practical alternatives to diesel-intensive road transport, increasing the long-term responsiveness of freight demand to economic incentives[60]. Over time, this could "flatten" the MAC curve, making price instruments

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[60] While the full NDC targets demonstrate a prohibitive economic challenge under a price-only mechanism, the MAC curve also reveals that initial, incremental abatement is substantially more economically factible. Reductions of 10.0% and 20.0% require MACs of BRL 228.77 and BRL 457.55 per tCO_2, re-

more effective and less costly. The magnitude of the simulated MAC values also suggests that the challenges extend beyond economics, encompassing potential socio-political constraints: abrupt increases in diesel prices, as observed during historical shocks in Brazil, including the 2018 truckers' strike, may provoke substantial social responses, particularly among operators with older and less efficient fleets[61].

Table XV: Simulated Marginal Abatement Cost (MAC) for 2035

Reduction (vs. 2005)	**%ΔQ**	**%ΔP**	**Implicit Tax (BRL/L)**	**MAC (BRL/tCO$_2$)**
10.0%	-10.0	16.39	0.61	228.77
20.0%	-20.0	32.79	1.23	457.55
30.0%	-30.0	49.18	1.84	686.32
40.0%	-40.0	65.57	2.45	915.10
59.0% (Lower target)	-59.0	96.72	3.62	1,349.77
67.0% (Upper target)	-67.0	109.84	4.11	1,532.79

Source: Own elaboration.
Obs: %ΔQ is assumed equal to the NDC reduction target for simplicity. Calculations based on a diesel base price of BRL 3.74/L (Dec 2019) and an emission factor of 2.68 kgCO$_2$/L.

Table XV illustrates the increase in MAC values as emission reduction targets become progressively more ambitious. The “Implicit Tax” column shows the diesel price increase required to achieve each reduction target. For example, attaining a 20.0% reduction would require an implicit tax of BRL 1.23/L, whereas a 40.0% reduction would demand BRL 2.45/L, doubling the additional cost to fuel consumers[62]. Achieving the NDC target range (59.0–67.0%) represents the higher reduction levels analyzed in this study, corresponding to the highest carbon prices on the simulated curve. The implicit taxes for these targets rise to BRL 3.62–4.11/L, indicating the relatively higher economic cost needed for deeper reductions under the current structurally rigid system, assuming a constant long-run price elasticity. Figure 13 complements this analysis by visually depicting the upward trend trajectory in costs.

It is important to acknowledge a key assumption underlying this simulation: the

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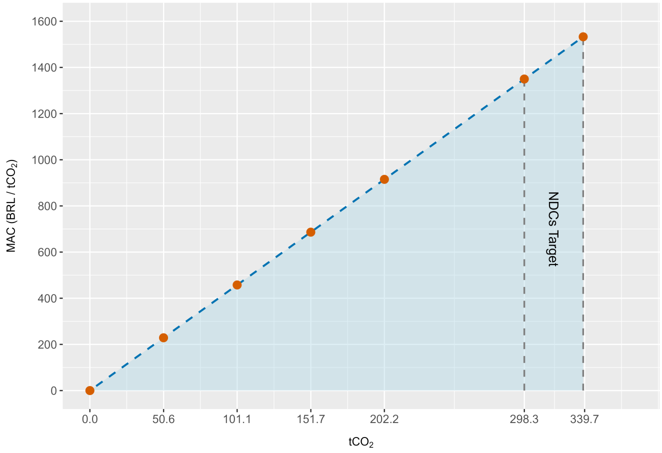
spectively1. These initial, lower-cost stages of the curve are likely associated with "low-hanging fruit" abatement options, such as increased operational efficiency, small-scale technological upgrades, or the early adoption of higher biofuel blends. This suggests that a phased policy approach, focusing on these achievable initial targets, would allow the sector time to implement necessary complementary non-price measures (like modal shift and BEV infrastructure) that can lower the cost of achieving the deeper cuts required by the final NDC.

[61] CNT (2024) indicates that the oldest and least efficient trucks are mostly owned by Autonomous Freight Carriers (AFC), whose fleet average age exceeds 22 years, and nearly 55.0% of the national truck fleet uses outdated technologies. This uneven distribution of capital means autonomous carriers would be disproportionately affected by diesel price increases. The estimated cost to replace all vehicles up to the P7 phase reaches BRL 845.58 billion, with AFC responsible for roughly BRL 422.75 billion, highlighting that the high MAC reflects not only market rigidity but also a major socioeconomic barrier.

[62] According to Stelling (2014), diesel demand is less price-sensitive than petrol, implying that freight transport reacts weakly to price changes. Forecasting the impact of carbon taxes on future freight emissions is difficult, and no sector-specific estimates are available. Price increases are likely to be largely passed on to transport buyers. Achieving full internalization would require substantial tax hikes; for UK road freight in 2006, this would imply a 50.0% increase.

long-run price elasticity of demand is held constant over the projection period. This reflects the technological and structural conditions embedded in the historical data, but elasticity is not static. The non-price structural interventions advocated in this chapter, such as large-scale investments in railways or the commercial viability of electric trucks, would provide new alternatives to diesel. The availability of these alternatives would likely increase the magnitude of the price elasticity of demand over time, effectively “flattening” the MAC curve in the long run. In such a scenario, future emission reductions could be achieved with lower carbon prices than those simulated here. The elevated MAC values presented should therefore be interpreted as the cost of decarbonization under the current structurally rigid system, not as a permanent feature of the Brazilian economy.

Figure 13: MAC curve for Brazilian road freight



Source: Own elaboration.

To illustrate the full economic impact of the freight sector under a climate policy scenario, the analysis extends the baseline calculation to include the cost of complying with Brazil’s 2035 NDC target[63]. This approach highlights the economic cost to the sector of achieving the emission reductions mandated by Brazil’s 2035 NDC target.

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[63] The baseline cost of transport as a share of GDP presented in Section 3.3.1 is adjusted to incorporate the sector’s price-responsive reduction in diesel consumption, based on the estimated long-run price elasticity of demand. For scenario s in year t, the total sector expenditure as a share of GDP is calculated as:

$$I_{\text{total},s,t}(\%\text{ of GDP}) = CT_{s,t} \times (1 + \%\Delta P_{s,t}) \times (1 + \%\Delta Q_{s,t})$$

where $CT_{s,t}$ is the original logistics cost as a share of GDP, $\%\Delta Q_{s,t}$ is the target percentage reduction in diesel consumption from the NDC, and $\%\Delta P_{s,t}$ is the required percentage increase in diesel prices to achieve it, calculated as:

$$\%\Delta P_{s,t} = \frac{\%\Delta Q_{s,t}}{\eta}.$$

This formulation captures the total cost incurred by the sector under the carbon pricing scenario. See detailed calculation in **Appendix F**.

The analysis focuses on 2035, using the *SSP2* scenario as the baseline, which represents a “business-as-usual” trajectory and isolates the cost associated specifically with meeting the NDC targets.

Table XVI presents the transport cost as a share of GDP in 2035 under the *SSP2* scenario for the 59.0% and 67.0% NDC targets, including the effect of carbon pricing and the sector’s price-sensitive reduction in diesel consumption. The values of 1.47% and 1.26%, respectively, are lower than the baseline logistics cost of 1.82% of GDP, indicating that transport costs are affected by the diesel consumption response to price changes. This suggests that price-induced reductions in diesel consumption can partially lessen the share of GDP required to meet the NDC targets. While the simulated MAC values remain high, the decrease in GDP share shows that carbon pricing alone, when combined with the assumed constant long-run diesel elasticity, does not result in larger macroeconomic costs. This reduction in transport costs may indicate a smaller relative impact on GDP, although it should not be interpreted as an actual increase or decrease in GDP; rather, it reflects the modeled effect of lower diesel consumption on the share of GDP allocated to transport. Notably, this analysis assumes that imposing a (potentially very high) carbon tax on diesel does not affect overall economic growth. In reality, large increases in diesel prices could have negative effects on GDP, which are not captured in the *SSP*-based projections used here.

Table XVI: Transport costs* as a share of GDP in 2035 under *SSP2*, including carbon pricing, for NDC emission targets

Scenario	**Transport Cost (% of GDP)**
Baseline logistics cost (no carbon pricing)	1.82%
59.0% NDC target (carbon pricing included)	1.47%
67.0% NDC target (carbon pricing included)	1.26%

Source: Own elaboration. *Costs account for diesel price adjustments and resulting fuel consumption changes, using long-run demand elasticity $\eta = -0.610$.

Building on these observations, the results suggest that carbon pricing, while influencing the economic cost of achieving the NDC targets, may not be sufficient on its own. The simulated MAC for 2035 should be understood as a result of the model assumption of constant long-run diesel elasticity ($\eta = -0.610$), rather than as an intrinsic structural property of the Brazilian road freight sector. The limited demand response to higher diesel prices, given this assumed elasticity, indicates that relying solely on price instruments may not achieve the modeled emission reductions efficiently. Moreover, national-average MAC values may obscure sectoral and regional differences: agribusiness, which relies heavily on long-distance road transport from inland regions, may display lower price responsiveness and higher abatement costs due to limited alternatives, whereas urban last-mile logistics in metropolitan areas may respond more readily to price signals and offer greater potential for electrification, yielding comparatively lower abatement costs.

The simulated MAC values reflect the model specification, which considers only emissions reductions achieved through decreased diesel demand and does not incorporate other potential pathways, such as fuel substitution with biofuels promoted under policies like RenovaBio. Future structural interventions, including expanded rail infrastructure or electrification, could increase demand responsiveness over time, thereby reducing the economic cost of mitigation. Consequently, the MACs calculated (BRL 1,349–1,532/tCO_2) represent the cost of relying exclusively on carbon pricing under the current system, rather than the full economic cost of achieving NDC targets. Incorporating alternative technological options could flatten the effective MAC curve, suggesting that a lower carbon price could be sufficient when implemented as part of a broader policy portfolio combining price instruments with direct incentives, mandates for low-carbon fuels, and efficiency improvements.

3.6 Conclusions

This study quantified the economic costs of GHG mitigation in Brazil's freight transport sector and assessed the potential of carbon pricing as a policy instrument. Projections indicate that the share of GDP allocated to freight logistics will rise from 1.82% in 2020 to between 2.04% and 2.22% by 2099, reflecting the link between GDP growth and transport demand. The long-run price elasticity of diesel demand, estimated at $\eta = -0.610$, demonstrates that road freight is weakly responsive to fuel price changes. Achieving the 2035 NDC target through carbon pricing alone would require diesel price increases of up to 109.8%, corresponding to a marginal abatement cost of BRL 1,532.79 per tCO_2. While theoretically efficient in Pigouvian terms, a purely price-based approach would entail significant economic, social, and political costs under current structural conditions.

The results also reflect the underlying configuration of Brazil's transport network. Road transport dominates, accounting for 64.9% of freight movements, while rail and waterway capacity remains limited and regionally uneven. Long distances between production centers and consumption markets, disparities in infrastructure quality across regions, and the concentration of industrial and agricultural production in inland areas reinforce reliance on diesel-based road transport. Inelastic fuel demand, combined with these structural factors, suggests that abrupt price interventions could have broader economic and social repercussions. Historical events, such as the 2018 truckers' strike, provide empirical evidence that sharp increases in fuel costs can disrupt logistics chains and economic activity, further emphasizing the limited feasibility of isolated price-based measures.

The model results demonstrate that diesel demand in road freight is weakly responsive to price changes. Given this inelasticity and the restricted availability of alternative transport modes, achieving effective decarbonization through carbon pricing alone is unlikely. Complementary policy instruments are therefore necessary. Regulatory measures, targeted infrastructure investments to expand rail and waterway capacity, and incentives for low-carbon technologies, including electrification and alternative fuels, can increase the responsiveness of freight demand. By facilitating modal shifts and enabling gradual adoption of low-carbon technologies, such measures support a transition toward a more efficient and sustainable transport system while mitigating the economic and social impacts associated with abrupt diesel price increases. This integrated approach provides a mechanism to translate price signals into effective emissions reductions without imposing excessive disruption on the economy.

This study contributes to the literature by providing quantitative estimates of mitigation costs under explicit assumptions, highlighting the limitations of carbon pricing in a sector characterized by inelastic demand, and identifying the conditions under which such instruments can effectively support emissions reductions. Limitations include the focus on the transport sector without capturing indirect economy-wide effects or co-benefits such as improvements in air quality, reductions in traffic accidents, or enhanced energy security. Future research could extend this analysis to account for these broader impacts, explore interactions with international supply chains, and integrate environmental and social co-benefits into mitigation assessments.

Effective decarbonization of Brazil's freight sector cannot be achieved through isolated measures. Maintaining the current trajectory would sustain high logistics costs, and reliance on carbon pricing alone would require considerable diesel price increases. A coordinated combination of price, regulatory, and structural interventions is therefore necessary to reduce emissions effectively while maintaining economic activity. Implementing such an integrated strategy provides a roadmap for a more resilient, efficient, and sustainable freight system, capable of supporting Brazil's NDC target of reducing net greenhouse gas emissions by 59.0–67.0% by 2035 relative to 2005 levels and fulfilling its international climate commitments.

4 FINAL REMARKS

This thesis examined the economic costs and challenges of the energy transition in Brazil's freight transport sector. As a contributor to national GHG emissions, accounting for nearly half of the emissions from the country's energy mix, this sector represents an area of focus for climate policy. The research objective was to provide a quantitative foundation for policymaking by examining both the long-term trajectory of freight demand and the economic feasibility of a primary mitigation instrument. This analysis was situated within the broader context of Brazil's economic growth and infrastructure.

The research was organized into two complementary essays. The first essay employed Autoregressive Distributed Lag (ARDL) models to develop a long-term forecast of freight demand through 2099 for road, rail, and air transport, identifying the main drivers of sectoral expansion. This analysis provided a baseline of future activity. The second essay used these projections to assess the economic implications of decarbonization, estimating the costs associated with the current trajectory and the potential effects of a price-based policy intervention designed to meet Brazil's nationally determined climate targets.

Projections from the first essay indicated that sustained socioeconomic growth is expected to increase freight activity across all transport modes, occurring within a system already dominated by road transport. Under a high-growth scenario (*SSP5*), road freight demand is projected to increase by up to 653.3% by 2099, while rail and air freight are expected to grow by 472.9% and 770.8%, respectively, relative to 2019 levels. These projections quantify the structural pressure on the existing network, showing that the transport system will need to accommodate higher volumes within a modal mix that exhibits limited diversity, which affects both emissions and the feasibility of mitigation policies. Furthermore, the model's projections of demand growth across all modes are premised on the continuation of the historical, road-dominated freight modal split, highlighting the high structural inertia of the Brazilian system and the reliance of future economic activity on the existing road network.

A direct environmental consequence of the projected growth in freight demand is an increase in emissions, which forms the basis for the economic assessment in the second essay. Historical RFCI, estimated at 120.7 gCO_2/TKU, indicates that emissions from road transport will rise as volumes increase. Even under a sustainable development scenario (*SSP1*), projected annual emissions remain elevated, showing that the sheer volume of new emissions from projected growth is likely to outpace the benefits of fuel substitution alone.

The second essay translated the physical demand projections into economic metrics, providing a detailed picture of the potential financial implications of maintaining Brazil's current freight transport system. Under existing structural conditions, logistics costs are projected to account for between 1.8% and 2.2% of Brazil's GDP through the end of the century. This range reflects not only the growth in freight volumes but also the inefficiencies inherent in a system dominated by road transport and heavy reliance on diesel fuel. By linking projected demand growth directly to macroeconomic outcomes, the analysis underscores the importance of evaluating the sector as an integrated system rather than focusing solely on isolated cost components. The results highlight that any policy intervention aimed at reducing emissions must account for these structural characteristics to avoid unintended economic disruptions and to design measures that are both feasible and effective in the long term.

Within this context, the second essay assessed carbon pricing as the main market-based mitigation instrument. The estimated long-run price elasticity of diesel demand, -0.610, highlights the limited responsiveness of the freight system to fuel price changes, reflecting structural rigidities in modal choice, vehicle technology, and logistics practices. Simulations targeting Brazil's 2035 NDC indicate MAC exceeding BRL 1,532.79 per ton of CO_2, illustrating the substantial reductions required if relying solely on pricing. These results suggest that carbon pricing, while important, must be complemented by structural and regulatory measures to achieve meaningful emissions reductions in a cost-effective manner.

The central contribution of this thesis emerges from the integration of its two complementary essays, which together reveal a direct causal link between the scale of projected freight demand and the economic feasibility of climate mitigation policy. The first essay's projection of a potential 653.3% increase in road freight demand by 2099 establishes immense structural pressure on a system already dominated by road transport, responsible for 64.9% of total cargo movement. This configuration creates a self-reinforcing path dependency whose consequences become clear in the second essay: the transport sector displays a low long-run price elasticity of diesel demand ($\eta \approx -0.610$), reflecting severely limited responsiveness to price signals and leading to prohibitively high Marginal Abatement Cost (MAC) values for achieving deep national climate targets solely through carbon pricing.

These findings point to a structural feedback loop in which demand growth strengthens reliance on road infrastructure, which in turn maintains low price elasticity and constrains the effectiveness of market-based climate policies. Overcoming this dynamic requires a strategy that breaks the cycle, and the thesis argues that Brazil's comparative advantage in bioenergy offers a concrete entry point. Leveraging initiatives such as RenovaBio to accelerate fuel substitution, while simultaneously pursuing large-scale investments that expand rail and waterway capacity, would increase long-run flexibility and provide the conditions necessary for a more cost-effective and resilient decarbonization pathway.

This thesis demonstrates that a strategy based exclusively on price-based instruments is unlikely to achieve significant emissions reductions in Brazil's freight sector. Such policies do not address the structural factors driving inelasticity in the transport system. Maintaining the current trajectory would sustain high logistics costs, and achieving national climate targets through pricing alone would require fuel price increases beyond feasible levels. The analysis indicates that an integrated approach combining structural, regulatory, and market-based interventions is essential. Such a coordinated strategy is fundamental to promote low-carbon transport alternatives, stimulate infrastructure and technological investments, and strengthen the sector's resilience against future economic and environmental challenges.

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Appendix A: derivation of road freight transport demand from PNLT data and the ABCR index

The Associação Brasileira de Concessionárias de Rodovias (ABCR) provides an indicator of vehicle flow on highways under private concession in Brazil. The ABCR index has become an important benchmark because it tracks economic activity at high frequency, enabling near real-time analysis. Road transport is directly linked to the movement of goods and to the activity of several sectors, including industry and retail. The methodology behind the ABCR Index uses the X-12 ARIMA procedure, a statistical method widely employed in economics for time-series treatment. This approach removes seasonal effects and noise such as holidays, leap years, and atypical fluctuations caused by specific events, allowing the underlying trend in vehicle flow to be observed.

The construction of the index involves two steps. First, a linear regression captures the average behavior of the series. Second, an ARIMA model projects the series in time and adjusts for random fluctuations, producing a smoother and more reliable seasonally adjusted index. The ABCR also applies careful methodological rules when incorporating new toll plazas or tariff changes: new plazas are included only after at least two years of data, ensuring stable seasonal pattern identification and avoiding abrupt breaks.

The National Logistics and Transport Plan (PNLT) reports that road freight transport in Brazil reached approximately 650 billion ton-kilometers (TKU) in 2011. This value represents the official and validated absolute TKU for that year and serves as a calibration point for reconstructing the historical series. To transform this annual value into a monthly TKU series, the ABCR Index was used as a proxy for fluctuations in transported volume. Since the index is expressed in relative terms (base 100), its average for 2011 was calculated as 156.74, which serves as the scaling benchmark. Monthly TKU is estimated according to:

$$TKU_t = 650 \text{ billion} \times \left(\frac{Index_t}{156.74} \right)$$

In practical terms, if the index in a given month stands 10.0% above the 2011 average, the TKU for that month is estimated to be 10.0% higher than the corresponding value for an average month of 2011. This procedure was applied retrospectively (2000-2010) and prospectively (2012-2019), producing a reconstructed annual TKU series consistent with the dynamics captured by the ABCR Index. The method combines a reliable absolute value (650 billion TKU in 2011) with a high-frequency indicator that is seasonally adjusted through X-12 ARIMA, corrects distortions such as holidays and toll changes, and shows documented correlation with relevant economic indicators.

Appendix B: Annual road freight demand

Table XVII: Appendix B – Annual road freight demand (billion TKU)

Year	*SSP1*	*SSP2*	*SSP5*
2020	663.99	642.94	668.00
2021	705.21	667.42	714.16
2022	729.90	685.21	742.49
2023	751.85	701.88	767.87
2024	773.34	718.37	792.75
2025	810.77	745.50	835.75
2026	848.28	770.39	881.32
2027	876.98	788.25	918.11
2028	904.23	804.96	953.46
2029	931.24	821.47	988.58
2030	971.61	848.76	1,039.15
2031	1,012.98	873.96	1,093.25
2032	1,047.44	892.15	1,140.55
2033	1,080.78	909.19	1,186.73
2034	1,113.92	926.04	1,232.73
2035	1,160.19	953.85	1,292.91
2036	1,206.41	980.41	1,354.42
2037	1,245.32	1,000.29	1,408.75
2038	1,283.04	1,019.07	1,461.89
2039	1,320.56	1,037.67	1,514.84
2040	1,369.61	1,066.91	1,580.29
2041	1,417.52	1,094.68	1,645.90
2042	1,458.46	1,115.83	1,704.67
2043	1,498.27	1,135.90	1,762.31
2044	1,537.88	1,155.78	1,819.77
2045	1,589.12	1,187.37	1,889.63
2046	1,637.99	1,217.07	1,958.23
2047	1,679.25	1,239.36	2,019.33
2048	1,719.25	1,260.42	2,079.20
2049	1,759.05	1,281.28	2,138.86
2050	1,809.29	1,314.60	2,209.81
2051	1,857.36	1,346.38	2,279.74

Continued on next page

Table XVII – *Continued from previous page*

Year	*SSP1*	*SSP2*	*SSP5*
2052	1,898.55	1,370.48	2,342.93
2053	1,938.61	1,393.32	2,405.00
2054	1,978.48	1,415.96	2,466.89
2055	2,027.79	1,448.12	2,539.03
2056	2,074.62	1,479.10	2,609.83
2057	2,114.99	1,504.23	2,674.29
2058	2,154.29	1,528.39	2,737.71
2059	2,193.42	1,552.39	2,800.95
2060	2,239.69	1,584.71	2,871.63
2061	2,282.55	1,615.51	2,939.71
2062	2,319.77	1,640.93	3,002.36
2063	2,356.05	1,665.47	3,064.13
2064	2,392.18	1,689.87	3,125.75
2065	2,433.96	1,721.62	3,193.09
2066	2,472.38	1,752.21	3,257.63
2067	2,506.01	1,778.14	3,317.60
2068	2,538.85	1,803.31	3,376.83
2069	2,571.56	1,828.35	3,435.93
2070	2,609.62	1,860.34	3,500.66
2071	2,645.16	1,891.71	3,563.65
2072	2,676.48	1,918.93	3,622.67
2073	2,707.10	1,945.47	3,681.03
2074	2,737.61	1,971.90	3,739.28
2075	2,771.92	2,002.90	3,801.49
2076	2,803.53	2,033.02	3,861.64
2077	2,831.69	2,060.17	3,918.56
2078	2,859.28	2,086.83	3,974.95
2079	2,886.78	2,113.41	4,031.26
2080	2,917.44	2,143.10	4,090.75
2081	2,945.25	2,172.14	4,147.84
2082	2,969.89	2,199.13	4,201.98
2083	2,994.01	2,225.78	4,255.63
2084	3,018.04	2,252.37	4,309.21
2085	3,048.51	2,280.47	4,368.90
2086	3,075.27	2,308.35	4,425.00

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Table XVII – *Continued from previous page*

Year	*SSP1*	*SSP2*	*SSP5*
2087	3,096.62	2,335.28	4,475.92
2088	3,117.09	2,362.06	4,525.99
2089	3,137.41	2,388.81	4,575.91
2090	3,161.41	2,416.12	4,629.14
2091	3,182.32	2,443.57	4,679.27
2092	3,199.66	2,470.79	4,726.03
2093	3,216.42	2,497.96	4,772.23
2094	3,233.07	2,525.13	4,818.34
2095	3,250.81	2,552.33	4,864.89
2096	3,265.68	2,579.74	4,908.17
2097	3,278.51	2,607.24	4,949.58
2098	3,291.01	2,634.76	4,990.69
2099	3,303.45	2,662.28	5,031.75

Appendix C: Annual rail freight demand

Table XVIII: Appendix C – Annual rail freight demand (billion TKU)

Year	*SSP1*	*SSP2*	*SSP5*
2020	348.00	347.79	348.23
2021	361.13	360.21	362.08
2022	375.61	373.92	377.35
2023	390.51	388.05	393.04
2024	405.54	402.32	408.87
2025	420.97	416.60	425.42
2026	437.60	431.25	443.93
2027	454.79	446.37	463.10
2028	472.18	461.66	482.47
2029	489.62	477.02	501.89
2030	507.51	492.41	522.10
2031	526.85	508.32	544.53
2032	546.89	524.81	567.75
2033	567.16	541.52	591.19
2034	587.50	558.31	614.72
2035	608.13	575.20	638.72
2036	629.68	592.62	664.05
2037	651.67	610.42	689.87
2038	673.80	628.36	715.84
2039	695.98	646.35	741.85
2040	718.25	664.38	768.13
2041	740.79	682.56	795.07
2042	763.46	700.85	822.18
2043	786.17	719.18	849.34
2044	808.89	737.53	876.52
2045	831.52	755.84	903.74
2046	853.83	773.96	930.96
2047	875.97	791.93	958.07
2048	898.07	809.86	985.13
2049	920.15	827.76	1,012.17
2050	942.13	845.68	1,039.27
2051	963.79	863.53	1,066.39

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Table XVIII – *Continued from previous page*

Year	*SSP1*	*SSP2*	*SSP5*
2052	985.29	881.26	1,093.41
2053	1,006.75	898.93	1,120.38
2054	1,028.19	916.59	1,147.33
2055	1,049.46	934.25	1,174.26
2056	1,070.19	951.72	1,201.00
2057	1,090.67	968.97	1,227.52
2058	1,111.06	986.14	1,253.95
2059	1,131.42	1,003.29	1,280.36
2060	1,151.44	1,020.32	1,306.52
2061	1,170.29	1,036.75	1,331.75
2062	1,188.59	1,052.70	1,356.45
2063	1,206.71	1,068.47	1,380.97
2064	1,224.78	1,084.18	1,405.43
2065	1,242.45	1,099.79	1,429.58
2066	1,258.89	1,114.82	1,452.64
2067	1,274.73	1,129.34	1,475.12
2068	1,290.38	1,143.66	1,497.40
2069	1,305.97	1,157.93	1,519.63
2070	1,321.29	1,172.18	1,541.68
2071	1,335.75	1,186.14	1,563.10
2072	1,349.79	1,199.77	1,584.14
2073	1,363.71	1,213.27	1,605.04
2074	1,377.58	1,226.72	1,625.90
2075	1,391.13	1,240.08	1,646.52
2076	1,403.62	1,252.91	1,666.26
2077	1,415.61	1,265.30	1,685.51
2078	1,427.43	1,277.52	1,704.60
2079	1,439.20	1,289.70	1,723.64
2080	1,450.61	1,301.77	1,742.37
2081	1,460.85	1,313.25	1,760.06
2082	1,470.52	1,324.25	1,777.19
2083	1,480.01	1,335.07	1,794.14
2084	1,489.44	1,345.83	1,811.04
2085	1,498.45	1,356.50	1,827.52
2086	1,506.10	1,366.55	1,842.65

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Table XVIII – *Continued from previous page*

Year	*SSP1*	*SSP2*	*SSP5*
2087	1,513.10	1,376.04	1,857.14
2088	1,519.88	1,385.33	1,871.41
2089	1,526.60	1,394.55	1,885.62
2090	1,532.93	1,403.70	1,899.43
2091	1,538.00	1,412.35	1,911.96
2092	1,542.48	1,420.49	1,923.90
2093	1,546.76	1,428.45	1,935.64
2094	1,550.98	1,436.34	1,947.32
2095	1,554.79	1,444.16	1,958.53
2096	1,557.26	1,451.44	1,968.27
2097	1,559.10	1,458.18	1,977.36
2098	1,560.72	1,464.72	1,986.25
2099	1,562.28	1,471.19	1,995.06

Appendix D: Annual air freight demand

Table XIX: Appendix D – Annual air freight demand (million TKU)

Year	*SSP1*	*SSP2*	*SSP5*
2020	966.91	942.96	964.32
2021	1,021.93	990.39	1,025.22
2022	1,075.35	1,038.90	1,085.06
2023	1,128.76	1,087.42	1,144.90
2024	1,182.18	1,135.93	1,204.74
2025	1,254.61	1,196.40	1,289.59
2026	1,318.47	1,244.78	1,369.38
2027	1,378.98	1,290.28	1,445.47
2028	1,439.49	1,335.79	1,521.57
2029	1,499.99	1,381.29	1,597.66
2030	1,576.70	1,438.94	1,695.82
2031	1,648.84	1,484.89	1,793.09
2032	1,718.43	1,527.99	1,887.51
2033	1,788.01	1,571.09	1,981.92
2034	1,857.60	1,614.18	2,076.33
2035	1,942.76	1,669.92	2,190.31
2036	2,020.55	1,716.19	2,298.26
2037	2,095.55	1,759.81	2,403.07
2038	2,170.55	1,803.44	2,507.89
2039	2,245.55	1,847.06	2,612.70
2040	2,333.90	1,902.86	2,735.19
2041	2,412.73	1,948.77	2,848.94
2042	2,488.81	1,992.03	2,959.49
2043	2,564.90	2,035.30	3,070.03
2044	2,640.98	2,078.56	3,180.58
2045	2,730.14	2,135.13	3,307.81
2046	2,806.35	2,180.05	3,422.76
2047	2,879.45	2,221.97	3,534.23
2048	2,952.55	2,263.90	3,645.70
2049	3,025.65	2,305.82	3,757.17
2050	3,110.49	2,362.08	3,883.36
2051	3,183.56	2,407.19	3,999.20

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Table XIX – *Continued from previous page*

Year	*SSP1*	*SSP2*	*SSP5*
2052	3,253.81	2,449.25	4,112.02
2053	3,324.07	2,491.31	4,224.84
2054	3,394.33	2,533.37	4,337.67
2055	3,475.03	2,586.39	4,463.22
2056	3,543.67	2,630.93	4,578.64
2057	3,609.64	2,673.14	4,691.31
2058	3,675.61	2,715.34	4,803.98
2059	3,741.58	2,757.54	4,916.65
2060	3,814.97	2,809.16	5,038.76
2061	3,875.03	2,851.98	5,148.39
2062	3,932.63	2,892.61	5,255.43
2063	3,990.24	2,933.25	5,362.46
2064	4,047.85	2,973.88	5,469.49
2065	4,111.12	3,022.90	5,583.61
2066	4,162.02	3,064.66	5,685.87
2067	4,210.81	3,104.54	5,785.90
2068	4,259.60	3,144.42	5,885.93
2069	4,308.39	3,184.30	5,985.95
2070	4,362.75	3,232.25	6,092.87
2071	4,407.19	3,274.67	6,191.28
2072	4,449.81	3,315.47	6,287.86
2073	4,492.43	3,356.26	6,384.44
2074	4,535.04	3,397.05	6,481.02
2075	4,581.34	3,443.02	6,581.33
2076	4,618.08	3,484.03	6,674.02
2077	4,653.26	3,523.84	6,765.39
2078	4,688.45	3,563.64	6,856.76
2079	4,723.64	3,603.45	6,948.13
2080	4,761.70	3,646.76	7,040.64
2081	4,790.14	3,686.54	7,126.36
2082	4,817.12	3,725.49	7,211.17
2083	4,844.11	3,764.44	7,295.98
2084	4,871.09	3,803.39	7,380.79
2085	4,904.55	3,844.07	7,463.35
2086	4,924.22	3,883.30	7,539.59

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Table XIX – *Continued from previous page*

Year	*SSP1*	*SSP2*	*SSP5*
2087	4,941.51	3,922.16	7,615.40
2088	4,958.80	3,961.02	7,691.20
2089	4,976.09	3,999.87	7,767.00
2090	4,996.80	4,039.45	7,838.94
2091	5,006.96	4,079.11	7,906.21
2092	5,015.50	4,118.69	7,973.42
2093	5,024.03	4,158.27	8,040.64
2094	5,032.57	4,197.85	8,107.86
2095	5,041.50	4,237.54	8,169.52
2096	5,041.89	4,277.80	8,226.14
2097	5,041.26	4,318.11	8,282.89
2098	5,040.63	4,358.42	8,339.65
2099	5,040.00	4,398.73	8,396.40

Appendix E: Transport cost as % of GDP

Table XX: Appendix E – Transport cost as % of GDP, by year, for *SSP1*, *SSP2*, and *SSP5*

Year	*SSP1*	*SSP2*	*SSP5*
2020	1.89%	1.82%	1.89%
2021	1.92%	1.83%	1.93%
2022	1.92%	1.82%	1.93%
2023	1.91%	1.80%	1.92%
2024	1.90%	1.79%	1.91%
2025	1.92%	1.80%	1.93%
2026	1.93%	1.81%	1.94%
2027	1.93%	1.81%	1.94%
2028	1.92%	1.80%	1.93%
2029	1.91%	1.79%	1.92%
2030	1.93%	1.81%	1.94%
2031	1.94%	1.82%	1.95%
2032	1.94%	1.82%	1.94%
2033	1.93%	1.81%	1.93%
2034	1.93%	1.81%	1.93%
2035	1.94%	1.82%	1.94%
2036	1.95%	1.84%	1.95%
2037	1.95%	1.84%	1.94%
2038	1.95%	1.83%	1.94%
2039	1.95%	1.83%	1.94%
2040	1.96%	1.85%	1.95%
2041	1.97%	1.86%	1.95%
2042	1.97%	1.86%	1.95%
2043	1.96%	1.86%	1.95%
2044	1.96%	1.86%	1.94%
2045	1.97%	1.88%	1.95%
2046	1.98%	1.89%	1.96%
2047	1.98%	1.89%	1.96%
2048	1.98%	1.89%	1.96%
2049	1.98%	1.89%	1.95%
2050	1.99%	1.91%	1.96%

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Table XX – *Continued from previous page*

Year	*SSP1*	*SSP2*	*SSP5*
2051	2.00%	1.92%	1.97%
2052	2.00%	1.93%	1.97%
2053	2.00%	1.93%	1.96%
2054	2.00%	1.93%	1.96%
2055	2.01%	1.94%	1.97%
2056	2.02%	1.95%	1.97%
2057	2.02%	1.95%	1.97%
2058	2.02%	1.96%	1.97%
2059	2.02%	1.96%	1.97%
2060	2.03%	1.97%	1.98%
2061	2.04%	1.98%	1.98%
2062	2.04%	1.98%	1.98%
2063	2.04%	1.98%	1.98%
2064	2.04%	1.99%	1.98%
2065	2.05%	2.00%	1.98%
2066	2.06%	2.00%	1.99%
2067	2.06%	2.01%	1.99%
2068	2.06%	2.01%	1.99%
2069	2.06%	2.01%	1.99%
2070	2.07%	2.02%	1.99%
2071	2.08%	2.03%	1.99%
2072	2.08%	2.03%	1.99%
2073	2.08%	2.03%	1.99%
2074	2.08%	2.03%	2.00%
2075	2.09%	2.04%	2.00%
2076	2.10%	2.04%	2.00%
2077	2.10%	2.05%	2.00%
2078	2.10%	2.05%	2.00%
2079	2.11%	2.05%	2.00%
2080	2.11%	2.05%	2.00%
2081	2.12%	2.06%	2.01%
2082	2.12%	2.06%	2.01%
2083	2.12%	2.06%	2.01%
2084	2.13%	2.06%	2.01%
2085	2.13%	2.07%	2.01%

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Table XX – *Continued from previous page*

Year	*SSP1*	*SSP2*	*SSP5*
2086	2.14%	2.07%	2.02%
2087	2.15%	2.07%	2.02%
2088	2.15%	2.07%	2.02%
2089	2.16%	2.07%	2.02%
2090	2.16%	2.08%	2.02%
2091	2.17%	2.08%	2.02%
2092	2.18%	2.08%	2.03%
2093	2.18%	2.08%	2.03%
2094	2.19%	2.08%	2.03%
2095	2.19%	2.08%	2.03%
2096	2.20%	2.08%	2.03%
2097	2.20%	2.08%	2.03%
2098	2.21%	2.08%	2.04%
2099	2.22%	2.08%	2.04%

Appendix F: Transport Cost as a Share of GDP in 2035 Under Carbon Pricing

This appendix details the calculation of the total cost of freight transport as a share of GDP for the year 2035 under the *SSP2* scenario, incorporating the economic impact of carbon pricing required to meet Brazil's Nationally Determined Contribution (NDC) targets. The methodology follows the framework presented in Chapter 3, which accounts for the price elasticity of diesel demand, providing a more accurate measure than a simple additive cost model.

Step 1: Baseline Data for 2035 (*SSP2* Scenario)

The analysis starts with the baseline projections for freight demand, modal costs, and GDP, which represent a "business-as-usual" trajectory without carbon pricing.

Table XXI: Appendix F – Projected demand and cost factors for 2035 (*SSP2*)

Transport mode	Projected Demand (billion TKU)	Cost Factor (BRL$/TKU)
Road	953.85	0.074
Rail	575.20	0.017
Air	1.67	0.531

Source: Own Elaboration. Air transport demand corresponds to 1,669.92 million TKU.

1.1. Calculate Baseline Logistics Cost: The total baseline logistics cost is the sum of the costs for each mode:

$$(953.85 \times 0.074) + (575.20 \times 0.017) + (1.67 \times 0.531) = 81.25 \text{ billion BRL}$$

1.2. Baseline GDP and Cost Share:

- Projected GDP for 2035 (*SSP2*): **BRL 4,479 billion**.
- Baseline Logistics Cost as a Share of GDP:

$$\frac{81.25}{4,479} \times 100 = \mathbf{1.82\%} \textbf{ of GDP}$$

Step 2: Define Parameters for the Carbon Pricing Scenario

The following parameters from Chapter 3 are used:

- **Long-run price elasticity of diesel demand (η):** -0.610.
- **NDC reduction targets for 2035 (vs. 2005 levels):** 59.0% and 67.0%.

Step 3: Calculate Adjusted Transport Cost as a Share of GDP

This step applies the methodology from Chapter 3 (footnote 54) to calculate the final economic cost to the sector, accounting for the reduction in fuel consumption due to higher prices. The formula is:

$$\text{Adjusted Cost (\% of GDP)} = \text{Baseline Cost (\% of GDP)} \times (1 + \%\Delta P) \times (1 + \%\Delta Q)$$

where $\%\Delta Q$ is the percentage reduction in diesel demand (assumed equal to the NDC target) and $\%\Delta P$ is the required percentage price increase ($\%\Delta Q/\eta$).

Scenario 1: 59.0% NDC Target

- Required reduction in quantity ($\%\Delta Q$): -59.0% or -0.59.
- Required increase in price ($\%\Delta P$): $(-0.59)/(-0.610) = 96.72\%$ or +0.9672.
- Adjusted Cost as a Share of GDP:

  $1.82\% \times (1 + 0.9672) \times (1 - 0.59) = 1.82\% \times 1.9672 \times 0.41 = \mathbf{1.47\%}$ **of GDP**

Scenario 2: 67.0% NDC Target

- Required reduction in quantity ($\%\Delta Q$): -67.0% or -0.67.
- Required increase in price ($\%\Delta P$): $(-0.67)/(-0.610) = 109.84\%$ or +1.0984.
- Adjusted Cost as a Share of GDP:

  $1.82\% \times (1 + 1.0984) \times (1 - 0.67) = 1.82\% \times 2.0984 \times 0.33 = \mathbf{1.26\%}$ **of GDP**

As shown, when accounting for the price elasticity of demand, the total expenditure of the freight sector as a share of GDP is lower than the baseline cost. This occurs because the significant reduction in fuel consumption partially offsets the higher per-unit cost of diesel.