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LUIS GUILHERME LARIZZATTI ZACHARIAS

RETHINKING THE BRAZILIAN TRANSPORT SECTOR: HISTORICAL LESSONS LEARNED AND SUPPORT PATHS FOR THE ENERGY TRANSITION

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Prof. Dr. ____

Institution: ____

Judgment: ____

Prof. Dr. ____

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Prof. Dr. ____

Institution: ____

Judgment: ____

Prof. Dr. ____

Institution: ____

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ABSTRACT

ZACHARIAS, L. G. L. **Rethinking the Brazilian transport sector: historical lessons learned and support paths for the energy transition**. 2022. 60p. M.Sc. Dissertation (M.Sc. in Environmental Science) – Graduate Program on Environmental Science, University of São Paulo, São Paulo, 2022.

The transport sector is Brazil's largest energy consumer and is responsible for a large part of Brazil's greenhouse gas emissions and air pollution. Therefore, Brazil must establish strategies and pathways for a low-carbon transition. In this context, the central aim of this research is to contribute with a historical analysis of the transport and fuel system in the face of the problems addressed above, seeking to understand how the dynamics of fuel transitions occurred in the history of Brazil. The first covers a historical approach to the events and facts that marked the evolution of transport in Brazil. The second covers a technical-economic analysis of the evolution of natural gas vehicle technology in two Brazilian states. Both perspectives are based on three essential aspects for the prosperity of an energy transition: technology, domestic fuel, and infrastructure. This research seeks to answer the following general research question: "What can we learn from the history of the Brazilian transport sector, rethinking new paths for a low carbon energy transition?" This work is divided into two articles. The first article seeks to review the history of the Brazilian transport sector, identifying the events that marked the evolution of the sector within the fields of technology, domestic fuel, and infrastructure. The second article aims to analyze the adoption and development of vehicles powered by natural gas at the state level (Rio de Janeiro and São Paulo) through seven performance parameters for vehicle adoption. As a result of the first paper, some lessons can be learned: (i) the formation of the Brazilian transport sector is mainly marked by the alliance between the bourgeoisie, the government, and foreign companies; (ii) the availability of natural resources (sugarcane) and the pressure from the sugar sector were decisive for the evolution and innovation of the transport sector throughout history; (iii) dependence on imported fuel and foreign technology and the late industrialization and discovery of oil determined the evolution of the sector (bottleneck); (iv) the predominance of roads over other modes occurred with the construction of the public perception of the modernism of automobiles and was pressured by foreign investments in the formation of an automobile consumer market. As a result of the second paper, it was found that state market incentives are fundamental for the continuous development of alternative fuels such as natural gas to the already established liquid fuels in the country. In Rio de Janeiro, the advantages obtained through tax incentives to compressed natural gas and motor vehicle property taxes are crucial to decrease payback time and strengthen the price of natural gas. Otherwise, in the state of São Paulo, the lowest state value-added tax levied on hydrated ethanol and, consequently, the smallest price difference between fuels hinders the development of the compressed natural gas market. Finally, the results extracted from the two articles are discussed, summarizing the main lessons that can be learned and prospected in the Brazilian transport sector for a more sustainable and low carbon transition.

Keywords: Energy transition, Technology, Fuels, Infrastructure, Transport Sector, Brazil.

RESUMO

ZACHARIAS, L. G. L. **Repensando o setor de transporte brasileiro: lições históricas aprendidas e caminhos de suporte para a transição energética.** 2022. 60p. Dissertação de Mestrado (Mestrado em Ciência Ambiental) – Programa de Pós-Graduação em Ciência Ambiental, Universidade de São Paulo, São Paulo, 2022.

O setor de transportes é o maior consumidor de energia do Brasil e é responsável por grande parte das emissões brasileiras de gases de efeito estufa e poluição do ar. Portanto, o Brasil deve estabelecer estratégias e caminhos para uma transição de baixo carbono. Nesse contexto, o objetivo central desta pesquisa é contribuir com uma análise histórica do sistema de transportes e combustíveis diante dos problemas abordados acima, buscando compreender como ocorreu a dinâmica das transições de combustíveis na história do Brasil A primeira abrange uma abordagem histórica dos acontecimentos e fatos que marcaram a evolução do transporte no Brasil. A segunda aborda uma análise técnico-econômica da evolução da tecnologia veicular a gás natural em dois estados brasileiros. Ambas as perspectivas se baseiam em três aspectos essenciais para a prosperidade de uma transição energética: tecnologia, combustível doméstico e infraestrutura. Esta pesquisa busca responder à seguinte questão geral de pesquisa: "O que podemos aprender com a história do setor de transporte brasileiro, repensando novos caminhos para uma transição energética de baixo carbono?" Este trabalho está dividido em dois artigos. O primeiro artigo busca rever a história do setor de transportes brasileiro, identificando os eventos que marcaram a evolução do setor nos campos de tecnologia, combustível nacional e infraestrutura. O segundo artigo tem como objetivo analisar a adoção e desenvolvimento de veículos movidos a gás natural em nível estadual (Rio de Janeiro e São Paulo) por meio de sete parâmetros de desempenho para adoção de veículos. Como resultado do primeiro artigo, algumas lições podem ser aprendidas: (i) a formação do setor de transporte brasileiro é marcada principalmente pela aliança entre a burguesia, o governo e empresas estrangeiras; (ii) a disponibilidade de recursos naturais (cana-de-açúcar) e a pressão do setor açucareiro foram determinantes para a evolução e inovação do setor de transportes ao longo da história; (iii) a dependência de combustíveis importados e tecnologia estrangeira e a industrialização tardia e descoberta de petróleo determinaram a evolução do setor; (iv) a predominância das rodovias sobre os demais modais ocorreu com a construção da percepção pública do modernismo dos automóveis e foi pressionada pelos investimentos estrangeiros na formação de um mercado consumidor de automóveis. Como resultado do segundo trabalho, verificou-se que os incentivos do mercado estadual são fundamentais para o desenvolvimento contínuo de combustíveis alternativos como o gás natural aos combustíveis líquidos já estabelecidos no país. No Rio de Janeiro, as vantagens obtidas por meio de incentivos fiscais ao gás natural comprimido e IPTU são fundamentais para diminuir o tempo de retorno e fortalecer o preço do gás natural. Por outro lado, no estado de São Paulo, o menor imposto estadual sobre o valor agregado do etanol hidratado e, consequentemente, a menor diferença de preço entre os combustíveis dificulta o desenvolvimento do mercado de gás natural comprimido. Por fim, são discutidos os resultados extraídos dos dois artigos, resumindo as principais lições que podem ser aprendidas e prospectadas no setor de transportes brasileiro para uma transição mais sustentável e de baixo carbono.

Palavras-chave: Transição energética, Tecnologia, Combustíveis, Infraestrutura, Setor de Transporte, Brasil.

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SUMMARY

1. INTRODUCTION

Structural transformations in energy systems (involving the production, consumption, distribution, conversion, and storage of energy and its management at all levels) must occur over the next decade to achieve a less carbon-intensive system (IEA, 2020). Accelerating the integration of transport and energy sectors has become one of the main challenges to achieving net zero. In addition, the transport sector produced approximately 7.3 billion metric tons of CO_2 (carbon dioxide) emissions in 2020, becoming the primary polluter sector globally (STATISTA, 2021).

The decarbonization of the transport sector needs urgent actions and sustainable measures. The energy transition debate focuses on drawing perspectives on which energy sources will move future vehicles. Vehicles powered by natural gas, hydrogen, and electricity are the main elements under discussion (NATIONAL RESEARCH COUNCIL, 2013). In the short term, biofuels and electric vehicles are the most promising (EPE, 2018). For this energy transition in support of the low-carbon development initiative, understanding the evolution of the transport sector at the local level is essential for a low-carbon transition.

It also is necessary to accelerate energy transitions to ensure that climate risks are minimized in time and that we do not have to face their consequences (IEA, 2020). However, there are no simple solutions to change complex energy systems or a specific sector such as transport. There is a tendency for new systems to face the *lock-in*[1] or *path dependence*[2] of existing systems, making the process even more difficult (ARAÚJO, 2014). Also, neither private markets nor government agencies seem likely to encourage a transition on their own (SOVACOOL, 2016a). The complexity of transitions to cleaner energy systems (e.g. electric, hydrogen, liquified natural gas vehicles, etc.) often requires significant changes not only in technologies, but in political regulations, tariffs, price regimes, and the behavior of users on different scales (GRUBLER, 2012a). Economic development, technological innovation, and policy change are especially important factors that shape energy transitions and that associates can better explain the energy transitions that have occurred (CHERP et al., 2018).

Given the urgency of transitions, the time scale on which energy transitions occur is a crucial debate among scholars (GRUBLER; WILSON; NEMET, 2016; SOVACOOL, 2016a).

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[1] *Path dependence* refers to inertia of prior choices constraining future pathways, based on self-reinforcing limits like sunk investment costs; increasing returns; inter-relatedness of technologies; and network effects (ARAÚJO, 2014).

[2] *Lock-in* refers to actors, institutions or technologies being locked in to the old dominant technological regime due to economies of scale and influence over the political system (CECERE et al., 2014).

Speed is argued to be intrinsically associated with the capacity of driving forces and the perceived urgency in each period (SOVACOOL, 2016a). Thus, each past transition's premises and conditions must be analyzed to characterize what led each process to be a long or rapid transition. Understanding how each of these energy transition processes occurred in history is essential to achieving future decarbonization goals, for example (ARAÚJO, 2014; GRUBLER, 2012b; SOVACOOL, 2014).

The transport sector is the largest energy consumer in Brazil and has grown consistently, especially with road transport (passengers and freight) (EPE, 2020). In 2020, the transport sector currently represents 54% of energy emissions in the country (OBSERVATÓRIO DO CLIMA, 2020). According to the projections of the Energy Research Company (EPE), it is estimated that the energy demand in this sector will grow due to the increase in the urban population (EPE, 2021). Thus, considering these associated aspects, emissions from the transport sector will tend to significantly increase if sustainable measures are not adopted, i.e., intensifying the global problem of climate change.

Based on the discussion above, the central aim of this research is to contribute with a historical analysis of the transport and fuel system in the face of the problems addressed above, seeking to understand how the dynamics of fuel transitions occurred in the history of Brazil. This research seeks to answer the following general research question: "What can we learn from the history of the Brazilian transport sector, rethinking new paths for a low carbon energy transition?". The results are expected to help in the development of policies and actions to change the current and future transport scenario, democratize access, ensure energy security, and become environmentally sustainable.

The choice of theme resulted precisely from the gap found in the literature on which pathways Brazil would seek for an energy transition in the transport sector. As much as the global transition focuses on heavy vehicles, shipping, and aviation, each country, and specifically each region in Brazil, has its particularities that need to be analyzed. In the last few years, for example, we have been facing discussions about whether natural gas would be a substitute for diesel in heavy trucks (MOUETTE et al., 2019). Recently, it started to discuss the entry of electric or hydrogen-powered trucks (KAST et al., 2018). In addition, we are still faced with rapid energy transitions typical of Brazil with the advent of flex-fuel cars (BROWN; SOVACOOL, 2011; SOVACOOL, 2016b). Or even in the development and improvement of a fuel such as alcohol (CORTEZ, 2016; GOLDEMBERG; COELHO; LUCON, 2004; MOREIRA; GOLDEMBERG, 1999). These facts make us reflect on the relevance of studying e analyzing the transport sector in Brazil towards several aspects such as infrastructure, public policies, technology, economy, among others, offer us support for this sustainable transition to occur in a fair and fast way.

The development and presentation of the research questions of this project followed an interdisciplinary approach and aligned with the themes of the graduate program. It is highlighted that the transport sector was looked at through two different lenses:

- The first covers a historical approach to the events and facts that marked the evolution of transport in Brazil between 1889-1989, concerning three aspects: technology, domestic fuel supply, and infrastructure, associated with their respective public policies;
- The second covers a technical-economic analysis of the evolution of vehicle technology in two Brazilian states.

In this way, the results of both articles complement each other, providing a more robust view of fundamental aspects that must be observed for the evolution of the transport sector. The last chapter presents some considerations that cover the results extracted from the two analyses and the research gaps.

This dissertation is the main result of the master's course held within the Graduate Program in Environmental Science at the University of São Paulo by the author. Although the Program requires the presentation of the dissertation combined with only one scientific paper published or accepted in a qualified journal, this study presents a second one deepening the research results of the first. In addition to this, the student during the period of the course produced several other publications and participated in congresses that subsidized its execution. The complete list of publications and events can be found in ***Appendix I***.

In summary, the presentation of this dissertation combines two scientific papers. The first will be submitted for publication in a journal focused on history. The second paper was accepted and published in the qualified international journal: ***Energy Policy Journal***. This dissertation consists of four main sections: this general introduction, a historical review paper, a technical-economic analysis paper, and the conclusions. Each of the papers comprises its own introduction, theoretical reference, materials and methods, results, discussion, conclusions, and references.

It is hoped that the discussions presented here can provide support for the formulation of strategies, actions, and public policies for improving international and mainly the national transport sector towards a sustainable future.

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2. RETHINKING THE BRAZILIAN TRANSPORT SECTOR THROUGH THE LENS OF TECHNOLOGY, DOMESTIC FUEL SUPPLY, AND INFRASTRUCTURE [3]

Abstract: Since the first vehicles landed in Brazilian territory in the early 20th century, transport infrastructure, vehicles, and fuels have evolved along with urban, social, economic, technological, and political growth. The decision-making of each government, policies of incentive, and economic protection were fundamental to leading the transitions of the transport sector and forming the current dependent road scenario. However, the urgency to decarbonize the current transport sector due to climate change has stimulated the search for strategies to carry out a sustainable and accelerated energy transition. In this sense, analyzing the historical process of the national evolution of the transport sector is essential to understanding the tools and mechanisms that were successfully adopted in the past to support current and future demands. This article aims to provide a historical overview, through a bibliographic review, of the evolution process of the Brazilian transport sector between 1889-1989. Three essential aspects for the adoption and development of the transport sector were analyzed: technology, domestic fuel supply, and infrastructure, associated with their respective public policies. Through historical review and analysis of primary and secondary sources, the periods were organized based on the identification and relevance of some aspects such as changes in government, global and national crises, programs, and policies adopted (milestones). As a result, an own timeline of the Brazilian transport sector was built. In addition, some lessons can be learned: (i) the formation of the Brazilian transport sector is mainly marked by the alliance between the bourgeoisie, the government, and foreign companies; (ii) the availability of natural resources (sugarcane) and the pressure from the sugar sector were decisive for the evolution and innovation of the transport sector throughout history; (iii) dependence on imported fuel and foreign technology and the late industrialization and discovery of oil determined the evolution of the sector (bottleneck); (iv) the predominance of roads over other modes occurred with the construction of the public perception of the modernism of automobiles and was pressured by foreign investments in the formation of an automobile consumer market.

Abstract: Transport Sector, Infrastructure, Technology, Domestic Fuels, Brazil.

[3] This paper will be submitted to a journal with contributions from Drielli Peyerl.

2.1. INTRODUCTION

Climate change associated with anthropogenic greenhouse gas (GHG) emissions is one of the main challenges of the global agenda to be faced today. Among the energy-intensive sectors, the transport sector has one of the highest growth rates in energy consumption and GHG emissions, mainly due to the consumption of fossil fuels (EPE, 2021). For this reason, it is one of the areas that must undergo major transformations and contribute to a low-carbon energy transition. Under the Paris Agreement, Brazil has committed, through the Nationally Determined Contribution, to reduce 37% of absolute emissions by 2025 and 43% by 2030, based on 2005 emissions (EPE, 2016). For a developing country, the commitment from Brazil is quite ambitious. Therefore, to achieve this objective, Brazil must promote actions and policies to decarbonize the transport sector. It is necessary to rethink which new technologies and fuels the country will adopt and how policies need to be designed to guarantee economic, technological, and resource independence.

Historical research plays an important role in helping contemporary energy systems or energy policies by identifying often overlooked features of energy systems(HIRSH; JONES, 2014). In particular, energy researchers and policymakers can learn a lot from historical events by analyzing and asking critical questions about their meaning and consequences (FOUQUET; PEARSON, 2012; HIRSH; JONES, 2014). For example, the rapid replacement of conventional engines with flex-fuel engines (gasoline and alcohol) in the 2000s is a reflection of the construction of the national fuel policy since the beginning of the 20th century. To understand this transition process, it is essential to understand the main driving forces, elements, and relevant dynamics of transformations in the energy transport sector throughout Brazil's history. Past experiences provide lessons, indicating which barriers and solutions can be applied in different contexts. Several studies in this field have gained valuable insights into the modification of the current energy transport system worldwide (BROWN, SOVACOOL, 2011, FOUQUET, PEARSON, 2012, GEELS, 2012, HIRSH, JONES, 2014).

In this sense, analyzing the historical events during the evolution of the Brazilian transport sector, highly dependent on roads and fossil fuels, is essential to understand all the decisions and mechanisms that were adopted in the past and that shaped the current scenario. Thus, this article aims to provide a historical overview, through a bibliographic review, of the evolution process of the Brazilian transport sector between 1889-1989. Three essential aspects for the adoption and development of the transport sector were analyzed: technology, internal fuel supply, and infrastructure, associated with their respective public policies.

2.2. MATERIAL AND METHODS

This study adopted the qualitative method through an exploratory-descriptive approach to analyze the process, development, and dynamics of the Brazilian transport sector throughout history. The historical milestones that changed the landscape of the transport sector, as well as its emergence, organization, and evolution, were presented. The main actors and/or organizations created and involved and their interests, influences, and responses to external factors are some examples researched.

A methodological framework was built, which identified three major changes that characterize the history of the transport sector in Brazil: technology, domestic fuel supply, and infrastructure, associated with their respective public policies. Through the historical review and analysis of primary and secondary sources, the periods were organized based on the identification and relevance of some aspects such as changes in government, global and national crises, programs, and policies adopted (landmarks). As a result, an own timeline of the Brazilian transport sector was built.

2.3. FIRST STEPS TOWARDS THE MODERNIZATION AND PROGRESS OF THE BRAZILIAN TRANSPORT SECTOR

Until the end of the imperial government (1822-1889), Brazil relied heavily on the agricultural sector, steam-powered railways as transportation, and wood and water to generate energy (SANTOS, 2018). At the end of the 19th century, the advent of oil, internal combustion engines, and replacing old steam engines with gasoline and diesel engines provided a new world energy scenario (PEYERL, 2019; PEYERL; FIGUEIRÔA, 2016). Then, the proclamation of the Republic (1889) brought debates in favor of modernization and progress; however, this process became slower than promised. The technology dependence and unavailability of the domestic fossil fuel supply were one of the main impediments to the development of the transport sector in the country.

At the beginning of the 20th century, cars began to be portrayed in newspapers as symbols of modernism and progress and became reality in some Brazilian cities such as Rio de Janeiro and São Paulo. Initially, the only option was to import fossil fuels to supply the newly arrived vehicles. However, the First World War (1914-1918) changed this landscape. The high price of imported fossil fuels made the Brazilian government search for new options to meet the growing demand for fuel (PEYERL, 2019).

The solution adopted was to search for alternative fuels from local natural resources. There was the first phase of debates and research on the use of alcohol and gasogene (gaseous fuel through the incomplete burning of solid substances such as mineral and vegetable coal, firewood, and even vegetable waste). In the 1910s, to produce these alternative fuels, there was a research effort focused on the use of forests as a resource. However, during this period, alcohol was only used on a small scale in trucks, tractors, and small installations with machines (MEIRA; CARELLI, 2018). On the other hand, the majority use of fossil fuels was maintained.

By the end of 1920, about 30,000 vehicles, including automobiles and trucks, had been imported (ALMEIDA, 1972). The increase in the population's interest in automobiles has led foreign auto companies in the followed years (e.g., Ford, Fiat, and General Motors) to target the Brazilian market (ALMEIDA, 1972). From that moment on, vehicle costs reduce, and the first process of assimilation of technological knowledge begins with the installation of vehicle assemblers in the country. From 1920 onwards, imports and consumption gradually increased, driven by the strong growth of the vehicle fleet, despite continued dependence on imported fuel.

If the transport sector was already highly dependent on foreign coal for the railways, it is now starting to become dependent on liquid fuels as well. The Brazilian government started to invest in research and the creation of institutes, specifically studying a solution to the problem of domestic fuel. In December 1921, for example, the Brazilian government created a specific technological institution to solve this problem the Experimental Station of Fuels and Ores (LOPES, 2019). It seeks to investigate energy resources – mainly coal and, in the second plan, oil). The Institute also hired technicians to start studies on alcohol in combustion engines (LOPES, 2019; SCHWARTZMAN; CASTRO, 1985).

As for infrastructure, as of 1910, the first sparks began to appear for the formation of a road campaign to replace the railway. In 1911, the government changed the name of the Federal Inspectorate of Railways to the Federal Inspectorate for Roads, expanding its attributions to include highways. The act determined that road inspection should be broad, involving expenses, revenues, tariffs, rents, conservation, police, security, and circulation (CAMARGO, 2019). In 1916, the consensus of support for the road modal began to strengthen with the holding of the 1st National Congress of Highways. It was the first meeting of actors interested in road construction, bringing together legislators, administrators and civil servants, engineers, technicians, contractors, business entities, and military sectors, among others (PAULA, 2010).

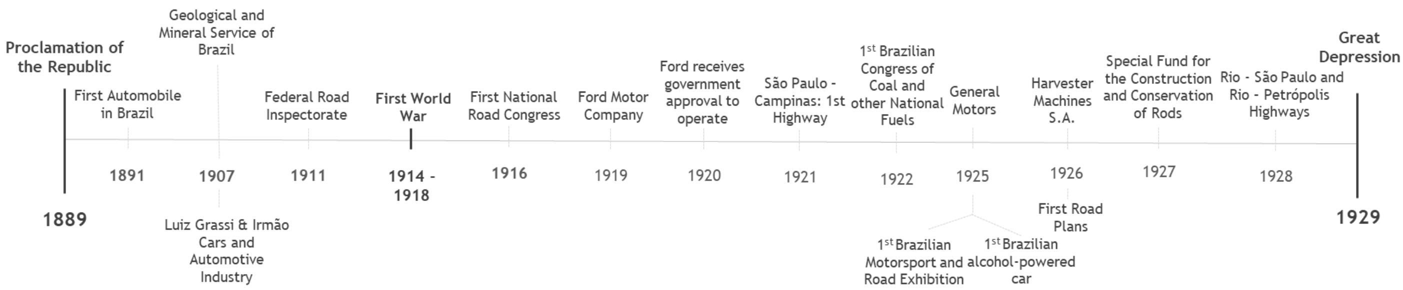
From the 1920s onwards, a more aggressive government road construction policy began. In 1926, Washington Luís took over the presidency of Brazil with the campaign slogan "*Governing is opening roads*" (PAULA, 2010). In a short time, the government invested in the construction of two of the leading Brazilian highways of the period (Rio–São Paulo and Rio–

Petropolis). In 1927, the Special Fund for the Construction and Conservation of Highways was created, receiving the additional tax on imported fuels and vehicles (PAULA, 2010). While the development of roads ensured the necessary infrastructure to increase the demand for vehicles, in 1930, the country reached the mark of 250,000 vehicles with a consumption of approximately 400,000 m³ of gasoline (ALMEIDA, 1972; IBGE, 1990).

In the technological field, more efficient engines than Otto engines appeared, and the production of diesel-powered vehicles began with French and German manufacturers. Then, the country starts to import this type of vehicle and its diesel oil. These technological advances shaped the future of the transport sector and the type of fuel used in the world.

Figure 1 shows the main events during the period 1889 and 1929. It was marked by importing vehicles and fuels and establishing the first local national and foreign enterprises related to the transport sector. In addition, the Brazilian government adopts a permissive stance, allowing foreign investments in the country. Despite this, driven by the First World War, the government created the first initiatives aimed at the search for new energy resources and national engine technologies. As an infrastructure, the government gradually builds the mentality of using highways, encouraging and financing the construction of the first roads.

Figure 1 – Timeline: landmarks that shaped the Brazilian transport sector between 1889-1929



Source: Elaborated by the authors.

In sum, this period of a global energy transition from coal to oil, including in the transport sector, awakened the country to research in oil, alternative fuels, and the shift from rail to road. The period also shows that the modernization and progress of the sector are related to international technological development and dependence on it. However, the problem of the domestic supply of fossil fuels persisted throughout history due to barriers mentioned in this section, such as the poor quality of coal and the late discovery of oil in the territory.

2.4. THE INSTITUTIONAL ORGANIZATION OF THE BRAZILIAN TRANSPORT SECTOR

In 1929, the Great Depression held back the growth of the Brazilian automobile market for about ten years. Although importing new vehicles has significantly weakened, this period was essential for developing the parts industry and repair shops in Brazil (ALMEIDA, 1972).

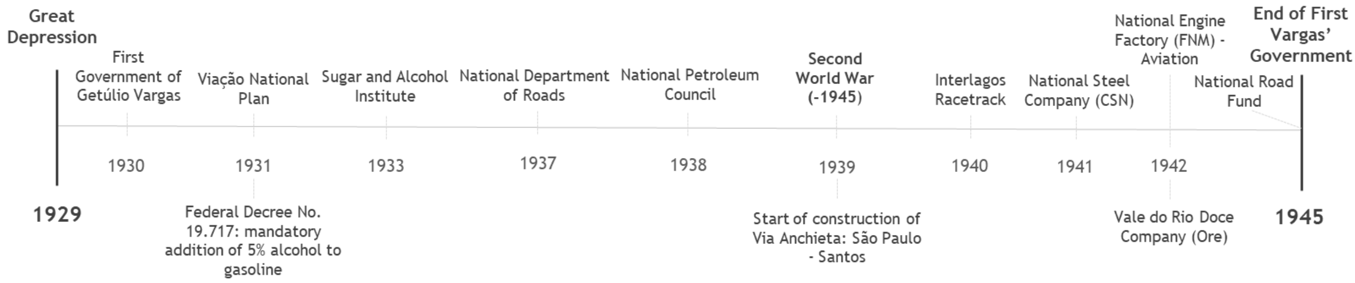
The 1930s began with a policy to encourage industrialization, mainly with basic industry. In the transport sector, the Vargas government (1930-1945) impulsed expanding the road network. However, the undiscovered oil in the national territory motivated the government to invest in refineries in the first years of 1930, which generated resources to search for oil (PEYERL, 2019, 2021).

Moreover, during the first Vargas government, alternative fuels received greater attention and investment. Important distilleries were set up, and experiments were carried out using alcohol and biomass as fuels. Inserted in the negative conjuncture caused by the depression of 1929, the sugar sector entered a crisis caused by the low prices of the external sugar market. Thus, the alcohol aspiration was resumed as the solution to the crisis of overproduction in the sugar sector allied to using alcohol as an alternative to the energy sector. The government began to support this view directly and, in 1931, implemented the mandatory blending of 5% alcohol in all imported gasoline. However, government intervention intensified even more with the creation of the Sugar and Alcohol Institute (IAA) in 1933. The objective was to centralize the commitments in an attempt to recover the golden times of the Brazilian sugar industry, transforming sugar into the main production base of alternative fuels (MEIRA; CARELLI, 2018). The IAA would play a fundamental role in technological innovation, production, the adaptation of vehicles to increase consumption, and mainly, in the policies to regulate the mandatory use of mixtures with alcohol.

During this period, the first official national project for the transport sector was created, the Viação National Plan of 1931. It recognized the importance of rail, sea, and river modes due to their low cost over long distances and highlighted the importance of improving road traffic conditions. Although the campaign in favor of the roads had existed since the mid-1910s, this document still gave primacy to the railroad(PAULA, 2010). Nonetheless, the government already understood that the Federal Roads Inspectorate (created in 1911, when transport was mostly rail) no longer met the new requirements of the transport area and, therefore, in 1937, the National Department of Roads was created (DNER). Through the availability of resources from the Special Road Fund (created in 1927), the DNER reorganized road plans by executing an entire road expansion program (PAULA, 2010).

From 1930 until 1945, the government invested in the creation of several state-owned companies such as National Steel Company (CSN), National Engine Factory (FNM), Vale do Rio Doce Company (ore). These companies were essential for the structuring of Brazilian industrialization, supplying raw materials. According to Almeida (1972), it was in the 1940s that the first national automotive parts began to be produced with national raw materials, thus forming the basis of national industry. The timeline of Figure 2 shows the leading investment in structuring the transport sector through an institutional organization.

Figure 2 – Timeline: landmarks that shaped the Brazilian transport sector between 1929-1945



Source: Elaborated by the authors.

In summary, the period 1929-1945 corresponds to the creation of the first nationalist governmental strategies in the face of external adversities in the transport sector. The government adopted a nationalist stance, creating the first regulations and institutes, seeking to protect, supervise and regulate the use of national resources, both in the sugar-alcohol sector and in the oil sector. In addition, the government created state-owned companies that supplied raw materials.

2.5. FOSTERING THE NATIONALIZATION OF THE TRANSPORT SECTOR

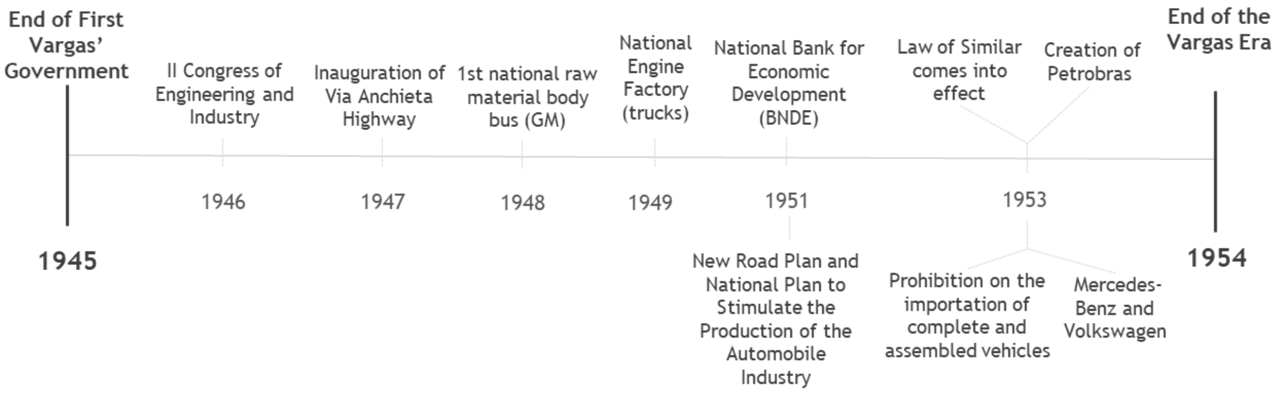
From mid-1945, the first results of the nationalization project emerged: the inauguration of the Anchieta Highway that connects the port of Santos to the city of São Paulo and the beginning of the use of Brazilian raw materials for the construction of buses. In 1949, the state-owned National Engine Factory, which produces engines for the aviation sector, began producing truck engines.

In the second government (1951-1954) of president Getúlio Vargas, the government strengthened the desire to establish a national automobile industry, creating the Industrial Development Commission, the Jeeps, Tractors, Trucks and Automobiles Subcommittee, and the Executive Commission for the Automotive Material Industry. During this period, the parts industry was also strengthened since the Similar Law, enacted in 1953, prevented similar parts produced in Brazil from being imported. This policy was also essential for foreign companies to be forced to produce automobile parts in the national territory if they wished to participate in the Brazilian parts market. Vargas' government desire for the national automobile industry was created, impregnated with concepts of modernity, speed, and comfort associated with the use of petroleum products and with the ideas of nationalism, representing the possibility of becoming an industrialized and modern nation (OTOYA, 2018).

In the mid-1940s, about 90% of the oil that the country used was imported from the US. This dependence worsened during and after the Second World War (1939-1945) since the country suffered from cuts in imports of oil products from the US. Thus, state support would mark the period for advancing and stimulating alternative energy projects such as gasogene. In 1939, the National Gasogene Commission was created in the Ministry of Agriculture. It was a direct reaction to the high import of foreign fossil fuels. This commission soon established that every owner with more than ten vehicles would have to own one gasogene vehicle, per group of ten (MEIRA; CARELLI, 2018). At that time, the government made real propaganda of alternative fuels in several newspapers of great circulation. Unfortunately, the gasogene resulted in a loss of up to 50% of the engine's efficiency. In addition, the loss of incentives for gasogene with the end of the Second World War would end up making its development unfeasible (MEIRA; CARELLI, 2018). Later, in 1941, the National Commission of Fuels and Lubricants was created. Through it, the alcohol industry received new support with the increase to 20% of the addition of alcohol to gasoline.

The scarcity of funding and policies aimed at railway construction accentuated the deterioration of the railway park in the 1940s. In addition, the road construction policy was strengthened, and widely publicized as a guarantor of faster financial returns and cheaper infrastructure. Besides, the road construction intensified, with roads being built parallel to the train tracks. Due to the new road mentality of the time, it was widely publicized as a guarantee of faster financial returns and cheaper infrastructure. Fostering this new perspective, in December 1945, the National Highway Fund was created with resources from the taxation of fuels and lubricants. Figure 3 presents the timeline with the first results of nationalization and the first strategies and policies for import substitution.

Figure 3 – Timeline: landmarks that shaped the Brazilian transport sector between 1945-1954



Source: Elaborated by the authors.

The period from 1945 to 1954 is characterized by the process of substituting imports by supporting national industry. It was the first effective process of reducing external dependence. If we were not successful with using new technologies and fuels such as gasogene, at least we advanced in the project to develop an oil industry with the creation of Petrobras in 1953. Meanwhile, the rise of the bourgeoisie and its road contractors established dominance ahead of the construction of Brazilian roads. The foundations for the effective industrialization of the country were being formed, albeit slowly. On the other hand, a nationalist feeling begins to take shape.

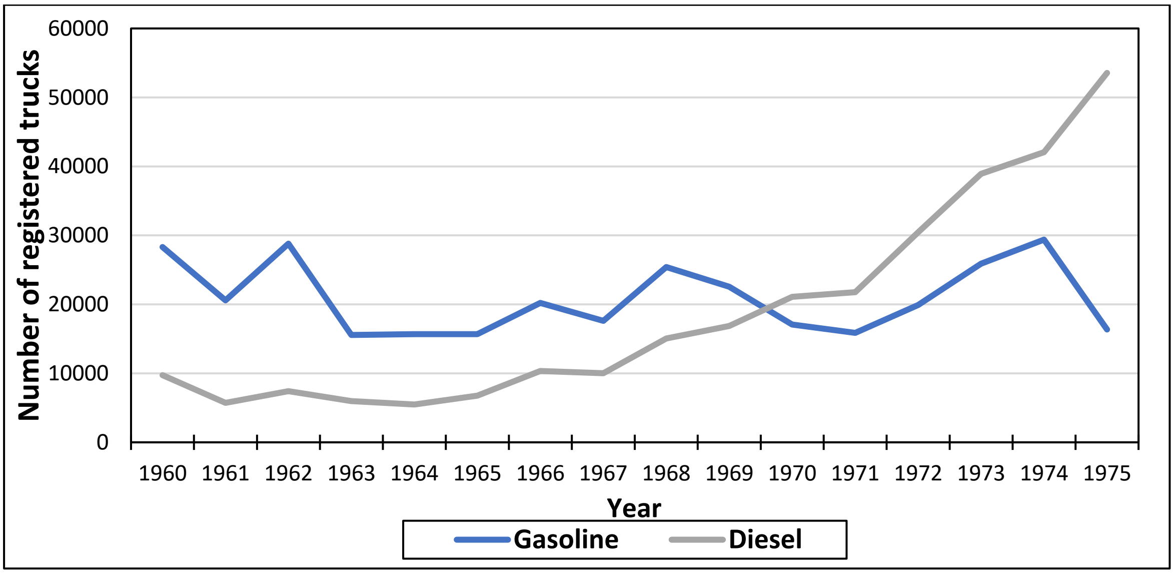
2.6. THE DEPLOYMENT OF THE AUTOMOBILE INDUSTRY TO THE STRUCTURE OF THE TRANSPORT SECTOR

In the 1950s, the automobile industry was established effectively. The market and industries expanded, guided by several policies enforced by the government. The government of Juscelino Kubitschek (1956-1961) created a robust strategic plan for developing the national economy, the so-called Plano de Metas. This plan aimed at a national industrial structure, favoring durable consumer goods. The energy production capacity, the development of the oil sector, and the transport infrastructure were privileged, including the integration of the road system between the Brazilian states (VARGAS, 1994). During this period, the national industry was strongly supported by the national capital and state-owned companies. The penetration of foreign capital occurred expressively, permeating the entire national industry, especially the automobile industry. The JK government had a decisive influence in encouraging investments that ended up attracting several automakers to the country.

In 1956, through Decree No. 39,412, a set of directives was established to create the Brazilian Automobile Industry. The Executive Group of the Automobile Industry (GEIA) was also created, whose main objective was to support the implementation of this sector. This executing agency elaborated, examined, supervised, recommended, and promoted projects and actions that encouraged national production. The government defined the production goals and the degree of nationalization that the factories needed to have. It was by Instruction 113 of the Superintendence of Currency and Credit (SUMOC), which allowed the importation of capital goods at the "free" exchange rate by foreign investors. This instruction granted a series of economic, exchange, tax, and credit incentives, encouraging foreign investments in the automotive sector. Finally, through the availability of government funding, it was possible to create a structure in which it was favorable and beneficial to produce vehicles in Brazil. Five years after the installation of the automobile industry in Brazil, it produced 393,352 vehicles and surpassed the production of highly industrialized first-world countries, such as Sweden (ELIAS; TELLES, 2015; LATINI, 2007). However, between 1964 and 1967, the establishment of the Brazilian automobile industry retracted. The annual growth of the industry was reduced compared to the expansion period, and prices in the automotive industry rose beyond the inflationary process.

During this period, the attention was focused on oil rather than alcohol. With the creation of Petrobras and the introduction of the automobile industry in the 1950s, it was thought that the country would quickly achieve self-sufficiency in oil and that it could create an economic development model based on the production of light and heavy vehicles using oil derivatives. Between 1956 and 1960, the Brazilian oil industry had indeed grown. The investment in refineries had made part of this scenario, mainly because of the increased use of derivates from fossil fuels such as diesel. After 1955, diesel started to be used in heavy vehicles as the primary fuel (SMITH, 1978). The technological and efficiency improvement of diesel engines boosted the replacement of gasoline trucks. For this reason, in 1964, Brazil stopped exporting diesel to other countries. Figure 4 shows a rapid energy transition process in the country when, in 1970, diesel-powered trucks surpassed gasoline in sales.

Figure 4 – Number of registered trucks in Brazil (1960-1974)

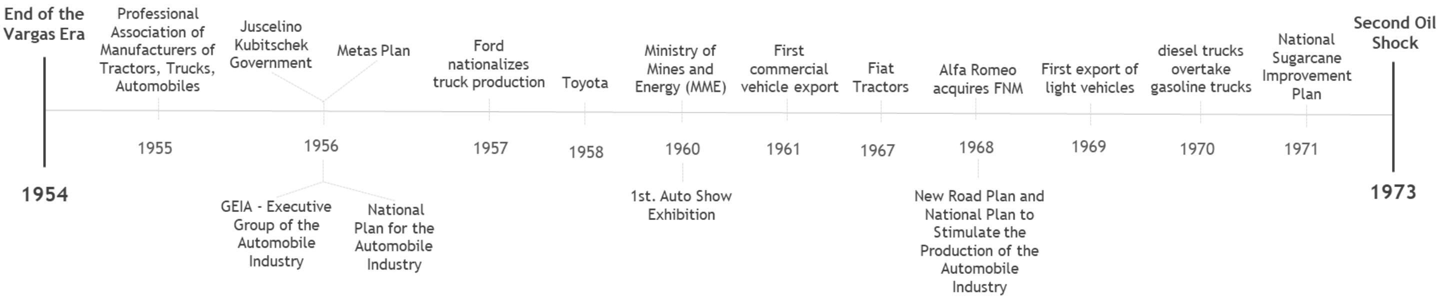


Source: Elaborated by the authors from (ANFAVEA, 2020).

Despite little progress for fuel alcohol, in 1971, the National Sugarcane Improvement Plan (Planalsucar) was created, an agency linked to the IAA, whose objective was to increase the sugarcane industry's productivity in the country (CORTEZ, 2016). It was an important initiative so that in the following decade, we could support the production of alcohol on a large scale.

The period marks the end of the use of railways as a means of transporting passengers and the hegemony of road transport. Although already with structural problems, there was an increase in the extension of the railway lines until the 1960s. However, since then, the retraction began with negative growth, reflecting the extinction of railway lines (PAULA, 2010). Thus, the government continued the road project and the resources invested prioritized expanding road infrastructure (PEREIRA; LESSA, 2010). In addition, the road plan had to be renewed, as the move from the capital from Rio de Janeiro to Brasília led to the creation of new roads from the new capital in all regions of the country. From 1955 to 1961, federal and state highways grew by 48%, and the paved network more than quadrupled (ELIAS; TELLES, 2015; LATINI, 2007). The aspirations for the development of the automobile industry were increasingly aligned with the construction of roads. The 1968 road plan was designed during this period to foster the necessary infrastructure to achieve the targets of national automotive industrialization. Figure 5 depicts in more detail the events that made up the evolution of the transport sector in the period.

Figure 5 – Timeline: landmarks that shaped the Brazilian transport sector between 1954-1973



Source: Elaborated by the authors.

2.7. THE PHENOMENON OF ALCOHOL

In 1973, with the second oil shock, the oil embargo by member countries of the Organization of Petroleum Exporting Countries (OPEC), raised the prices of a barrel of oil exponentially. At that time, about 80% of the oil consumed was imported. Thus, high prices became a major problem for the country's development (CORTEZ, 2016). At the same time, the sugar sector was experiencing difficult times. The price of sugar on the international market was falling rapidly, and it became advantageous to switch from sugar to ethanol production (MOREIRA; GOLDEMBERG, 1999). In this context, the Brazilian government decided to encourage the production of alcohol to solve the problem of fluctuating sugar prices on the international market and replace gasoline, reducing oil imports. Thus, on November 14, 1975, through Decree n. 76,593, the Brazilian government created the National Alcohol Program (Proálcool). Through Proálcool, the Brazilian government hoped that the development of alcohol would insulate the economy from the unpredictable changes in the global market and solve the problem of domestic fuel. In addition, Proálcool was also strengthened by scientific and technological events, driven by a great deal of interaction between the private sector and public universities (CORTEZ, 2016).

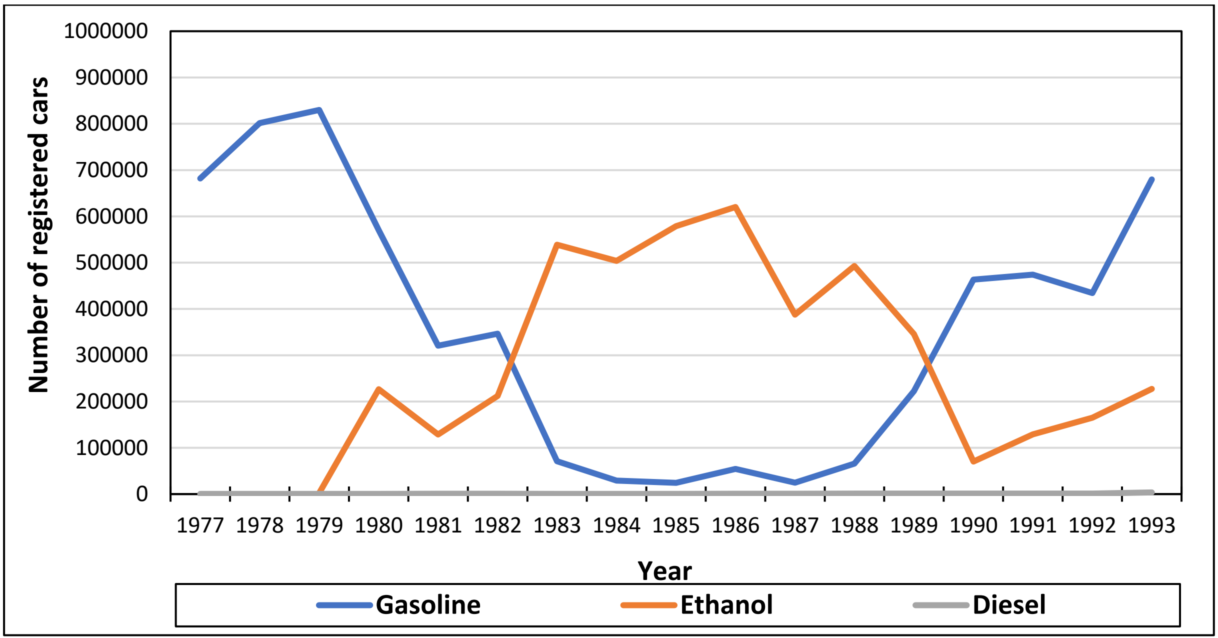
Also, in this period, it was decided to subsidize the price of diesel and limit its use only to productive means and cargo transport. The diesel was destined exclusively for trucks and buses as a strategy to reduce dependence on imported oil. In addition, the diesel ban was encouraged at the time due to the incipient development of technologies for the use and production of diesel oil: diesel engines were noisy, had low performance, and the fuel had a high sulfur content without prior control of its emissions (CARMO, 2020). Therefore, in 1976, the sale of diesel passenger cars in Brazil was prohibited. This ordinance was later updated by the National Traffic Council (CONTRAN), which prohibits the consumption of diesel oil in national and imported passenger vehicles and mixed-use vehicles with a transport capacity of less than 1,000 kg.

Proálcool had two main components: a compulsory order that all gasoline should have at least a percentage of its mixture in alcohol and a voluntary order that car manufacturers should create vehicles to run on 100% alcohol (MOREIRA; GOLDEMBERG, 1999). The decision to gradually add percentages of alcohol to gasoline was crucial for the political learning of the program. Percentages slowly increased from 4.5% in 1977 to 15% in 1980, giving producers and users the ability to adjust and allowing targets to be raised or lowered as market conditions change (BROWN; SOVACOOL, 2011).

The continuous monitoring and adaptation to external shocks was a fundamental strategy for the progress and implementation of Proálcool. In 1979, when the third oil shock occurred as a result of the Persian Gulf War between Iran and Iraq, oil prices rose significantly again, leading to a further deterioration of Brazilian accounts, already severely damaged due to the second shock of 1973, and to the growing external indebtedness held by the Brazilian government (CORTEZ, 2016). Due to this external shock, a new impulse for fuel alcohol was provoked, aiming to increase investments, both for the expansion of the sugarcane planted area and the construction of new distilleries. The government strengthened incentives, through loans at low or negative interest, for the construction of distillation plants, in addition to credits for purchasing vehicles that ran on alcohol.

During Proálcool, between 1975 and 1985, sugarcane production quadrupled, and alcohol became the most essential fuel in the country. In 1985, the sale of ethanol-only cars represented 96% of the market, and by the end of that decade, 4.5 million vehicles had been sold (MOREIRA; GOLDEMBERG, 1999). Figure 6 shows how quickly replacing gasoline vehicles with alcohol vehicles was.

Figure 6 – Number of registered cars in Brazil (1977-1992)



Source: Elaborated by the authors from (ANFAVEA, 2020).

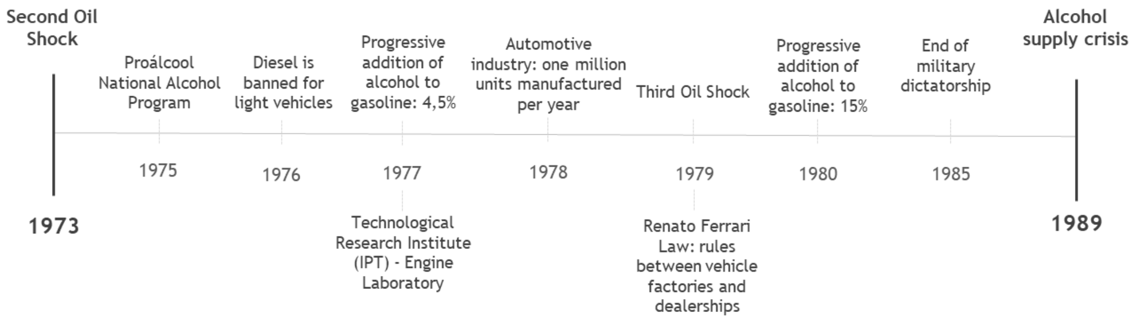
This process, with strong positive environmental, economic, and social aspects, has become one of the most important biomass renewable energy programs in the world (GOLDEMBERG; COELHO; LUCON, 2004). According to Sovacool (2016), Brazil may have had the fastest energy transition ever recorded worldwide, as the results of the program are considered impressive. In 1981, six years after its implementation, 90% of all new vehicles sold in Brazil could use alcohol (SOVACOOL, 2016b).

The support of Proálcool from different stakeholders allowed a degree of political consensus to be reached and ensured that the program was well protected in the country (BROWN; SOVACOOL, 2011). Proálcool portrays how, in the formulation of national energy policy, the integration of different actors and the establishment of a consensus, through policies regarding the problem faced, are efficient for the replacement of an energy source, even when the costs are initially higher.

The end of the military period in 1985 brought about changes in the political and economic structure of Brazil. There was a period of liberalization that did not allow more subsidized sectors with an economy quite weakened by successive crises. The new democratic government reduced strong subsidies and incentives, formally ending the program. It should be noted that other support policies were maintained since the production of alcohol vehicles by the automobile industry was still growing (CORTEZ, 2016). However, low oil prices in 1987 and 1988 led to a reduction in ethanol subsidies, a ban on the use of federal funds to purchase sugar, and a restriction on government investments in ethanol infrastructure. In this context, there was a mismatch between the production of alcohol vehicles and the corresponding production of fuel alcohol. Thus, in 1989, intensified by the high prices of sugar in the foreign market, there was a lack of alcohol to supply the vehicles (BROWN; SOVACOOL, 2011; CORTEZ, 2016). The shortage of ethanol has led to drastic increases in prices, which has caused people with ethanol cars to become distrustful and switch to gasoline vehicles. From 1989 onwards, sales of ethanol cars dropped sharply to just 11% of all sales (BROWN; SOVACOOL, 2011).

In the 1970s, the government continued the road project and the resources invested prioritized the expansion of road infrastructure. However, the constant investments in maintenance and recovery of the transport system did not happen as promised. From the mid-1980s, due to the economic and financial crisis, roads and transport infrastructure were scrapped. Figure 7 outlines the main events that marked the period of Proálcool, from the beginning to the end of the program.

Figure 7 – Timeline: landmarks that shaped the Brazilian transport sector between 1973-1989.



Source: Elaborated by the authors.

2.8. DISCUSSION

The evolution of the Brazilian transport sector is marked by the alliance between the bourgeoisie, the government, and foreign capital. The modernization of the transport sector was possible through direct investments in the Brazilian economy, building not only the national industry but encouraging the construction of roads and the financing of research on alternative fuels. The three fields analyzed (technology, fuels, and infrastructure) that began at the 20th century were organized separately, but throughout history become integrated and inseparable, exchanging interests and support (advertising, financial or political). Table 1 presents the most striking points in each period and investigated areas that shaped the Brazilian transport sector.

Table 1 – Summary of the stages of development and structuring of the Brazilian transport sector (1889-1989)

Period	Development Area		
	Technology	Domestic Fuel Supply	Infrastructure
1889 - 1929	The beginning of the importation of new vehicular technologies (combustion engine) and the establishment of the first local and foreign automobile assembler companies.	The high prices of imported coal triggered the first search and research initiatives for a national fuel (coal, oil, and alcohol). However, the fully imported fuel regime was maintained during the period.	The period is marked by the bourgeoisie's desire for modernity, which foresaw the country's progress in the road modal. The creation of the first highway fund supported the financing of the first Brazilian highways.
1929 - 1945	Development of research to adapt engines to receive the increasing additions of alcohol to gasoline. The country established a preliminary auto parts industry due to the 1929 crisis.	The beginning of government interventions with the formation of the first governmental institutions to regulate and control national energy resources (IAA and CNP). The sugar crisis leads to the creation of public policies for the addition of alcohol to gasoline.	Nationalism, in effect, promotes the creation of raw material industries necessary for the industrialization of the country in the following period. Roads are strengthened by creating government institutions and funds, and planning and expanding roads.
1945 - 1954	A strong period of public policies to replace imports of automotive parts. Imports of parts manufactured outside the country were prohibited. The creation of the first commissions for the development of the national automobile industry.	Formation of commissions to research alternative fuels such as gasogene. Strengthening of the policy of adding alcohol to gasoline (20%).	Beginning of scrapping of railways as a means of transporting passengers. Design of new road plans and the creation of a new road fund (fuel and lubricant taxation) to support the construction of roads. Formation of the lobby of road contractors.
1954 - 1973	Strategic and aggressive policies for the development of the national car industry. Substantial national funding for industry formation and foreign investment attraction.	The predominance of the development of the oil sector with the creation of Petrobras, nationalizing and encouraging research and exploration.	End of railways as a means of transporting passengers. Restructuring of road plans with the move from the capital to Brasília. A strong period of expansion of highways.
1973 - 1989	Partnerships were established between universities and automakers for the technological development of the entire ethanol chain: planting, harvesting, distillation, and maturation of ethanol engines.	The oil crises redirect the use of fuels in the country towards alcohol. Besides, Diesel became prohibited for light cars. The implementation of Proálcool received large government subsidies for the formation of the entire alcohol production chain.	In the 1970s, the government continued the road project, and the resources invested prioritized the expansion of road infrastructure. However, from the mid-1980s onwards, roads and transport infrastructure were scrapped due to the economic and financial crisis.

Source: Elaborated by the authors.

In the **technological field,** the late industrialization of the country demanded that robust policies of import substitution or import ban be adopted, in an attempt to develop the national technology. In the same way, the late discovery of oil wells required efforts to improve vehicle engines so that they could run increasing amounts of alcohol. However, the development of technologies for vehicles powered by alcohol is the result of a process of partnerships with German companies. Unfortunately, there was no development of fully national know-how that would eliminate such agreements with foreign companies. In the oil sector, the same is repeated, with the importation and direct use of foreign technology. On the other hand, the country was a pioneer in several technological innovations to produce alcohol, (including farming, harvesting, fermentation, and distillation) that were important for the energy transition process of Proálcool.

In the **fuel field**, the events show that the problem of domestic fuel has always been under debate in Brazil. It is observed that the concerns about nationalizing the production of fuels were present since the beginning of the 20th century. Several research attempts were developed for alternative fuels using local resources (e.g., gasogene and alcohol), but the efficiency and prices did not make them attractive compared to fossil fuels. Initially, the shortage and the high price of petroleum derivatives led the country to establish several strategies such as adding alcohol to gasoline and disposing of diesel only for heavy vehicles. The redirection of diesel for heavy vehicles led the country to the first technological transition with the replacement of gasoline trucks. Subsequently, the combative implementation of Proálcool, through various subsidies, transformed the Brazilian transport scenario in a short period, replacing light gasoline vehicles with alcohol. Despite Proálcool being the result of a long process of defending the national cane market and the search for a national fuel, the end of government support in 1985 and the return of the sector's influence to foreign hands with liberalization made the country remain in a position of foreign dependence reversing the energy transition process.

In the **infrastructure field**, road transport in the early 20th century was strongly related to the country's image of modernism and progress. From the beginning, road construction policies were established. If initially, the road interest came from the government, little by little it was captured by the bourgeoisie, forming the lobby of the road contractors. At the same time, the rapid increase in the number of vehicles and the development of the automobile industry put pressure on the government to draw up plans and expand the road network. The railways were abandoned, and the dominance of the roads has been in force since then. However, from the 1970s onwards, with the sequence of crises, the government stopped maintaining the roads, leading to scrapping. Therefore, in the 1990s, a new maintenance discourse emerged "If the government cannot afford infrastructure, then it transfers it to the private sector". Thus, the transport system (rail, road, and port) was transferred to the private sector, under a concession regime (PEREIRA, LESSA, 2010). This dynamic is still valid today.

2.9. CONCLUSION

To date, Brazil remains sensitive to changes in the global energy sector, influenced by prices and external demand. We are heading towards the same dependence problems that we faced in the last century. For example, electric cars have entered the country and we have not yet invested in national infrastructure and technology. As a result, some lessons can be highlighted:

- the formation of the Brazilian transport sector is mainly marked by the alliance between the bourgeoisie, the government, and foreign companies;
- the availability of natural resources in the territory (sugarcane) and the pressure from the sugar sector were decisive for the evolution and innovation of the transport sector throughout history;
- dependence on imported fuel and foreign technology and the late industrialization and discovery of oil determined the evolution of the sector (bottleneck);
- the predominance of roads over other modes (rail, maritime, and river) occurred with the construction of the public perception of the modernism of automobiles and roads and was pressured by foreign investments in the formation of an automobile consumer market.

Based on these points, we must rethink national strategies and policies so that we are not again dependent on foreign technology and fuel and that the infrastructure is available for the insertion of new technologies. In a scenario of urgency imposed by climate change, a rapid energy transition will only be possible when these three pillars are aligned to appropriate existing natural resources and develop national infrastructure and technology. It is expected that the government will take more conscious actions, considering the learnings observed and analyzed here during the history of the Brazilian transport sector.

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3. NATURAL GAS AS A VEHICULAR FUEL IN BRAZIL: BARRIERS AND LESSONS TO LEARN [4]

Abstract: This study aims to analyze the adoption and growth of light-duty natural gas vehicles in Brazil and observe how state incentives and taxes impacted the development of this market at the state level. Brazil's light-duty natural gas vehicles market has slowed its growth considerably since the states with the largest share in the country, Rio de Janeiro and São Paulo, have diverged in the progress of natural gas vehicles. To clarify what led to this scenario, we selected and explored seven parameters: i) availability of natural gas distribution network; ii) the number of certified conversion garages; iii) historic compressed natural gas fuel prices; iv) state value-added taxes; v) motor vehicle property taxes; vi) vehicle-to-refueling-station index and; vii) payback period. In conclusion, it was found that state market incentives are fundamental for the continuous development of alternative fuels such as natural gas to the already established liquid fuels in the country. In Rio de Janeiro, the advantages obtained through tax incentives to compressed natural gas and motor vehicle property taxes are crucial to decrease payback time and strengthen the price of natural gas. Otherwise, in the state of São Paulo, the lowest state value-added tax levied on hydrated ethanol and, consequently, the smallest price difference between fuels hinders the development of the compressed natural gas market.

Keywords: Light-duty natural gas vehicle, Compressed natural gas, Transport, Tax policies, Brazil.

3.1. INTRODUCTION

Natural gas (NG) is a fossil fuel composed of a mixture of the simplest alkanes: methane (CH4), ethane (C2H6) and propane (C3H8). CH4 is the most dominant molecule (sometimes more than 95% by weight), followed by C2H6 with between 2 and 7% and C3H8 typically just 0.1–1.3% (SMIL, 2015). The NG can be considered as a “bridge fuel” or “transitional fuel” or “a potential fuel for transition toward low-carbon economy” (CATHLES, 2012; HAFEZNIA; POURFAYAZ; MALEKI, 2017; HOWARTH, 2014; LEVI, 2013; ZHANG et al., 2016) or cleaner and environmentally-friendly (DONDERO; GOLDEMBERG, 2005; HAGOS;

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AHLGREN, 2018; HEKKERT et al., 2005; TILAGONE; VENTURI; MONNIER, 2005; WEI; GENG, 2016), due to lower level of greenhouse gas emissions than other fossil fuels (Khan, 2017a). On average, compressed natural gas (CNG) produces fewer greenhouse gases compared to conventional gasoline and diesel vehicles (on a well-to-wheels basis) (Khan et al., 2015). Compared to gasoline, CNG has an average reduction potential of 68% carbon monoxide (CO), 35% nitrogen oxides (NOx), 25% carbon dioxide (CO2) and 10% particulate matter (PM) (KHAN et al., 2015). Therefore, NG has been used as a fuel in low-emission road transportation in many countries, as Germany, the United States, Russia and Argentina (ATABANI et al., 2011; ENGERER; HORN, 2010; ENRIQUE; ALLENDE, 2015; WANG-HELMREICH; LOCHNER, 2012).

According to Yeh (2007a), the main factors that motivated governments in the world to promote the adoption of NG, mainly in the last two decades, as vehicle fuel are i) the environmental benefits of reducing local air pollution; ii) the availability of NG resources and existing transport and distribution structure (pipelines) and; iii) reduction of dependency on imported oil. However, in order to promote this adoption, Khan (2017a) defined some basic transition conditions for the use of Natural Gas Vehicles (NGVs): i) sufficient availability of NG to supply the fuel stations; ii) a distribution system on an adequate scale that provides good opportunities for the construction of NG stations in places of interest; iii) availability of vehicles for conversion to NG on a commercial scale; iv) clear regulatory framework and; v) strong government support.

After the oil crisis of the 1970s, governments in both developed and developing countries have promoted NGVs as a clean alternative, replacing gasoline and diesel (YEH, 2007b). In addition, after this strong initial support through subsidies and policies, some NGVs markets have failed to maintain themselves and collapsed due to government and industry's lack of endless support. In these cases, the strategies and policies adopted were decisive for the success or failure in using this fuel (JANSSEN et al., 2006a; KHAN, 2017b, 2017c; YEH, 2007b). For instance, Canada and New Zealand were two countries where incentive policies were poorly coordinated and led to the failure of the NGV market. In Canada, initially, there was an accelerated and rapid development of the NGV market, benefiting from the subsidies and grants offered by the government on vehicle conversion and installation of NG stations. However, the leading initial investors never achieved the expected financial return since the stations did not reach the necessary load to become profitable. This interruption in the investment of refueling stations induced, in turn, a decrease in conversion sales and, finally, the collapse of the NGVs market in Canada (FLYNN, 2002). In the same way as Canada, New

Zealand had initial success in the NGV market due to strong government incentives (loan programs) (KHAN, 2017a). However, after political and policy changes, the government ended up rescinding loan conditions favorable to the development of the CNG industry. Consequently, the public lost their confidence in the NGVs industry. As a result, car owners stopped converting their cars to NGV because they assumed that the absence of government incentives indicated a failure of this industry, ultimately leading to the disappearance of the NGV market in New Zealand (KHAN, 2017c; YEH, 2007b).

In developing countries, the adoption of new fuel has a strong relationship with the socio-economic condition of the end-user and financial risk. Therefore, the perceived risks must be mitigated through reduced conversion and maintenance costs and fuel prices, guaranteeing a favorable cost-benefit ratio. For instance, the success of NGVs in Argentina resulted from the extremely low price of NG since there was an attractive profit margin for both refueling stations investors and future NGVs owners (JANSSEN et al., 2006b). Besides, despite the growing use of other alternative fuels such as ethanol, NGVs have still been enabled in developing countries such as Brazil due mainly to public incentive policies. At the end of 2019, the world reached approximately 28 million NGVs, while Brazil was ranked fifth in NGVs with around 6.8% (IANGV, 2019). It should be noted that Brazil is recognized as one of the countries in which the adoption of NGVs has been successful, experiencing strong market penetration and growth (JANSSEN et al., 2006b; KHAN, 2017d; YEH, 2007b).

In the case of Brazil, after the oil crisis and the problem of domestic supply of fossil fuels, the government invested in actions to replace diesel with CNG in public transport transport (MACHADO; CORDEIRO DE MELO; LASTRES, 2006a; PEYERL et al., 2018). In 1984, the first four buses powered by 80% CNG and 20% diesel started to run in Rio de Janeiro city (BRASIL, 1984). In 1987, the Ministry of Mines and Energy launched the National Plan of Natural Gas (Plano Nacional de Gás Natural – PLANGÁS) to replace or move diesel consumption and support states to adhere to this policy (FGV, 2014a). The companies, as Petrobras (Brazilian National Oil Company), Mercedes-Benz (bus constructor) and Ipiranga (Brazilian fuel company), started to invest in actions to support the use of CNG, mainly in buses. In the big cities as São Paulo and Rio de Janeiro, around 150 new experiments on buses powered by CNG were implemented (CAVALCANTI, 2005a). However, PLANGÁS did not achieve the intended targets due to the scarcity of refueling stations, low autonomy, and limited resale of used vehicles (CAVALCANTI, 2005b; FGV, 2014b).

In 1992, the second phase of PLANGÁS was launched by the government to increase the share of NG in the energy mix from 2% to 12% by the end of the 1990s (FGV, 2014b;

MARTINS et al., 2004). The incentive to light-duty vehicles (LDVs), mainly for the use of CNG in cabs, started to increase significantly in the 1990s due to the advantage of the low price of fuel (MARTINS et al., 2004b). Between 1992 and 1994, the annual growth rate of the NGVs market in Brazil reached a total of 115% (CAVALCANTI, 2005b; MARTINS et al., 2004b). In addition, some states have approved policies to reduce the motor vehicle property tax, as in the case of the state of Rio de Janeiro, from 4% to 1% on the current value of the vehicle. Besides, technological advances of conversion-kits to NGV, increase in the price of gasohol (gasoline blended with 27% anhydrous ethanol), and better logistics for the distribution of NG were factors that favored the growth in the use of fuel, mainly in the states of São Paulo and Rio de Janeiro (CAVALCANTI, 2005b; MACHADO; CORDEIRO DE MELO; LASTRES, 2006b; MARTINS et al., 2004b).

In 2006, the nationalization of the hydrocarbon sector in Bolivia, one of the main suppliers of NG in Brazil, generated insecurity in terms of gas supply, causing a deceleration in vehicle conversions to NGVs (FGV, 2014b). However, in some specific Brazilian states as Rio de Janeiro, the continuous reduction in the motor vehicle property tax of vehicles converted to NGVs and the increase in the number of refueling stations resulted in one of the most massive global adoption cases of light-duty NGVs (FGV, 2019a). In the last decade, it has been observed more frequently that the freezing and variation of gasohol prices have directly impacted the conversion of vehicles to NG (FGV, 2014b). In 2018, NGVs represented 3% of the Brazilian fleet, with approximately 2.25 million vehicles (SANTOS, 2020).

Most international studies assess the penetration dynamics of NGVs only on a national scale (KHAN et al., 2016). The analysis carried out in this work will consider details of the two Brazilian states, which have not yet been addressed in the literature. The policies and strategies adopted by each state government have influenced the success or failure of the adoption of different types of vehicle fuels. The aim of this work is to analyze the adoption and development of light-duty NGVs in Brazil and observe how state incentives and taxes impacted the growth of this market at the state level. To achieve the goal, the development of NGVs is systematically examined through performance parameters such as relevant infrastructures and economic incentives in two Brazilian states: Rio de Janeiro (RJ) and São Paulo (SP). These two states were chosen because they are responsible for almost the entire participation of NGVs in the country (DENATRAN, 2019a). In these cases, the approach of this work is relevant due to the different behavior that the two states have been presenting. While RJ maintains a constant development of the CNG market, SP shows a slowdown in growth.

The article is organized as follows: Section 2 addresses the performance parameters selected to characterize and assess the evolution of the NGVs market in RJ and SP. Section 3 presents the results, considering the development of economic and infrastructure parameters. In addition, this section exposes the external factors that hinder the evolution of the NGVs market. Considering the results, Section 4 presents the current discussions that cover the topic and can modify the future scenario of the NGV market. Finally, Section 5 presents the final considerations that summarize the main implications of the policies adopted and the lessons to be learned for increasing the participation of NGVs in RJ and SP.

3.2. RESEARCH METHOD

3.2.1. Research Focus

This paper systematically examines the LDVs, disregarding the insertion of NG in heavy-duty vehicles (HDVs). HDVs are still in the initial phase of adoption in Brazil, without a significant NGVs fleet. LDVs cover the passenger vehicles and commercial vehicles categories. However, the absence of disaggregated data on NGVs prevents the comparison between these two categories in Brazil.

This paper focuses on two branches, infrastructure (availability) and economics (price). Low-income consumers are less able to pay the costs and tend to opt for fuel-related cost savings in the future (DIAMOND, 2009). The adoption of alternative fuels is considered by consumers when prices are competitive compared to fossil fuels. Environmental aspects tend to be overlooked for price and availability (KHAN, 2017b). In addition, Brazil is a developing country with a gross national income (GNI) per capita of US$7,850 (THE WORLD BANK, 2021). Considering the Brazilian GNI, the low purchasing power makes the financial aspects one of the most important in decision-making for NGVs investment.

3.2.2. Review and selection of the indicators used in scientific literature

This paper is organized into four steps: i) review of the literature related to theme NGVs; ii) identification of commonly used indicators in the literature; iii) selection of the most relevant indicators; iv) application of indicators to the case study; and v) analysis and discussion of results.

The identified indicators are inspired and based on the results and issues addressed by the scientific literature to assess the promotion of the NGVs market worldwide. The identified indicators are mainly derived from the literature shown in Table 2.

Table 2 – A summary of previous research on NGVs

Author	Research objectives	Countries analyzed	Indicators or policies observed by the authors
Flynn (2002)	Lessons learned from NGVs: What limited growth of NGVs.	Canada; U.S.	Infrastructure profitability; The alternate fuel must be available publicly; Fuel retailing must become profitable; OEM equipment for aftermarket conversion; Aftermarket dealer parts markup needs to be controlled; Promotional programs need to be designed for market effectiveness.
Greene et al. (2005)	Study of incentives for increased fuel economy.	U.S.	Incentives, Taxes; feebates; fuel savings and costs; rebates
Janssen et al. (2006)	The introduction of alternative fuel vehicles on the market: difficulties and chances in the market penetration process of NGVs.	Switzerland	Policy variables; vehicle-to-refueling-station index (VRI); type coverage; NGV investment pay-back time; Sales per type; Subsidies per car;
Yeh (2007)	An empirical analysis on the adoption of alternative fuel vehicles: NGVs.	Argentina; Brazil; China; India; Italy; New Zealand; Pakistan; U.S.	Infrastructure: vehicle-to-refueling-station index (VRI); Economic indicator: fuel price ratio; payback period.
Wiedmann et al. (2011)	Adoption barriers and resistance; Risks perceived by consumers.	Germany and Commonwealth of Independent States (CIS)	Financial Risk; Performance Risk; Physical Risk; Time Risk; Social Risk; Psychological Risk.
Khan et al. (2014)	Development of NG as a vehicular fuel: Issues and prospects.	Pakistan	Government policy & support; Supply and demand gap; CNG technology; NG infrastructure; Economic benefits: Fuel prices; Cost comparison of CNG vs other fuel.
Wang et al. (2015)	Development of NGVs: enabling factors and barriers.	China	NG supply; vehicle-to-refueling-station index (VRI); Price ratio of NG to gasoline; Incentives Policies
Khan (2017)a	Policy options for the sustainable development of NG as transportation fuel.	Worldwide	Market based instruments (tax incentives, vehicle taxes, fuel taxes, tax credits, custom and excise duty, taxation regime); Innovative financial mechanisms (loans and leasing, performance contracting, insurance rebate) Non-monetary incentives; and Command and control measures (regulatory actions).
Khan (2017)b	To analyze NGVs adoption patterns and the evolution of pertinent market structures throughout the world; Identifying and assessing qualitative aspects of the barriers and consequently defining measures for their resolutions.	China, Iran, Pakistan, Argentina, India, Brazil, Italy, United States, Germany, Sweden and South Korea.	Financial barriers; Technical or commercial barriers; Institutional and administrative barriers; Public acceptability; Legal or regulatory barriers; Policy failures and unintended outcomes; Physical barriers; Information-related barriers to NGV purchasers and fueling infrastructure providers; Barriers to private investment in NGVs and fueling infrastructure; Information-related barriers to private investment; Legal and regulatory barriers to private investment; Coordination failure in complementary markets.

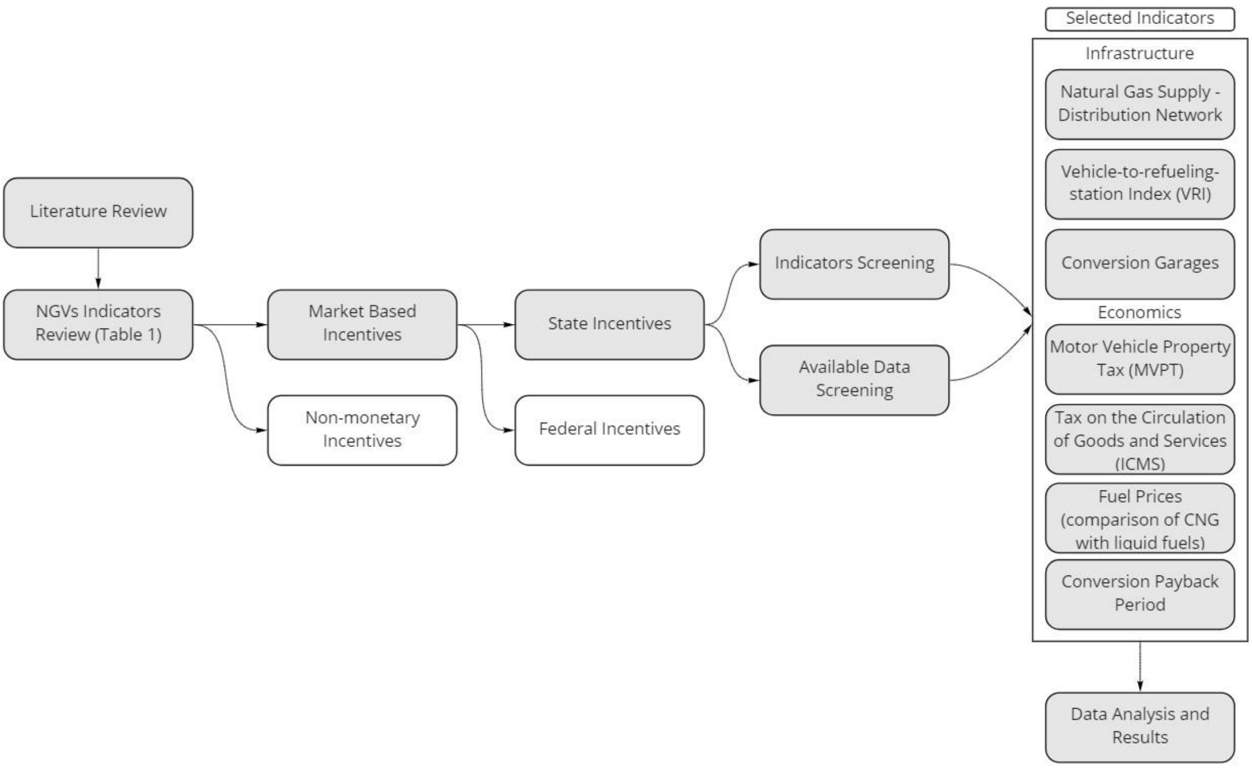
The selection or exclusion of the identified indicators was defined through the following criteria: types of incentives (infrastructure and economic), existence of incentives in Brazil, spatial scale (only state incentives), and availability of data.

In Brazil, the incentives given to NGVs are essentially financial (based on the market). Non-monetary incentives are not applied to the Brazilian NGV market (e.g., free parking, car rotation exemption, exclusive lanes, permission to use the bus lane, control of CNG prices, etc.). It is noteworthy that non-monetary incentives could be considered to strengthen the NGV market in the future. In the same direction, the NG and automotive parts industry and other stakeholders should be encouraged through incentive policies, as they play an important role in building the market.

The parameters were chosen based on their relevance at the state level, without considering the influencing factors at the federal level. It is noteworthy that other types of existing incentives such as loans and financing are important, but they are not addressed in this study as it is assumed that they impact states uniformly. When relevant, federal incentives are mentioned during the results.

Founded on the information above mentioned, to establish a consistent structure for analyzing the insertion and development of light-duty NGVs in Brazilian states, seven parameters in two categories (infrastructure indicators and economic indicators) were considered. A summary of the research procedure and the selected indicators is presented in Figure 8.

Figure 8 – Research procedures and indicators of support and incentive to NGVs



Source: Elaborated by the authors

3.2.3. Available Data

This paper used and analyzed data collected from various sources such as policy documents, secondary data from a variety of national agencies, government reports, gas industry reports, technical reports, and others. The period of data used extends from 1989 to 2019. However, due to the limited availability of data from 1989 to 2008, which in many cases were absent, incomplete and/or openly unavailable, this work focuses mainly on the period between 2009 and 2019. The data used are shown in Table 3.

Table 3 – A summary of data sources

Data	Source	Date/Period
Extension of NG transport and distribution network	ABEGÁS - Brazilian Association of Pipeline Gas Distribution Companies	2013-2019
	EPE - Energy Research Company (Brazil)	2019
Number of certified garages for conversion	INMETRO - National Institute of Metrology, Quality and Technology	2020
Number of CNG refueling stations	ABEGÁS - Brazilian Association of Pipeline Gas Distribution Companies	2013-2019
Vehicle fleet by fuel	DENATRAN - National Traffic Department	2013-2019
Value-Added Taxes (VAT)	ICL - Instituto Combustível Legal (Legal Fuel Institute)	2019
Historical of the fuel prices	ANP - National Agency of Petroleum, Natural Gas and Biofuels	2002-2019
Motor vehicle property taxes	Legislative bodies (State laws)	1989-2015
Average NGVs mileage	KBB - Kelley Blue Book	2019
	CNT - National Transport Confederation	2016

Source: Elaborated by the authors

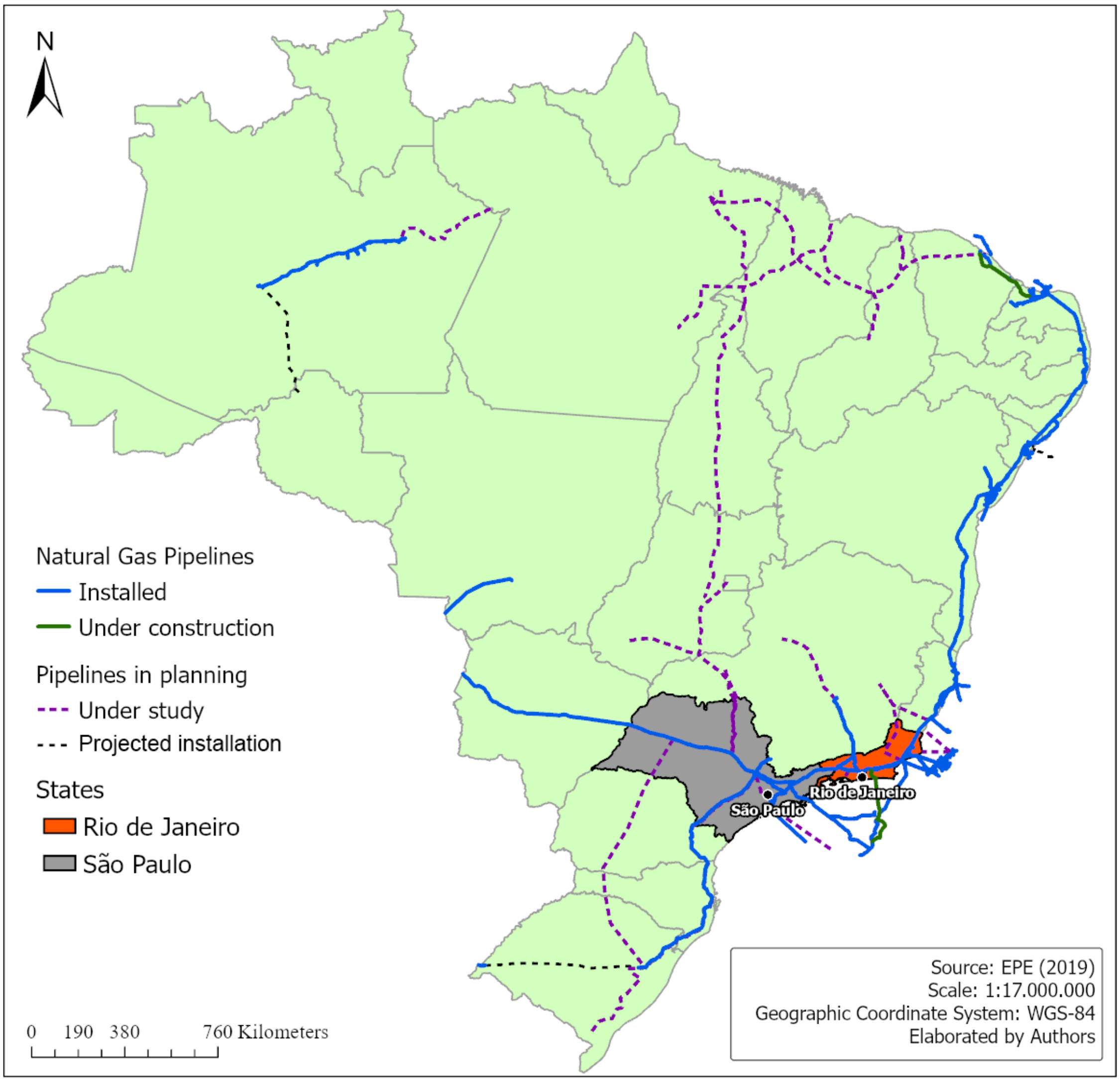
3.3. RESULTS

3.3.1. Infrastructure indicators

Natural gas transport and distribution network

Currently, the network of NG transportation pipelines in Brazil extends for 9,409 [km] (EPE, 2019a), predominantly along with the southeast and northeast areas, from the states of Rio Grande do Sul to Ceará (EIA, 2019) (See Figure 9). Concerning the distribution regulation, this is the responsibility of the State and the NG distribution service, which is operated by - state and private - companies with an exclusive geographical permit (FGV, 2014).

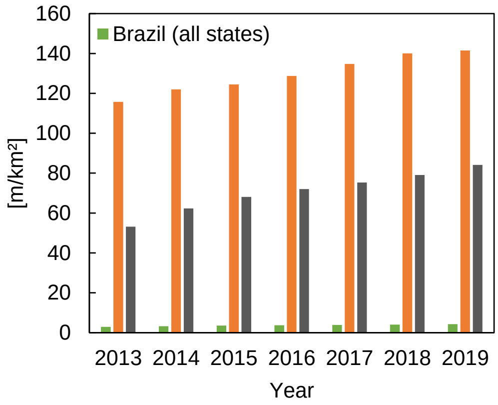
Figure 9 – Natural gas transport network in Brazil.



Source: Based on data from EPE (2019).

The distribution pipeline network (downstream) in SP is the largest in the country. There was an increase of 58% in SP's network, from 13,188 [km] in 2013 to 20,871 [km] in 2019 (ABEGAS, 2019a). In the same period, RJ increased its distribution network by 22%, from 5,058 [km] to 6,183 [km] (ABEGAS, 2019a). Despite the strong growth in the distribution network in SP, RJ still has the most extensive distribution pipeline coverage per area (Figure 10): in 2019, the distribution pipeline coverage is about 142 [m/km²] (82 [m/km²]) for RJ (SP respectively).

Figure 10 – Ratio of gas pipeline network (downstream) [m/km²]



Source: Based on data from ABEGAS (2019).

The increase in the coverage of distribution gas pipelines in SP was mainly driven by the rise in the consumption of NG by the residential and commercial sectors since for the same period, the NG consumption in the transport sector simultaneously collapsed by 52% (SP, 2019).

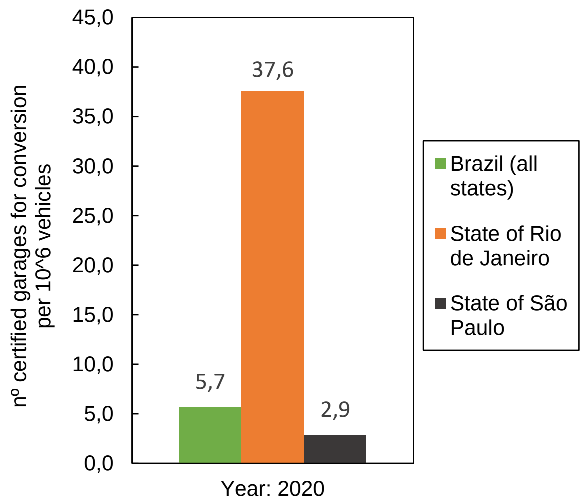
In RJ, greater coverage of gas pipelines for the distribution of NG allowed consumers easier access to CNG. In 2019, RJ represented about 53% of the total CNG consumption of the Brazilian transport sector (FIRJAN, 2019). This higher coverage facilitates the supply and the existence of a more significant number of CNG refueling stations in the state, as will be seen later.

It is worth mentioning that gas distributors are the main players that have carried out advertising campaigns in Brazil. Although SP and RJ have different companies responsible for the distribution of NG, both have tried to promote the NGVs. For example, both offer cost-benefit analysis simulators for vehicle conversions on their websites. Along with the parts industry, they are the main stakeholders responsible for pressuring the government to make incentives available.

Certified garages for conversion

The majority of NGVs in Brazil are aftermarket conversions, although vehicle manufacturers have made attempts to introduce some original equipment manufacturer (OEM) models. The number of certified garages can be considered a structural indicator for vehicle conversions and sector development. It is essential for the consumer that there are enough garages for maintenance and inspection of converted vehicles. According to Flynn (FLYNN, 2002), a combination of OEM and high-quality aftermarket suppliers is the best way to develop the conversion market, since aftermarket products have lower dependability in the eye of the consumer than OEM products, in addition to the concern that the conversion will void the vehicle's warranty. Therefore, the certification of components and conversion garages are essential to offer consumer safety and dependability. In Brazil, the National Institute of Metrology, Quality and Technology - INMETRO (or Instituto Nacional de Metrologia, Qualidade e Tecnologia) is responsible for verifying and certifying the quality and safety of products and services, according to strict technical standards. Figure 11 shows the ratio of certified garages for the conversion of vehicles to NGVs in Brazil.

Figure 11 – Certified garages for conversion per 10^6 vehicles



Source: Based on data from INMETRO (2020).

Besides, from Figure 11, there is the largest number of registered garages for installing the CNG kit in RJ compared to the whole country with a significantly higher number than SP. This proportion suggests that there is a sufficient vehicle conversion infrastructure in RJ that ensures greater convenience, safety and reliability for consumers who intend to convert their vehicle, since they are garages certified by the main Brazilian quality certification body. Likewise, this proportion may also reflect a strong demand for vehicle conversion and, consequently, the development of the CNG market. Conversely, the smaller number of certified garages in the state of SP can promote uncertainty and lesser convenience, discouraging vehicle conversion.

It should be noted that in Brazil, the conversion parts are mostly from the Italian parts industry (YEH, 2007). In recent years, this industry has strived to offer economic attractions for the Brazilian market, such as partnerships for financing the conversion of ridesharing cars.

Vehicle-to-refueling-station index (VRI)

The existence of CNG refueling stations is a necessary precondition for the consumer to choose to convert one's vehicle to NGV (infrastructural bottleneck) (FLYNN, 2002). Khan (2017b) and Yeh (2007) noted that there must be a balance between the number of vehicles and the number of refueling stations. There must be enough refueling stations close to their places of work and housing and along the route between them for their adequate supply and comfort for NGVs owners. Likewise, to increase the number of refueling stations, it is necessary to have a sufficient number of NGVs for investment in a CNG refueling station to maintain an acceptable profit margin (FLYNN, 2002).

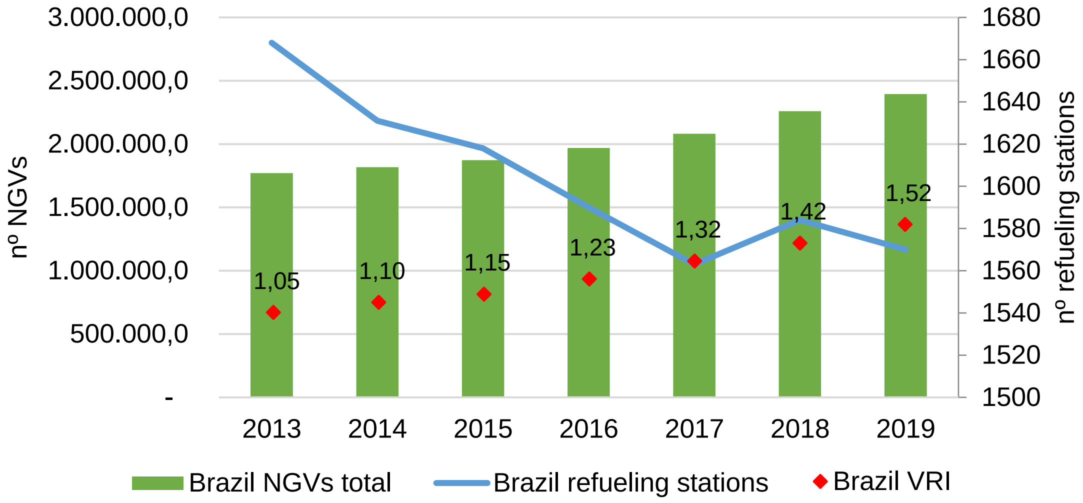
In this context, vehicle-to-refueling-station index (VRI) is considered one of the indicators to measure this balance and the development of NGVs markets (NIJBOER, 2010). VRI (dimensionless) is defined as the ratio between the number of NGVs (demand expressed in thousands of vehicles) and refueling stations (supply expressed in thousands), that is, a balance between minimum profitability for refueling stations and a minimum density of refueling stations needed by NGV drivers (JANSSEN et al., 2006). Although the VRI is commonly used to analyze national scales, it was used to understand the density of CNG fuel stations for the number of NGVs in each state. Figures 12, 13 and 14 show the observed VRI in the case-study states and the Brazilian average.

The latest review of VRI values, carried out by Khan (2017b), suggests that successful NGV markets tend to gravitate toward VRI of 1.1 in developing countries; in addition, there seems to exist an upper boundary of 1.25–1.5 (to avoid long lines for refueling) and lower limit of 0.5-0.6 (accessible refueling stations). These results are close to the first ones obtained by Janssen et al. (2006), Yeh (2007) and von Rosenstiel et al. (2015), who conclude that an optimal VRI is around 1.

In RJ, the VRI has increased from 1.75 in 2013 to 2.47 in 2019 (Figure 13), considerably exceeding the upper limit of 1.5 observed by Khan (2017b). The reasons are not very clear; however, it can be inferred that there is still some resistance from investors to deploy CNG at traditional refueling stations, even with the considerable growth of the NGV fleet in the state, from 964,140 in 2013 to 1,472,999 in 2019 (DENATRAN, 2019). The slow increase in the number of refueling stations was also noted by Khan (2017b) at VRI > 1 in several countries. This scenario could discourage the adoption of NGVs because of the small number of refueling stations per number of vehicles. However, as in Brazil NGVs are mostly converted flex-fuel vehicles (gasohol and ethanol), this problem becomes less detrimental to the development of the market, since, in situations of absent of CNG refueling stations or long queues, there is the possibility of filling with gasohol or hydrated ethanol at other refueling stations.

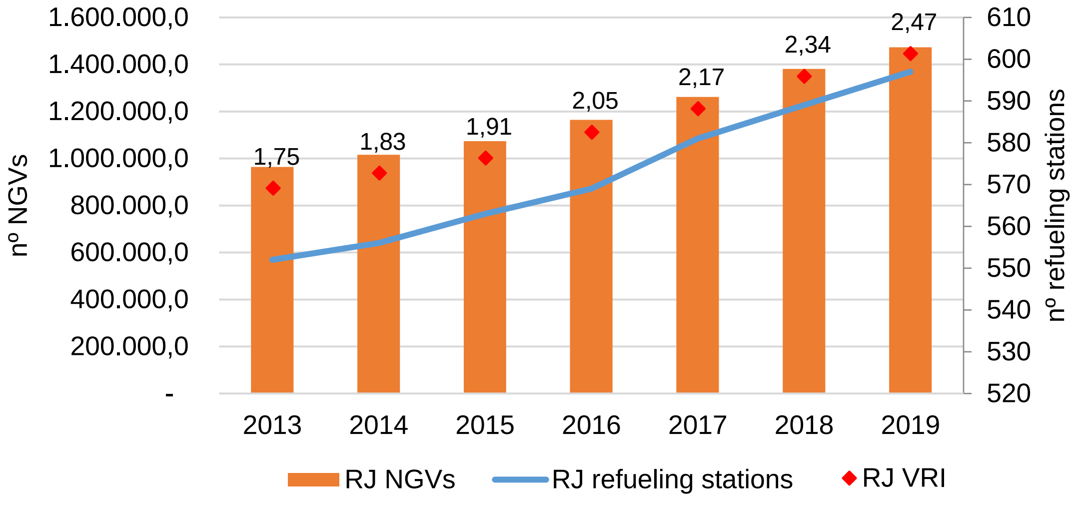
In SP, the VRI has increased from 0.83 in 2013 to 1.09 in 2019 (Figure 14). This is due not to the increase in the number of converted vehicles but mainly to the decrease in the number of CNG refueling stations during the period. In addition, the NGV fleet in SP decreased from 291,220 in 2013 to 285,989 in 2019 (DENATRAN, 2019). This change may reflect two possible trends: (1) a decrease in the demand for CNG fuel (higher prices) or (2) an increase in the costs involved to operate a CNG station profitably in SP make investment and maintenance less attractive (in order to reach breakeven).

Figure 12 – VRI of Brazil (all states)



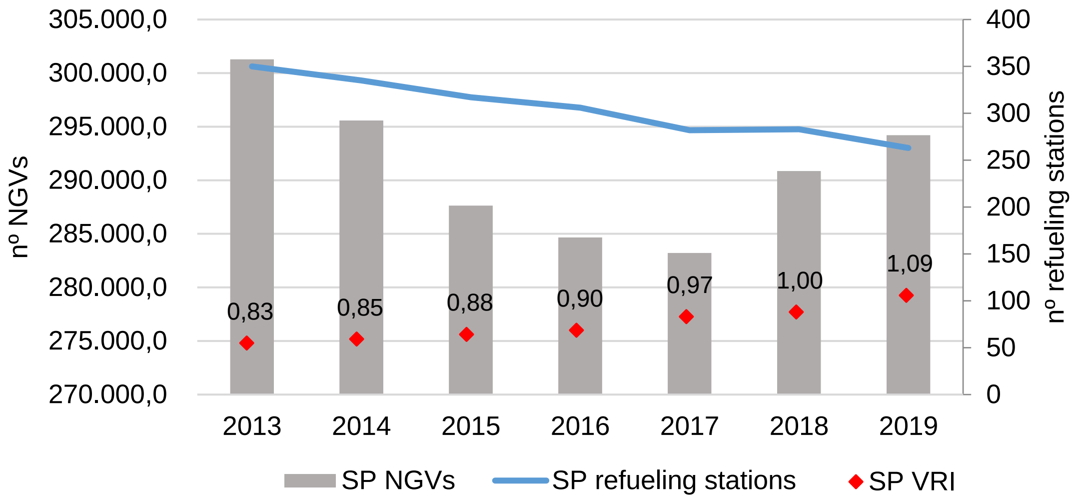
Source: Elaborated by the authors based on ABEGAS (2019) and DENATRAN (2019).

Figure 13 – VRI of RJ



Source: Elaborated by the authors based on ABEGAS (2019) and DENATRAN (2019).

Figure 14 – VRI of SP



Source: Elaborated by the authors based on ABEGAS (2019) and DENATRAN (2019).

3.3.2. Economic indicators

Tax on the Circulation of Goods and Services (ICMS)

Currently, the main taxes levied on fuels in Brazil are made up of (1) Contribution for Intervention in the Economic System (Contribuição de Intervenção no Domínio Econômico - CIDE), (2) Contribution to the Social Integration Program (Programas de Integração Social e de Formação do Patrimônio do Servidor Público, - PIS/PASEP), (3) Finance Social Security Contribution (Contribuição para Financiamento da Seguridade Social - COFINS) and (4) Tax on the Circulation of Goods and Services (Imposto sobre Operações Relativas à Circulação de Mercadorias e Serviços - ICMS). The levies of CIDE, PIS, PASEP and COFINS are federal charges, therefore they are not distinguished among states. However, it is noteworthy that the composition CIDE/PIS/PASEP/COFINS is different among different types of fuels. The amounts collected, in decreasing order, are higher for gasohol, followed by hydrated ethanol and lastly CNG (CAVALCANTI, 2006), demonstrating an incentive policy for CNG and hydrated ethanol at the federal level.

The Tax on Circulation of Goods and Services (ICMS), or Value-Added Tax (VAT) as it is known internationally, was instituted by the Brazilian Constitution of 1988, with two fundamental differences about the tax previously collected: (1) the tax started to apply to fuels and lubricants, and (2) to imports (BRAZIL, 1988). From that moment, the states acquired the power to issue laws with the competence to tax fuel trading operations (ICMS) and set rates within their territories. By giving states the right to tax energy imports and trade, the Constitution allowed the states to influence energy policy and the automotive fuel market in

Brazil (CAVALCANTI, 2006). The ICMS rates currently charged are shown in Table 4.

Table 4 – State value-added tax (ICMS)

Fuel	Brazil[1]	RJ	SP
Gasohol	28%	34%	25%
H. Ethanol	24%	32%	12%
CNG	17%	12%[2]	12%

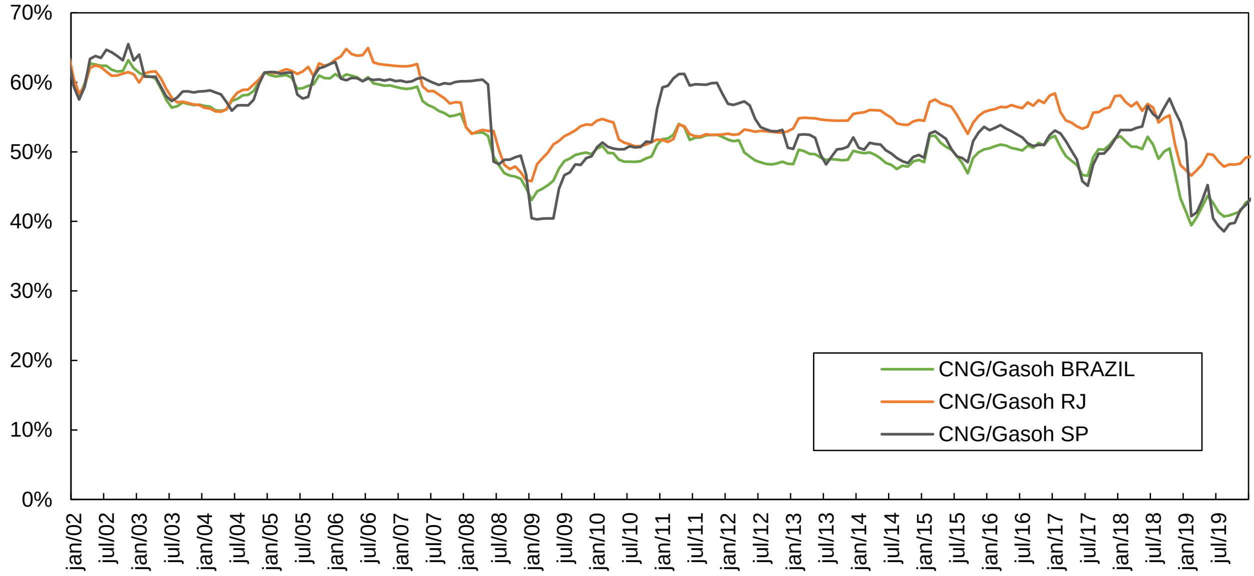
[1] States average
[2] 13% considering the increase due to the Fund to Combat Poverty and Social Inequalities (FECP)
Source: based on Combustível Legal (2019).

It can be seen from Table 4 that the Brazilian average of ICMS is considerably lower for CNG regarding gasohol and hydrated ethanol, since almost all states use this tax to encourage the use of CNG (except Amapá and Amazonas States, and Federal District). It should also be noted that SP and RJ have a 12% rate for CNG, which is well below the national average. Also, it is observed that RJ despite having a lower rate for hydrated ethanol regarding gasohol, it is not as substantial as the one defined by SP, which is equaled with the rate of CNG (COMBUSTÍVEL LEGAL, 2019).

Historical of the Fuel Prices

A decisive factor for the consumer adoption of NGV is the price of NG compared to other available fuels (DONDERO; GOLDEMBERG, 2005b; JANSSEN et al., 2006b; KHAN, 2017d; YEH, 2007b). Even in the absence of other market subsidies, if the price of CNG is attractive enough, it becomes interesting for the consumer to convert one's vehicle to NG (NIJBOER, 2010b). As the fuels under analysis do not have the same energy efficiency in the same engine, it is not possible to directly compare prices between them. In this way, we compare prices in concern to the distance traveled for each fuel based on a model tetra-fuel car. To calculate the fuel cost savings, as an official measure of fuel efficiency demand (e) for an average car, this study adopted the fuel demand figures of the 2010 Fiat Tetra-Fuel: 13.2 [km/m³], 10.7 [km/l] and 7.5 [km/l], running on CNG, gasohol and hydrated ethanol, respectively (INMETRO, 2010). Based on this car model, Figures 15 and 16 were produced.

Figure 15 – CNG Price Advantage over Gasohol

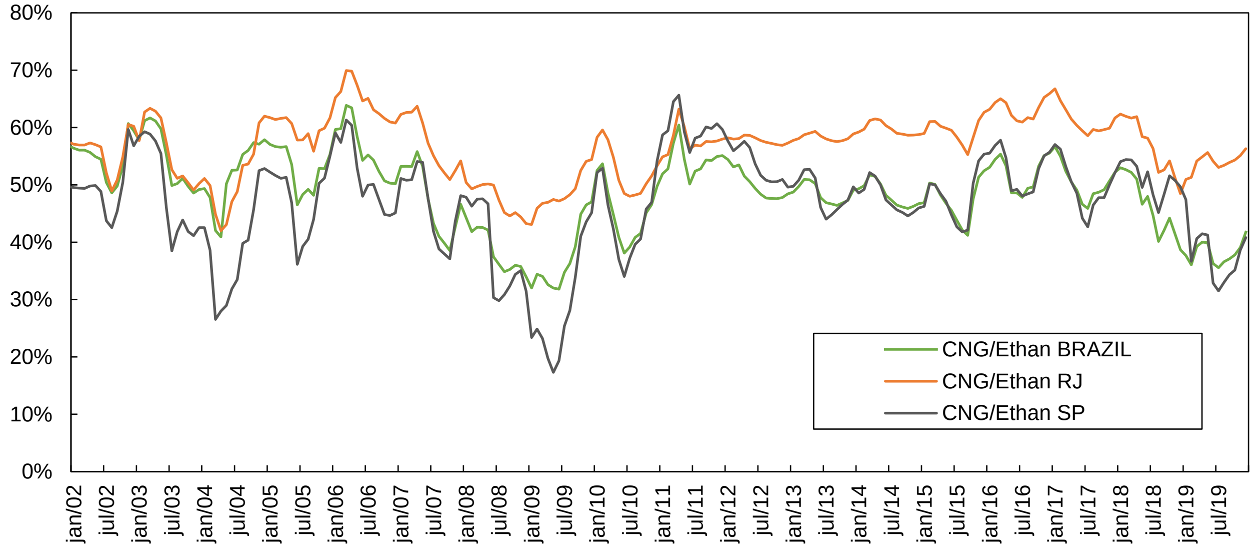


Source: Elaborated by authors based on (ANP, 2019).

When comparing the relative price of CNG with gasohol, we find that there are significant economic advantages. In the three curves of Figure 15, savings can reach up to 65% of the value relative to gasohol. In RJ, the minimum savings in the analyzed period is 45%, while in SP and the Brazilian average it is 37%. It is also observed that there are no excessive fluctuations in the percentages, being quite stable in the case of RJ.

As shown in Figure 16, the reduction in the ICMS tax rate charged in SP accentuated the decrease of the curve, reducing the percentages of the advantage of CNG over ethanol in SP. The RJ curve remains practically higher than the Brazilian and SP curves throughout the period, ranging from 47% to a maximum of 70% with an average of 58%. It should also be noted that the SP curve fluctuates considerably, ranging from 17% to 61% with an average of 48%. Unlike the previous graph, the curves shown in Fig. 8 show large oscillations, being more accentuated in the case of SP.

Figure 16 – CNG Price Advantage over Ethanol.



Source: Elaborated by authors based on (ANP, 2019).

It appears that a price for the end consumer of CNG of at least 40 to 60% below the price of gasoline is usual in most countries that have had a successful penetration of NGVs (KHAN, 2017b; YEH, 2007). In RJ, the variation margin is within the average values observed worldwide. However, in SP, which at a given time achieved savings of only 17%, it is out of the results observed for those sites that successfully develop the market. This fact is aggravated by the fact that there is a strong oscillation of these cost savings in the state, causing insecurity and lack of confidence in NG as an advantageous fuel.

Motor Vehicle Property Tax (MVPT)

The motor vehicle property tax (MVPT) (or *Imposto sobre a propriedade de veículos automotores* (IPVA) as known in Brazil) is a tax on vehicle ownership that must be paid annually by those who own a vehicle on its annual value. Although the MVPT is charged throughout the country, this tax varies by states. Several states use this tax as a public policy instrument to reduce the tax on vehicles powered by cleaner fuels, as a way to encourage its use and to reduce air pollution. As it is an annual tax set on the car's total value, it is a financial parameter of considerable importance for reducing the costs of conversion to NGV. Most Brazilian states do not differentiate the amounts charged following the type of fuel used. However, SP and RJ charge different rates following the type of fuel used by the vehicle (Table 5).

Table 5 – Motor Vehicle Property Tax (MVPT)

Fuel	Brazil[1]	RJ	SP
Gasohol	2.7%	4.0%	4.0%
H. Ethanol	2.6%	2.0%	3.0%
CNG	2.5%	1.5%	3.0%

[1] States average

Source: legislative bodies (state laws)

We observed through the Brazilian averages (Table 5) that there are not considerable disparities in the aliquots between the fuels analyzed since most Brazilian states do not distinguish rates between different fuels. However, when we analyzed SP and RJ, we identified discrepancies. Based on the rates in Table 5, for a car valued at R$ 50,000.00 (US$ 1.00 is equivalent to an average R$5.32, quotation in August 2020), when it can be filled with Ethanol, there is an annual savings of R$ 1,000.00 in RJ and R$ 500.00 in SP compared to gasohol. When we analyze, for the same car, the savings concerning CNG in RJ, this savings becomes greater, with an annual savings of R$ 1250.00. An annual savings of R$ 1250.00 can be considered substantial, being used to offset the conversion costs and, thus, reduce the payback as we will see in the next section. The state of SP could take advantage of this tax as an incentive to adopt NGVs, offsetting the conversion costs.

NGV Conversion Payback period

The *NGV Conversion Payback Period* depicts how long the financial return will take due to investment in the conversion of a car to NGV regarding the gains from the lower price of NG and taxes, for the main consumer segments. The NGV conversion payback period varies with the car model (vehicle efficiency), previously used fuel (gasohol or hydrated ethanol), generation of conversion-kit (3º or 5º generation), driving distance per month, and, mainly, the different tax burdens by the states. Reductions in taxes lessen the payback period for converting an existing vehicle, greater competitiveness against other fuels, and attracting consumer attention to the potential cost savings associated with the use of CNG fuel (Khan, 2017b). To calculate the payback period in the analysis (Table 6), the following parameters were considered: conversion cost (C), fuel efficiency demand (e), mileage per month (m), fuel price (p), monthly fuel savings (MFS) and motor vehicle property tax savings (MVTS). Conversion cost (C) includes the price of conversion-kit, labor and regulatory taxes. To compare the relative monthly savings between CNG (b) and liquid fuels (a), it was calculated using:

$$MFS = \left(\frac{m * p_a}{e_a}\right) - \left(\frac{m * p_b}{e_b}\right)$$

In the same way, to calculate the savings obtained through the MVPT aliquot, it was used:

$$MVT = (car\ value) * MVPT$$

$$MVTS = MVT_a - MVT_b$$

Finally, considering all this input data, the payback period (P), in months, was calculated using:

$$P = \frac{C - MVTS}{MFS}$$

Thereby, the results in Table 6 were calculated, for two types of mileage (35.8 [km/day] for medium driver and 140.3 [km/day] for taxi driver) (CNT, 2016; KBB, 2019), based on the gains due to the price difference between liquid fuels and CNG in Brazil and each state, associating the different discounts obtained through MVPT in the first year.

Table 6 shows notable deviations in the payback period between states. For a medium driver accustomed to filling up with gasohol, the Brazilian average ranges from 20 to 31 months and, SP ranges from 12 to 29 months, while RJ stands out with a payback time ranging from 12 to 20 months. When compared to hydrated ethanol, the Brazilian average ranges from 23 to 33 months and SP ranges from 23 to 36 months, RJ again stands out with a range of 15 to 22 months. For a taxi driver, the payback time is shorter for all cases, ranging from 4 to 10 months. Even so, RJ stands out, ranging from 4 to 6 months in both situations.

Table 6 – Payback Period

Payback Period[1] for Medium Drivers[2] [months]						
	CNG x Gasohol			CNG x Hydrated Ethanol		
Year	Brazil	RJ	SP	Brazil	RJ	SP
2013	31	20	29	33	22	36
2014	30	19	28	31	20	35
2015	27	16	25	30	18	32
2016	24	15	22	23	15	25
2017	24	14	23	23	15	26
2018	20	12	18	24	15	23
2019	24	14	23	28	15	31

Table 6 – Payback Period (*continuation)*

	Payback Period[1] for Taxi Drivers[3] [months]					
	CNG x Gasohol			CNG x Hydrated Ethanol		
Year	Brazil	RJ	SP	Brazil	RJ	SP
2013	8	5	8	9	6	10
2014	8	5	8	8	6	9
2015	7	5	7	8	5	9
2016	6	4	6	6	4	7
2017	6	4	6	6	4	7
2018	6	4	5	6	4	6
2019	7	4	6	8	4	8

[1] Annual average for a car value of R$ 50,000.00 and R$ 4,200.00 for conversion cost (C)

[2] Mileage (m) of 1075.0 [km/month] (KBB, 2019)

[3] Mileage (m) of 4210.5 [km/month] (CNT, 2016)

Source: Own calculations; periods computed on the basis of (ABEGAS, 2018; ANP, 2019; CNT, 2016; INMETRO, 2010; KBB, 2019)

The payback period should be short enough for a faster return on investment and to compensate for the inconveniences associated with CNG, especially the reduced availability of refueling stations. Several studies consider that the payback period must be at most 3-4 years, with a period of 2 years or less being considered optimal in order to attract consumers (GREENE et al., 2005; JANSSEN et al., 2006b; KHAN, 2017d; YEH, 2007b). For this reason, the results indicate that RJ remains within the range considered optimal for the development of the CNG market (≤ 2 years). On the other hand, for the other Brazilian states, especially SP, the payback time can reach up to 3 years for a medium customer, reducing the desired benefits considerably. For taxi drivers, the advantages of opting for CNG are substantial throughout the country.

3.4. DISCUSSIONS

3.4.1. Lessons to learn for the development of the NGVs market

Competitiveness with liquid fuels

Some important factors should be noted on the ICMS taxes. In 2003, the manufacture and sale of flex-fuel vehicles (gasohol and hydrated ethanol) began in the country. In the following year, in 2004, SP approved the reduction of ICMS from 25% to 12% for ethanol, contributing to stimulate this type of vehicle and hydrated ethanol as a fuel. As a result, in February 2006, about 76.6% of the new vehicles sold already were flex-fuel (XAVIER, 2007), while in 2011 this number reached more than 92% (KOHLHEPP, 2010). Since then, consumers were able to supply their vehicles with ethanol when the price was attractive.

As noted in the results in Figure 16 and Table 6, the principal fuel with which the CNG competes economically is hydrated ethanol. The government's incentives largely explain the composition of the price of hydrated ethanol in Brazil to producers and consumers. The study carried out by Cavalcanti et al. (2012) indicates that the differentiated tax treatment applied to ethanol promotes successive gains in productivity and cost reduction along the ethanol chain.

It should also be noted that SP has a strong history of developing the sugar cane industry, as well as ethanol (KOHLHEPP, 2010). In 2019, SP accounted for approximately 51.8% of hydrated ethanol consumption in the country. Besides, 46.5% of the total ethanol production in the country was produced by SP, while not even 0.02% of the total was produced by RJ (UNICA, 2019). In this way, the lowest ICMS rate was a favorable policy for development of the ethanol industry in SP.

In this context, the lowest ICMS taxes for CNG observed in RJ prove crucial for improving ethanol competitiveness and for the superior expansion of the NGV market in the state. On the other hand, in SP, the existence of strong incentives to ethanol weakens the development of the CNG market. In this way, the prospects of the NGVs sector are directly linked to the political decisions and policies adopted since they can completely modify the scenario of competitiveness of conventional fuels against CNG. Likewise, for a transition to a low-carbon economy, higher taxes on gasohol are an effective strategy to stimulate these cleaner fuels.

Also, it is noteworthy that in 2018 there was an increase in the consumption of CNG and conversion to NGVs due to the truckers’ strike that occurred in the country (as seen in Figure 14 in SP). The truckers’ strike, motivated by a change in the pricing policy of Petrobras, hindered the supply of liquid fuels, leaving several gas stations short of gasohol and ethanol. As the pipeline infrastructure allowed the supply of CNG regularly during the strike period, there was an increase in consumers' perception of security of CNG supply (ABEGAS, 2018).

New Gas Market program

Petrobras was created in 1953 by Law nº 2.004 and represented the beginning of the oil and NG industry phase in Brazil, becoming the state monopoly in this sector. In 1997, the Petroleum Law (Law No. 9,478 / 1997) established a breakthrough with opening markets and attracting investments from private agents to the oil sector. However, there were no significant changes in the structure in the NG market, with Petrobras remaining the main dominant industry (MME, 2019). Until mid-2018 in the NG sector, Petrobras had a large presence in the main links of the chain, being responsible for 77% of production, for 100% of imports, for 100% of essential structures, for the entire capacity of the transport network and participation in all gas pipelines, that is, being responsible for most of the refining, transportation, marketing and distribution, showing the lack of competitiveness in the sector (CBIE, 2019; MME, 2019; ODDONE, 2019).

Based on in the scenario above mentioned, a new strategy was instituted in 2019 by the federal government with the creation of the Competition Promotion Committee of the Natural Gas Market in Brazil, with competencies to propose measures to stimulate competition in the NG market and recommend guidelines and improvements in energy policies. The proposals made by this Committee led to the approval of Resolution No. 16/2019 by the CNPE (National Energy Policy Council), which improved and established guidelines for energy policies aimed at promoting free competition in the NG market. From that moment on, the New Gas Market program (Novo Mercado de Gás) was created (MME, 2019). This program seeks to establish guidelines for energy policies that promote free competition in the NG market, intensify the unbundling of the NG chain, create the conditions for access to gas pipelines, develop and expand processing units and Liquefied Natural Gas (LNG) terminals, opening up the market and promoting effective competition (FGV, 2019a). The program is based on four main pillars: the promotion of competition, the integration of NG with the electric and industrial sectors, the harmonization of state and federal regulations and the removal of tax barriers. Thus, the aim is to create access to essential infrastructure, improve the transport system and stimulate competition (FGV, 2019b).

In Brazil, the price of NG is practically governed by the lack of competition in the supply of the molecule and transport, for this reason, the opening of the market will promote the growth of NG and the development of new gas distribution projects, covering more consumers, especially those in the interior of the country (ABEGAS, 2019b). Thus, the program will guarantee greater competition and the available infrastructure, with CNG being able to have a greater number of consumers and benefiting economically regarding other fuels. In this way, Petrobras still has decisive participation in the gas market. In the last years, the company started a new phase of investments prioritizing the development of NGV within cities through the use of CNG and LNG. However, a more competitive market is being built in the country, with new investments from third parties in production and infrastructure, providing the market with new and varied sources of supply (FIRJAN, 2019).

3.5. CONCLUSION AND POLICY IMPLICATIONS

The results found that state market incentives are fundamental for the continuous development of a transitional fuel such as NG. Some lessons learned can be highlighted:

- The great results in RJ were only possible due to the set of incentive measures that favored the use of NGVs in the state. It is learned that successful interventions through public incentive policies lead to the market's maturation and overcome the existing barriers (financial risk and infrastructure) to consumer adoption.
- The support of the NGV market are directly linked to two taxes in Brazil: ICMS and MVPT. While the ICMS tax impacts fuel prices, the MVPT impacts the technological cost of vehicles. The combination of these taxes results in economic advantages for the consumer who will have to carry out a cost-benefit analysis.
- Isolated from the federal government, Brazilian state governments have the power to influence the development of the fuel and vehicle market according to their interests. It is observed that the experience and results of the incentive policy for light-duty vehicles powered by CNG in these Brazilian states provide key lessons on which paths should be followed for the insertion of alternative fuels as biomethane or ethanol in the country effectively and current advent of heavy-duty vehicles powered by LNG.

3.6. REFERENCES

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4. FINAL REMARKS

The first article presented the importance of the interaction between the fields of technology, domestic fuel, and infrastructure. These three fields are integrated and support each other in some way. However, it was observed that the problem of dependence on foreign technology and fuel delayed and/or prevented the development of ethanol as a fuel in Brazil. In addition, the influence that foreign companies exerted over the country stimulated road transport and the automobile market and gave up government incentives for the production of national fuel. History shows that national fuel programs and subsidies were efficient during their lifetime. However, when these were abandoned, foreign pressure in a liberal context decimated the possibilities of developing national production.

The second article analyzed a vehicle adoption process from a more detailed perspective. Among the analyzed aspects of infrastructure, technology, and incentives, it is concluded that the tax policy and subsidies are one of the most effective tools for the development of natural gas as a fuel in the transport sector. Public policies on taxes and subsidies in the state of Rio de Janeiro were important for the success of natural gas, unlike in the state of São Paulo. In addition, the tariff advantages of ethanol and the costs of adapting cars made CNG less attractive in the state of São Paulo. This regional-scale analysis was important to observe the role that state governments play in encouraging or deterring a particular fuel development.

In this sense, what can we learn from the history of the Brazilian transport sector, rethinking new paths for a low carbon energy transition? To answer this question, we can combine two points, essential results of the articles. In the first one, it is noted that regardless of which fuel is used, the external dependence on technologies and energy resources is a problem to be faced in Brazil. The late technological development and lack of appropriation of Brazilian natural resources prevented us from developing a national fuel. In the second, we observe that in Brazil taxes and financial subsidies are the main tools that support the insertion of new transport technologies, new fuels and associated infrastructure. Throughout history, the premature extinction of these incentives has led to the failure to adopt these technologies, as seen in the case of the end of Proálcool and the development of NGVs in São Paulo.

The paths towards a less carbon-intensive energy transition are hampered when the country does not have its own technology and energy resources. Costs increase greatly with imports, preventing competition with existing technologies and fossil fuels. Thus, the Brazilian government needs to design and maintain policies to encourage clean technologies long enough for the Brazilian market to be protected and mature.

It is important to reflect on what type of energy transition Brazil is heading towards. Managing this new transition is the new challenge. How can history help in this process? For example, since 1980, in addition to climate change, other issues such as environmental awareness have been pushing for changes in the transport sector. Understanding the role of new forces in society is important to know how strong this aspect will be in the decision-making power of consumers in the search for energy alternatives. As a research gap, a study covering the period after the one addressed in this project (1989-2022), may bring new and valuable lessons for the modification of the Brazilian transport sector, since new dimensions may have emerged.

5. APPENDIX I

PUBLISHED SCIENTIFIC ARTICLES

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