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THIAGO LUIS FELIPE BRITO

UNDERSTANDING THE DIFFUSION OF ALTERNATIVE FUELS TECHNOLOGIES FOR TRANSPORT

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THIAGO LUIS FELIPE BRITO

UNDERSTANDING THE DIFFUSION OF RENEWABLE ENERGY TECHNOLOGIES FOR TRANSPORT

Dissertation presented at the Energy Graduation Program from the Institute of Energy and Environment from the University of São Paulo to obtain a Doctorate in Science.

Supervisor: Prof. Dr. Edmilson Moutinho dos Santos

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ABSTRACT

BRITO, T. L. F. **Understanding the Diffusion of Alternative Fuels Technologies for Transport**. 2019. 100 p. PhD Dissertation – Graduate Program on Energy, University of São Paulo, São Paulo. 2019.

This thesis brings together three individual studies that were produced by the author throughout his doctoral period. Each one provides quantitative parameters that seek to understand how the diffusion of technologies that use alternative fuels for vehicles occurs. In the first two, we studied a well-documented and widely discussed case in the literature: the National Alcohol Program, which started in Brazil in the 1970s. The first article uses an innovative variation of the Bass model to identify how financial incentives for the acquisition of ethanol and flex vehicles impacted on the diffusion of these technologies. The results allowed us to observe for the first time how the loss of consumer confidence contributed to the failure of ethanol technology in the early 1990s. At the same time, our results reinforced the importance of government incentives and self-sufficiency in the medium or long term. In the second article, we seek to understand how much the market share of vehicles is sensitive (elastic) to fuel price variations. The results point to cross-influence, mainly when gasoline and ethanol compete against each other. When flex-fuel cars enter the market, both its versatility and increased engine efficiency make it the dominant technology in a remarkably short period. These results provide relevant reflections for the suggestion of public and market policies for the diffusion of new technologies such as electric, hybrids and natural gas. The latter is the subject of study of the third article. We adopt the concept of the Blue Corridors - routes that enable the use of trucks with liquefied natural gas (LNG) through the installation of the necessary supply infrastructure. In the article, we elaborated different LNG distribution scenarios for the state of São Paulo and calculated the costs and the potential to reduce emissions. The results point to the centralised liquefaction model in the early stages of the project, which could eventually evolve to hybrid or local, as the technology diffuses. Our general conclusions demonstrate that our studies provided complementary and relevant interpretations of the adoption of alternative vehicle technologies.

Keywords: diffusion of innovations, market-share, ethanol and flex vehicles, blue corridors.

RESUMO

BRITO, T. L. F. **Entendendo a Difusão de Tecnologias de Combustíveis Alternativos para Transporte**. 2019. 100 f. Tese de Doutorado – Programa de Pós-Graduação em Energy. Universidade de São Paulo, São Paulo. 2019.

Esta tese reúne três estudos individuais que foram produzidos pelo autor ao longo de período doutoral. Cada um prove parâmetros quantitativos que buscam entender como ocorre a difusão de tecnologias que utilizam combustíveis alternativos para veículos. Nos dois primeiros, estudamos um caso bem documentado e amplamente discutido na literatura: o Programa Nacional do Álcool, iniciado no Brasil na década de 1970. O primeiro artigo utiliza uma variação inovadora do modelo de Bass para identificar como os incentivos financeiros para a aquisição de veículos etanol e flex impactou na difusão destas tecnologias. Os resultados permitiram, pela primeira vez, que observássemos como a perda de confiança dos consumidores contribuíram para a falha da tecnologia etanol no início dos anos 1990. Ao mesmo tempo nossos resultados reforçaram a importância dos incentivos governamentais e da obtenção de autossuficiência em médio ou longo prazo. No segundo artigo, buscamos entender o quanto a participação de mercado de veículos é sensível (elástica) às variações de preço dos combustíveis. Os resultados apontam para a influência cruzada, especialmente quando gasolina e etanol competem entre si. Quando os carros flex adentram o mercado, tanto sua versatilidade quanto o incremento da eficiência dos motores, o tornam a tecnologia dominante em um período consideravelmente curto. Estes resultados fornecem relevantes reflexões para a sugestão de políticas públicas e de mercado para a difusão de novas tecnologias como elétricos, híbridos e gás natural. Este último é o alvo de estudo do terceiro artigo. Nós adotamos o conceito dos Corredores Azuis – rotas que viabilizam a utilização de caminhões a gás natural liquefeito (GNL) através da instalação de infraestrutura de abastecimento necessária. No artigo, elaboramos diferentes cenários de distribuição do GNL para o estado de São Paulo, calculamos os custos e o potencial para redução de emissões. Os resultados apontam para o modelo de liquefação centralizada nos estágios iniciais do projeto, que eventualmente poderia evoluir para híbrida ou local, à medida que a tecnologia se difunde. Nossas conclusões gerais demonstram que nossos estudos proporcionaram interpretações complementares e relevante para a adoção de tecnologias veiculares alternativas.

Palavras-chave: difusão de tecnologias, participação de mercado, veículos etanol e flex, corredores azuis

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SUMMARY

1 INTRODUCTION

This work compiles the findings of three different papers that were developed by the author and his colleagues. Chart 1 shows the current status of those articles by the submission of this thesis final version. The overall objective of this set of studies is to quantitively analyse how incentive programs affect the diffusion of technologies for alternative fuel vehicle (AFV). We seek to understand the different manners of how variables such as price and tax incentives might impact diffusion or the market-share of a technology. As an illustration, we simulate the application of the particular policy for natural gas vehicles (Blue Corridor) to check whether if it fits the Brasilian reality and how it can benefit from the models proposed in this thesis.

Chart 1 – Status and Target Journal of each Article from this Thesis

Theme	Status	Journal
1. Diffusion model of vehicle technologies	Published	Energy Policy
2. Market share model of ethanol and flex cars	Under development	Energy Economics
3. Blue Corridor Simulation for São Paulo State	Published	Science of the Total Environment

Source: self-elaboration.

The first paper brings insights into how government incentives can accelerate renewable and cleaner vehicle technologies. It seeks to understand the influence of taxes on the diffusion of ethanol and flex vehicles in Brazil. It also brings some a historical overview of the Brazilian Alcohol Program and the cultural impact of technological diffusion. Thus, the parameters obtained in this study can serve as a starting point for estimating the spread of new technologies.

The second article approaches these same technologies by a market share analysis perspective. It brings insights on the elasticity of gasoline, ethanol, and flex vehicles with regards to fuel price. Both this and the previous study are complementary to each other, discussing the same technologies by different methodologies and variables.

The last article is a product of Project 25's team associated with the Research Centre for Gas Innovation (RCGI), in which the author has been part of since its kick-off. The author has contributed to the article's introduction and literature review, as well as the scenarios' premises and the final evaluation of the paper. The project's objective is to simulate the implementation of Blue Corridor (a route for road transport by natural gas heavy vehicles) in the State of São Paulo, Brazil. The paper discusses infrastructure costs and environmental impacts for the introduction of LNG trucks in Brazil. It also presents cartographical figures for the different proposed distribution scenarios.

The remaining sections of this introduction will present the general motivation for this work as well as some thoughts regarding the originality of these set of papers. Chapter 2 will discuss in more depth the theory and methodologies for the diffusion of innovations and market-share paradigm. The following Chapters (3, 4 and 5) follow a typical article structure. They will expose the outlines and relevant literature review for each paper developed but might differ from the published paper’s version due to the reviewer’s comments. Results and discussion might present additional information that was removed from the final versions due to space constraints. Despite each of these Chapters giving their conclusion, Chapter 6 will show the overall findings of this whole work.

1.1 The motivation for this Study

Environmental concerns about global warming and air quality have addressed motorised transport issues in developing countries where demand and access are increasing. In 2010, the transportation sector accounted for 23% of energy-related CO2 emissions (IPCC, 2014). The report emphasises that if countries do not promote more aggressive and sustained policies, transport greenhouse gas (GHG) emissions will be the fastest to increase. The Paris Agreement recognises the need for rapid GHG reductions to keep global average temperature increases below 2 ° C above pre-industrial levels (UNFCCC, 2015).

Developed countries are still responsible for promoting a significant replacement of their fossil fuel-based fleets such as biofuels, hybrids and plug-in electric and natural gas. In Europe, 96% of passenger cars use gasoline (gasoline) and diesel (ACEA, 2018), while in the United States, 84% of transportation energy consumption comes from these fuels (EIA, 2019). Market forces alone do not seem to be pressuring fast enough to diffuse and market share these technologies. Also, the diffusion of vehicles to alternative fuels faces uncertainties inherent in any innovation. Costs, compatibility issues and complexity of new technologies are all risks to be assessed from the consumer's perspective (ROGERS, 2003).

In Brazil, gasoline and diesel account for a smaller share of the energy consumption in the transportation sector - almost 77%. This scenario happens due to the country's extensive experience with alternative fuel vehicles, encouraged by the National Alcohol Program (Pro-Alcohol), a policy created in the late 1970s that sought, among other issues, to protect consumers from oil price shocks by promoting an alternative liquid fuel for sugarcane for cars (MOUTINHO DOS SANTOS; PARENTE, 2006). Although not designed to address environmental issues, the program has become part of the country's strategy to reduce the use of fossil fuels for transportation. Both ethanol vehicles and flex cars have benefited from various incentives at different stages of the program to compete with gasoline (COELHO et al., 2006; MOREIRA; GOLDEMBERG, 1999).

The inclination in the use of biofuels has been a natural choice for Brazil. However, some studies suggest that competition with biofuels is a barrier to the entry of other technologies (BENVENUTTI; RIBEIRO; URIONA, 2017; ISABELLA et al., 2017; RODRIGUES; LOSEKANN; SILVEIRA FILHO, 2018). Battery-powered (plug-in) and hybrid electric vehicles, as well as hydrogen, which have been viewed in many countries as sustainable alternatives, have not yet found their place in the Brazilian automotive market. Natural gas, known as CNG, has good penetration in specific niches, especially for taxis, but for heavy vehicles such as buses and trucks, the gas is still restricted to initial studies and pilot tests.

The CNG literature points to three main benefits for its use: improved human and environmental health (ANDRÉ et al., 2019; GALBIERI et al., 2017), lower economic impact (BRITO et al., 2017a; MOUETTE et al., 2019) and greater energy security (PEREGRINO et al., 2001; YEH, 2007). Natural gas vehicles produce less toxic pollutants than diesel-powered cars (OSORIO-TEJADA; LLERA-SASTRESA; SCARPELLINI, 2017).

On the topic of pollution, according to the Environmental Company of São Paulo - (CETESB, 2015), the truck fleet in 2013 had more than 435,000 units, accounting for only 3% of circulating vehicles in the state (over 14.8 million). However, trucks are responsible for the emission of more than 13,300 tons of CO_2 equivalent, about a third of the total issued in 2013 and most of the nitrogen oxides emissions (47% from a total of 109,500 tons), particulate matter (60% from a total of 3 tons) and sulphur oxides (44% from a total of 8.6 tons) in the same year.

At least 100,000 deaths and 70,000 hospitalisations for respiratory complications are attributed to these and other pollutants, throughout the state of São Paulo between 2006 and 2011 (VORMITTAG et al., 2013). Since many Brazilian highways are near major urban areas, it is possible to establish a relation between road transport and air quality in cities. The source of these emissions is diesel oil (with a small blend of biodiesel), the primary fuel used by this kind of vehicles. Thus, the adoption of cleaner fuels can bring a substantial improvement to human health and greenhouse gases mitigation.

However, the adoption of natural gas in vehicle (NGV) fleets face specific challenges that are context-sensitive and not easy to overcome (BRITO et al., 2017b). Many approaches have tried to promote NGV, but the most successful one is the Blue Corridor Concept[1], which is a route for road transport by natural gas vehicles. Natural gas for heavy-duty (HDV) vehicles has already gone through a series of attempts in Brazil. However, except for a few demonstration vehicles, the country's natural gas-powered HDV fleet is inexistent. Many projects have tried to establish a relevant fleet in the country but have failed due to legislation barriers, economic unfeasibility or technical problems.

Now the challenge is how to spread this technology, once it has been proven feasible. Diffusion of Innovations is a complex social phenomenon that does not rely only on straight-forward variables. Elements such as the structure of a social system, individual's perception of new technologies and the communication channels have a significant impact over diffusion. The Blue Corridor Project, which has been in operation in Europe for more than a decade, already presents some results that will be able to help this research. Also, understanding the variables that impacted previous vehicle technologies, such as ethanol and flex vehicles, under the Brazilian Alcohol Program (Pro-Alcool), does bring meaningful insights on how they might diffuse and penetrate in the country's market. Nevertheless, the widespread of biofuels in Brazil might pose a barrier to the diffusion of other technologies such as natural gas and electric vehicles

1.2 Originality

This thesis brings three different studies. The first two (Chapters 3 and 4) analysed the diffusion and the market share elasticity, respectively, of ethanol and flex vehicles in Brazil. These technologies have not yet been studied under such methodological frameworks. The first one evaluates the impacts of taxes incentives, while the second analyses the fuel prices. The articles offer different perspectives for understanding the adoption of such technologies in Brazil.

Altogether, these studies offer quantitative parameters to evaluate diffusion and market behaviour of these technologies. A country-wide policy known as the Alcohol Program (*Pro-Álcool*) boosted the ethanol and flex vehicles sales by reducing taxation, as well as ensuring competitive fuel price against gasoline. These articles test each one of these variables by applying different methodologies in order to quantitatively evaluate and provide a historical interpretation for the Program's achievements. By shedding this light on effective policies, we

[1] The "blue" is a reference to the flame caused by methane's complete combustion (the main component of natural gas), which is clean and stable.

seek to study further programs for the promotion of alternative fuel vehicles such as electric, hydrogen and natural gas.

The Blue Corridor Project is a cutting-edge initiative to encourage the use of natural gas in heavy-duty vehicles, such as trucks (Chapter 5 presents an in-depth revision of the European project). However, despite showing significant developments in Europe, where a cohesive institutional structure advocates in favour of natural gas as transportation fuel, this concept is relatively new in Brazil. Besides the article reported in Chapter 5, the only other study, and the first of such kind in Brazil, was developed by ALMEIDA et al. (2005). They demonstrated that a relatively modest investment could enable compressed natural gas (CNG) infrastructure in cities around South America. Their estimations have indicated that the construction costs of 34 CNG refuelling stations and vehicle conversions could range from 89 to 136[2] million BRL. Besides these investments, the feasibility of the project would require substantial governmental support to reduce direct taxes and ensure competitive price against diesel oil.

Our study revisits the Blue Corridor concept and follows the same assumption as Almeida et al. (2005), in which a project of this kind could be a catalyst for manufacturers to produce dedicated CNG vehicles. Since the publishing of their study, the concept has benefited of several improvements, the main one being the increased focus on LNG instead of CNG. The coordinators of the European Blue Corridor project have concluded that in the case of heavy-duty trucks, LNG is much more feasible both technically and economically (LEBRATO; RIBAS, 2012).

Differently from the previous studies, the availability of data for natural gas vehicles is still limited, thus impeditive of a diffusion or market share analysis of a Blue Corridor. For this reason, we adopted a similar approach as Almeida et al. (2005), by estimating costs and emission mitigation, while considering the new developments of the Blue Corridor concept, as shown by Lebrato and Ribas (2012), and the European Comission (2017). We simulated scenarios for São Paulo State in Brazil, but the scale of our study is also considerably smaller than the studies as mentioned above.

Chapter 6 establishes the link among all the main findings from the conducted studies and bringing some lessons for new technologies, inspired by the experience with ethanol and flex vehicles in Brazil.

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[2] From 35 to 54 million USD, in 2005 conversions rates.

2 THEORY AND METHODS

Different approaches seek to study the adoption of innovations. Overall, studies seek to understand how technology changes or improves over time (new patents registration) and how consumers get information about them. The models adopted for this study latter described in this section, are based on the social learning theory, which assumes that new behaviours and practices acquired through the process of observation and imitation (BANDURA, 1971).

Ahead, in section 2.1, we present a brief review of the most important concepts regarding this framework's paradigm. Later, in section 2.1.1, we describe the basic definitions of the model adopted in the article (Chapter 3 discusses further developments of the model). Similarly, but for the study reported in Chapter 4, section 2.2 presents a review of the Market Share Analysis and some of its application in the literature. Section 2.2.1 describes methods used for estimating the market share elasticity of AFVs with regards to fuel price. The third article does not require any previous explanation because Chapter 5 includes additional information to the one exposed in the published paper that covers its theoretical and methodological framework.

2.1 Diffusion of Innovations

Everett Rogers (ROGERS, 2003) first presented this theory as a demand-side explanation of the reasons and how innovations diffuse through a society (VISHWANATH; CHEN, 2011). The first edition of his book, in 1962 was more a compilation of the incipient diffusion theory by that time in the United States, which already accounted for roughly 400 publications. These numbers grew as more researchers learned about and contributed to the framework.

Rogers' (2003, p. 5) main statement of his theory is that "diffusion is the process in which an innovation is communicated through certain channels over time among the members of a social system". Hence, it is a particular type of communication because it seeks to exchange messages about new ideas, which can spread spontaneously or in a planned manner. Also, diffusion is a form of social change since the adoption or rejection of new ideas leads to some consequences. For this reason, newness causes uncertainty because one cannot predict what will be these consequences (VISHWANATH; CHEN, 2011). Also, innovations may conflict with society's values. So, individuals who are about to make decisions seek information to reduce uncertainty, which may provide new perspectives over a set of choices (ROGERS, 2003). When risk reaches an upper or lower threshold, individuals then decide to whether adopt or reject an innovation.

Four main elements compose the diffusion of innovations, all of which present in Rogers' (2003) statement. The first element is the innovation itself, or more specifically, the potential adopter's perception regarding it. Something can be perceived as new by a unit of adoption by the time it was noticed, independently of when it was 'discovered' or first used. Thus, innovations exist as such, not only when a given individual knew about it, but also when he/she/it decided to adopt it. Nor it has to be desirable, since they may be harmful, uneconomical or unsuitable for specific consumers or situations (ROGERS, 2003).

From a potential adopter's perspective, five attributes define an innovation. The relative advantage measures how new technologies are better than the ones they supersede, which are not always objective but related to the user's perception of economic, social prestige, convenience or satisfaction. A compatible innovation is one that is consistent with the existing structure, values, past experiences and the need of the potential adopters. Trialability refers to the innovation's capacity to be tested and experimented, hence reducing uncertainties. When it is easy to observe or to spread the results and consequences of an already adopted innovation (observability), individuals will feel more likely to discuss it within their peer-to-peer networks. Finally, adopters will generally prefer less complicated ones, since it would require less effort to understand and to learn how to use it – intuitive technologies are more likely to be adopted (ROGERS, 2003).

Islam (2014) describes how these attributes are relevant for adopters in his study about photovoltaic (PV) solar cells in Canada. According to him, the diffusion of this technology is slow due to its cost and incompatibility with energy systems, despite its environmental benefit. Based on household-level preferences, he developed a prediction diffusion model where these preferences served as antecedents for the parameter definition, such as technology and energy conservation awareness, as well as socio-demographic indexes. The model's results have shown that innovativeness of households is deeply related to higher awareness level and costs sensitivity (comparative advantages and complexity), while imitation relates to the potential cost savings, rewards for exported energy and neighbourhood adoption (relative advantages, compatibility and observability). This research concluded that education campaigns for the adoption of PVs should focus on investment criteria, feed-in tariffs and environmental impacts, besides the explanation of technology itself.

The second element of diffusion of innovations is the communication channels. Communication is an information creation and sharing process among a group to reach a mutual understanding. Therefore, it must involve a) an innovation; b) an individual that has knowledge or experience regarding this innovation; c) another one that does not have; and d) a communication channel, how the message goes from b to c. Mass media channels, such as TV, radio, newspapers, are essential means of diffusion since it can reach many individuals to create awareness-knowledge, but it hardly persuades people to adopt an innovation. On the other side, interpersonal channels may prove more effective influence potential adopters, mainly if they correspond to the same social group (social, economic, education, interests). Finally, the advent of the internet has allowed a mix of mass media and interpersonal through interactive communication (ROGERS, 2003).

Time is the third element and refers to several aspects of the diffusion process. The innovation-decision process is the period between the knowledge of the innovation to the decision to adopt or reject it. It is an information-seeking and processing activity to reduce uncertainties and may vary widely among individuals. Although some agents can force the adoption of innovations (inside companies, for example), when individuals have the freedom to choose, they will usually go through this information seeking process.

Finally, time also measures another aspect of diffusion: the system's innovation rate, which is the speed by which a system adopts an innovation. The resulting distribution of any given successful technology (by plotting cumulative frequency over time) is an S-shaped curve (ROGERS, 2003). Studying such a curve can bring researchers some light on an innovation's rate of adoption (take-off point) and to what extent has it achieve full diffusion on a social system or market.

Individual behaviour only cannot explain many aspects of diffusion. Social systems are formed by a set of interrelated units (individuals, informal groups, organisations and other subsystems). These units engage in accomplishing a common goal. The sharing of this goal is what binds them together. The social structure of a system allows an estimation of its participants' behaviour due to its norms. Norms serve as a guide or standard for the system's members and prescribe what behaviour individuals are expected to perform (ROGERS, 2003). Hence, they may help or pose barriers to diffusion.

Chart 2 – Innovation Adopters Categories Definitions

Adopter category	Definition
Innovators	Innovators are willing to take risks, and usually have the highest social status, financial liquidity, and a better understanding of new technologies scientific bases as well as close interaction with other innovators. Their tolerance to risk allows them to adopt technologies that may eventually fail.
Early Adopters	Early adopters have a high degree of leadership as well as higher social status, financial stability and advanced education. They are more resistant to adoptions than innovators because they usually are more judicious and tend to choose the option that will help them maintain a central communication position.
Early Majority	Early Majority takes a considerable amount of time to adopt an innovation. Most of the time, they are a little above average social status, but they rarely occupy opinion leader positions. Nevertheless, reaching the early-majority status is often considered the most critical step of successful innovations.
Late Majority	Member of this category approach an innovation with a high degree of scepticism and after the majority of society has adopted it. Late Majority are usually dubious about new technologies. Their average social status implies that they have limited financial resources and are, thus less acceptable to risk.
Laggards	Laggards are the most resistant group to adopt innovations. Most times, it happens because they hold stronger to traditions, or because of low social and economic levels. Advanced age also seems to characterise most laggards. They usually only adopt new technologies when they are the only option left.

Source: Rogers (2003)

In this context, innovative adopters may be perceived as deviant and will be faced with low credibility, unless they are opinion leaders or change agents. While the former are individuals who can influence others due to their position within the social structure, the latter is more like professionals who act together with them. Opinion leadership does not necessarily represent a formal position or higher status, but it is instead acquired and maintained by technical competence, social accessibility and conformity to the system's norms. As shown in Chart 2, opinion leaders are fundamental for the adoption of innovations, because they often occupy a high and central position in the communication channels and networks. However, opinion leaders can be innovative or conservative, and since a system will often have both of them, new ideas always struggle against oppositions.

2.1.1 Diffusion Model

Frank Bass has firstly presented his model in a paper published in 1969. Although he used the term 'new product' instead of technology or innovation, the approach is very similar, and researchers from different areas prefer their nomenclature (i.e. marketing studies prefer the term new product; while social scientists prefer innovation). Likewise, Bass Model, most models were developed in the 1970s and then received contributions from various authors to add, modify and make them more flexible (MEADE; ISLAM, 2006).

The model assumes that the number of acquisitions at a time *t* is determined by the previous number of buyers (BASS, 1969), as shown in Equation (1), which generates a bell-shaped curve for annual sales.

$$f_t = p + \left(\frac{q}{m}\right) F_t \tag{1}$$

Where:

f_t is the density function of sales at time t;

p is the coefficient of innovation;

q is the coefficient of imitation;

m is the total potential market;

F_t is the cumulative fraction of the potential achieved at time *t*,

Variables *p* and *q* represent the communication channels by which individuals become convinced to adopt an innovation. Most adoptions at the beginning of a diffusion process are due to mass media channels. As the number of adopters rises, interpersonal communication plays a more critical role in ‘spreading the word’. By the end of a successful diffusion process, most adoptions happened due to imitation, but without the innovators, diffusion would not even have started (MAHAJAN; MULLER; BASS, 1990; ROGERS, 2003).

Cumulative adoption (F_t) or saturation, given in the potential market share, can be obtained by Equation (2), which generates the S-shaped curve.

$$F_t = \frac{1 - e^{-(p+q)t}}{1 + \frac{p}{q} e^{-(p+q)t}} \tag{2}$$

The predicted time of peak (T*), is given by Equation (3) while Peak Magnitude (n_{T^*}), which represents the number of products sold in T*, is given by Equation (4).

$$T^* = \frac{\ln\left(\frac{q}{p}\right)}{p+q} + 1 \tag{3}$$

$$n_{T^*} = \frac{m(p+q)^2}{4q} \tag{4}$$

For the total number of sales, the Bass Model can also be expressed by Equation (5), which is the discrete analogue of Equation (1).

$$n_t = \frac{dN_t}{dt} = p \times m + (q-p)N_t - \frac{q}{m}N_t^2 \tag{5}$$

Where:

n_t is the number of products purchased in period t;

N_t is the cumulative product purchases until the beginning of period t.

Parameters *p*, *q* and *m*, can be estimated by the ordinary least squares procedure (OLS) (BASS, 1969; MASSIANI; GOHS, 2015; SATOH, 2001) since Equation (5) is a quadratic equation, in which yearly adoptions are a function of cumulative purchases. Thus, by calling: $\alpha_1 = p \times m$; $\alpha_2 = q - p$; and $\alpha_3 = -{}^{q}/_{m}$, parameters p, q and m are then estimated by Equations (6), (7) and (8), respectively, which use the quadratic equation's regression coefficients.

$$p = \frac{-\alpha_2 + \sqrt{\alpha_2^2 - 4\alpha_1\alpha_3}}{2} \tag{6}$$

$$q = \frac{\alpha_2 + \sqrt{\alpha_2^2 - 4\alpha_1\alpha_3}}{2} \tag{7}$$

$$m = \frac{-\alpha_2 - \sqrt{\alpha_2^2 - 4\alpha_1\alpha_3}}{2\alpha_3} \tag{8}$$

It is also possible to use an exogenous definition of the market potential (*m*). This practice is usual when researchers have little knowledge of the cumulative data or when assume specific scenarios, such as in Zhu, Tokimatsu and Matsumoto (2015). A study by Massiani and Gohs (2015) have compiled a wide range of *p* and *q* parameters estimation for different vehicle technologies and countries, which can serve as a comparison basis for modelling with little or no data.

Although the OLS is the simplest method for regression, it has been criticised in literature because it can lead to wrong signs (negative probabilities) and unstable estimates (MEADE; ISLAM, 2006). Besides these issues, Mahajan et al. (1990) also point out that OLS procedures do not provide standard errors for the estimated parameters and "there is a time bias due to discrete time-series data used for estimating a continuous model (i.e., the solution of the differential equation specification of the Bass model)" (MAHAJAN; MULLER; BASS, 1990, p. 9). For this reason, other methods like non-linear least square (NLS) and the maximum likelihood estimation (MLE) have been used, with superior performance than OLS.

Our article, presented in Chapter 3 proposes a variation to the standard Bass Model by approaching the diffusion of multiple generations of vehicle technologies. The model considers three generations and follows methods proposed by Norton and Bass (1987) as well as further developments by Danaher et al. (2001) and Stremersch et al. (2010). Section 3.4 describes in detail the changes and new formulas used for our model.

2.2 Market Share Analysis

In competitive environments, companies always care about their position within markets. According to Cooper and Nakanishi (2010), some managers appear to be more interested in their market shares than on profits or returns on investments. Thus, it is paramount that they have the knowledge to analyse and compare how changes in marketing variables might cause their firms to gain or loss of market share. Price and advertising are widely studied examples of how a product or brand market share might be affected. These changes are consequences the company's action, as well as from their competitors – a phenomenon called cross-effects.

By definition, market-share represents the sales amount (in quantity sold or currency volume) that a product, brand or firm has relative to the market, in a determined geographical area and historical period. In order to estimate the market share of a given product, besides its stake, one must also know the individual percentage of each of its competitors as well as the whole sum of sales. This kind of data, depending on the type of industry, is considered strategic and is hardly available for public access. However, some sectors, such as the automobile, have associations or governmental agencies that compile and track sales periodically. Our study, reported in Chapter 3 and 4 makes use of data from the Brazilian Automotive Industry Association (ANFAVEA, 2018).

An important concept to analyse market shares is elasticity, whose definition is "(…) the ratio of the relative change in a market share corresponding to a relative change in a marketing-mix variable" (COOPER; NAKANISHI, 2010, p. 31–32). However, elasticities are not constant over time. Also, we can observe that, in general, brands with large market shares are less responsive to changes (inelastic), and vice-versa. The elasticity approach also enables us to observe how a brand's market share might be affected by the actions of another. Thus, one could develop a model to study how sensitive a product's share is regarding its price, but also the competing products' prices. A broad literature, which we will present ahead, has already employed market share and elasticity models to analyse energy and transport technologies and products.

Studies have noted the importance of market share models to capture complementary and substitution effect between fossil fuel cars and renewable options. Fazeli et al. (2016) have used market share elasticity parameters to study inter-fuel replacement for space heating in Nordic countries by adopting autoregressive with exogenous variables and two-stage-least-square models. On a similar study, Sahi and Erdmann (1981) have estimated, through a top-down approach, market-share elasticities for fuel use in Canada's residential, commercial and industrial sectors. They identified that consumers are more sensitive to own, instead of a cross-price elasticity.

Market share models are useful for energy planning because they allow, among others, predictions for products penetration on households appliances (RADPOUR; HOSSAIN; KUMAR, 2017) and renewable electricity generation (LUND, 2010). Extant literature has found that policy interventions that affect the final price to the consumer's impact market share of alternative fuel vehicles. Endo (2007) points out the need for severe carbon (CO_2) taxes over conventional cars to increase the market share of hydrogen fuel-cell vehicles in Japan. Klier and Linn (2015) have observed that CO_2 charges do affect vehicle registration in some European countries in favour of cleaner technologies. Shafiei et al. (2014) have shown that combined increase of fossil fuel prices, carbon taxes and infrastructure investment could reduce half of Iceland's transportation sector by 2050.

Similar models also analysed the penetration of electric vehicles (NOORI; TATARI, 2016; RIESZ et al., 2016), but they have not estimated cross-elasticities. Diamond (2009) has studied the elasticity of hybrid electric vehicles (HEV) in the US, with regards to variables such as government incentives, gasoline price, travelled mileage and income. He found out that an increase of 10% in gasoline prices almost double HEV market share, which reflects the consumer's desire to be protected against future price variations. Also, he observed that HEV market share is inelastic to incentives due to their conceded way they – tax reductions are more effective than rebates or tax credits.

For Morais et al. (2017), the population size and income, mobility behaviour and governmental incentives determine the demand for cars. Thus, they employ a multi-channel attraction model to consider the cross-effects of advertising between brands when studying the automobile market in France from 2005 to 2015. Their results show a positive own-elasticity for a television advertisement for all brands. Nevertheless, the analysis of cross-elasticities has demonstrated that investing in different media, such as radio or outdoors, may increase the market share of some competitors.

Wei (2001) have used market share model to evaluate a range of industry (manufacturers and dealers) incentives to consumers to increase cars sales in Japan. Literature has widely employed such models to study vehicle consumers preferences (AL-ALAWI; BRADLEY, 2013; BROWNSTONE; BUNCH; TRAIN, 2000). These models can also estimate alternative vehicle's probability of being adopted with regards to variables such as household, drivers and vehicle characteristics (FENG; FULLERTON; GAN, 2013) as well as time, cost, performance, range and refuelling rates (EWING; SARIGÖLLÜ, 1998).

Studies show that price is a significant driver of renewable energy. Cohn (1980) have applied an MNL model and found that energy prices impact more the commercial sector's demand than the residential. Electricity has the highest elasticities for both areas regarding its own-price (-0.329 for commercial and -0.231 for residential in the short run). Natural gas and oil show the smallest response to variations in price cross-elasticity, which the author attributes to the lack of substitutes for electric uses in residences and commerce. Chern (1976) have used a linear market share model to show that each 1% increase in oil prices could reduce its demand by 1.6%, the highest among electricity and natural gas for residential and commercial sectors in the US.

Elasticity studies have evaluated price effects in fuel demand. Bakhat et al. (2017) results show low own-price elasticity for gasoline and diesel oil in Spain. Vance and Mehlin (2009) have found out that all German transport market segments are highly elastic with regards to circulation taxes and fuel costs. Burke and Nishitateno (2013) indicate that, in 43 countries, price elasticity of gasoline demand ranges from -0.2 to -0.5, and also has a positive relationship with the acquisition of more efficient vehicles. Klier and Linn (2013), through the use of a linear regression model, did not find evidence that fuel price can affect the market share of diesel vehicles, it does, however, increases the fuel economy of new ones. In a survey conducted in Indonesia, Irawan et al. (2018) concluded that hybrid cars could reach about 33% market share if their price is competitive with the traditional ones. Their results also suggested restricting vehicle age and removing the subsidies of fossil fuels can have a small, but still positive impact on hybrid cars market share. Next session will present the model we adopted.

2.2.1 Market Share Model

In the study present in Chapter 4, we adopted the market-share models, as described by Cooper and Nakanishi (2010). It is based on attraction models developed by Kotler (1984) and Bell et al. (1975), which assumes that the market share of a firm, brand or technology (in our case) is proportional to its marketing/attraction effort (CANTAMESSA; MONTAGNA, 2016). It can measure, for example, how much price, advertising expenditures and other variables related to the product would contribute to its attractiveness (MORAIS; THOMAS-AGNAN; SIMIONI, 2016). The market share analyses provide information on the competitive structure so that planners can draw appropriate strategies. Marketing variables (fuel price – in our case) affect each technology's share distinctively. This differential effectiveness measures the degree by which the products respond to changes in these variables. Equations (9) and (10) describe the attraction model for products market share.

$$A_i = exp(\alpha_i + \varepsilon_i) \prod_{k=1}^{K} f_k(X_{kit})^{\beta_{ki}} \tag{9}$$

$$s_{it} = \frac{A_{it}}{\sum_{j=1}^{m} A_{jt}} \tag{10}$$

Where:

s_{it} is the market share of technology *i* at time *t*

A_{it} is the attractiveness of technology *i* at time *t*

m is the number of technologies

X_{kit} is the value of the k^{th} explanatory variable X_k for technology *i* at time *t*

K is the number of explanatory variables

f_k is the log-normal transformation of *X*

α_i is the parameter for the constant influence of technology *i*

β_{ki} is the parameter for variable *k* effectiveness on technology *i*

ε_i is the error term

However, competing products and firms do not differentiate themselves only on their capacity to influence their sales, but on each other's as well. Thus, our model also considers the impacts of these cross-effects – e.g. how do changes on gasoline price affects ethanol and flex vehicle market shares? Two market-share models, Multiplicative Competitive Interaction (MCI) and Multinomial Logit Model (MNL) are widely used (COOPER; NAKANISHI, 2010). The predicted market share of a good in MCI model is defined by the product of all its marketing variables, weighted by their respective effectiveness constant, as shown by Equation (11).

$$\log\left(\frac{s_{it}}{\tilde{s}}\right) = (\alpha_i - \bar{\alpha}) + \sum_{k=1}^{K} \beta_{kij} \log\left(\frac{x_{kit}}{\tilde{x}_{kt}}\right) + \epsilon_i \qquad (11)$$

Where:

$\tilde{s}_t$ is the geometric mean of s_{it} at in period *t*

$\bar{\alpha}$ is the arithmetic mean of α_i

β_{kij} is the parameter for variable *k* effectiveness of technology *i* on technology *j*

$\tilde{x}_{k_t}$ is the geometric mean of the k^{th} explanatory variable at time *t*

Market-share data and fuel price went through the log-centred transformation to allow the use of linear-regression techniques to estimate the parameters of a non-linear model (COOPER; NAKANISHI, 2010). With these coefficients, we can calculate the product's market share elasticity regarding a given variable, as shown in Equation (12). If e_{s_i} is equal or higher than one, it means that technology *i* is elastic in relation to variable X_k, and inelastic if it is lower than one.

$$e_{s_i} = \beta_{kij} \times (1 - s_{it}) \tag{12}$$

In the case of the MNL model, the explanatory variables are mean centred. Equation (13) expresses the MNL model, while Equation (14) gives the elasticity.

$$log\left(\frac{s_i}{\tilde{s}}\right) = (\alpha_i - \bar{\alpha}) + \sum_{k=1}^{K} \beta_{kij}(X_{kit} - \bar{X}_{kit}) + \epsilon_i \tag{13}$$

$$\mathrm{e}_{s_i} = \beta_{\mathrm{kij}} \times (1 - \mathrm{s_i}) \times X_{kit} \tag{14}$$

The study reported by Chapter 4 applied both the MCI and MNL models directly. Differently from the diffusion study presented in the next chapter, we did not propose improvements to Cooper and Nakanishi's (2010) model; thus, ahead we show only the data and results of this study.

3 IMPACT OF TAX ON DIFFUSION OF VEHICLES TECHNOLOGIES

This Chapter presents the full text of the article submitted to Energy Policy under the title: "Transitions between Technological Generations of Alternative Fuel Vehicles in Brazil". The structure here follows the same one used in the final paper, but the published version contains changes suggested by the journal's editor and reviewers. We also made a few alterations to adapt the article to this thesis format.

Sub-chapter 3.1 will present the study's motivations and objectives. Sub-chapter 3.2 reviews some papers that approached the use of incentives for enhancing the diffusion of renewable technologies and alternative fuels for vehicles. Later, we present a historical overview of ethanol and flex in Brazil, along with policy and economic factors that contributed to such development. Sub-chapter 3.3 will describe the multi-generation diffusion model we have used in this study and explain our assumptions, limitations, and hypothesis. Section 3.4 presents data and sources we have used in our model and how we have pre-processed it. In Section 3.5, we show our model's results and discuss their implications. Finally, Section 3.6 will draft our conclusions and policy recommendations for the diffusion of future generations of AFV or other countries who wish to reproduce similar programs.

3.1 Introduction

The diffusion of alternative fuel vehicles (AFV) for transport faces uncertainty inherent of any innovation. Costs, compatibility issues, and the complexity of new technologies are all risks to be assessed from the consumer's perspective (ROGERS, 2003). In the case of transport, there is the imperative of reducing CO_2 emissions. In 2010, transportation accounted for 23% of energy-related CO_2 emissions according to the Intergovernmental Panel for Climate Change (IPCC, 2014). Their report emphases that, if countries do not promote more aggressive and continuous policies, emissions of transport greenhouse gases (GHG) would be the fastest to increase. The Paris Agreement recognises the need to undertake rapid reductions of GHG to hold the growth of global average temperature under 2ºC above pre-industrial levels (UNFCCC, 2015).

Past experiences, where technologies have gone through their full diffusion cycle, show how these policies may impact positively and negatively. A significant example found in the literature is the Brazilian Alcohol Program (*Pró-Álcool*). Officially established in 1975, its goal was to supply the internal market with an alternative liquid fuel to gasoline, thus reducing imports of oil products by producing ethanol from sugarcane (GOLDEMBERG et al., 2004; MOREIRA; GOLDEMBERG, 1999). It was Brazil's primary strategy to overcome the oil crisis from the 1970s. Despite the program's shortcomings during the 1990s, the rapid adoption of flex-fuel technology has enabled a rebirth of ethanol as a widespread vehicle fuel. Throughout its history, government support was an important variable.

Through diffusion studies, we can understand how a new idea or product spreads among a social system, such as a country or region, and which communication channels they use to reach each of its individuals (ROGERS, 2003). Nevertheless, social systems are complex entities where change agents (e. g. government, companies) can push or discourage new technologies among a pool of competing options. Some modelling frameworks have sought to study the diffusion of renewable energy technologies (RET) and AFV, but few have investigated the latter's relationship with government incentives and taken into account the interaction of successive generations of technologies.

Danaher et al. (2001) show that single generation models miss essential components of diffusion processes, especially when considering marketing factors. Thus, models that incorporate multiple technological generations can bring substantive insights into strategic and policy decisions. Norton and Bass (1987) argue that applying multi-generation models is plausible and historically accurate, with plenty of examples (e. g. in marine power, steam engines replaced ship's sail, and then it was substituted by internal combustion engines).

Our objective is firstly to understand the evolution of a successive generation of vehicle technologies associated with the Brazilian Alcohol Program, namely ethanol and flex-fuel; and secondly to investigate how government incentives (tax reduction) have affected the diffusion of such technological generations. The contributions of this paper are the extension of the multi-technology diffusion model by incorporating the effects of leapfrogging and marketing effects. We also include the acceleration of diffusion speed (ISLAM; MEADE, 1997) and social learning (i.e., imitation) on the diffusion of multi-generations of AFV.

For many authors, vehicle innovations are less likely to have a wide diffusion if supporting refuelling stations are absent; however, building costs are prohibitive if the scale is small (BRITO et al., 2017b; GNANN; PLÖTZ, 2015; KLOESS; MÜLLER, 2011; LEIBOWICZ, 2018; MEYER; WINEBRAKE, 2009). They consent that, in order to break this so-called chicken-and-egg dilemma, infrastructure must come first, and that is where government incentives are essential. We did not address this issue for ethanol in Brazil, because it follows a similar distribution chain to gasoline – however, we acknowledge that this issue is relevant for diffusion studies about non-liquid fuel technologies such as hybrid/plug-in electric, hydrogen, and natural gas.

3.2 Review of Literature

Innovation diffusion models have been used since the 1960s to study the diffusion of consumer goods, such as electronics and house appliances; farming techniques; drug consumption and many others (ROGERS, 2003). Traditional models generally assume that consumer innovativeness and social learning (imitation) are the main drivers of the diffusion process (BASS, 1969). Nevertheless, governments, companies or other change agents can also stimulate the spread of technologies. The following subsections discuss how literature has approached the diffusion of alternative fuel vehicles and how government incentives can promote them. We then present a brief history of the ethanol program in Brazil, along with technological innovations that contributed to its development to clarify the context of our study.

3.2.1 Innovation Diffusion of Energy Technologies

Single generation diffusion models have been used to study natural gas (ZHU; TOKIMATSU; MATSUMOTO, 2015), electric cars (CAO; MOKHTARIAN, 2004; WANSART; SCHNIEDER, 2010), and fuel cell (COLLANTES, 2007), solar PV systems (MASINI; FRANKL, 2002; PETER, 2002), and wind energy (IBENHOLT, 2002; RAO; KISHORE, 2009). These applications are usually one of three types: general spread, pricing a diffusion variable or forecasting. However, they focus on commercial products and few paid attention to policy impacts and interactions with successive technology generations (AL-ALAWI; BRADLEY, 2013; RAO; KISHORE, 2010).

Islam and Meade (1997) argue that rather than a radical innovation of the first generation, in most cases, successive technologies are less extreme but can bring significant performance improvements. They do not require the user to acquire considerable new skills, as observed in computers and electronics products. In this context, later adopters may prefer to purchase a more modern version of a product, without buying the earlier product, while early adopters will subsequently upgrade (MEADE; ISLAM, 2006). Part of the pool of potential adopters of the previous technology shifts to swell the pool of total potential adopters (NORTON; BASS, 1987; STREMERSCH; MULLER; PERES, 2010). Some authors used multiple generational approaches to study high technology products, such as computers and video games (SHI; FERNANDES; CHUMNUMPAN, 2014), cellular phones (KIM; SHON, 2011), memory chips (JUN; PARK, 1999; VERSLUIS, 2002), and milk containers (SPEECE; MACLACHLAN, 1992).

In the context of RET, Guidolin and Guseo (2016) employed a model incorporating competition and regime change to investigate the substitution of fossil and nuclear energy in Germany. They identified a high word-of-mouth influence on the diffusion of wind and solar power and confirmed that this model was the best option for the German case, where the predominant energy transition is directed to electricity production. Meade and Islam (2015) developed a model to study the impacts of 10 covariates on the diffusion of wind, solar and bioenergy in 14 European countries. The model provided relevant insights regarding such covariates, accurate forecasting densities and divided the countries into four groups concerning their rate of RET adoption (slow, normal, fast and very fast).

While studying substitution of internal combustion engines (ICE) vehicles by hydrogen and hybrid-electric cars, Struben and Sterman (2008) applied a dynamic behavioural model by introducing the willingness to consider the adoption of those vehicles. They point out that awareness and adoptions must pass given thresholds to allow a self-sustaining diffusion, and that a positive word of mouth effect might have a significant impact on lowering this threshold. Jeon (2010) modelled successive technologies for hybrid, plug-in hybrid and electric vehicles in the United States by applying a multi-generation diffusion model to capture the impacts of vehicle and gasoline price (NORTON; BASS, 1987). The study projected that these technologies could achieve 8 million sales annually by 2030. These studies are examples of the need to identify how AFV will fare amid the competition with conventional energy sources.

3.2.2 The Impact of Tax Incentives on Diffusion Rates

Despite the availability of financial and fiscal incentives, renewable energy technologies spread rates are still low, which is concerning in the face of the urgency posed by climate change and other environmental issues (RAO; KISHORE, 2010). According to Pfeiffer and Mulder (2013), diffusion of RET (except hydro) across 108 developing countries, from 1980 to 2010, has accelerated in stable and democratic regimes with high per capita income and schooling. Conversely, the probability of adopting RET has reduced if the country is a large producer of hydro or fossil energy sources.

Freitas et al. (2012) indicated that Kyoto Protocol mechanisms incentivised the increase of energy generation from renewables rather than promoted efficient and sustainable energy usage in BRICS countries (Brazil, Russia, India, China, and South Africa). Aguirre and Ibikunle (2014) suggest that some public policies fail to promote renewable technologies in BRICS countries because environmental concerns drive them, but the commitment to RET decreases under energy supply constraints.

Diffusion models have been used to study the effectiveness of government incentives in the photovoltaic (PV) sector in several countries. These studies suggest that incentives must be timed to coincide with the technology's diffusion stage as renewable technologies have a low innovation tendency (GUIDOLIN; MORTARINO, 2010). Studies further suggest that several policies such as feed-in tariffs, trust funds, specific lines of credit and the regulation of distribution tariffs for final consumers are necessary to effectively diffuse PV energy (FERREIRA et al., 2018; MUÑOZ; OSCHMANN; DAVID TÀBARA, 2007; PINTO; AMARAL; JANISSEK, 2016). In a review of 50 case studies throughout developed countries, Negro et al. (2012) indicate the necessity of stable long term, but flexible, incentives.

Governmental policy is regarded as essential for the successful diffusion of vehicle technologies, regardless of a country's development level. Jenn et al. (2018) concluded that in the US, for each $1000 incentive, electric vehicle sales rise by 2.6%. Lieven and Rietmann (2018) found that the number of charging stations magnifies the effect of monetary incentives on the diffusion of electric vehicles. Other studies also identified that economic stimulus has a significant and positive impact on electric cars diffusion rates (LANGBROEK; FRANKLIN; SUSILO, 2016; SIERZCHULA et al., 2014). Egbue and Long (2012) found out that the use of tax credits to subsidise the cost of EVs increases consumer confidence. Benvenutti et al. (2016) suggest that tax reductions are more effective when given to manufacturers than directly to car owners.

For the diffusion of hybrid electric vehicles in Brazil, Benvenutti et al. (2017) modelled a range of policy scenarios such as importation tax exemption, local tax reduction, ten-year federal tax exemption and a radical policy, which bans conventional combustion engine cars. Their results reinforced the importance of incentives, especially when combined. Similarly, Baran and Legey (2013) simulated the diffusion of electric vehicles in Brazil and its impact on energy consumption. They used exogenous parameters under different penetration scenarios and concluded that the Brazilian market is open to new technologies. The following historical overview corroborates these findings.

3.2.3 The Alcohol Program and Ethanol Vehicles

The choice for ethanol as an alternative fuel for gasoline had deep foundations in Brazilian history. The country had built up a 400-year tradition with the sugar-cane industry since its colonisation period, due to its favourable tropical climate, with abundant water and land availability (MOUTINHO DOS SANTOS; PARENTE, 2006). Since 1931, the federal government has authorised a 5% blend of anhydrous ethanol to imported gasoline, but until 1970, the industry used 70% of its production (PUGLIERI, 2013).

By the end of the 1970s, after petroleum prices had two consecutive sudden rises (on 1973 and 1979) – also referred as oil shocks (BRITO et al., 2012), Brazil has started its Alcohol Program to substitute gasoline-fueled passenger cars for ethanol ones (MOREIRA; GOLDEMBERG, 1999). Ethanol blend in gasoline has also increased to about 20% during this period, a mark that has been kept throughout history. Along with the oil shock, the national sugar industry was facing a crisis due to the collapse of this commodity's price in the international market. The creation of the Alcohol Program sought to give sugarcane producers a new commercial use for their crops, rather than only promoting the country's energy security (MOUTINHO DOS SANTOS; PARENTE, 2006).

The automobile industry, on its side, had a more recent development in Brazil (mainly after the 1950s), commenced by multinational companies such as Volkswagen, Ford, GM, and Fiat, who imported their oil-based technologies. By the start of the Alcohol Program, these gasoline engines had presented grave deficiencies regarding fuel pulverisation, an inadequate mixture of fuel-air control and corrosion when converted to run on pure ethanol (MOREIRA; GOLDEMBERG, 1999). The development of electronic fuel injection technology that substituted the carburettor during the 1970s was the innovation that allowed the use of ethanol as a complete substitute to gasoline in Otto-cycle engines, as well as a higher compression ratio engine made of corrosion-resistant materials (YU et al., 2010).

The first passenger ethanol vehicle registrations were in 1979 and significantly raised during the 1980s (ANFAVEA, 2018). By that time, the government had started to give incentives to ethanol producers and dedicated vehicles (COELHO et al., 2006; MOREIRA; GOLDEMBERG, 1999). Taxes over ethanol vehicles were about five percentual points lower than the ones charged over gasoline vehicles (ANFAVEA, 2018), and ethanol fuel price for final consumers was exempt from taxes. Confidence in technology has also played an essential role in the Program's success since it carried a nationalistic aspect (MOUTINHO DOS SANTOS; PARENTE, 2006).

The first shortcoming for the ethanol came in the 1990s. From 1989 to 1992, Brazil experienced an ethanol shortage because sugarcane farmers decided to shift their production to sugar, whose price had become more competitive than ethanol (PUGLIERI, 2013). This period is called the first ethanol shock, which coincided with the oil 'counter-shock' when oil prices returned to competitive levels. Fuel price ratio (ethanol's price compared to gasoline) went, on average, from 62%, during the 1980s to 77% during the 1990s

This situation has frustrated consumers that bought ethanol vehicles as a means to prevent themselves against oil products price raise, such as in the 1970s (MOUTINHO DOS SANTOS; PARENTE, 2006). Moreover, the government started to give incentives to low cylinder displacement vehicles (popular cars), targeted for low-income and middle-class population (BASTIN; SZKLO; ROSA, 2010). Ethanol vehicles sales have systematically decreased during this period, which exposed that ten years after the launch of ethanol car, it was still dependent on government incentives (MOREIRA; GOLDEMBERG, 1999).

Regardless of sales drops, the government has kept high levels of ethanol blending with gasoline, since the former works as an efficient additive. Mixtures of up to 20% ethanol were allowed by the government. Such policy sustained the Program since it allowed the producer's security against international sugar prices volatility and long-term stable ethanol production (GOLDEMBERG; COELHO; GUARDABASSI, 2008).

Environmental concerns expressed by the Kyoto Protocol brought a new perspective to ethanol as a mean of reducing carbon dioxide (CO_2) emissions (MOREIRA; NOGUEIRA; PARENTE, 2005). This new phase of the Brazilian Alcohol Program, marked by the Petroleum Law in 1997, has started a series of liberalisation policies and expansion of cogeneration and electricity commercialisation with sugarcane bagasse, which increased ethanol's competitiveness (GOLDEMBERG et al., 2004; PUGLIERI, 2013). By early 2000s, a new sudden rise of oil prices along with Kyoto Protocol's rising number of ratifications have turned the world's attention to biomass as a vital source of renewable energy (MOUTINHO DOS SANTOS; PARENTE, 2006). By this period, Brazil has used its expertise to become a leader in international clean fuels discussion and a lead exporter by 2004, since a new technological development gave a fresh breath to use of ethanol as a vehicle fuel.

3.2.4 Flex-Fuel Technology

By the 1980s, researchers from the US and Brazil were testing an engine that could operate on all blends of gasoline and ethanol (PEFLEY et al., 1980). The technological breakthrough was the development of a software sensor installed into the electronic injection module that could measure each fuel concentration and automatically adjust the engine's components (TEIXEIRA, 2005; YU et al., 2010). In the US, these engines can use only up to 85% ethanol, since it may have problems on cold start (BASTIAN-PINTO; BRANDÃO; DE LEMOS ALVES, 2010). The Brazilian system, however, memorises the last composition regardless of its concentrations; thus it can burn any ethanol/gasoline blend or any one of them separately (COELHO et al., 2006; MESQUITA et al., 2013; TEIXEIRA, 2005).

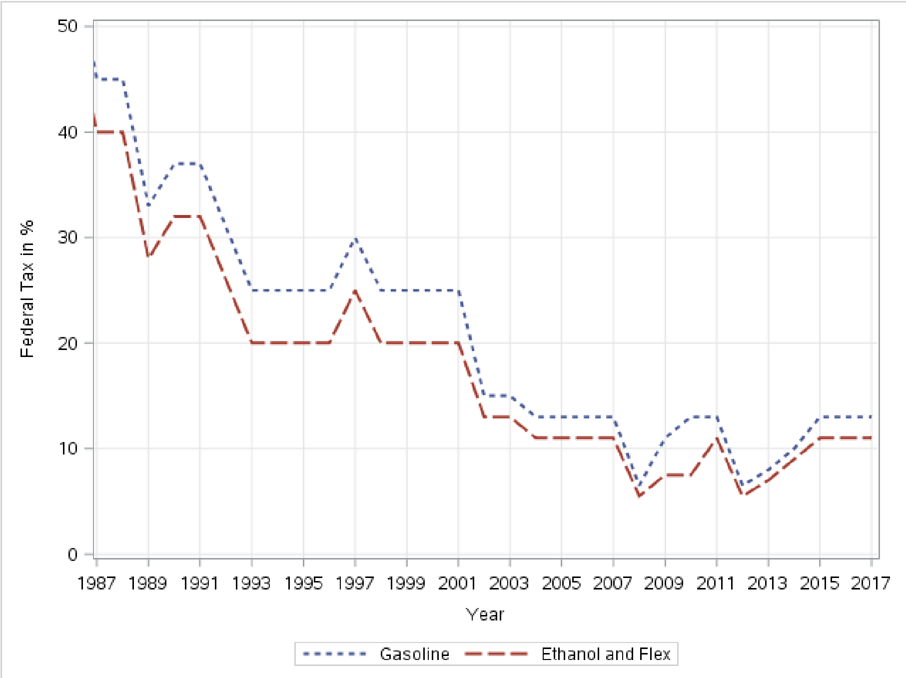
The first flex vehicles were registered in the Brazilian market by 2003 under the same taxation applied to ethanol ones. Sales took off quickly, and in only three years, flex cars corresponded to more than 90% of the market share. Different from ethanol, flex sales have been kept dominant since 2006, and now are the mainstream vehicle technology in the country. By the time of its launch, there was some concern about fuel efficiency. Nevertheless, current figures point out that flex technology, when using gasoline, shows equivalent consumption to single fuel vehicles and, when burning ethanol, had an increased efficiency by roughly 40%, compared to its initial models (CETESB, 2017). Ethanol and flex vehicles presented both economic and technological improvements over gasoline vehicles. From the consumer's perspective, the flexibility of choosing which fuel is a relative advantage regarding older technologies.

As shown, the total flex technology available in Brazil was only possible due to previous knowledge obtained through the experience with dedicated ethanol vehicles. We then consider that ethanol and flex technologies represent new technological generations over gasoline. Also, the Brazilian Alcohol Program is a long-term policy that sought to promote technologies by, among others, reducing taxation over them. Given these premises, we check the impact of government incentives by developing a multigeneration diffusion model, described ahead.

3.3 Data Description

Before we discuss our multi-generation model of the Brazilian vehicle market, we will first describe the data available for analysis. The main covariate in this study is the Tax over Industrialized Products (IPI), a Brazilian federal tax applied to any manufactured national or imported product which is modified by governmental decrees. Each product has a different rate based on the incentive or restriction the government intends to promote. Since IPI taxpayers are wholesalers and retailers, the tax rate has a direct impact on the final product price. Current rates are available at the Brazilian Ministry of Finance (MF, 2018); however, a historical series is not available. The Brazilian Automotive Industry Association (ANFAVEA, 1994, 2018) has collected data for the tax rate applied to gasoline and ethanol/flex passenger vehicles of 1 to 2-litre engine capacity; these figures are available from 1987 for both gasoline and ethanol vehicles. For years without a tabulated rate, we extrapolate it based on the last observations, see Figure 1.

Figure 1 – Federal Taxes Over Passenger Vehicles



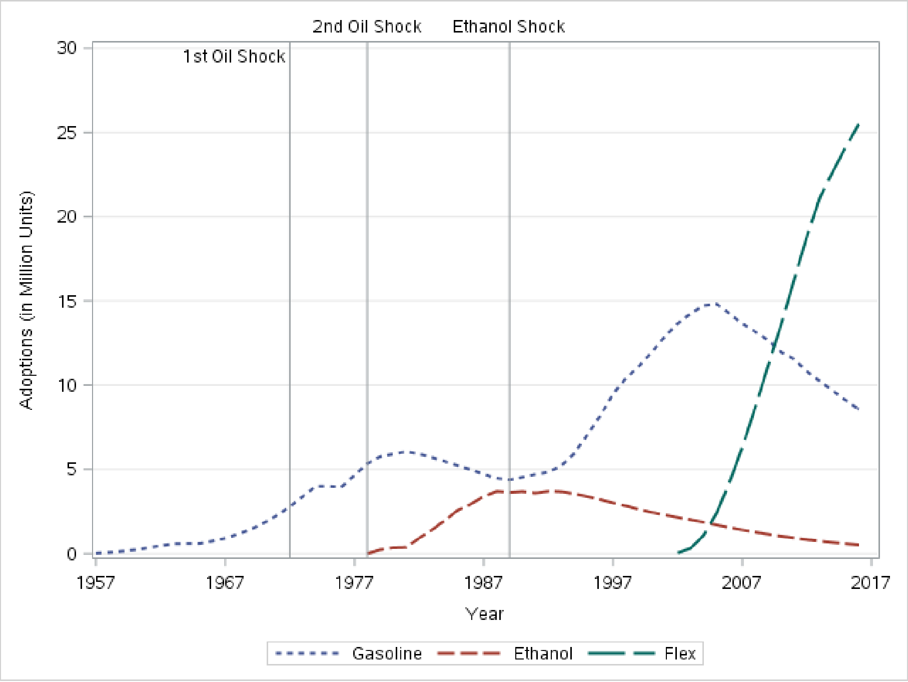
Source: ANFAVEA (2018)

We obtained vehicle sales data from the Brazilian Automotive Industry Association (ANFAVEA, 2018). However, since cars are durable goods with a finite life span, we must consider the fleet size and its composition to distinguish real year-by-year new adoptions from replacement purchases. We apply a scrapping curve, a statistical estimation of vehicles removed from the fleet due to total loss accidents, theft without recovery, dismantling and abandonment. Studies showed that a Gompertz function could express vehicle scrapping (ANDERSEN; LARSEN; SKOVGAARD, 2007; CETESB, 2017; ZACHARIADIS; SAMARAS; ZIEROCK, 1995), which shown in Equation (15).

$$S_t = 1 - exp(-exp(a + bt)) \tag{15}$$

Where S_t is the surviving fraction of vehicles, t years after purchase. Both a and b values were parameterised for cars (1.798 and 0.137, respectively) using the Brazilian National Household Sample Survey (IBGE, 1988; MMA, 2014). By applying this scrapping curve to the vehicle sales data, we estimate each year's operating fleet, its growth and composition. In Figure 2, we see the estimated fleet sizes of gasoline, ethanol and flex vehicles plotted over time, the two oil shocks and the ethanol shock are also shown.

Figure 2 – Cumulative Adoptions



Source: Estimated with data from ANFAVEA (2018)

We see that the growth in the size of the Brazilian gas vehicle fleet slows in the mid-1970s as a consequence of the first oil crisis, followed by a recovery. In 1979, ethanol vehicles were introduced; in 1985, their sales represented more than 95% of total vehicle sales; in 1986, their sales peaked at almost 700 thousand units. After the ethanol shock, at the beginning of the 1990s, growth in gasoline vehicle sales resumes, and ethanol vehicles sales drop to less than 1% of new cars. Flex-fuel vehicle adoptions in Brazil started in 2003 and overtook gasoline vehicle sales in only two years. Since 2007, flex-fuel has a yearly market share of about 90%.

3.4 The Multi-Generation, Multi-Country Model and its Estimation

In order to capture the changing dynamics of the Brazilian vehicle market and the effects of the changing fiscal environment, we propose a multi-generation model in discrete time which draws on the generalised Bass model (BASS; KRISHNAN; JAIN, 1994). There are several alternative models for single generation diffusion processes (MEADE; ISLAM, 2006, 2015); however, unlike the Bass model, these do not typically generalise to multiple generations. Massiani and Gohs (2015) point out the difficulty of choosing adequate parameters for a Bass Model of the diffusion of automotive technologies. They find that most studies present a wide range of estimated parameters that show no pattern and thus cannot be adopted reliably in future studies. We address this issue by applying a multi-generational model that can estimate different parameters for newer technologies substituting for earlier ones.

3.4.1 The multi-generational model structure

We consider three generations, denoted by the subscripts G, E and F, for gasoline, ethanol and flex respectively. At time *t*, the fleet sizes or numbers of cumulative adopters in each generation are Y_{Gt}, Y_{Et} and Y_{Ft}. An increase in fleet size may occur due to a fresh adoption, denoted by A_{Gt}, A_{Et} and A_{Ft}, alternatively a change will occur due to an adopter upgrading from one generation to another. Upgraders from gas to ethanol are denoted by U_{GEt}, from gas to flex, U_{GFt}, and from ethanol to flex U_{Eft}. Thus, the gasoline vehicle fleet size at time *t* is

$$Y_{Gt} = A_{Gt} - U_{GE,t} - U_{GF,t} \tag{16}$$

We denote the period to period change using lower case, e.g. $y_{Gt} = Y_{Gt} - Y_{Gt-1}$, thus it follows that

$$y_{Gt} = a_{Gt} - u_{GE,t} - u_{GF,t} \tag{17}$$

The ethanol vehicle fleet size at time *t* is

$$Y_{Et} = A_{Et} + U_{GE,t} - U_{EF,t} \tag{18}$$

and the period to period change is

$$y_{Et} = a_{Et} + u_{GE,t} - u_{EF,t} \tag{19}$$

Thirdly, the flex vehicle fleet size at time *t* is

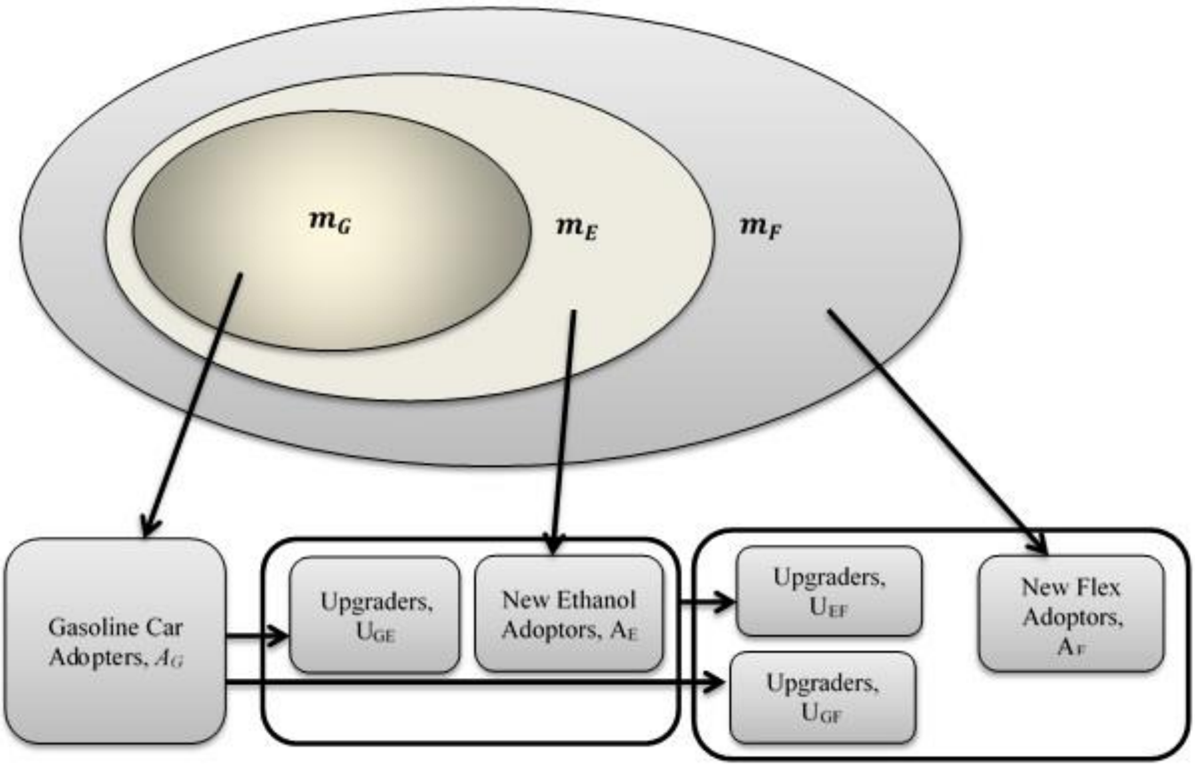
$$Y_{Ft} = A_{Ft} + U_{GF,t} + U_{EF,t} \tag{20}$$

and the period to period change is

$$y_{Ft} = a_{Ft} + u_{GF,t} + u_{EF,t} \tag{21}$$

We hypothesise that there are m_G potential adopters of the gasoline car, those who would eventually adopt a gasoline vehicle if no alternatives became available. There are m_E additional potential adopters of ethanol vehicle and m_F incremental adopters of a flex vehicle. Figure 3 illustrates the dynamics of this multi-generation adoption process.

Figure 3 – Flow Diagram of the multi-generation adoption process



Source: Adapted from Stremersch; Muller and Peres (2010)

In our study, we were able to observe only the cumulative number of current adopters of each generation, Y_{Gt}, Y_{Et} and Y_{Ft}, the adopters of gasoline, ethanol and flex cars respectively. In equations (16), (18) and (20), we hypothesise that these observable variables aggregate six underlying, but unobserved, adoption processes: A_{Gt}, A_{Et}, A_{Ft}, U_{GEt}, U_{GFt}, U_{Eft}. The total number of potential adopters for gasoline vehicles is m_G; for ethanol vehicles is $m_G + m_E$, and for flex vehicles is $m_G + m_E + m_F$.

The approach of the discrete generalised Bass model (BASS; KRISHNAN; JAIN, 1994) is that the number of adopters in a time interval is a random variable determined by the conditional probability of adoption and the number of possible adopters, with an additive noise term as shown for the gasoline generation in (22).

$$a_{Gt} = \left\{\left(p_G + q_G\left(\frac{Y_{G(t-1)}}{m_G}\right)\right)x_{Gt}\right\}\left[m_G - Y_{G(t-1)}\right] + \varepsilon_{Gt} \tag{22}$$

Considering gasoline cars before the introduction of ethanol cars, the number of adoptions of gasoline cars per period at time t is $\tau_G \leq t < \tau_E$. The Bass coefficients p and q are the coefficient of innovation and the coefficient of imitation, respectively, we interpret q as the effect of word of mouth. The marketing factor x_t reflects the tax environment, ε_{Gt} is a noise term representing the random variation in this adoption process. The coefficients p, q and x are estimated for each generation and are identified by a subscript G, E or F. Note that before ethanol and flex cars are introduced, $Y_{Gt} \equiv A_{Gt}$, after the introduction of the ethanol and flex generations, Y_{Gt} is modified by (16), in recognition of the erosion of potential adoptions due to upgrading. The observability of gasoline adoptions is now decreased, but we can still discern the relative importance of gasoline adoptions and upgrading, for example, when the cumulative number of gasoline users falls, we can tell that upgrading is dominating gasoline adoption.

When the cumulative number of gasoline adoptions decreases, the magnitude of this decrease forms a lower bound on the number of ethanol cars bought by upgraders. The upper bound on the number of ethanol cars purchased by upgraders is the number of gasoline car users in the previous period. For upgraders, the market factor is the relative benefit offered by the ethanol generation compared to the gasoline cars, which these upgraders currently enjoy, see (23).

$$u_{GEt} = \left\{\left(q_{GE}\left(\frac{Y_{E(t-1)}}{m_G + m_E}\right)\right)x_{Et}\right\}\left[Y_{G(t-1)}\right] + \varepsilon_{GEt} \tag{23}$$

The remaining new ethanol car adopters are relatively observable in aggregate coming from the new potential created by ethanol cars.

$$a_{Et} = \left\{\left(p_E + q_E\left(\frac{Y_{E(t-1)}}{m_G + m_E}\right)\right)x_{Et}\right\}\left[\,m_E - \ A_{E(t-1)} - \ U_{EF(t-1)}\right] + \varepsilon_{Et} \tag{24}$$

Upon the introduction of the flex generation, its cumulative number of adoptions comes from three different sources: flex new adoptions, upgraders from gasoline cars and ethanol cars, see (16) and (17). We adopt the same assumptions underlying (23) to model the adoptions of flex cars originating from upgraders from gasoline and ethanol cars, see (25) and (26) respectively.

$$u_{GFt} = \left\{\left(q_{GF}\left(\frac{Y_{F(t-1)}}{m_G + m_E + m_F}\right)\right)x_{Ft}\right\}\left[Y_{G(t-1)}\right] + \varepsilon_{GFt} \tag{25}$$

$$u_{EFt} = \left\{\left(q_{EF}\left(\frac{Y_{F(t-1)}}{m_G + m_E + m_F}\right)\right)x_{Ft}\right\}\left[Y_{E(t-1)}\right] + \varepsilon_{EFt} \tag{26}$$

The remaining new flex car users are relatively observable in aggregate. These are adoptions from the new potential created by flex cars - Equation (27).

$$a_{Ft} = \left\{\left(p_F + q_F\left(\frac{Y_{F(t-1)}}{m_G + m_E + m_F}\right)\right)x_{Ft}\right\}\left[m_F - A_{F(t-1)}\right] + \varepsilon_{Ft} \tag{27}$$

We use the marketing effort factor to capture the impact of government tax rates described in Section 3, see Equations (*28*), (29) and (30).

$$x_{Gt} = exp(\beta_G TAX_{Gt}) \tag{28}$$

$$x_{Et} = exp(\beta_E TAX_{Et}) \tag{29}$$

$$x_{Ft} = exp(\beta_F TAX_{Gt}) \tag{30}$$

3.5 Results

Following Stremersch et al. (2010), we estimated the parameters of the multigeneration model described in Section 4 using SAS 9.4 by using the seemingly unrelated regression option on the PROC MODEL procedure. Table 1 shows parameter estimates, and Figure 4 the overall performance of the data alongside the model predictions for gasoline, ethanol, and flex vehicles. The model has captured both the move away from gasoline technology, represented by negative adoptions during the first half of the 1980 and since 2005, and the relative failure of ethanol technology. The model fit (R^2) for the three technologies is 68%, 33%, and 94%, respectively. The reasons for the relatively poor fit for the ethanol generation become clear as we go through the implications of the parameter estimates.

Table 1 – Diffusion Model Parameter Estimation

	Parameters		Estimate	Std Error	t Value	Pr > $\lvert t \rvert$
Gasoline	Innovation	$\boldsymbol{P_G}$	0.029	0.011	2.74	0.008
	Word-of-Mouth	$\boldsymbol{q_G}$	0.876	0.154	5.70	<.001
	Market Potential	$\boldsymbol{m_1}$	33.531	4.613	7.27	<.001
	Tax Coefficient	$\boldsymbol{\beta_G}$	-0.042	0.004	-9.98	<.001
Ethanol	Innovation	$\boldsymbol{P_E}$	1.057	0.228	4.63	<.001
	Word-of-Mouth	$\boldsymbol{q_E}$	-5.316	2.768	-1.92	0.060
	Market Potential	$\boldsymbol{m_2}$	-0.023	0.036	-0.63	0.530
	Tax Coefficient	$\boldsymbol{\beta_E}$	-0.048	0.013	-3.77	0.004
Flex	Innovation	$\boldsymbol{P_F}$	0.003	0.001	2.32	0.024
	Word-of-Mouth	$\boldsymbol{q_F}$	1.022	0.154	6.64	<.001
	Market Potential	$\boldsymbol{m_3}$	25.927	0.585	44.33	<.001
	Tax Coefficient	$\boldsymbol{\beta_F}$	-0.012	0.016	-0.77	0.443
Upgraders Parameters	Gasoline to Ethanol	$\boldsymbol{q_{12}}$	0.541	0.313	1.73	0.090
	Gasoline to Flex	$\boldsymbol{q_{13}}$	0.075	0.032	2.33	0.024
	Ethanol to Flex	$\boldsymbol{q_{23}}$	-0.071	0.097	-0.74	0.464

Source: self-elaboration based on our model's output

Looking first at the values of the estimated market potentials in Table 1, the potential for gasoline vehicles is 33.53 million; for ethanol cars, the potential is not significantly different from zero; for flex vehicles, the increased potential is 25.93 million. Thus, in total, the model predicts about 60 million units in the long run, in December 2017, the market penetration is 35 million, of which flex vehicles represent 74% of the fleet, gasoline 25% and ethanol 1%. The model captures the failure of ethanol car diffusion as it failed to bring new people into the market.

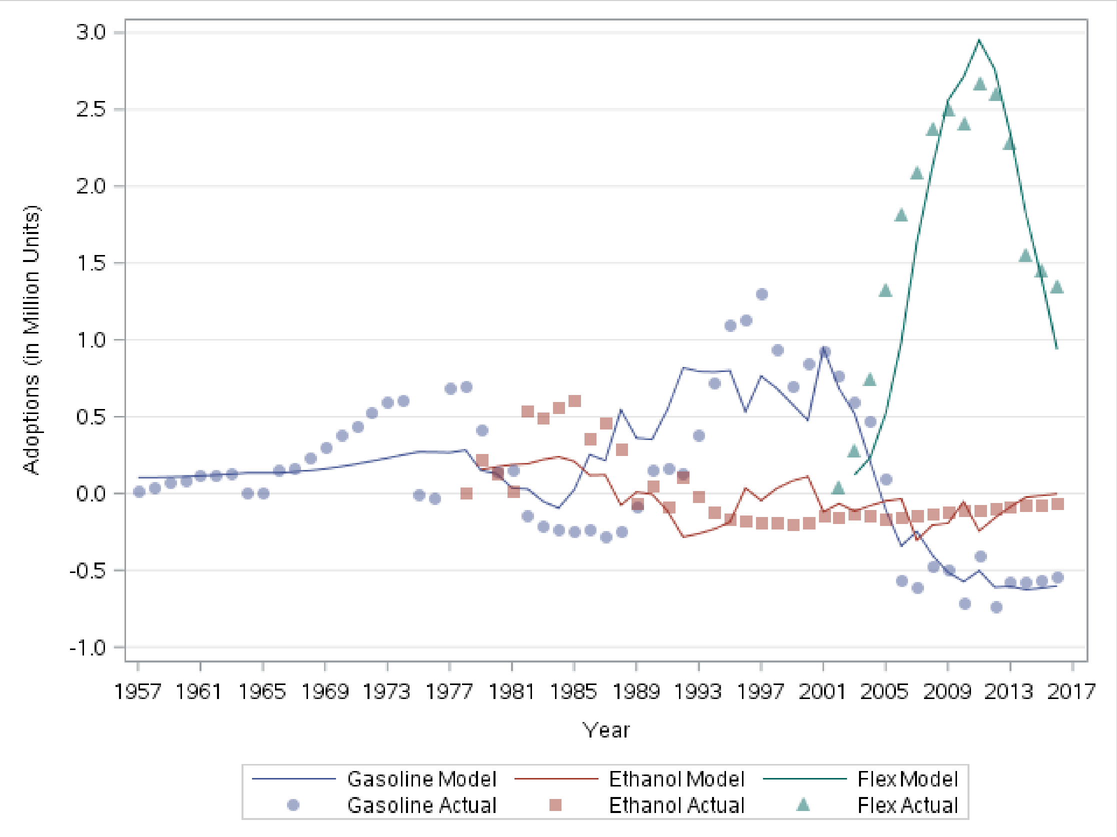
The market for gasoline vehicles behaves like that of a single technology model, with significant coefficients of innovation (p_G = 0.029, p-value 0.008) and imitation (q_G = 0.876, p-value 0.001). Likewise, the market for flex vehicles has parameters of similar sign and magnitude, (p_G = 0.033, p-value 0.024, q_G = 1.022, p-value 0.001). The exception is the model for ethanol vehicles which presents a high value for innovation coefficient (p_G = 1.06, p-value 0.001), and a negative imitation coefficient (q_G = -5.32, p-value 0.06). According to Meade and Islam (2006), this corresponds to a pure innovation scenario, where the adoption curve follows a modified exponential. As discussed by Mahajan et al. (1984), imitation (word of mouth) can be favourable, unfavourable or indifferent towards a product. Here, it has acted against the diffusion of ethanol vehicles. These findings show that the model's parameters are consistent with the loss of trust faced by this technology during the ethanol shock period, as described in our literature review[3]. For flex vehicles, we have a low estimate of the coefficient of innovation (p_G = 0.003, p-value 0.024) for flex-fuel as it is modified version of ethanol cars but flex-fuel received strong word of mouth impact (q_G = 1.02, p-value 0.001).

We investigated whether innovation acceleration occurred across successive generations of technologies. Acceleration happens when the difference between the two parameters is positive and significant (PAE; LEHMANN, 2003); thus, our model indicates a significant acceleration when comparing ethanol and gasoline cars ($p_E - p_G$ = 1.028, p-value 0.001), which confirms that the diffusion of ethanol vehicles was entirely driven by innovation. The flex vehicle market has a higher diffusion speed than gasoline, but the difference is not statistically significant ($q_F - q_G$ = 0.15, p-value 0.47).

Considering the effect of taxation, represented by the marketing effort parameter, β_F, we see that the effect of the tax rate is significantly negative for gasoline (β_G = -0.042, p-value 0.001) and ethanol vehicles (β_E = -0.048, p-value 0.004). Thus, for these two generations, the effect of taxation is to stifle adoption. However, for flex vehicles, the effect of taxation is not significant, indicating that the stifling effect of taxation has been reduced or virtually removed. Finally, considering the parameters of the upgrading processes, we see a positive and significant (leapfrogging) upgrading from gasoline to flex vehicles (q_{GF} = 0.075, p-value 0.024), a marginally significant upgrading from gasoline to ethanol cars (q_{GE} = 0.541, p-value 0.09). There is no significant evidence of upgrading from ethanol to flex vehicles.

[3] A negative word-of-mouth parameter for nuclear energy was also found by Guidolin and Guseo (2016) when studying the possible effects of the energy transition that is going on in Germany.

Figure 4 – Model and Data Comparison for Vehicle Technologies in Brazil (1957-2017)



Source: self-elaboration based on our model's output

3.6 Conclusions and Policy Recommendations

This article has adapted a multi-generation innovation diffusion model to evaluate the impact of governmental incentives on the diffusion of three vehicular technologies in Brazil. 'Leapfrogging' was introduced to capture the frequently observed phenomenon of an adopter of gasoline switching to flex technology, skipping the ethanol technology. A marketing factor was introduced to the multigenerational model to capture the effect of the tax/incentive scheme, the main instrument used by the Brazilian government's Alcohol Program. We tested the literature-based assumption that tax exemptions can increase the diffusion rates of technologies. Our results reinforce this narrative by showing the negative effect of taxes on adoptions of gasoline and ethanol vehicles but not for flex vehicles in Brazil. The markets for the first generation of vehicle fuel technology, gasoline, and the third generation, flex vehicles, behave as smooth, well behaved, S-shaped diffusion models.

The ethanol vehicle's experience demonstrates that even though incentives are necessary for the beginning, in the long run, some level of self-sustainability must be achieved. Our results showed that ethanol vehicle adoptions were mainly due to innovation by new adopters from a pool of insignificant magnitude, with some upgrading from gasoline. The model captured the consumers' loss of confidence in ethanol vehicles, evidenced by negative word-of-mouth (MOUTINHO DOS SANTOS; PARENTE, 2006).

The flex vehicle technology represents, as both data and model suggest, the mainstream technology in the country. Although still consuming some gasoline, flex vehicles are the current strategy for Brazil to achieve its CO_2 reduction goals in transportation. Since the diffusion of flex vehicles occurred predominantly by positive word-of-mouth, it seems that, regardless of any setback in the ethanol industry, flex vehicles will remain the dominant mainstream technology.

Our results have policy implications for countries wishing to introduce a new generation of vehicle technology. Tax reduction is necessary for the first steps to the diffusion process; however, policymakers should not only rely on these incentives. Since cars are durable goods, word-of-mouth plays a vital role in the long run. For flex vehicles, the versatility of being able to choose which fuel is preferred can be considered the main relative advantage.

Fuel price stability is a marketing variable that is likely to have an impact on the continued adoption or discontinuance of ethanol technology, and it deserves further studies. Besides, as potential future research, there is the possibility of a 4^{th} technological generation of hybrid-electric flex cars in the Brazilian vehicle market. Toyota indicates that its first model will start being produced in Brazil by the end of 2019 (MUNIZ; GASQUES, 2018). Such technological innovation that allows the use of electricity for vehicle traction would represent an efficiency improvement over both flex and current hybrid electric vehicles.

4 MARKET SHARE ELASTICITIES OF VEHICLE TECHNOLOGIES

This Chapter presents the developments of the paper: “Price Elasticities of Technological Generations of Alternative Fuel Vehicles Market Share in Brazil”. We plan to submit this article to the Journal Energy Economics by the second semester of 2019. Similarly, to the previous chapter, this one will follow an article structure. Ahead, sub-chapter 4.1 presents the motivation and objectives of this study. Section 4.2 gives an in-depth literature review for market share and elasticity models, and summarises the Brazilian ethanol program’s history. Section 2.2.1 describes most of the methodology adopted for this paper, and, since we did no change to Cooper and Nakanishi (2010) model, section 4.4 describes the data used for our market share model. Section 4.5 presents and discusses our results, as well as further conclusions.

4.1 Introduction

Recent environmental concerns regarding global warming and air quality have addressed motorised transportation issues in developing countries, where its demand and access is crescent. Nevertheless, developed countries are still responsible for promoting a great substitution of their fossil-based fleets to alternative fuel vehicles (AFV), such as biofuels, hybrid and plug-in electric and natural gas. In Europe, 96% of passenger cars run on petrol (gasoline) and diesel oil (ACEA, 2018), while in the United States, 84% of the transport energy consumption comes from these fuels (EIA, 2019). Market forces alone do not seem to push fast enough the diffusion and share of AFV.

For this reason, governments have promoted a range of incentives to increase the number of cleaner fuel technologies in car fleets. For example, in Canada, Ontario and the federal government used taxes and rebates based on fuel economy and carbon price on the consumption of fossil fuel (Rivers and Schaufele, 2017). Moreover, the US Federal Government offered, in 2005, a $2000 tax reduction for all qualifying hybrids (Diamond, 2009). Another notable is the Brazilian Alcohol Program, which sought to promote ethanol as an alternative liquid fuel for gasoline. Although it was not created to address environmental issues, the program eventually became part of the country’s strategy to reduce its use of fossil fuels in transport. Ethanol and flex[4] cars have benefited from several incentives, throughout different phases of the program, to compete against gasoline ones.

The success of these incentives largely depends on the responsiveness of gasoline and other fuel prices. According to Rivers and Schaufele (2017), consumers need constant price elasticities for promoting fuel economy and gasoline cars and noted that little is known how about gasoline prices impact fuel economy cars. The importance of precise price elasticity has been echoed by Havranek, Irsova and Janda (2012) for government policy concerning energy security. They emphasised that taxes will be more effective in reducing the emissions of greenhouse gases if empirical findings show price elasticity for gasoline is inelastic.

The extant literature mainly investigated own price effect of gasoline where findings varied from inelastic price effect (HAVRANEK; IRSOVA; JANDA, 2012) to elastic effect for OECD countries (GRAHAM; GLAISTER, 2002). Several studies investigated gasoline price effects on market shares of fuel-efficient cars such as electric cars (Noori and Tatari 2016; Riesz et al. 2016), hybrid cars (DIAMOND, 2009). These market share studies modelled each brand (e.g. Prius, Civic, Escape) separately without accounting substitution effects. Fazeli et al. (2016) is an exception who studies market shares of multiple renewable technologies (e.g. space heating) in Nordic countries and concluded superiority of simultaneous modelling approach as it captures the substitution effects. A few studies (Burke and Nishitateno 2013; Klier and Linn 2013) estimated cross-effect of gasoline price on fuel efficient cars. In all extant studies investigation was on the impact of fossil fuel energy on either gasoline car or on fuel efficient cars.

In order of address the existing gap in the literature, we use the advances of market share models to simultaneously estimate the market share elasticity, both own and cross effects, of each technology taking into account substitution effects. Market share models tend to focus more on brands than technologies. Our study seeks to fill up this gap by analysing the transition of elasticities for the successive generations of technologies with regards to both fossil and environment-friendly ethanol fuels.

4.2 Literature Review

This section discusses market share and elasticity approaches in energy and transport literature. We present articles that studied energy technologies diffusion and impacts

[4] Flex or flex-fuel vehicles can use gasoline, ethanol or any mixture of both fuels.

on their market shares as well as price and demand elasticity studies. Then, we give a brief historical vision of ethanol and flex technologies in Brazil – for a complete overview, check (COELHO et al., 2006; GOLDEMBERG et al., 2004; MOREIRA; GOLDEMBERG, 1999; MOUTINHO DOS SANTOS; PARENTE, 2006).

4.2.1 Ethanol and Flex Vehicles

The Brazilian Alcohol Program (Pro-Álcool) was a policy created at the end of the 1970s that sought, among other issues, to protect consumers from oil price shocks by promoting an alternative liquid fuel for cars from sugarcane (MOUTINHO DOS SANTOS; PARENTE, 2006). The program's highlight was the launch of a pure ethanol engine, developed by national scientists, which was resistant to corrosion and capable of a higher compression ratio (YU et al., 2010). Tax incentives and price policies were promoted during this period to encourage consumers to acquire ethanol vehicles instead of a gasoline-powered one (COELHO et al., 2006; GOLDEMBERG et al., 2004; MOREIRA; GOLDEMBERG, 1999).

However, despite the initial sales success (Section 4.4 presents market share data), ethanol fuel price has experienced price shocks during the 1990s, due to production shifting to sugar (PUGLIERI, 2013). Besides, the government started to give a new incentive for low cylinder capacity vehicles (popular cars), which, to be cheaper, could not use ethanol technology. This situation frustrated many consumers and led to a systematic decrease in ethanol vehicles sales, followed by a rise of gasoline ones (ANFAVEA, 2018; MOUTINHO DOS SANTOS; PARENTE, 2006).

At the beginning of the 2000s, the introduction of flex technology has refreshed the alcohol program. It was part of a new series of policies such as the creation of the National Agency for Petroleum, Natural Gas and Biofuels (ANP) as well as liberalisation and commercialisation of electricity produced from sugarcane bagasse, which gave producers a new incentive (PUGLIERI, 2013). Ethanol was also elevated as one of Brazil's primary strategies for reducing CO_2 emissions to achieve the Kyoto Protocol's target (MOREIRA; NOGUEIRA; PARENTE, 2005). As a result, three years after its introduction, flex cars dominated the passenger vehicles market, with market shares superior to 90%.

When launched, flex car was criticised due to its lower fuel consumption averages compared the single fuel ones. A flex vehicle would cover 6.9 km for each litre of ethanol it burned and 10.3 km for each litre of gasoline, while dedicated ethanol and gasoline vehicles, would do 7.5 km and 11.2 km, respectively (CETESB, 2017). Technological improvements have led flex vehicles efficiency increase by 40% since its first models. Nevertheless, despite technological advances, flex engines burning ethanol would always have, on average, 70% of efficiency compared to gasoline due to different energy content and density (COELHO et al., 2006).

The final price for consumers has to reflect this variation: if ethanol is at least 30% cheaper than gasoline, consumers can save money by refuelling with the former. An article by Du and Carriquiry (2013) have concluded that, since the introduction of flex vehicles in Brazil, ethanol and gasoline prices tend to converge to a long-run equilibrium level. They also suggest that price dynamics are highly influenced by market supply and demand factors, such as sugar price, ethanol exports and the increase of flex vehicles in the fleet.

4.3 Endogeneity of Fuel Prices

In our study, we assume that fuel price drives vehicle sales. However, fuel price itself might be a reflect the increased number of vehicles. In order to avoid this so-called endogeneity issue, we must conduct a check by adopting an instrumental variable (IV) for gasoline and ethanol prices. Burke and Nishitateno (2013) employed proved oil reserves per capita and international oil prices to study gasoline price elasticity in 132 countries. Because their IV and OLS regression results were similar, these tests have improved the confidence of their estimation methods.

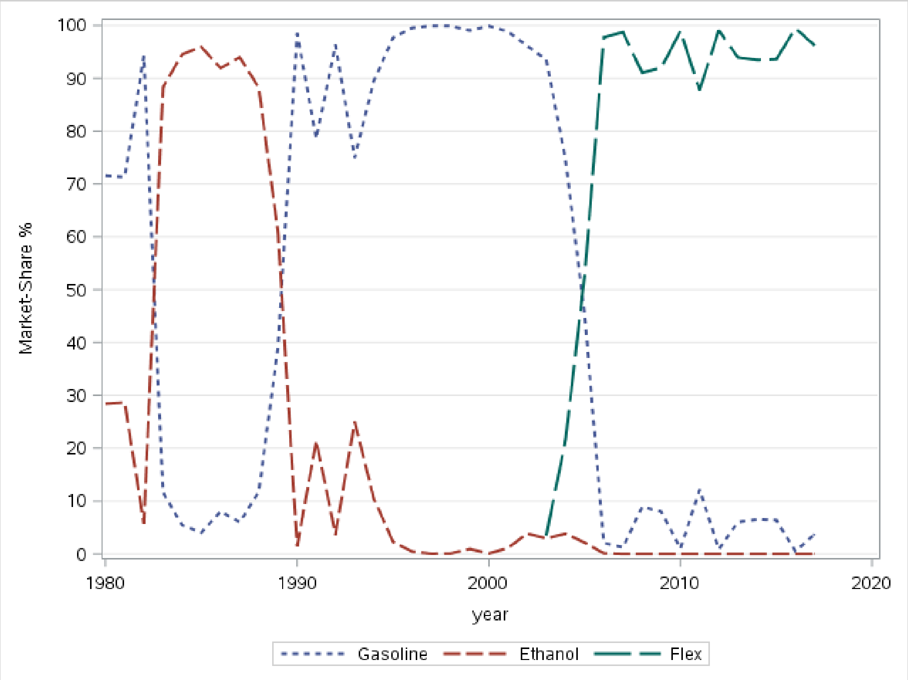
Despite recognizing the limitations of their model with regards to endogeneity, Tenkorang et al. (2015) do not adopt any IV and uses the more popular estimation procedure – the seemingly unrelated regression (SUR) since literature could not find any significative difference from the suggested more robust three stages least square (3SLS) procedure. Rodrigues et al. (2018) emphasised the importance of adopting a stochastic trend, rather than deterministic ones, to avoid biased results when the model does not incorporate technological progress as an exogenous process.

Rodrigues and Bacchi (2017) argue that endogeneity problems are minimised in the Brazilian market because a single company (Petrobras) virtually controls gasoline supply and stablishes prices regardless of market conditions. Ethanol, whose because its price cap is coupled with gasoline, follows the same trend. Despite the arguments presented by those authors, in this study, we decided to adopt instrumental variables that we can observe a clear relation to the fuel price formation but does not directly affect vehicle sales.

4.4 Data and Methodology

In this study, we had used vehicle sales data available from the Brazilian Automotive Industry Association (ANFAVEA, 2018) to calculate the yearly market share for each technology. Their Yearbook reports annual vehicle registrations by type (passenger, light commercial, trucks and buses) and by fuel type. Figure 5 shows the market share of gasoline, ethanol and flex-fuel technology among passenger vehicles since 1980.

Figure 5 – Yearly Market Share for Vehicle Technologies



Source: Adapted from ANFAVEA (2018)

We have divided our analysis into two phases. The first one corresponds to the period from 1980 to 2002, when only gasoline and ethanol were available. The second phase of our study refers to the period from 2003 to 2017, when flex-fuel technology started competing for market share. Despite the report showing sales for diesel and electric cars, we have not included these technologies in our study. The reason for this is that diesel-fueled vehicles have limitations for manufacturers and are most commonly used for off-road purposes, which classifies them as a particular niche market. In the case of electric cars (which are hybrid-electric ones), despite increasing sales in the last few years, their numbers are still pretty much irrelevant in terms of market share.

The annual average price to final consumers for gasoline and ethanol was extracted from the Energy Research Office (EPE, 2019) and converted to 2018 USD (USBLS, 2018). Since technologies have different efficiencies regarding the fuel type, we levelled all price to a comparable metric (USD per km). Thus, we have estimated these values based on consumption rates for each technology provided by São Paulo State's Environmental Company (CETESB, 2017) by using Equation (31).

$$C_{ge} = P_{ge} \times A_{gef} \tag{31}$$

Where:

C_{ge} is the estimated cost (in USD) per kilometre for either gasoline or ethanol;

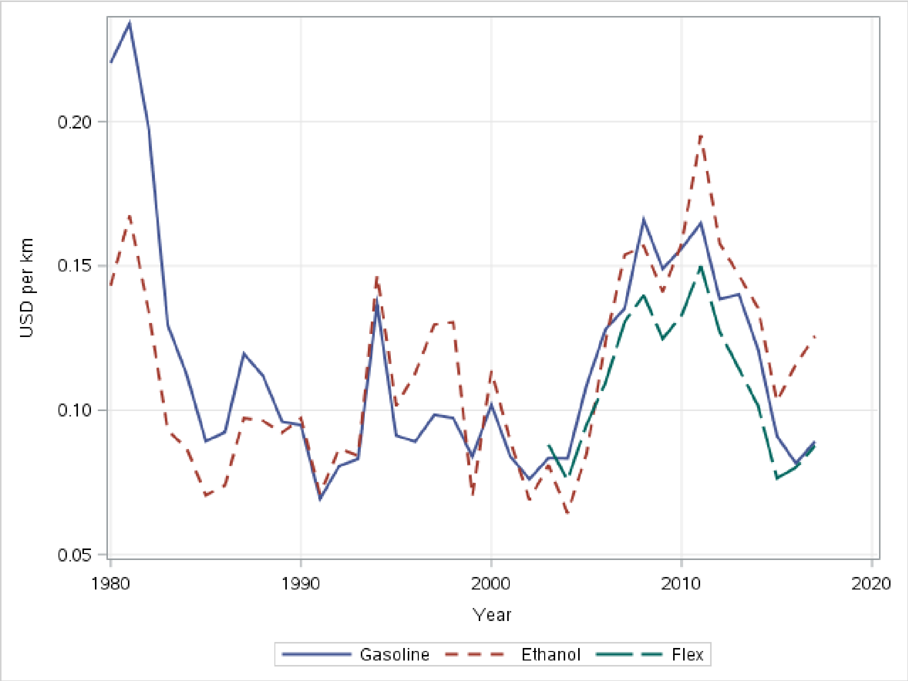
P_{ge} is the gasoline or ethanol's price per litre (in current USD);

A_{gef} is the gasoline, ethanol and flex vehicle autonomy (in km/L)

Estimations for gasoline and ethanol price per kilometre, by either dedicated and flex[5] technologies, is presented in Figure 6. Our estimates indicate the ethanol shock period mentioned in the literature. During the 1990s, ethanol car owners were spending more per kilometre than gasoline car owners. Higher fuel prices for ethanol vehicles after 2007 were due to lack of technological improvement for this technology. Flex ownership has been cheaper than gasoline car since 2004. However, flex vehicles do not necessarily use ethanol every time, because there are years when fuelling with gasoline was less expensive than with ethanol.

[5] Flex vehicles have different price per km depending on the fuel it is using. We have assumed the lowest cost for its curve in Figure 6.

Figure 6 – Average Fuel Price to Final Consumers in Brazil



Source: self-elaboration based on CETESB (2017) and EPE (2018)

4.5 Results and Discussion

The premises of our model stipulate the nature of our results based on the data we are using. If the market share of a given technology is elastic with regards to its own fuel price, we expect it to be a negative value. This means that the more the price of a fuel increases in a year, the less will be the market share its respective technology, and vice-versa. Similarly, cross-elasticities are expected to be positive, because we assume that if a given fuel becomes more expensive, consumers would be inclined to purchase the competitive (and cheaper) technologies. This section discusses the results obtained from the MCI Model. MNL model findings are similar to the MCI one, so results are omitted for parsimony but are available from the authors on request.

Table 2 summarises the model estimates from the MCI cross effects model for the first phase of our study. The parameters are symmetrical because we have only two products competing. Figure 7 shows the predicted log market share with the data. Price explains about 68% of the variability of the market share in this period.

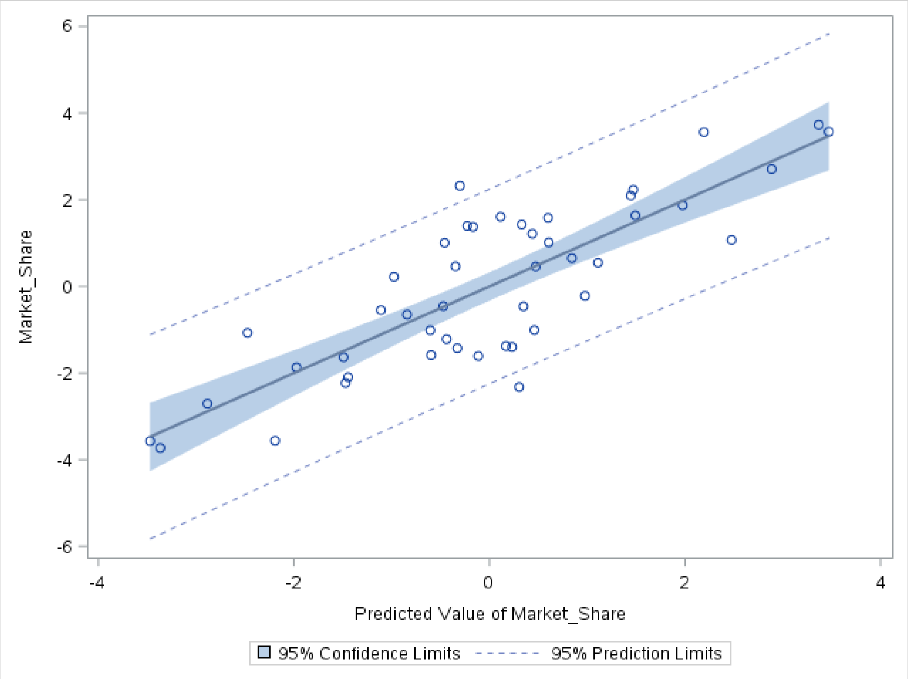
Table 2 – Parameter Estimation for Gasoline and Ethanol from 1980 to 2002

Parameters		Parameter Estimate	Standard Error	t Value	p-value
$\alpha_{gasoline}$	Alternative Specific Constant	0.959	0.241	3.98	<.001
$\alpha_{ethanol}$	Alternative Specific Constant	-0.959	0.241	-3.98	<.001
	Own Effects				
β_{gg}	Gasoline	-5.513	1.166	-4.73	<.001
β_{ee}	Ethanol	-7.383	1.463	-5.05	<.001
	Cross-Effect				
β_{eg}	Ethanol on Gasoline	7.383	1.463	5.05	<.001
β_{ge}	Gasoline on Ethanol	5.513	1.166	4.73	<.001

Source: self-elaboration based on our model's output

Table 3 presents the MCI results for own and cross effects of fuel prices on the technologies' market share for the second phase. The introduction of the flex-fuel cars characterises the 2003-2017 period as well as a significantly reduced ethanol vehicles market share. Figure 8 shows that fuel price explains 97% of market-share variability. Ahead we present and discuss elasticity results for each phase separately.

Figure 7 – MCI Results for Market Share for Gasoline and Ethanol from 1980 to 2002



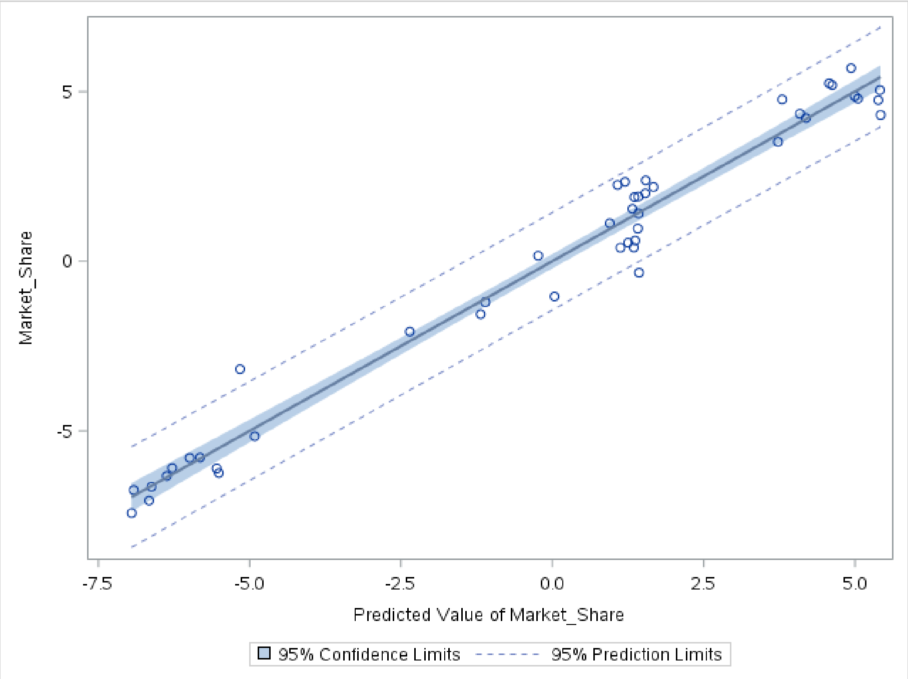
Source: self-elaboration based on our model's output

Table 3 – Parameter Estimation for Gasoline, Ethanol and Flex from 2003 to 2017

Parameter		Parameter Estimate	Standard Error	t Value	p-value
$\alpha_{gasoline}$	Alternative Specific Constant	1.364	0.208	6.57	<.001
$\alpha_{ethanol}$	Alternative Specific Constant	-5.160	0.208	-24.83	<.001
α_{flex}	Alternative Specific Constant	3.796	0.208	18.27	<.001
	Own Effect				
β_{gg}	Gasoline	1.982	2.985	0.66	0.511
β_{ee}	Ethanol	-10.514	1.315	-8.00	<.001
β_{ff}	Flex	-14.074	3.619	-3.89	0.005
	Cross Effect				
β_{eg}	Ethanol on Gasoline	0.196	1.315	0.15	0.882
β_{fg}	Flex on Gasoline	-2.624	3.619	-0.73	0.474
β_{ge}	Gasoline on Ethanol	-7.563	2.985	-2.53	0.016
β_{fe}	Flex on Ethanol	16.700	3.619	4.61	<.001
β_{gf}	Gasoline on Flex	5.581	2.985	1.87	0.070
β_{ef}	Ethanol on Flex	10.317	1.315	7.85	<.001

Source: self-elaboration based on our model’s output

Figure 8 – MCI Results for Market Share from 2003 to 2017

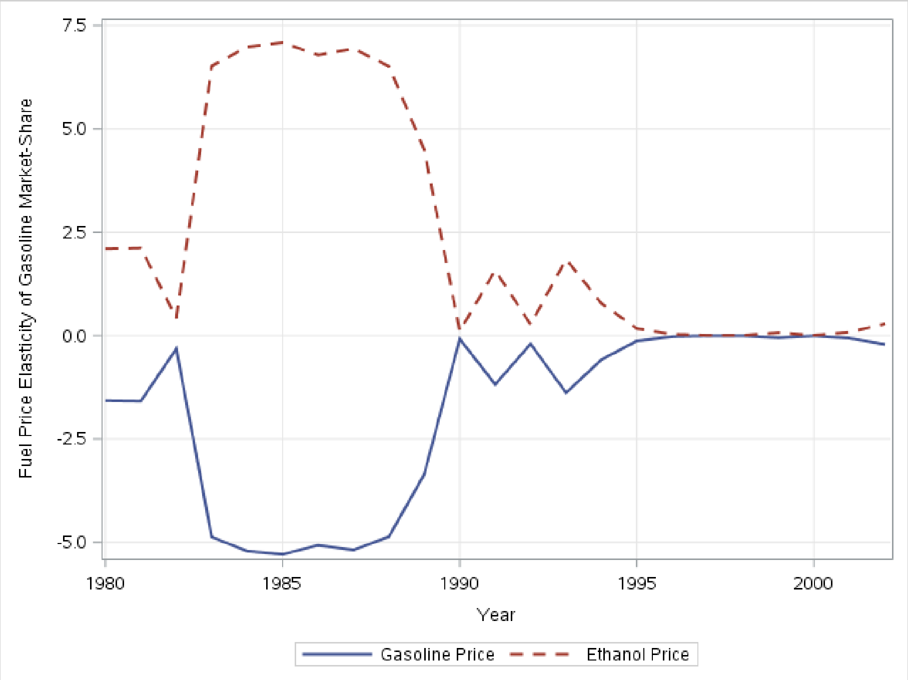


Source: self-elaboration based on our model’s output

4.5.1 Fuel Price Elasticity from 1980 to 2002

According to Table 2, all parameters are highly significant ($p < 0.001$). The parameter estimates are in the expected direction: own elasticities are negative, while cross-elasticities are positive. Figure 9 shows that gasoline vehicles market share was quite sensitive to price during the years of 1983 to 1989, when own and cross elasticity with ethanol price reached -5.29 and 7.08, respectively. The first half of the 1990s experienced some elasticity variations when ethanol's recovered part of its market share to 21% and 25% in 1991 and 1993, respectively. Nevertheless, after 1995, gasoline vehicles market-share becomes highly inelastic until the end of the first phase. These results reinforce the idea that gasoline technology has always been the mainstream and changes in these variables will hardly affect the variations in its market share.

Figure 9 – Fuel Price Elasticity of Gasoline Market Share (1980-2002)



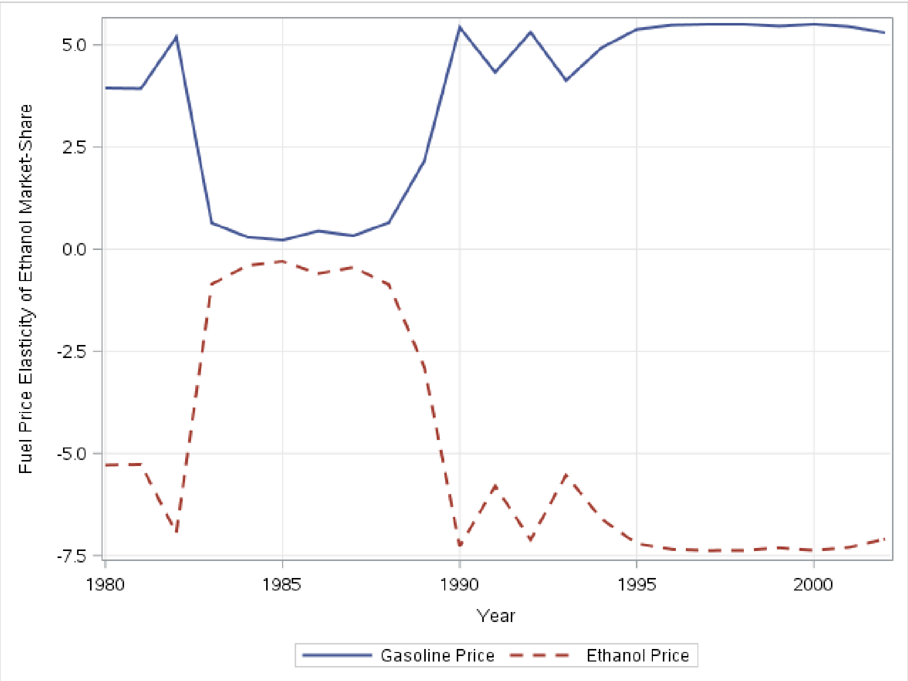
Source: self-elaboration based on our model's output

According to Figure 10, ethanol vehicle's market-share is highly sensitive to price right after its launch, at the beginning of the 1980s. However, when the technology becomes dominant between 1983 and 1988, its elasticity dropped to values close to zero. As soon as the fuel price start to rise compared to gasoline, at the start of the 1990s in the period referred to as

'Ethanol Shock', elasticity levels resume to high levels (above –7.27), meaning that the more expensive it becomes to own an ethanol car resulting in a decline in sales.

Alves and Bueno (2003) have studied price elasticity of ethanol and gasoline demand using data from 1984 to 1999. They concluded that the former is an incomplete substitute of gasoline because, although they have positive cross-elasticities, their coefficients are close to zero. These results are in agreement with the historical facts because, up to 2003, consumers would not have the option to use both fuels; thus, they were inelastic. Our results, however, indicate that changes in price did influence consumers to acquire the other technology whose cost per kilometre was cheaper on each given year.

Figure 10 – Fuel Price Elasticity of Ethanol Market Share (1980-2002)



Source: self-elaboration based on our model's output

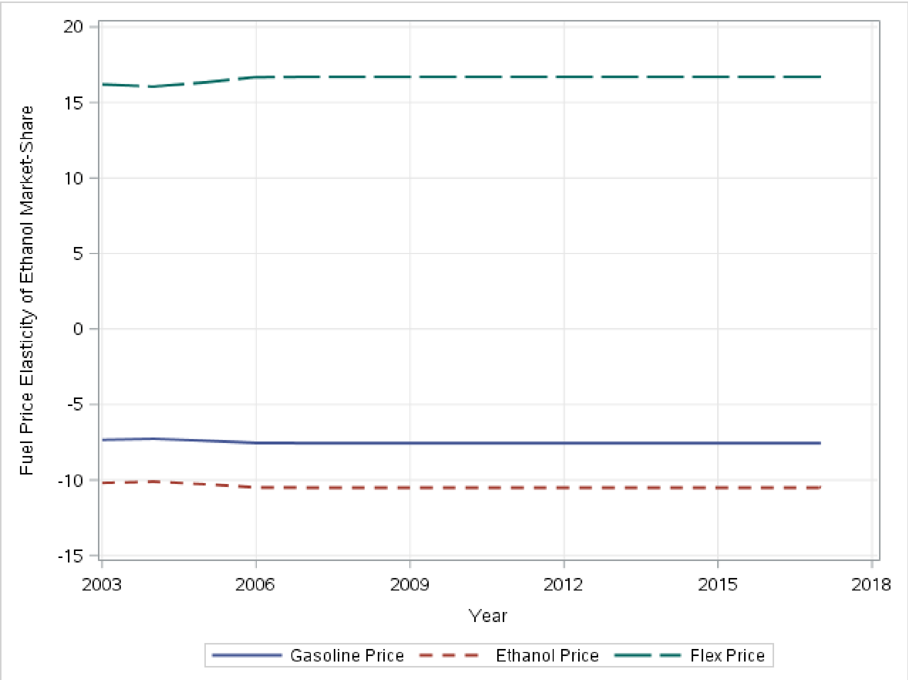
Despite the shortcomings of the Brazilian Alcohol Program, Goldemberg et al. (2004) have shown that final ethanol price to consumers (at refuelling stations) was becoming more competitive due to an increased learning curve, which reduced production costs. This fact posed a favourable situation for the entrance of flex-fuel vehicles, as discussed ahead.

4.5.2 Fuel Price Elasticity from 2003 to 2017

The second phase of the study marks the introduction of flex-fuel technology in the Brazilian automobile market and the complete submission of ethanol technology with very low market-shares. Table 3 shows that out of our nine estimated parameters (besides the constants), all of those referring to own and cross effects on gasoline vehicles market-share is not significant. These results suggest that fuel prices offer little explanation for the variations of such technology during this period.

When flex vehicles enter the market, it became impossible for ethanol to resume its phase 1 levels. Figure 11 shows the extreme and constant elasticities expected for products with low market share. According to these results, a 1% increase in ethanol price would provoke a decrease of about 10% of the technology's market share. Since few new vehicles have entered the market, efficiency improvement has been discontinued, which increases the cost per kilometre of using an ethanol car. By observing the flex price cross-elasticity (Figure 11), the model suggests that if owning a flex car becomes more expensive, ethanol's market share might increase at a higher rate (roughly 16) than if ethanol price decreases.

Figure 11 – Fuel Price Elasticity of Ethanol Market Share (2003-2017)

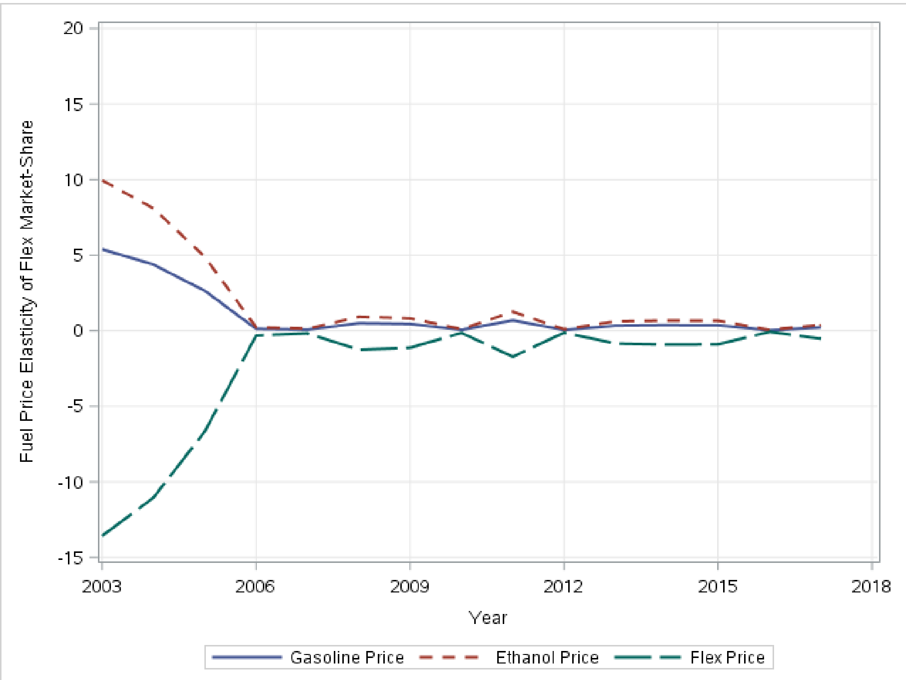


Source: self-elaboration based on our model's output

Figure 12 reflects the reduced efficiency of the first flex vehicles models when compared to single fuel ones. Despite being more expensive to refuel on the three years that followed its launch, sales snowballed due to high own-elasticity from 2003 to 2005. Cross elasticity with regards to gasoline and ethanol vehicles fuel price also contributed to pushing the new technology sales in the first three years. Flex vehicles become inelastic to price as soon as technology improves and market share increases. Our results show some correlation to the ones obtained by Rivers and Schaufele (2017) found that the fuel economy of new cars tends to increase by 0.8%, for each 10% increase in gasoline price in Canada.

Regarding fuel demand, Debnath et al. (2017) show that high crude oil price generates a substantial increase for ethanol. Rodrigues et al. (2018) identified that demand for ethanol in Brazil is more price elastic than gasoline and that both fuels are highly competitive against each other. Rodrigues and Bacchi (2017) results indicate that, in the short term, demand for gasoline and ethanol in Brazil is inelastic to income and price, but in the long run, these fuels sensitivity might increase to the former and decrease to the latter. These findings suggest the widespread of flex-fuel technology have consolidated the light fuels market in the country. Our results complement these fuel demand studies in the sense that the long-term stability of flex vehicle dominance over the market share will keep competition among gasoline and ethanol prices.

Figure 12 – Fuel Price Elasticity of Flex Market Share (2003-2017)



Source: self-elaboration based on our model's output

These findings might raise some concerns regarding the refuelling choice of flex car owners. Huse (2018) has shown that gasoline is preferred by flex-fuel vehicle drivers in Sweden, when in price parity with ethanol. He also found out that ethanol has a high price elasticity, while gasoline is quite inelastic; thus, the former would need to have a premium price over the later. In the United States, Tenkorang et al. (2015) concluded that ethanol used to be a substitute to gasoline between 1982 and 2005, but since 2006, its consumption has been complementary to the latter because US flex cars cannot use blends higher than E85. These studies show that, despite the specific characteristics of the Brazilian ethanol development, different markets might yield similar results to ours.

Moreover, Salvo (2018) identified that Brazilian consumers often purchase fuel that yields fewer miles per dollars despite having a flex car. His study shows that consumers must understand how such price differences, especially on flex engines, are calculated so they can make full use of the vehicle’s flexibility. This knowledge is required to ensure that policies for promoting alternative technologies and reducing fossil fuel consumptions are impactful.

4.6 Conclusions

This study has conducted a market-share analysis of different technological generations of alternative fuel vehicles in Brazil. We applied an MCI and MNL models to estimate price own and cross elasticities. Our results, as expected, have shown small elasticities for technologies with large shares. The study of cross-elasticities has allowed further comprehension of the effects of fuel prices.

When gasoline and ethanol are the only competing technologies, variations in price profoundly impact on the market share of new vehicles. The limitation of being able to use only kind one fuel in each car required a consumer to have both vehicles if they were hedging against price fluctuations. However, ethanol prices grew up way higher than the recommended 70% ratio, a distrust in the technology starts to grow up until it became entirely discontinued. Other support from the government along with a nationalistic proudness of the ethanol technology, which was outside the scope of this work, also drove its sales during the 1980s.

The second phase of this study shows how a new technological generation can become dominant in terms of market share. In our analysis, the efficiency increment of flex-fuel engines, which reflected on the cost per kilometre, has significantly contributed to the widespread of this technology. We also conclude that the market share of flex vehicles is hedged against price recent price fluctuation as shown by the near-zero elasticities obtained by the model. A more in-depth study for this period can use the surveys from the National Agency for Petroleum, Natural Gas and Biofuels (ANP, 2018), who collects weekly data on fuel price at gas stations at major cities in Brazil since 2004. According to ANP's historical series, we can observe that several ethanol shocks throughout the second phase period, which did not affect flex vehicles' market share.

Finally, the results of this study provide policy implications that might be useful for decision makers who seek to increase the market share of alternative and clean fuel technologies in either municipal, state or national levels. The first one is assuring competitive prices for the alternative fuels and technologies through programs that provide support for producers, credit lines for consumers, fiscal reduction for manufacturers or non-monetary incentives such as exclusive park and exemption of traffic fees. A combination of two or more of such policies might enable a more robust and successful program.

5 COSTS AND EMISSIONS OF A BLUE CORRIDOR

This Chapter reports the main findings and additional information from the article “Costs and Emissions Assessment of a Blue Corridor in a Brazilian Reality: the Use of Liquefied Natural Gas in the Transport Sector”, which was a joint work of RCGI’s Project 25’s team and other colleagues. It was accepted to publish at the journal: Science of the Total Environment, in February 2019 (MOUETTE et al., 2019).

The objective of this paper was “to evaluate the economic and environmental impacts of Liquefied Natural Gas (LNG) use as a substitute to Diesel oil, by proposing four scenarios for a Blue Corridor in São Paulo territory” (MOUETTE et al., 2019, p. 1105). This study has used a different approach than the one used in the previous ones because the data for natural gas vehicles in Brazil for passenger and commercial vehicles is either limited for trucks and buses. Thus, this article has assessed costs and emissions from a simulated truck fleet over some defined routes and scenarios.

5.1 Literature Review

Blue Corridors are routes for road transport that compressed (CNG) or liquefied (LNG) natural gas as motor fuel. The primary feasibility factor for a BC is the existence of gas stations, to encourage the use of natural gas vehicles, breaking the vicious "chicken and egg" cycle (IGU; UNECE, 2012). This concept went through some changes throughout time, and the three following reports will describe each one of its phases.

5.1.1 The Primitive Concept

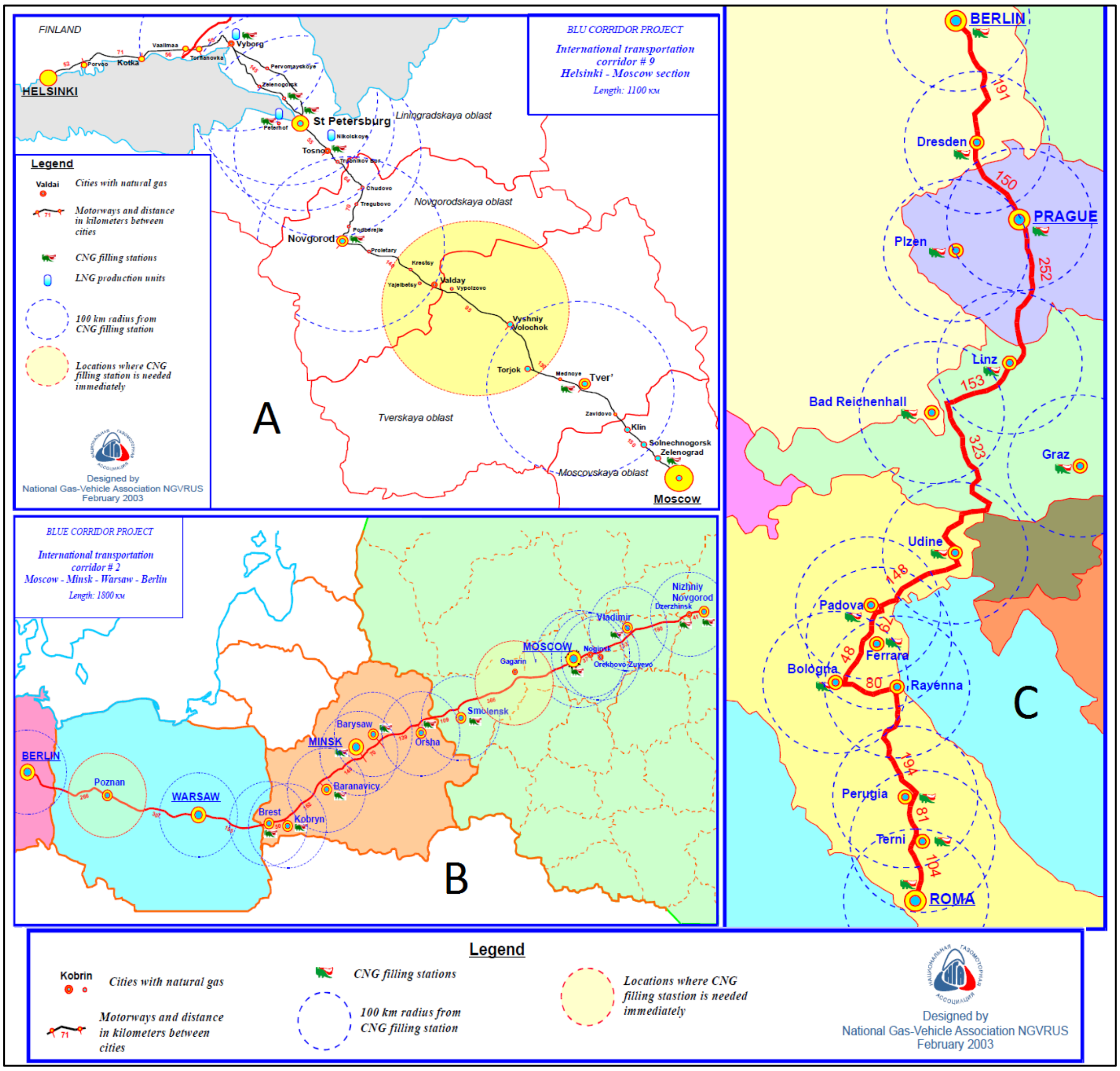
The first study to propose a Blue Corridor (UNECE, 2003) has defined its fundamental concept and recommended some routes. The document ‘Blue Corridor Project’ was developed by a working group from the Gas Inland Transport Committee of the European Commission for Economy (ECE) and by the Vernadsky Foundation (Russian Federation) in early 2000, aiming to establish a European corridor infrastructure for natural gas vehicles (UNECE, 2003). It presents three Blue Corridors initiatives in the European territory.

Since CNG trucks’ autonomy, by the report’s time, was limited to 200 km, several stations would have to be placed along the corridors to allow frequent refuelling, as shown in

Figure 13. This report used a simple bottom-up methodology to estimate variations in emissions (pollutants and CO_2) and costs, assuming a total substitution of the heavy-duty fleet by compressed natural gas vehicles. The study had to adapt to different corridors due to uncertainties and data availability.

Their findings present some limitations. The first one is that, due to the report's publishing date, 2003, the emissions standards are compared to EURO II diesel engines. Nevertheless, in terms of pollution, all three pilot corridors summed would present a reduction of 272.4 thousand tonnes of carbon monoxide equivalent per year. Also, natural gas could substitute a total of 157.8 thousand tonnes of diesel oil per year.

Figure 13 – Blue corridor's Project



Source: UNECE (2003)

Regarding infrastructure, for the Berlin-Moscow route (B in Figure 13), for example, around 19-25 fuelling stations would have to be constructed to achieve the aims of the project. Some countries, such as Italy, which already had a robust distribution and fuelling network, but had stations that were far away from the primary motor roads. The report pointed out that most of these stations were quite old and built near existing NG pipelines instead of main roads. This problem revealed the differences among European countries regarding gas distribution; however, the grid is now much more extensive, which solves this issue.

In economic terms, their projections suggest saving of up to 37.10 million Euros per year, just by using natural gas, since it was 40% cheaper and presented lower maintenance costs. All in all, the materialisation of the Blue Corridor would need almost 80 million Euros, for both conversion kits and stations, as shown in Table 4.

Table 4 – Required Investments, in million Euro

Blue Corridor	On-board gas equipment	Fuelling infrastructure	Total
Helsinki-St. Petesburg-Moscow	13.0	6.6	19.6
Moscow-Minsk-Warsaw-Berlin	25.2	5.2	30.4
Berlin-Rome	25.2	4.1	29.3
TOTAL	63.4	15.9	79.3

Source: UNECE (2003)

The Report's conclusion assesses the classic chicken and egg dilemma, in which NGV buyers always feel hesitant to acquire new vehicles if the fuel access is hard. On the other side, fuelling station owners will be reluctant to invest in infrastructure if they do not see an apparent demand for NG. Thus, to break this vicious cycle, a range of policies and incentives, such as natural gas favourable legislation and funding, are required. It also points out the Blue Corridor's replicability potential to the entire European continent, Asia and North and Latin America, which were already developing their own Blue Corridor Projects.

5.1.2 Expanding out the concept

The next document that deals with Blue Corridors has been published after almost ten years and has dedicated to ensuring the continuity of the studies by showing examples the Blue Corridor concept's functionality since it was spreading to other regions of the world (IGU; UNECE, 2012). They aimed to attract the attention of local authorities, car manufacturers, mass media and the general public by promoting study projects and demonstrations. It also sought to investigate developments in the NGV during the 2009-2012 Triennium by compiling changes in the field of natural gas use in its different kinds that occurred around the world since the report published by the International Energy Agency in 2011 (IEA, 2011).

As forecasted, the global NGV market kept growing and started to cover a vast range of synergies among methane-based fuel, which is clearly stated and recognised in the Report. Compressed and liquefied natural gas, biomethane and hydrogen are now combined into one terminology called ‘NGV related infrastructure’, such as filling stations, mobile refuelling units, conversion shops, cylinder requalification facilities and training centres.

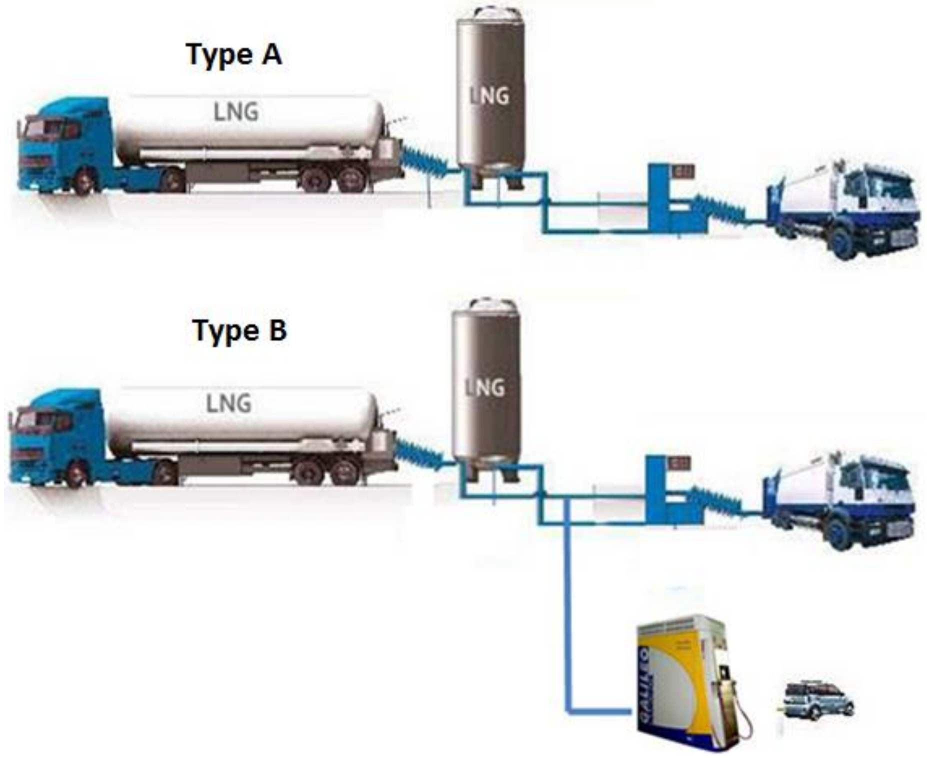
This document also included considerations from the Natural Gas Vehicle Association’s (NGVA) position paper, which aimed to bring some light on the required infrastructure for developing methane refuelling throughout Europe (NGVA EUROPE, 2011). It strongly emphasises that technology-neutral approaches do not help to promote oil dependency and emissions reduction.

It is clear how this Association argued for the European Directive to create the conditions for the development of NG vehicles markets – that is the strategy they used to break the chicken-and-egg dilemma. According to them, in 2011, an investment of roughly € 400 thousand would be necessary for public refuelling stations, plus more 1 million euros for depots. Thus, they appealed for the European Directive in demanding member states to promote this minimum essential infrastructure for both CNG and LNG vehicles.

In the case of heavy-duty vehicles (HDV), the required infrastructure depended on the vehicle’s purpose: passenger or freight transport, urban or road. An LNG refuelling network for goods transport would need to be developed near terminals together with companies and truck operators and throughout the European motorways. In this case, an initial goal of offering refuelling stations every 400 km was established, which is about for times more the required distance for CNG refuelling, as presented in (UNECE, 2003), so L-CNG stations (Type B Station in Figure 14), which could refuel both compressed and liquefied natural gas, best fits for this purpose.

For HDV used in the urban fleets such as buses and refuse trucks, CNG/biomethane refuelling infrastructure is the most viable. According to the Expert Group Future Transportation Fuels (FTF, 2011), European cities should aim at least 50% methane driven HDVs in public fleets, following Madrid’s example, where its whole refuse truck fleet (468 vehicles), and around 42% of its bus fleet (790 units) run on CNG only (ALONSO, 2013).

Figure 14 – Types of Permanent Refuelling Stations



Source: Lebrato and Ribas (2012).

So, NGVA Europe (2011) point out complementary measures for the EU to fund this minimum infrastructure: permits for multifuel stations of CNG or L-CNG and demanding that stations above a specific total volume of sales must offer methane refuelling facilities. These suggestions have no cost for the European Union budget, but press on retailing companies. Also, by using the L-CNG concept, which does not require a direct link to the pipeline since trucks transport the gas, all European filling stations are qualified to offer natural gas.

NGVA Europe (2011) also provides some additional information on costs. CNG HDV may cost from 13% to 25% more than the diesel version, depending on vehicle type. Moreover, the cost of NG pipeline construction ranges from 300 to 600 Euros per metre, depending on land characteristics. Their world statistics show that NGV has grown 12 times compared to 2000 (from 1.2 million to 14.55 million vehicles). During the period considered in this Report, Asia took leadership over Latin America in terms of numbers. Pakistan had the highest fleet in the world (2.85 million of NGV) and a sizeable governmental program supporting the development in the field. Iran, India and China have also shown spectacular dynamics. According to IGU and UNECE (2012), a market share of 20% of natural gas in transport fuels would allow a 5% reduction of the CO_2 emissions from all European Vehicles.

Assuming that 20% of the gas used would be made up of biomethane, the CO_2 reduction would increase to 7%.

There is a synergy between biomethane and natural gas. By 2030, natural gas consumption in the European Union should increase by around 16%. With the supply of natural gas becoming even more dependent on imports, the papers evaluate the possible contribution that substitute products such as biomethane could make to satisfy the future of natural gas. Today, natural gas and biomethane represent the most practical, realistic and easy way to reduce pollution coming from road transportation.

Since 2011, a white paper (EC, 2011) sought to remove the significant barriers and bottlenecks in the transport system across the continent. Their objective is to develop a Single European Transport Area with a more integrated network, connecting to the different modes for both passager and freight transport. By achieving the transformations proposed in this White Paper, the European Union would be able to reduce its CO_2 emissions by 60% by 2050, through the use of cleaner fuels and new technologies.

The document underlines that building additional refuelling stations to ensure public supply and that setting harmonised standards for biomethane injection into the gas grid are absolute priorities. In particular, the group underlines a need for an infrastructure development plan and stresses how investments in the sector can open the way for further environmental improvements. In a 2030-2050 perspective, bio-methane could account for a considerable part of the total volume of methane used in Europe and “the total potential of bio-methane supply is comparable to the total present natural gas consumption of the EU”.

5.1.3 The concept’s reformulation – learning from experience

In 2013, this idea took a new approach, as described by Lebrato and Ribas (2012), who focused on demonstrating the use of LNG as a truck fuel and sook to define a road map for scale development of the market. According to the authors, CNG is a viable and beneficial solution for municipal use in Europe, such as urban buses and garbage collection truck. Inside cities, the engine performance as well as the vehicle’s autonomy were good enough, with present technologies, adapted to natural gas. However, this restricted autonomy would not be suitable for road transportation because:

i. Five litres of CNG (compressed at 200 bar) are required to match the energy content of 1 litre of diesel, thus preventing the use of CNG in heavy road transport, because its volume and weight would be too high for a long-distance truck.

ii. Refuelling stations: as can be seen in Figure 13, an autonomy of 200 km would require refuelling stations not much farther than 100 km from each other. The cost building/adapting all these stations could be prohibitive to the project's operationality.

So, Lebrato and Ribas (2012) have proposed that the use of natural gas in its liquefied state (LNG) would overcome these problems caused by the autonomy restriction. Although the liquefaction process consumes about 5% of NG's energy content, the gas volume drops significantly from 5 litres to 1.8 litres to match diesel's autonomy. This proposal would break the radius restrictions of the first CNG Blue Corridor Project. For this reason, the Blue Corridor concept now is dedicated to LNG. Thus the LNG Blue Corridor Projects has set a goal to build approximately 14 new LNG stations (some that were could supply both CNG and LNG), both permanent and mobile, on critical locations along the Blue Corridor. A fleet of about 100 trucks was acquired to use this LNG infrastructure.

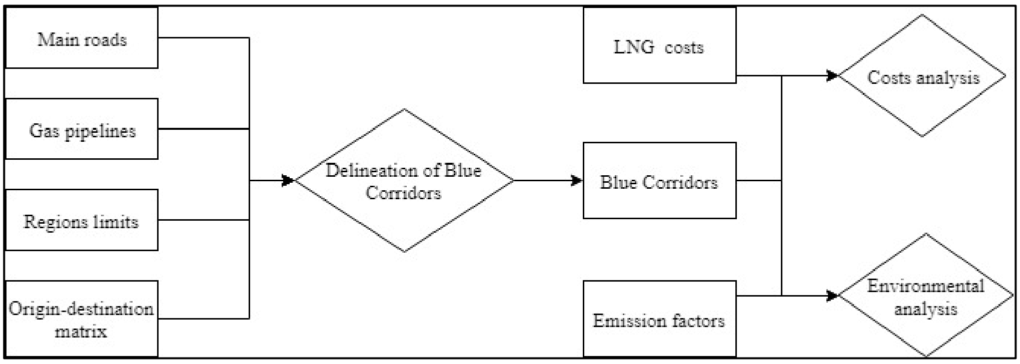
The Natural Gas Vehicle Association (NGVA) in Europe targets a 5% penetration on its market by 2020. It recognises that CNG is already a robust energy source for urban vehicles such as municipal buses and garbage collection trucks, and the spread of this technology will keep on for the next ten years. Currently, there are more than 15 thousand buses fuelled with CNG in Europe, showing the evident technical and financial maturity of these solutions, while many others are still under pilot or subsidised operation.

Hence, the European Blue Corridor project has acquired a new perspective. Rather than promoting CNG, which required refuelling station every 100 km, it is now the first initiative in that continent that sees LNG as the most recommended fuel for road transport. The project was concluded in April 2018 and promoted the building 12 LNG stations and adding a fleet of 140 new LNG trucks. The project encouraged the widespread of this technology in Europe by raising the number of refuelling LNG stations from 50 in 2013 to 155 in 2018.

5.2 Methodology

The methodology used in this study combines the strategies pinpointed in the literature review and try to adapt them to the Brazilian Reality. This work has conducted an economic and environmental analysis for the simulated Blue Corridor, such as presented in Figure 15. At first, we have delineated the Blue Corridor by considering the existent roads, pipelines, geographical limits and travel data (origin-destination). Then we have estimated the implied cost and emissions for our scenarios.

Figure 15 – Flowchart Scheme Detailing Steps of the Research



Source: Mouette et al. (2019)

5.2.1 Delineation of the Blue Corridor

Figure 16 shows the State's main roads and gas pipelines. We obtained shapefiles for the construction of the maps from the Brazilian Institute of Geography and Statistics (IBGE, 2017); the Ministry of Transport, Ports and Aviation (DER, 2005); the Department of Roads and Traffic from the State of São Paulo and the Energy Research Company (EPE, 2018). Our study considered sixteen zones for determining the Blue Corridors in SP, corresponding to the geographical regions of the State of São Paulo.

Figure 16 – State of São Paulo Main Roads and Gas Pipelines

Source: Mouette et al. (2019)

From these regions and flows, we defined two Blue Corridor base scenarios. The first one, the Restricted Scenario (RS), includes only the geographic areas served by gas pipelines, totalising seven regions and more than 145 million trips per day (73% of the total). The Origin-Destination daily data refers exclusively to diesel trucks. Chart 3 shows the assumptions for defining the LNG refuelling stations placement in the RS. It sought to maximise the coverage area for liquefied natural gas trucks.

Chart 3 – Assumption for location and placement of refuelling station

	Descriptions
A	The stations' location must be on main roads to minimise demand risks.
B	Stations must be located as near as possible to the central pipelines to secure NG supply for local liquefaction, respecting assumption A.
C	Stations dispositions must allow production drain from the State extreme (farthest regions from the Capital) to the centre and then to the seacoast, near the Port of Santos, respecting assumptions A and B.
D	The capital must have at least one refuelling station to allow the return to the extremities.
E	Maximise the State covered area with a maximum of one refuelling, respecting assumptions A through D.

Source: Mouette et al. (2019)

Figure 17 – Cartographical Representation for Scenarios 1 (RS) and 2 (SS).

Source: Mouette et al. (2019)

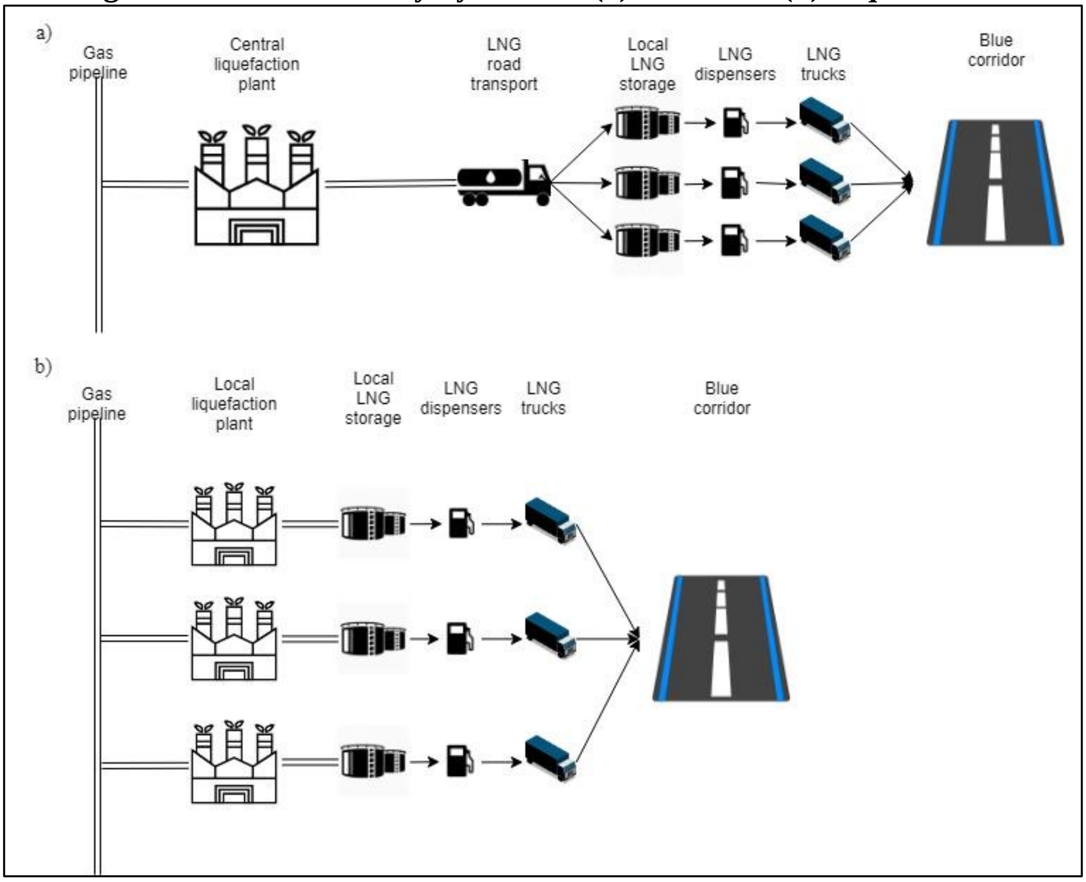
For each scenario, we analysed two ways of distributing LNG (Figure 18). The first option considered was a Centralized Liquefaction (CL) with road distribution, which generated two sub-scenarios for Restricted and State Scenarios, namely RSCL and SSCL, respectively. The second mode of LNG distribution was a Local Liquefaction (LL) in the region, which dispenses with the need for LNG road distribution. This model derives two new scenarios: State Scenario with Hybrid Liquefaction, (local and central) (SSHL) and Restricted Scenario with Local Liquefaction (RSLL). Chart 4 summarises the four sub-scenarios characteristics for the Blue Corridors associated with LNG delivery options.

Chart 4 – Scenarios Characteristics Summary

Scenario	Regions	Trips/Day	Liquefaction	Acronyms
State Scenario	All (16)	199,519	Central	SSCL
			Hybrid	SSHL
Restricted Scenario	7 regions (2-6-10-12-14-15-16)	145,662	Central	RSCL
			Local	RSLL

Source: Mouette et al. (2019)

Figure 18 – LNG Delivery by Central (a) and Local (b) Liquefaction.



Source: Mouette et al. (2019)

5.2.2 Costs Analysis

The cost analysis sought to calculate the absolute difference between the diesel and LNG prices under the four scenarios. We divided the variation in structure cost into Capital Expenditures (CAPEX) and Operational Expenditures (OPEX) for liquefaction, distribution and refuelling. Diesel prices served as a basis for comparing the viability of LNG as a fuel for HDVs. We obtained fuel price data from the National Agency for Oil, Natural Gas and Biofuels (ANP, 2018) and taxes were discounted (12% in diesel prices). Equation (32) calculates the cost of LNG per energy unit using the minimum selling price method.

$$LNG_{p,k} = NG_m + \frac{\sum C_{L,k} + \sum_n \frac{O_{L,k_n}}{(1+i)^n} + C_{D,k} + \sum_n \frac{O_{D,k_n}}{(1+i)^n} + C_{R,k} + \sum_n \frac{O_{R,k_n}}{(1+i)^n}}{\sum LNG_k \times N \times d_a} \qquad (32)$$

Where:

$LNG_{p,k}$ is the price of LNG (in USD/MMBTU) in region k;

NG_m is the price of the natural gas molecule (USD/MMBTU);

$C_{L,k}$, $C_{D,k}$, $C_{R,k}$ are the capital expenditure in region k, for the liquefaction, distribution and refuelling components, respectively in USD;

i is the expected rate of return;

O_{L,k_n}, O_{D,k_n}, O_{R,k_n} are the operational expenditures in each region for each year for each component in USD;

LNG_k is the demand for LNG in region k (mtpa);

N is the number of years of the project (in years);

d_a is the number of days in a year (360 days in a commercial year).

Table 6 describes the model's specifications. The absolute difference between diesel and LNG prices were calculated by subtracting diesel prices with the LNG price, following Equation (33). Where PD_k is the absolute price difference between Diesel (D_k) and Liquefied Natural Gas (LNG_k) in each region k in USD/MMBTU.

$$PD_k = D_k - LNG_k \qquad (33)$$

5.2.2.1 Liquefaction Costs

The regional demand for LNG defines capital and operation cost calculations. The scale of the liquefaction plants, either central or local, assume that LNG ones will substitute 10% of trucks that travel in each region. The LNG demand in each area was calculated based on the tank size studied by Hartounian and Roche (2008) of 135 kg, considering one refuelling per truck per day. Equation (34) shows the regional annual amount of LNG demanded and its estimations are shown in Table 5.

$$LNG_k = \frac{T_k \cdot \mu_k \cdot \varphi_{tank} \cdot d_a}{10^9} \tag{34}$$

Where:

LNG_k is the total demand for LNG in region *k* in million tons per annum (mtpa);

T_k is the number of trucks departing from region *k;*

μ_k is the substitution share of trucks replaced with LNG trucks;

φ_{tank} is the tank size of an LNG truck (in kilograms);

d_a is the number of days in a year.

For both options (central and local), the CAPEX for the liquefaction stage was calculated based on the parameters for scales between 0.05 and 1.00 mtpa, which is 981.62 USD per ton (GARCIA-CUERVA; SOBRINO, 2009). In the case of local liquefaction scale smaller than 0.05, CAPEX was adjusted using Equation (35) such as in Towler and Sinnott (2008), where C2 is the capital cost (USD) associated with scale S2, based on a known cost of C1 for scale S1. The exponent *n* is equal to 0.6, which is an average for the whole chemical industry (GERRARD, 2000).

$$C_2 = C_1 \cdot \left(\frac{S_1}{S_2}\right)^n \tag{35}$$

Capital costs in the liquefaction stage encompass the feed gas treatment unit, one liquefaction train, utilising the mixed refrigerant technologies (PRICO process), one LNG storage tank of 150,000 m^3 (single containment) and LNG lorry loading facilities (GARCIA-CUERVA; SOBRINO, 2009). Operational costs include personnel (operations, maintenance and administration), electricity consumption, general maintenance, insurance and the consumption of refrigerants. We adopted the parameters obtained from Garcia-Cuerva and Sobrino (2009), MTE (2018), and the World Bank (2015) to calculate the Liquefaction OPEX.

Table 5 – Estimated Annual Demand for LNG in Each Region.

Region	Number of daily departures	Tonnes of LNG/d	LNG (mtpa)
1	9,134	123.31	0.04
2	3,814	51.49	0.02
3	7,759	104.75	0.04
4	3,408	46.01	0.02
5	3,125	42.19	0.02
6	6,306	85.13	0.03
7	6,064	81.86	0.03
8	7,775	104.96	0.04
9	10,100	136.35	0.05
10	18,568	250.67	0.09
11	2,693	36.36	0.01
12	52,695	711.38	0.26
13	3,799	51.29	0.02
14	37,594	507.52	0.18
15	13,654	184.33	0.07
16	13,031	175.92	0.06
Total SS	199,519	2,693.52	0.97
Total RS	145,662	1,966.44	0.71

Source: Mouette et al. (2019)

5.2.2.2 Distribution Costs

Small scale-LNG is assumed to be distributed in two types of insulated tanks to maintain the temperature at -160 °C. These tanks have two classifications: conventional and container type. The first has capacities varying from 20m^3 to 42 m^3; the latter can transport 32 m^3 and allows modal transference between ships, lorries and trains (FRAGA, D. M.; LIAW, C.; GALLO, 2017). Cost estimate for the main types of expenditures for logistics, which are related to drivers, tires, maintenance and labour costs was obtained from Araújo et al. (2014).

Table 6 – Model's Specs

Description	**Value INPUT**	**Unit**
Distance from the Liquefaction Plant to Regas	Variable*	km
Average transportation speed	50	km/h
Truck Capacity	30	m^3 of LNG
Tank CAPEX	75,749	USD/unit
Vessel capacity	7,500	m^3 of LNG
Fillable Volume	98.5%	% of capacity
Boil off	0.1%	% per day
Vessel Availability	8,400	hours/year
Vessel Flow rate	1,000	m^3/hour
Vessel Speed	26	km/h
Loading/offloading time	7.5	hours/operation
Preparation for departure	29	hours/operation
Anchoring and Arrival	29	hours/operation
Preparation for returning	5	hours/operation
OPEX	0.06	USD/mmbtu
Storage capacity time	3	days
Liquefaction plant capacity	0.72	million ton/year
Max hours of working	20	hour
Regas plant capacity	1.00	million ton/year
Liquefaction CAPEX	981.62	USD/ton
Regas plant CAPEX	104.81	USD/ton
Storage Tanks CAPEX	2016.50	USD/m^3
Storage capacity per tank	500.00	m^3 of LNG
Liquefaction plant electricity capacity	471.00	kwh/tpa
Electricity cost	504.00	R$/kwh

Source: from the authors

5.2.2.3 Refuelling Infrastructure Costs

LNG infrastructure is considered technologically mature and settled by Mariani (2016). However, it still suffers from lack of scale effect, since as much as 70 stations were operative in Europe in 2015, and while China accounted for 1,500 posts. In Brazil, LNG is not currently an option for the transport sector, and Compressed Natural Gas is available in some regions for light-duty vehicles only.

The capital and operational costs for the refuelling infrastructure follow the parameters reported by Mariani (2016) and MTE (2018). They include civil work, electrical, remote control and payment systems, LNG storage for one day based on local demand, LNG pumping and dispensers. The calculation of the necessary number of distributors for the operation and supply of daily demand required an average of 5 minutes per refuelling. The technology chosen for the refuelling procedure was the saturated LNG at 7 to 8 bar, which works through differential pressures and presents Relatively Low CAPEX and OPEX, besides its low space requirements.

5.2.3 Environmental Analysis

This analysis has estimated the resultant emission of adopting LNG trucks in terms of pollutants: nitrogen oxides (NOx), hydrocarbons (HC) and particulate matter (PM). For calculating GHG emissions and pollutants, we have analysed only the State Scenario (SS) and the Restricted Scenario (RS), since the others only differ in the mode of distribution and supply of LNG. This section discusses its impacts on emissions for each scenario.

We have adopted a bottom-up method that considers fuel consumption and emission factors for the calculation of pollutants and GHG emissions. Table 5 has already estimated fuel consumption. Pollution emission factors for LNG vehicles were obtained from Verbeek and Verbeek (2015) while GHG emissions factors from the American Environmental Protection Agency (EPA, 2014) since there are no LNG trucks in Brazil.

For diesel, we have estimated emissions by using the data from the Environmental Company of the State of São Paulo (CETESB, 2017). It reflects real driving conditions and presents emission factors for pollutants and greenhouse gases for the different phases of the Brazilian Program for Control of Air Pollution from Automotive Vehicles (PROCONVE), which a vehicle labelling program based on the EURO standards. Emission factors for PM, HC and NOx, have been reduced due to the renewal of the vehicle fleet. We have used Equation (36) to establish a single emission factor per pollutant or emitted gas, to get a weighted value for different vehicle categories and age.

$$EF_p = \sum_{i=1}^{N} V_i \cdot YEF_{i,p} \tag{36}$$

Where:

EF_p is the weighted emission factor (g/m³) for pollutant p;

V_i is the share (%) of the total fleet circulating in year N produced in the year i;

$YEF_{i,p}$ is the emission factor (g/m³) of pollutant p of vehicles produced in the year i.

São Paulo's diesel truck fleet was estimated using data from the State Department of Traffic of São Paulo (DETRAN, 2018) and corrected through a scrappage curve defined by (MMA, 2014). The scrappage function result is a renormalised logistic function expressed by Equation (37).

$$S(t) = \frac{1}{1 + \exp\left(a(t - t_0)\right)} + \frac{1}{1 + \exp\left(a(t + t_0)\right)} \tag{37}$$

Where:

$S(t)$ is the fraction of the remaining vehicles, t is the age of the vehicles in years;

t_0= 17.0 for trucks

a = 0.10 for trucks.

Under PROCONVE 7 (equivalent to Euro 5) standards, 61% of the vehicles have the potential for being replaced, while the remaining may adopt PROCONVE 5 standards (EURO 3). Since pollutant emissions are of local interest, we elaborated an index to represent the combined reduction in pollution, which we called "Avoided Pollution Index", calculated using Equation (38).

$$API_r = \frac{\sum_i \frac{P_{i,r}}{P_{max}}}{n} \tag{38}$$

Where:

API_r is the Avoided Pollution Index of region r, ranging from 0 to 1.

$P_{i,r}$ is the total emissions of pollutant i in region r,

P_{max} is the highest emission of pollutant P in all the regions

n is the total number of pollutants (n = 3).

5.3 Results and Discussion

This section shows and comments the resulting economic and environmental analysis for each Blue Corridor scenario. The Blue Corridor total length was 3.1 (for Restricted-based Scenarios) and 8.9 (for State-based Scenarios) thousand kilometres each. The Restricted Scenarios (RSLL and RSCL) is limited to gas pipelines, which reduce the length of the Blue Corridor. Conversely, the state scenarios SSCL and SSHL do not require natural gas delivery through the pipe network, since liquefaction is conducted offsite and delivers LNG by truck transportation.

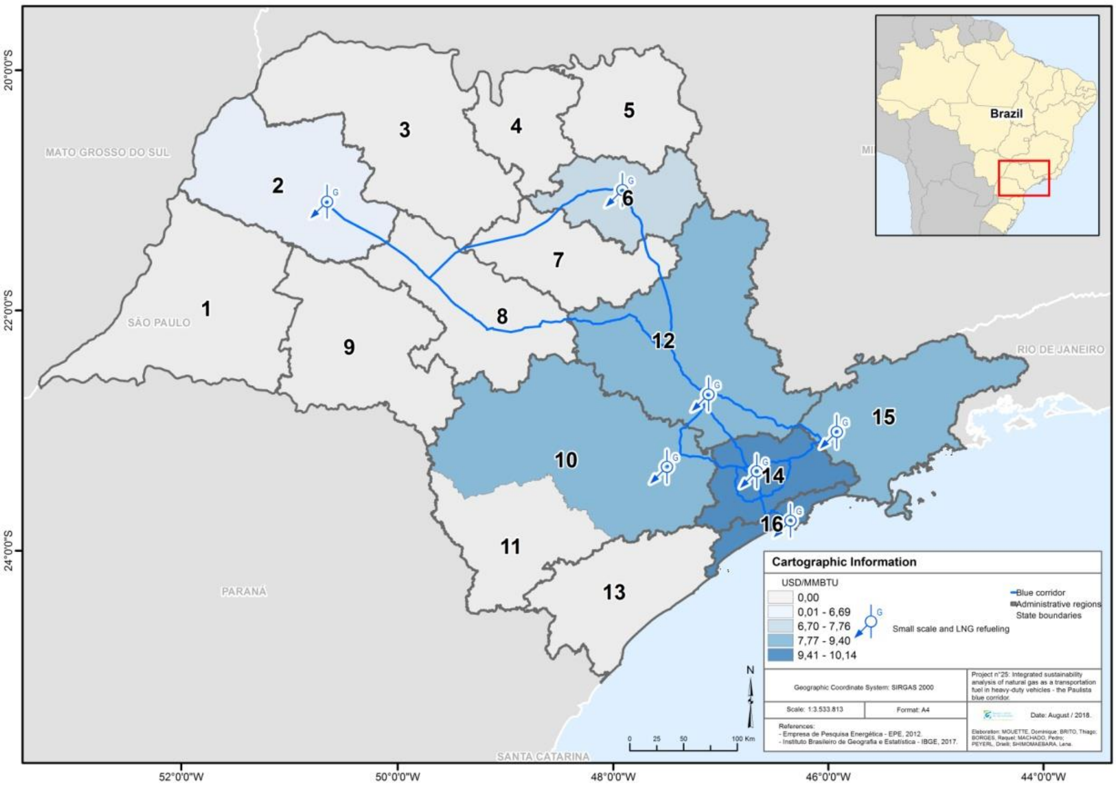
Table 7 – Absolute Price Difference between Diesel and LNG (in USD/MMBTU)

Region	RSLL	SSCL	SSHL	RSCL
1	-	13.7	13.7	-
2	9.7	14.1	9.7	13.4
3	-	13.9	13.9	-
4	-	13.3	13.7	-
5	-	13.0	13.9	-
6	10.8	13.4	10.8	13.5
7	-	13.7	13.7	-
8	-	13.8	13.1	-
9	-	14.7	14.0	-
10	12.4	13.5	12.4	13.9
11	-	13.3	13.3	-
12	12.4	14.0	14.0	14.0
13	-	12.8	13.8	-
14	13.0	14.8	13.0	14.7
15	11.8	13.6	11.8	13.6
16	13.3	15.4	13.3	15.2
Total average	9.5	9.8	9.6	10.1

Source: Mouette et al. (2019)

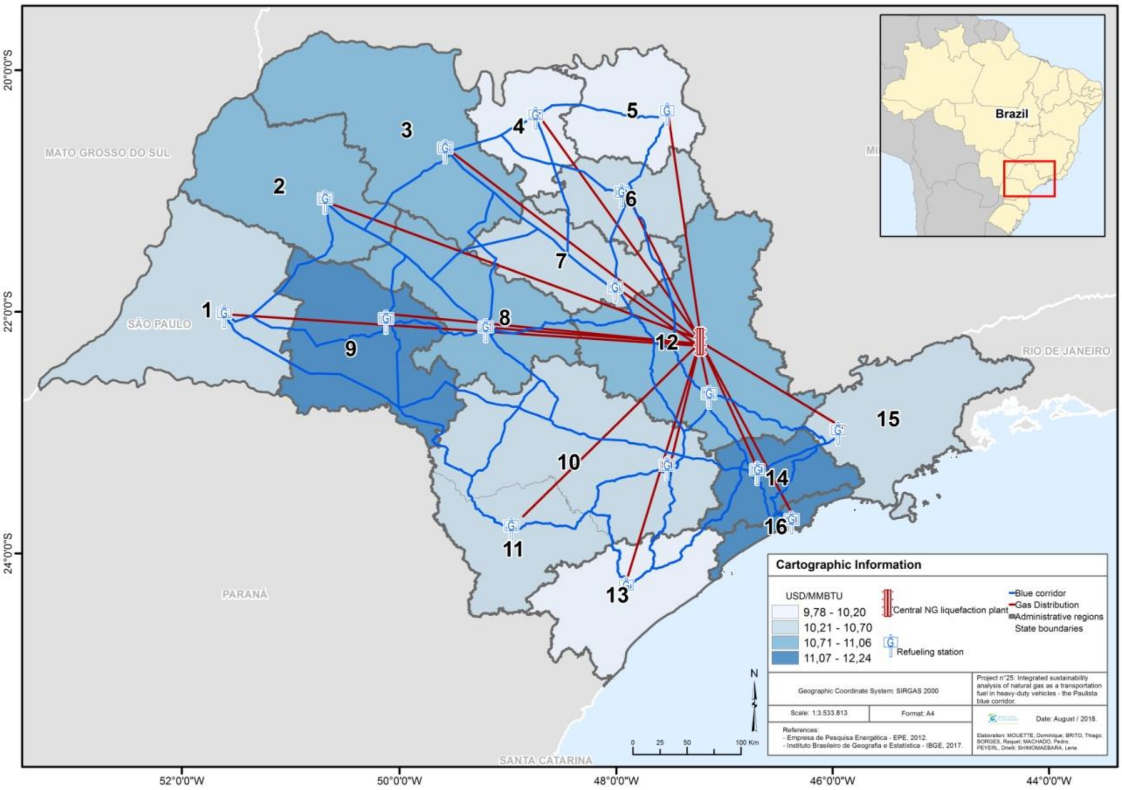
Table 7 shows the absolute difference between diesel and LNG prices in each region for each scenario. The RSLL shows the smallest average absolute difference between diesel and LNG, meaning that the LNG delivery process in this scenario is more costly than others. Figure 19 through Figure 22 show the corresponding cartographical representation for scenario Blue Corridor scenario and the absolute price differences between diesel and LNG.

Figure 19 – RSLL with Suggested Refueling Stations



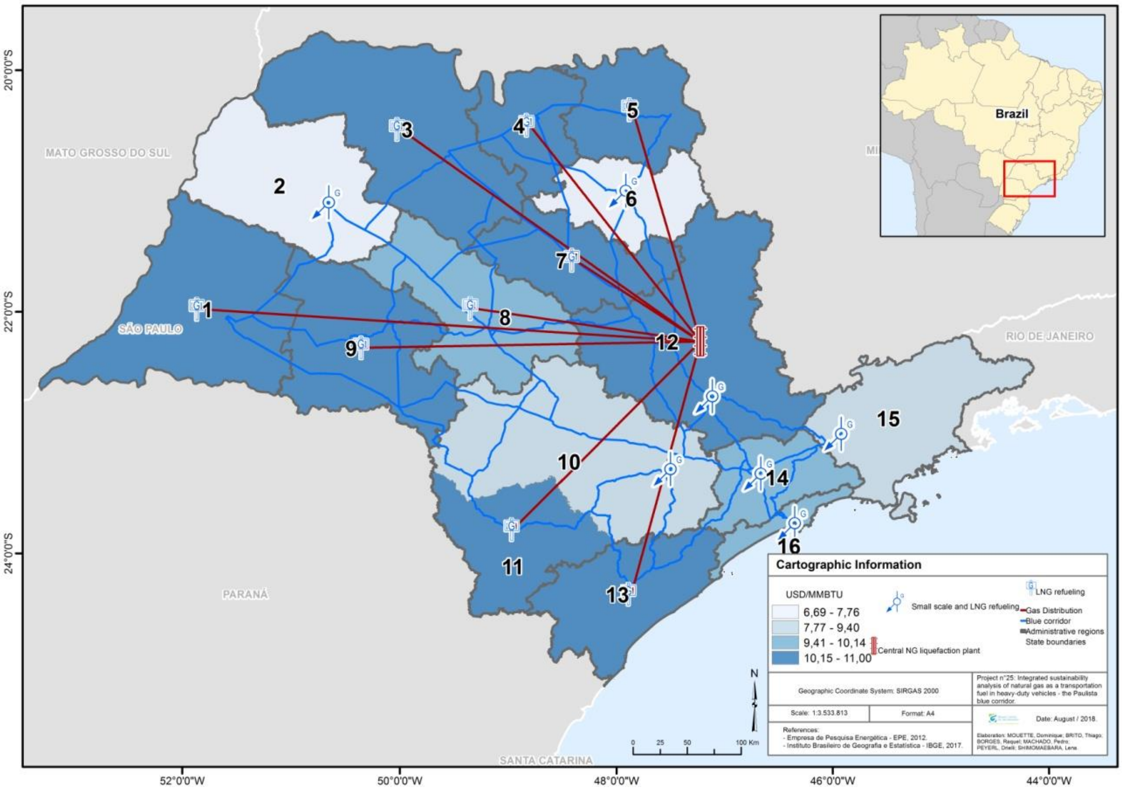
Source: Mouette et al. (2019)

Figure 20 – SSCL with Suggested Refueling Stations



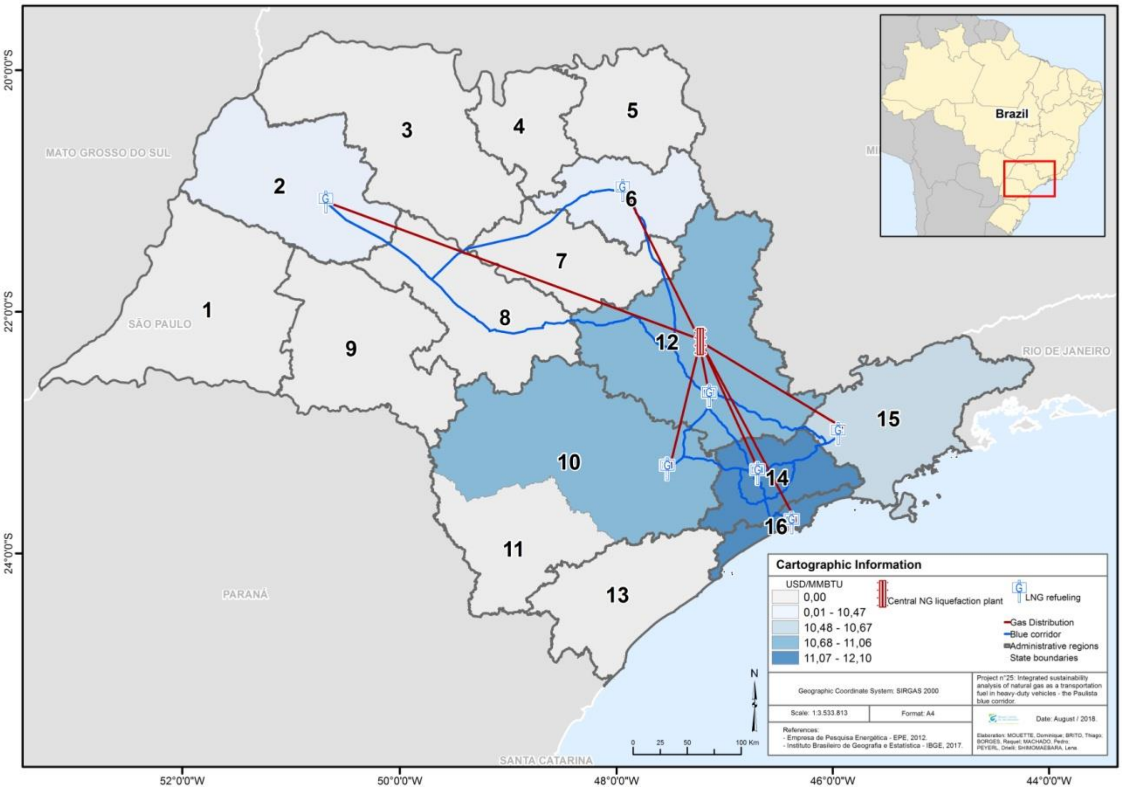
Source: Mouette et al. (2019)

Figure 21 – SSHL with Suggested Refueling Stations



Source: Mouette et al. (2019)

Figure 22 – RSCL with Suggested Refueling Stations



Source: Mouette et al. (2019)

The Restricted Scenario with Local Liquefaction (Figure 19) requires a total investment of 243.1 USD per meter of the Blue Corridor, including local liquefaction and refuelling stations. The operating costs reach 1,765.5 USD per ton of LNG, reaching a final average price of 12.6 USD/MMBTU. Regional differences are considerable. There is a 51% difference from region 16, which has the most considerable absolute difference between fuel prices to zone 2, with the lowest absolute difference. Viability, however, is still possible in both areas.

With a higher delivery of LNG, SSCL (Figure 20) takes advantage of the scaling effect, which reduces the necessary investments to 123.4 USD per meter of the Blue Corridor. Even though SSCL has a logistic component in the total capital expenditure, it only represents 4% of the total investments. The overall CAPEX increase by 44% compared to RSLL to increase 37% of total LNG delivered. The Blue Corridor, however, increases considerably due to the higher possible interconnections between regions. The operating costs per ton of LNG in SSCL are 11% lower than RSLL, reaching 1,562.8 USD per ton. In SSCL, LNG reaches a final price of 12.4 USD/MMBTU. Regional differences are smaller than RSLL, with a 25% difference between the highest absolute difference (16) and the lowest (13).

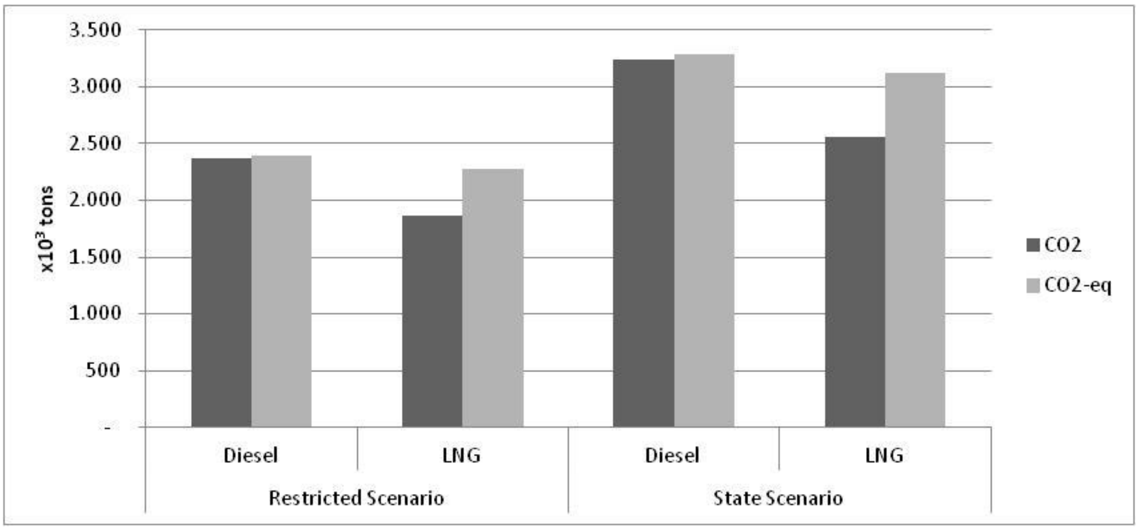
Investments in SSHL (Figure 21) show a marginal decrease in comparison to SSCL, primarily due to the scale effect in region 12, which will be responsible for 73% of all the LNG in the State in SSHL. The total CAPEX increases by 43% in comparison with RSLL, which allows the same 37% increase as SSCL in LNG delivery. With a required investment of 122.1 USD per meter of Blue corridor, SSHL is the cheapest scenario when it comes to cost per meter. For operating costs, it shows a reduction of 6% in USD per ton of LNG as compared to RSLL, with 1,656.0 USD per ton of LNG. The final LNG price in this scenario is 12.5 USD/MMBTU. In SSHL, regional differences are higher than RSLL, reaching 64% between region 12 (the centre of distribution) and 2.

Finally, RSCL (Figure 22) presents the lowest LNG price, with an average of 12 USD/MMBTU. However, with the smaller blue corridor, the total investment per meter increases to 243.4 USD/m. Operating costs in RSCL are lower due to its centralised nature and due to the smaller scale of production, costing 1,426.6 USD/ton. RSCL represents the slightest regional difference, with 17% between the highest and lowest absolute difference between diesel and LNG prices (region 16 and 2).

5.3.1 Environmental assessment of LNG trucks

The use of LNG shows benefits regarding fuel costs as compared to diesel. Figure 23 shows the greenhouse gases (GHG) emissions for the restricted and state scenarios. The relative reduction in CO_2 emissions is 21%, which represents an absolute reduction of almost 500 thousand tons and roughly 683 thousand tons, respectively.

Figure 23 – GHG Emissions in the Restricted and State Scenarios

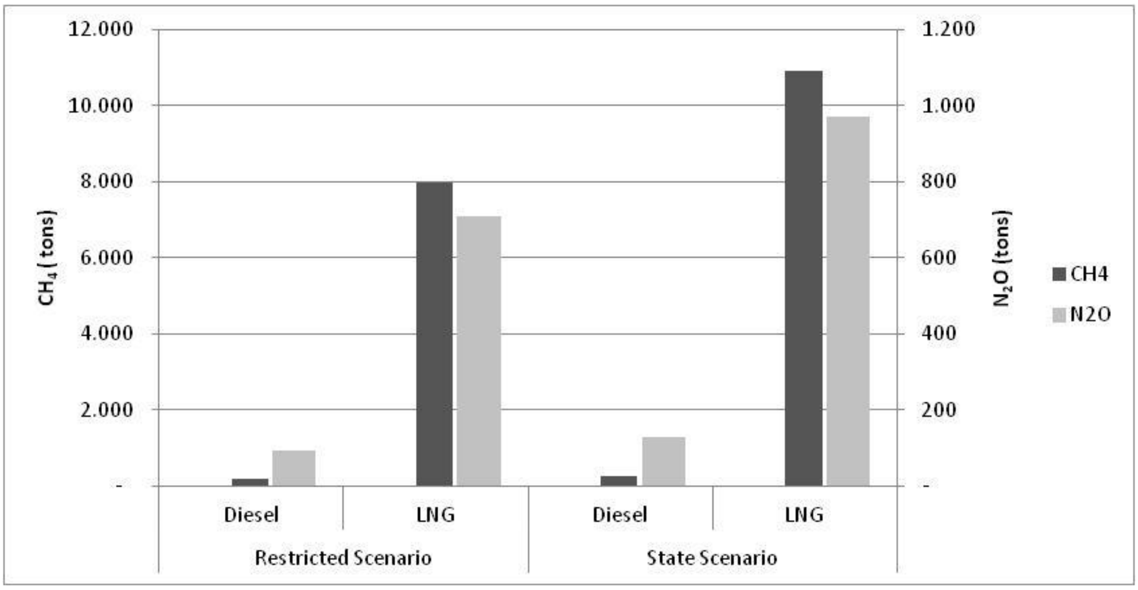


Source: Mouette et al. (2019)

When it comes to the use of LNG, GHG emissions differ from diesel emissions in terms of CH_4 and N_2O, greenhouse gases with Global Warming Potential (GWP) of 28 and 265, respectively (IPCC, 2014). When diesel is used, CO_2 accounts for 99% of $CO_{2\text{-eq}}$ emissions, and when the fuel used is LNG, it accounts for 82% of $CO_{2\text{-eq}}$ emissions, while CH_4 accounts for 10% and N_2O for 8%.

Figure 24 shows the CH_4 and N_2O emissions. The adoption of LNG increases CH_4 emissions to 7,775 tons in the Restricted Scenario and to 10,650 tons in the State Scenario. For N_2O, there is an increase of 615 tons in the first and 842 tons in the second. Nevertheless, as Figure 23 shows, the resulting decrease in $CO_{2\text{-eq}}$ emissions reaches 118,170 tons in the Restricted Scenario and 161,863 tons in the State Scenario, which corresponds to a 5.2% reduction. Regarding LNG transport logistics emissions, the worst-case scenario refers to the state scenario with centralised LNG production and corresponds to 1% of the total emitted $CO_{2\text{-eq}}$ in the use of trucks. In SSHL, logistics represent 0.34% of emissions, and in RSCL, logistics corresponds to 0.28%.

Figure 24 – CH_4 and N_2O emissions in the RS and SS



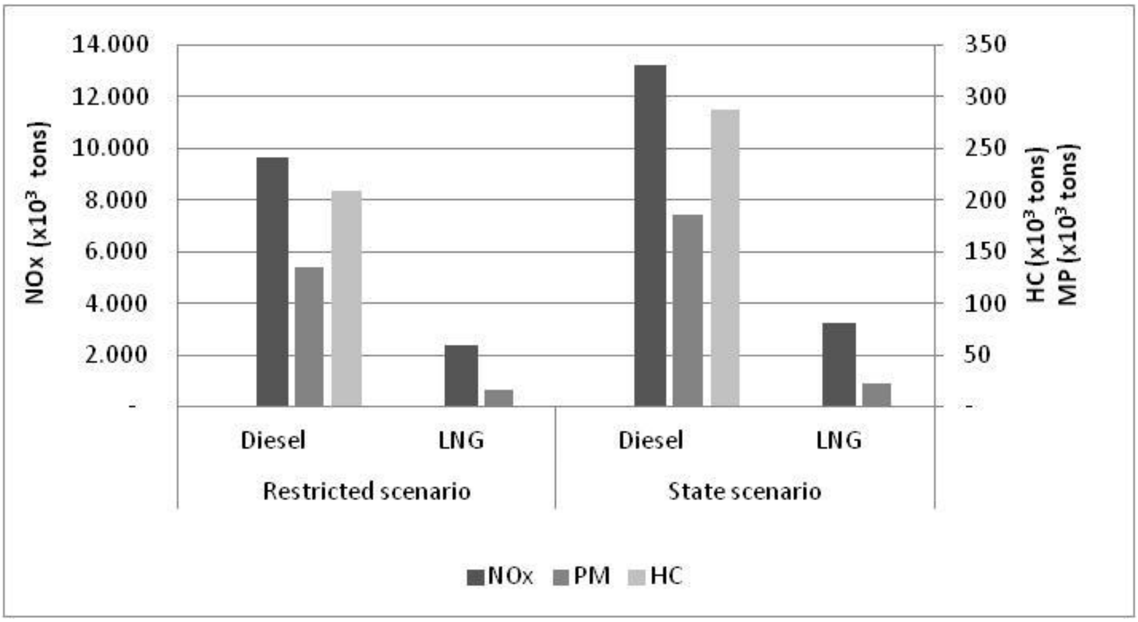
Source: Mouette et al. (2019)

5.3.2 Pollutant emissions

The use of natural gas provides a great benefit to the population by drastically reducing the emission of local pollutants. Figure 25 shows that the adoption of LNG causes a reduction of 88% for PM, 75% for NOx and virtually total elimination of hydrocarbon emissions. These figures correspond, in the restricted scenario, to a total of 119,129 tons of PM emissions, 7.3 million tons of NOx and 209,230 tons of HC avoided. In the State Scenario, the benefits are even higher, with reductions of 163 thousand tons of PM, 10 million tons of NOx and 286 thousand tons of HC.

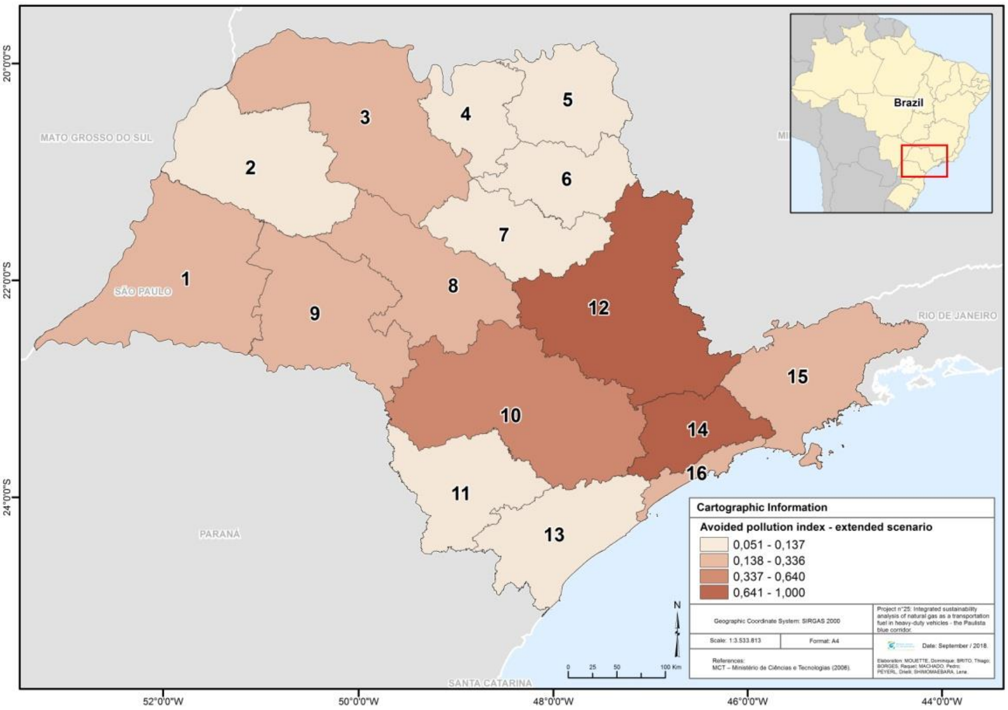
Since the benefits of pollution reduction are perceived locally, the total pollutant reductions were plotted for the State regions, using the Avoided Pollution Index, shown in Figure 26. It shows that the benefits of reducing diesel consumption would benefit the most populated areas, which are compatible with RSLL and RSCL.

Figure 25 – NOx, PM and HC Emissions in the Restricted and State Scenarios



Source: Mouette et al. (2019)

Figure 26 – Avoided Pollution Index for the state of São Paulo.



Source: Mouette et al. (2019)

5.4 Conclusions

Results show that LNG is an affordable fuel choice when compared to diesel fuel, which could be on roughly 10 USD cheaper than diesel oil per MMBTU consumed. Even though regional differences are present in the State of São Paulo, no region shows disadvantages for LNG. Price differences range from 9.7 USD/MMBTU in Araçatuba (2) in RSLL to 15.2 USD/MMBTU in Santos (16) in RSCL.

Regarding environmental benefits, we observed a 5% reduction in GHG emissions in terms of CO_2 equivalent. Moreover, local pollutant emissions of NO_x, PM and HC have significant cuts of 75, 88 and 100%. The highest reductions in overall pollution are in the regions of São Paulo (14) and Campinas (12), where higher LNG substitution.

The future implementation of such an infrastructure depends on the viability of investments. In this sense, the recommendation is to start the distribution with centralised liquefaction and road transportation of LNG, as represented by RSCL that would supply LNG to the regions with the highest concentration trips and refuelling demand. With the evolution of demand for LNG, it is of interest to reduce fuel road transportation, bringing liquefaction closer to end consumers, which goes to meet the sustainable goals of the transport sector, reducing kilometres travelled and, consequently, emissions of GHG gases and pollutants. These conclusions imply that RSCL should evolve into SSHL, with a hybrid liquefaction infrastructure.

Future studies might bring a time perspective to the implementation of one or more of the scenarios described here, by adopting a diffusion approach, such as the article presented previously. Despite the difficult access to natural gas vehicles in Brazil, studies might use the results presented in this article as a way to define realistic parameters for the diffusion of LNG vehicles in the country.

6 FINAL CONCLUSIONS

This section contains comments and comparison from all reported papers and suggestions for future studies. An overall reading of our articles brings us some lessons regarding the use of diffusion and market share models for alternative fuel vehicles. Despite their limitations, which we will discuss ahead, these models provide innovative comprehensions regarding the adoption of new vehicle technologies.

The diffusion model paper exposed in Chapter 3 sums up to the current literature by providing an innovative explanation for the impacts of tax reduction on the diffusion of successive vehicle technologies in Brazil. We conducted a broad review of diffusion models and studies about incentives on renewable energy technologies. The Brazilian Alcohol Program brings insightful elements and lessons for alternative techniques for vehicles although many of its policies were not adequately designed since its beginnings. In other words, the PROALCOOL also learned with its own experience.

The multi-generational diffusion model adopted in Chapter 3 is innovative in two ways: on the theoretical/methodological perspective since it incorporated elements such as marketing variables and leapfrogging; and on the approach side, since it is the first time we study the Alcohol Program under such framework. The estimations could be significantly improved if more a more robust historical series could be accessed, which exists, but is not publicly available. The results evidence the importance of such incentives in the early stages of the diffusion process, but also reinforce the need to achieve self-sustainability on the medium-long run. The parameters of our model were able to capture consumer's loss of confidence in technology due to contrary word-of-mouth, and we observed how it contributed to its failure.

As mentioned before, the published paper from our Chapter 3 has discussed the cultural and behavioural impacts of the new technology in Brazil (BRITO et al., 2019). The creation of the Alcohol Program, launched in 1975, when the country was under a period of the military government, reflects a top-down push of the ethanol technology, strongly supported by this regime's policy to substitute imported oil products by domestic produced ethanol (DUARTE; RODRIGUES, 2017; NASTARI, 1983). This fact echoes the cultural dimension of high-power distance where inequality in power structure is widely accepted in the society, such as discussed by HOFSTEDE (2001). Later, during the 1990s, when the country had resumed democratic government, a new regulatory system, the Petroleum Law, gave strong support to ethanol producers (GOLDEMBERG et al., 2014). More recently, a new government policy

(Renovabio) still shows the program's dependence on regulation to sustain itself (CORDELLINI, 2018).

The inclusion of ethanol as a vehicle fuel has also caused changes to the population's fuelling and driving habits. Isabella et al. (2017) surveyed consumer's preferences in Brazil from the perspective of diffusion theory and supply change management and found that the environmental and convenience concerns of flex-fuel vehicle owners meant that they do not invariably make economically rational decisions. Subsequently, we will review our results in the context of these cultural dimensions.

The study presented in Chapter 4 has estimated the market share cross elasticities of different vehicle technologies in Brazil. Our literature review has shown research gaps in the field of market share modelling, which has mostly focused on brands rather than technologies. A few studies have analysed the impact of fossil fuel energy on either gasoline car or fuel-efficient cars, but no association between fuel price and vehicle sales elasticity for other technologies have been conducted.

We use the advances of market share models to simultaneously estimate the market share elasticity, both own and cross effects, of each technology taking into account substitution effects. The market-share analysis has provided us with tools to analyse the transition of elasticities for the successive generations of technologies with regards to both gasoline and ethanol fuels.

This analysis shows how vehicle sales are sensitive to fuel price fluctuations. We observe this elasticity when only two technologies are competing, such as gasoline and ethanol during the first phase of the Alcohol program. The parameters obtained also brings a new perspective on the contribution of price to the failure of the ethanol dedicated technology. When a third technology enters the market, we observed that efficiency gains have substantially contributed to making flex vehicles dominant compared to other technologies. We argue that assuring competitive prices for alternative fuels and technologies might be as crucial as providing financial incentives, as we analysed in the previous article.

In Chapter 5, we revisited the Blue Corridor concept and proposed a range of scenarios in the State of São Paulo for the adoption of LNG trucks. The Blue Corridor project was a long-term policy developed in Europe at the start of the 2000s (by the time Brazil was introducing flex cars into its market). Similar to the Brazilian ethanol program, the Blue Corridor project was a joint effort of government, gas retailers, vehicle manufacturers and associations, which face a sort of challenges and adaptations through the process.

The employed methodology integrated econometric, supply and logistic factors, as well as a technical specification to provide a set of pictures of possible penetrations of LNG trucks. Due to data limitation, we were not able to conduct a diffusion or market share study for Brazil or any other country. However, our scenarios might provide resources to develop spatial diffusion studies, possibly by adopting contagion/epidemic approaches to account for both vehicle adoptions and infrastructure installation.

Nevertheless, our results presented affordable and realistic adaptation costs that could lead to substantial environmental gains. We concluded that central liquefaction facility that distributes the LNG to refuelling stations might be the most effective initial strategy until the technology takes off and justifies the adoption of local liquefaction. Under the current assumptions, the change from diesel oil to LNG would still increase the total emissions of greenhouse gases, in terms of CO_2 equivalence. Although this might suggest that technology still need to be improved, the most significant gains could be obtained if the national pipeline grid were enhanced, which would require LNG transportation by road.

The limitations of our studies fall on the very nature of quantitative approaches. Some of the historical elements that might impact on market share or diffusion are not measurable, and therefore cannot be included in the models, such as the versatility of flex vehicles and future ethanol shortage problems during the 1980s, which caused long waiting lines at stations. We also recognise the intrinsic relation of our first two studies' results to the Brazilian reality. Since it is hard to find a country with similar geographical and historical developments, our findings might not be replicable for other regions. Nevertheless, due to the size and continental importance of Brazil, such studies are still relevant to better understand the countries response to new technologies, such as we did in our published paper from Chapter 3.

This fact raises a debate about biofuels participation in renewable energy sources for transportation. Since many countries are unable to produce ethanol due to climate, land availability or water use restrictions, they prefer to invest in renewable sources of power generation and focus on electrification of their fleet. Unless we see further developments of the anhydrous ethanol international market and signs that ethanol supply would be enough for a worldwide demand, its use would still be restricted to producing countries such as Brazil and the United States. Even on the latter's case, ethanol is more used as an additive rather than an individual fuel competing against gasoline.

For those reasons, electric vehicles have acquired prominence over the last years, which we observe in the scientific literature. This debate makes us wonder more about the diffusion of electric vehicles in Brazil. As discussed in Chapter 4, this technology is still quite insignificant in terms of market share in the country, but as we suggest in Chapter 3's conclusion, the introduction of a hybrid flex vehicle may bring a new perspective on this technology. It may even acquire the status of a 4^{th} technological generation, under the definitions of our diffusion model, which a future study was proposed. Plug-in electrical vehicles might require a policy similar to the one presented in Chapter 5 since they demand the construction and adaptation of the current refuelling infrastructure.

The Brazilian experience with the National Alcohol Program has enabled significant participation of biofuels in the country's transportation sector. However, the dominance of this energy source is a barrier to the entry of other technologies capable of providing environmental gains, such as natural gas, and hybrid electric, battery and hydrogen cars. Therefore, a natural development of this thesis would be to elaborate a new integrated model for the diffusion and market share analysis of LNG trucks using parameters of similar technologies as a basis, including biofuels, and the decision making processes of drivers and fleet owners. Despite its application to the study of LNG trucks, it is possible to adapt it to the study of other types of vehicles and fuels. The results obtained are expected to point to specific market conditions (price ranges) and policies (tax rate values), as well as deadlines for LNG penetration. For example: if the target market target for LNG vehicles at the end of 10 years is m, the price of natural gas must be p_1 and diesel oil p_2, the price of vehicles v_1 and v_2 respectively. At the same time, the rate for the acquisition of the vehicle equal to a_1 and a_2, respectively.

In conclusion, this thesis marks a vital professional and personal achievement for the author. Coming from a background in International Relations, the use of quantitative methods has always been considered a deadlock. Nevertheless, with immense dedication, frequent trial and error, and substantial support from the professors, the author overcame his insecurities and mastered the use of such tools. To face the challenges of interdisciplinary research, one requires a great deal of open-mindedness, persistence and humility to learn new methods and propose original studies.

REFERENCES

ACEA. **ACEA Report Vehicles in use Europe 2018**. [s.l.] European Automobile Manufacturers Association, 2018.

AGÊNCIA NACIONAL DO PETRÓLEO, GÁS NATURAL E BIOCOMBUSTÍVEIS - ANP **Price Survey System: search by State**. Disponível em: <http://www.anp.gov.br/preco/prc/resumo_por_estado_index.asp>. Acesso em: 18 dez. 2018.

AGUIRRE, M.; IBIKUNLE, G. Determinants of renewable energy growth: A global sample analysis. **Energy Policy**, v. 69, p. 374–384, 2014.

AL-ALAWI, B. M.; BRADLEY, T. H. Review of hybrid, plug-in hybrid, and electric vehicle market modeling Studies. **Renewable and Sustainable Energy Reviews**, v. 21, p. 190–203, 2013.

ALMEIDA, E. L. F. DE et al. **Relatório Final - Corredores Azuis:** um estudo da viabilidade da difusão do GNV em rotas internacionais do Cone-Sul. Rio de Janeiro: Instituto de Economia - UFRJ, 2005.

ALONSO, J. A. T. **Public Transport and Natural Gas:** experience with CNG buses in Madrid (Spain). São Paulo: Oral communication, 2013.

ALVES, D. C. O.; BUENO, R. DE L. DA S. Short-run, long-run and cross elasticities of gasoline demand in Brazil. **Energy Economics**, v. 25, n. 2, p. 191–199, 2003.

ANDERSEN, F. M.; LARSEN, H. V.; SKOVGAARD, M. A European model for the number of End-of-Life Vehicles. **International Journal of Automotive Technology and Management**, v. 7, n. 4, p. 343–355, 2007.

ANFAVEA. **Brazilian Automotive Industry Yearbook**. São Paulo and Brasilia: Brazilian Automotive Industry Association, 1994.

ANFAVEA. **Brazilian Automotive Industry Yearbook**. São Paulo and Brasilia: Brazilian Automotive Industry Association, 2018.

ARAÚJO, M. P. S.; BANDEIRA, R. A. M.; CAMPOS, V. B. G. Costs and freights charged in road cargo transportation: a comparative analysis between owner, operators and companies. **Journal of Transport Literature**, v. 8, n. 4, p. 187–226, 2014.

BAKER, C.; BEER, T. Comments on “Emissions from a vehicle fitted to operate on either petrol or compressed natural gas” by Ristovski et al. (2004). **Science of the Total Environment**, v. 366, n. 1, p. 392–394, 2006.

BAKHAT, M. et al. Elasticities of transport fuels at times of economic crisis: An empirical analysis for Spain. **Energy Economics**, v. 68, p. 66–80, 2017.

BARAN, R.; LEGEY, L. F. L. The introduction of electric vehicles in Brazil: Impacts on oil and electricity consumption. **Technological Forecasting and Social Change**, v. 80, n. 5, p. 907–917, 2013.

BASS, F. A New Product Growth for Model Consumer Durables. **Management Science**, v. 15, n. 5, p. 215–227, 1969.

BASS, F. M.; KRISHNAN, T. V; JAIN, D. C. Why the Bass Model Fits without Decision Variables. **Marketing Science**, v. 33, n. 3, p. 203–223, 1994.

BASTIAN-PINTO, C.; BRANDÃO, L.; DE LEMOS ALVES, M. Valuing the switching flexibility of the ethanol-gas flex fuel car. **Annals of Operations Research**, v. 176, n. 1, p. 333–348, 2010.

BASTIN, C.; SZKLO, A.; ROSA, L. P. Diffusion of new automotive technologies for improving energy efficiency in Brazil's light vehicle fleet. **Energy Policy**, v. 38, n. 7, p. 3586–3597, 2010.

BELL, D. E.; KEENEY, R. L.; LITTLE, J. D. C. A Market Share Theorem. **Journal of Marketing Research**, v. 12, n. 2, p. 136–141, 1975.

BENVENUTTI, L. M. M. et al. The Effectiveness of Tax Incentive Policies in the Diffusion of Electric and Hybrid Cars in Brazil. In: CONGRESSO LATINOAMERICANO DE DINAMICA DE SISTEMAS, 45, 2016, São Paulo. São Paulo: 2016

BENVENUTTI, L. M. M.; RIBEIRO, A. B.; URIONA, M. Long term diffusion dynamics of alternative fuel vehicles in Brazil. **Journal of Cleaner Production**, v. 164, p. 1571–1585, 2017.

BRITO, T. et al. The Dialectics of Energy Security and Nations Interdependence: Reflections Focused on the Role of Oil and the Brazilian Dimension. In: MONIÉ, F.; BINSZTOK, J. (Eds.). **Petroleum Geography and Geopolitics**. 1ª ed. Rio de Janeiro: Mauad X, 2012. p. 15–50.

BRITO, T. L. F. et al. Qualitative Comparative Analysis of cities that introduced compressed natural gas to their urban bus fleet. **Renewable and Sustainable Energy Reviews**, v. 71, p. 502–508, maio 2017.

BROWNSTONE, D.; BUNCH, D. S.; TRAIN, K. Joint mixed logit models of stated and revealed preferences for alternative-fuel vehicles. **Transportation Research Part B: Methodological**, v. 34, n. 5, p. 315–338, 2000.

BURKE, P. J.; NISHITATENO, S. Gasoline prices, gasoline consumption, and new-vehicle fuel economy: Evidence for a large sample of countries. **Energy Economics**, v. 36, p. 363–370, 2013.

CANTAMESSA, M.; MONTAGNA, F. **Management of Innovation and Product Development:** integrating business and technological perspectives. Torino, Italy: Springer, 2016.

CAO, X.; MOKHTARIAN, P. L. **The Future Demand for Alternative Fuel Passenger Vehicles:** a diffusion of innovation approach. Sacramento: The California Department of Transportation, 2004.

CEBRAT, G.; ANACKER, C. **ALTER-MOTIVE:** documentation and evaluation of international case studies. [s.l.] The ALTER-MOTIVE Project, 2010. v. WP4 D6

CETESB. **Air Quality in the State of São Paulo 2014.** São Paulo: São Paulo State's Environmental Company, 2015.

CETESB. **Vehicle Emissions in São Paulo State 2016**. São Paulo: São Paulo State Environmental Company, 2017.

CHERN, S. W. **Energy Demand and lnterfuel Substitution in the Combined Residential and Commercial Sector**. Oak Ridge: Energy Research and Development Administration, 1976.

COELHO, S. T. et al. Brazilian sugarcane ethanol: lessons learned. **Energy for Sustainable Development**, v. 10, n. 2, p. 26–39, 2006.

COHEN, J. T. Diesel vs compressed natural gas for school buses: A cost-effectiveness evaluation of alternative fuels. **Energy Policy**, v. 33, n. 13, p. 1709–1722, 2005.

COHN, S. M. Fuel choice and aggregate energy demand in the residential and commercial sectors. **Energy**, v. 5, n. 12, p. 1203–1212, 1980.

COLLANTES, G. O. Incorporating stakeholders' perspectives into models of new technology diffusion: **The case of fuel-cell vehicles**. v. 74, p. 267–280, 2007.

COOPER, L. G.; NAKANISHI, M. **Market-share analysis:** evaluating competitive marketing effectiveness. [s.l.] Kluwer Academic Publishers, 2010.

D'AGOSTO, M. D. A.; RIBEIRO, S. K.; DE SOUZA, C. D. R. Opportunity to reduce greenhouse gas by the use of alternative fuels and technologies in urban public transport in Brazil. **Current Opinion in Environmental Sustainability**, v. 5, n. 2, p. 177–183, 2013.

DANAHER, P. J.; HARDIE, B. G. S.; PUTSIS, W. P. Marketing-Mix Variables and the Diffusion of Successive Generations of a Technological Innovation. **Journal of Marketing Research**, v. 38, n. 4, p. 501–514, 2001.

DEBNATH, D. et al. Complement or substitute: Ethanol's uncertain relationship with gasoline under alternative petroleum price and policy scenarios. **Applied Energy**, v. 191, p. 385–397, 2017.

DER. **Classificação e Codificação de Rodovias Estaduais**. São Paulo: Departamento de Estradas e Rodagem, 2005.

DETRAN. **Frota de Veículos em SP - por tipo de veículo**. São Paulo: Departamento Estadual de Trânsito, 2018.

DIAMOND, D. The impact of government incentives for hybrid-electric vehicles: Evidence from US states. **Energy Policy**, v. 37, n. 3, p. 972–983, 2009.

DU, X.; CARRIQUIRY, M. A. Flex-fuel vehicle adoption and dynamics of ethanol prices: Lessons from Brazil. **Energy Policy**, v. 59, p. 507–512, 2013.

EUROPEAN COMISSION. **White Paper on Transport**: roadmap to a single european transport area–towards a competitive and resource-efficient transport system. [s.l.] European Comission, 2011.

______. **LNG Blue Corridors**. [s.l.] European Comission, 2017.

EGBUE, O.; LONG, S. Barriers to widespread adoption of electric vehicles: An analysis of consumer attitudes and perceptions. **Energy Policy**, v. 48, n. 2012, p. 717–729, 2012.

ENERGY INFORMATION ADMINISTRATION. **Annual Energy Outlook 2019 with projections to 2050**. Washington : EIA D. C.: U. S., 2019.

ENDO, E. Market penetration analysis of fuel cell vehicles in Japan by using the energy system model MARKAL. **International Journal of Hydrogen Energy**, v. 32, n. 10–11, p. 1347–1354, 2007.

EMPRESA DE PESQUISA ENERGÉTICA -EPE **Brazilian National Energy Balance - Historical Series**. Rio de Janeiro : Brasilia: Energy Research Office, 2018a.

EMPRESA DE PESQUISA ENERGÉTICA - EPE. **Zoneamento Nacional de Recursos de Óleo e Gás**. Rio de Janeiro and Brasilia: Energy Research Office, 2018b.

ENVIRONMENTAL PROTECTION AGENCY. **Emission Factors for Greenhouse Gas Inventories**. Washington, D. C.: EPA , 2014.

EWING, G. O.; SARIGÖLLÜ, E. Car fuel-type choice under travel demand management and economic incentives. **Transportation Research Part D:** Transport and Environment, v. 3, n. 6, p. 429–444, 1998.

FAZELI, R.; DAVIDSDOTTIR, B.; HLYNUR, J. Residential energy demand for space heating in the Nordic countries: Accounting for interfuel substitution. **Renewable and Sustainable Energy Reviews**, v. 57, p. 1210–1226, 2016.

FENG, Y.; FULLERTON, D.; GAN, L. Vehicle choices, miles driven, and pollution policies. **Journal of Regulatory Economics**, v. 44, n. 1, p. 4–29, 2013.

FERREIRA, A. et al. Economic overview of the use and production of photovoltaic solar energy in Brazil. **Renewable and Sustainable Energy Reviews**, v. 81, n. June 2017, p. 181–191, 2018.

FRAGA, D. M.; LIAW, C.; GALLO, A. **Technical Visits to LNG Import Terminals from ENAGAS at Cartagena in Spain and REN Atlantico at Sines in Portugal**, 2017.

FREITAS, I. M. B.; DANTAS, E.; IIZUKA, M. The Kyoto mechanisms and the diffusion of renewable energy technologies in the BRICS. **Energy Policy**, v. 42, p. 118–128, 2012.

FUTURE TRANSPORT FUEL. **Infrastructure for alternative fuels: Report of the European Expert Group on Future Transport Fuels**. [s.l.], FTF, 2011.

GARCIA-CUERVA, E. D.; SOBRINO, F. S. A new business approach to conventional small scale LNG. WORLD GAS CONFERENCE, 24., 2009, Argentina. Argentina: IGU, 2009

GERRARD, A. M. **Guide to Capital Cost Estimating**. Rugby, UK: Institution of Chemical Engineers, 2000.

GOLDEMBERG, J. et al. Ethanol learning curve - The Brazilian experience. **Biomass and Bioenergy**, v. 26, n. 3, p. 301–304, 2004.

GOLDEMBERG, J.; COELHO, S. T.; GUARDABASSI, P. The sustainability of ethanol production from sugarcane. **Energy Policy**, v. 36, n. 6, p. 2086–2097, 2008.

GUIDOLIN, M.; GUSEO, R. The German energy transition: Modeling competition and substitution between nuclear power and Renewable Energy Technologies. **Renewable and Sustainable Energy Reviews**, v. 60, p. 1498–1504, 2016.

GUIDOLIN, M.; MORTARINO, C. Cross-country diffusion of photovoltaic systems: Modelling choices and forecasts for national adoption patterns. **Technological Forecasting and Social Change**, v. 77, n. 2, p. 279–296, 2010.

HARTOUNIAN, S.; ROCHE, G. **How far can you go in an LNG truck ?** How about to Boron and back — with fuel to spare? Boron: Boron, 2008.

HUSE, C. Fuel choice and fuel demand elasticities in markets with flex-fuel vehicles. **Nature Energy**, v. 3, n. 7, p. 582–588, 2018.

IBENHOLT, K. Explaining learning curves for wind power. **Energy Policy**, v. 30, p. 1181–1189, 2002.

IBGE. **National Household Sample Survey - PNAD**. Rio de janeiro: Brazilian Institute of Geography and Statistics, 1988.

IBGE. **Divisão Regional do Brasil em Regiões Geográficas Imediatas e Regiões Geográficas Intermediárias 2017**. Rio de Janeiro: Brazilian Institute of Geography and Statistics, 2017.

INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE -IPCC. **Climate Change 2014: Mitigation of Climate Change.** Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press, 2014.

INTERNATIONAL ENERGY AGENCY. **World Energy Outlook Special Report:** are we entering the golden age of gas? Paris: IEA , 2011.

INTERNATIONAL GAS UNION AND UNITED NATIONS. UNECE. **Natural Gas for Vehicles**. [s.l.] IGU: European Comission for Economics, 2012.

IRAWAN, M. Z. et al. A market share analysis for hybrid cars in Indonesia. **Case Studies on Transport Policy**, v. 6, n. 3, p. 336–341, set. 2018.

ISLAM, T. Household level innovation diffusion model of photovoltaic (PV) solar cells from stated preference data. **Energy Policy**, v. 65, p. 340–350, 2014.

ISLAM, T.; MEADE, N. The Diffusion of Successive Generations of a Technology: A More General Model. **Technological Forecasting and Social Change**, v. 56, p. 49–60, 1997.

JENN, A.; SPRINGEL, K.; GOPAL, A. R. Effectiveness of electric vehicle incentives in the United States. **Energy Policy**, v. 119, n. July 2017, p. 349–356, 2018.

JEON, S. Y. **Hybrid & Electric vehicle technology and its market feasibility**. [s.l.] Massachusetts Institute of Technology, 2010.

JUN, D. BIN; PARK, Y. S. A Choice-Based Diffusion Model for Multiple Generations of Products. **Technological Forecasting & Social Change**, v. 58, p. 45–58, 1999.

KIM, K. H.; SHON, Z. H. Long-term changes in PM10 levels in urban air in relation with air quality control efforts. **Atmospheric Environment**, v. 45, n. 19, p. 3309–3317, 2011.

KLIER, T.; LINN, J. Fuel prices and new vehicle fuel economy-Comparing the United States and Western Europe. **Journal of Environmental Economics and Management**, v. 66, n. 2, p. 280–300, 2013.

______. Using Taxes to Reduce Carbon Dioxide Emissions Rates of New Passenger Vehicles: Evidence from France, Germany, and Sweden. **American Economic Journal: Economic Policy**, v. 7, n. 1, p. 212–242, 2015.

KLOESS, M.; MÜLLER, A. Simulating the impact of policy, energy prices and technological progress on the passenger car fleet in Austria-A model based analysis 2010-2050. **Energy Policy**, v. 39, n. 9, p. 5045–5062, 2011.

KOTLER, P. **Marketing Management:** analysis, planning, and control. Fifth ed. Englewood Cliffs: Prentice-Hall Inc., 1984.

LANGBROEK, J. H. M.; FRANKLIN, J. P.; SUSILO, Y. O. The effect of policy incentives on electric vehicle adoption. **Energy Policy**, v. 94, p. 94–103, 2016.

LEBRATO, J.; RIBAS, X. **LNG Blue Corridors position paper - LNG BC Deliverable 7.1**. [s.l.] European Commission’s Senventh Framework Programme (FP7), 2012.

LEIBOWICZ, B. D. Policy recommendations for a transition to sustainable mobility based on historical diffusion dynamics of transport systems. **Energy Policy**, v. 119, n. May, p. 357–366, 2018.

LIEVEN, T.; RIETMANN, N. Do policy measures in fact promote electric mobility? A study across 20 countries. **International Journal of Transport Development and Integration**, v. 2, n. 1, p. 39–48, 2018.

LUND, P. D. Exploring past energy changes and their implications for the pace of penetration of new energy technologies. **Energy**, v. 35, n. 2, p. 647–656, 2010.

MAHAJAN, V.; MULLER, E.; BASS, F. M. New Product Diffusion Models: A Review and Directions for Research. **Journal of Marketing**, v. 54, n. 1, p. 1–26, 1990.

MAHAJAN, V.; MULLER, E.; KERIN, R. A. Introduction Strategy for New Products with Positive and Negative Word-of-Mouth. **Management Science1**, v. 30, n. 12, p. 1389–1404, 1984.

MARIANI, F. **Cost analysis of LNG refuelling stations**. Brussels: LNG Blue Corridors, 2016.

MASINI, A.; FRANKL, P. Forecasting the diffusion of photovoltaic systems in southern Europe: A learning curve approach. **Technological Forecasting & Social Change**, v. 70, p. 39–65, 2002.

MASSIANI, J.; GOHS, A. The choice of Bass model coefficients to forecast diffusion for innovative products: An empirical investigation for new automotive technologies. **Research in Transportation Economics**, v. 50, p. 17–28, 2015.

MEADE, N.; ISLAM, T. Modelling and forecasting the diffusion of innovation – A 25-year review. **International Journal of Fore**, v. 22, p. 519–545, 2006.

______. Modelling European usage of renewable energy technologies for electricity generation. **Technological Forecasting and Social Change**, v. 90, n. PB, p. 497–509, 2015.

MESQUITA, D. L. et al. O desenvolvimento de processos de inovação sob a ótica da teoria dos custos de transação: o caso da tecnologia flex-fuel. **Revista de Administração e Inovação**, v. 10, n. 1, p. 119–140, 2013.

MEYER, P. E.; WINEBRAKE, J. J. Modeling technology diffusion of complementary goods: The case of hydrogen vehicles and refueling infrastructure. **Technovation**, v. 29, n. 2, p. 77–91, 2009.

MINISTRY OF FINANCE - MF. **Table of Incidence of the Tax over Product Industrialized (TIPI.** MF: Brazilian, 2018.

MINISTERIO DO MEIO AMBIENTE - MMA. **2nd National Inventory of Atmospheric Emissions by Motor Road Vehicles**. Brasilia, Brazil: Ministry of Environment, 2014.

MORAIS, J.; THOMAS-AGNAN, C.; SIMIONI, M. Modeling market-shares or compositional data: An application to the automobile marke**t**. In: INTERNATIONAL WORKSHOP ON STATISTICAL MODELLING, 31., 2016, Rennes. Rennes, INSA: 2016

MORAIS, J.; THOMAS-AGNAN, C.; SIMIONI, M. Impact of advertising on brand’s market-shares in the automobile market: a multi-channel attraction model with competition and carryover effects. **HAL**, 2017.

MOREIRA, J. R.; GOLDEMBERG, J. The alcohol program. **Energy Policy**, v. 27, n. 4, p. 229–245, 1999.

MOREIRA, J. R.; NOGUEIRA, L. A. H.; PARENTE, V. Biofuels for Transport, Development, and Climate Change: Lessons from Brazil. In: BRADLEY, R.; BAUMERT, K. A. (Eds.). . **Growing in the Greenhouse**: protecting the climate by putting development first. [s.l.] World Resources Institute, 2005. p. 132.

MOUETTE, D. et al. Costs and emissions assessment of a Blue Corridor in a Brazilian reality: The use of liquefied natural gas in the transport sector. **Science of The Total Environment**, v. 668, p. 1104–1116, 2019.

MOUTINHO DOS SANTOS, E.; PARENTE, V. The Second Alcohol Shock in Brazil - Looking for More Flexibility. INTERNATIONAL ASSOCIATION OF ENERGY ECONOMICS. Potsdam: 2006

MTE. **Relação Anual de Informações Sociais**. [s.l.] Ministry of Work and Employment, 2018.

MUNIZ, G. B.; GASQUES, M. V. **É do Brasil:** Toyota confirma produção do primeiro carro híbrido flex do mundo. [s.l.] Revista Autoesporte, 2018.

MUÑOZ, M.; OSCHMANN, V.; DAVID TÀBARA, J. Harmonization of renewable electricity feed-in laws in the European Union. **Energy Policy**, v. 35, n. 5, p. 3104–3114, 2007.

NEGRO, S. O.; ALKEMADE, F.; HEKKERT, M. P. Why does renewable energy diffuse so slowly? A review of innovation system problems. **Renewable and Sustainable Energy Reviews**, v. 16, n. 6, p. 3836–3846, 2012.

NGVA EUROPE. **NGVA Europe Position Paper :** minimum infrastructure needs for methane (ng/biomethane) refuelling across Europe. Madrid and Brussels: European Natural Gas Vehicle Association, 2011.

NOORI, M.; TATARI, O. Development of an agent-based model for regional market penetration projections of electric vehicles in the United States. **Energy**, v. 96, p. 215–230, 2016.

NORTON, J. A.; BASS, F. M. A Diffusion Theory Model of Adoption and Substitution for Successive Generations of High-Technology Products. **Management Science**, v. 33, n. 9, p. 1069–1086, 1987.

OSORIO-TEJADA, J. L.; LLERA-SASTRESA, E.; SCARPELLINI, S. Liquefied natural gas: Could it be a reliable option for road freight transport in the EU? **Renewable and Sustainable Energy Reviews**, v. 71, n. January, p. 785–795, 2017.

PAE, J. H.; LEHMANN, D. R. Multigeneration innovation diffusion: The impact of intergeneration time. **Journal of the Academy of Marketing Science**, v. 31, n. 1, p. 36–45, 2003.

PEFLEY, R. K. et al. **Feedback controlled fuel injection system can accommodate any alcohol-gasoline blend**. INTERNATIONAL SYMPOSIUM ON ALCOHOL FUELS TECHNOLOGY. São Paulo: 1980

PETER, R. Conceptual model for marketing solar based technology to developing countries. **Renewable Energy**, v. 25, p. 511–524, 2002.

PFEIFFER, B.; MULDER, P. Explaining the diffusion of renewable energy technology in developing countries. **Energy Economics**, v. 40, p. 285–296, 2013.

PINTO, J. T. M.; AMARAL, K. J.; JANISSEK, P. R. Deployment of photovoltaics in Brazil: Scenarios, perspectives and policies for low-income housing. **Solar Energy**, v. 133, p. 73–84, 2016.

PUGLIERI, R. **Analysis of the Sugar-Alcohol Industry Under the Optics of the Competition Defense: How to Define Relevant Markets.** [s.l.] University of São Paulo, 2013.

RADPOUR, S.; HOSSAIN, A.; KUMAR, A. Market penetration modeling of high energy efficiency appliances in the residential sector. **Energy**, v. 134, p. 951–961, 2017.

RAO, K. U.; KISHORE, V. V. N. Wind power technology diffusion analysis in selected states of India. **Renewable Energy**, v. 34, n. 4, p. 983–988, 2009.

______. A review of technology diffusion models with special reference to renewable energy technologies. **Renewable and Sustainable Energy Reviews**, v. 14, n. 3, p. 1070–1078, 2010.

REN21. **Renewables 2019 Global Status Report**. Paris: Renewable Energy Policy Network for the 21st Century, 2019.

RIESZ, J. et al. Quantifying the costs of a rapid transition to electric vehicles. **Applied Energy**, v. 180, n. 2016, p. 287–300, 2016.

RIVERS, N.; SCHAUFELE, B. Gasoline price and new vehicle fuel efficiency: Evidence from Canada. **Energy Economics**, v. 68, p. 454–465, 2017.

RODRIGUES, L.; BACCHI, M. R. P. Analyzing light fuel demand elasticities in Brazil using cointegration techniques. **Energy Economics**, v. 63, p. 322–331, 2017.

RODRIGUES, N.; LOSEKANN, L.; SILVEIRA FILHO, G. Demand of automotive fuels in Brazil: Underlying energy demand trend and asymmetric price response. **Energy Economics**, v. 74, n. 451, p. 644–655, 2018.

ROGERS, E. M. **Diffusion of Innovations**. 5th. ed. New York: Free Press, 2003.

SAHI, R. K.; ERDMANN, R. W. Energy prices and conservation - The Canadian experience. **Energy Policy**, n. June 1979, 1981.

SALVO, A. Flexible fuel vehicles, less flexible minded consumers: Price information experiments at the pump. **Journal of Environmental Economics and Management**, set. 2018.

SATOH, D. A discrete Bass model and its parameter estimation. **Journal of the Operations Research Society of Japan**, v. 44, n. 1, p. 16–18, 2001.

SHAFIEI, E. et al. Potential impact of transition to a low-carbon transport system in Iceland. **Energy Policy**, v. 69, p. 127–142, 2014.

SHI, X.; FERNANDES, K.; CHUMNUMPAN, P. Diffusion of multi-generational high-technology products. **Technovation**, v. 34, n. 3, p. 162–176, 2014.

SIERZCHULA, W. et al. The influence of financial incentives and other socio-economic factors on electric vehicle adoption. **Energy Policy**, v. 68, p. 183–194, 2014.

SPEECE, M. W.; MACLACHLAN, D. L. Forecasting Fluid Milk Package Type with a Diffusion Model. **IEEE Transactions of Engineering Management**, v. 39, n. 2, 1992.

STREMERSCH, S.; MULLER, E.; PERES, R. Does new product growth accelerate across technology generations? **Marketing Letters**, v. 21, n. 2, p. 103–120, 2010.

STRUBEN, J.; STERMAN, J. D. Transition challenges for alternative fuel vehicle and transportation systems. **Environment and Planning B:** planning and design, v. 35, p. 1070–1098, 2008.

TEIXEIRA, E. C. **The Development of Flex-Fuel Technology in Brazil**. São Paulo: Instituto DNA Brasil, 2005.

TENKORANG, F. et al. Relationship between ethanol and gasoline: AIDS approach. **Energy Economics**, v. 50, p. 63–69, 2015.

TOWLER, G. P.; SINNOTT, R. K. **Chemical engineering design**: principles, practice and economics of plant and process design. London: Elsevier, 2008.

TURRIO-BALDASSARRI, L. et al. Evaluation of emission toxicity of urban bus engines: Compressed natural gas and comparison with liquid fuels. **Science of the Total Environment**, v. 355, n. 1–3, p. 64–77, 2006.

UNECE. **Blue Corridor Project**: on the use of natural gas a motor fuel in international freight and passenger traffic. New York and Geneva: [s.n.].

UNFCCC. **Adoption of the Paris Agreement -** Conference of the Parties COP 21**.** Proposal by the President. [s.l.] United Nations Framework Convention on Climate Change, 2015.

USBLS. **Consumer Price Index**. Washington: United States Bureau of Labor Statistics, 2018.

VANCE, C.; MEHLIN, M. **Tax Policy and CO2 Emissions -** An Econometric Analysis of the German Automobile Market. Bochum: Ruhr University Economic Papers, 2009.

VERBEEK, R.; VERBEEK, M. **LNG for trucks and ships:** fact analysis**:** review of pollutant and GHG emissions Final. Delft: TNO Innovation for Life, 2015.

VERSLUIS, C. DRAMs, fiber and energy compared with three models of market penetration. **Technological Forecasting and Social Change**, v. 69, p. 263–286, 2002.

VISHWANATH, A.; CHEN, H. Towards a Comprehensive Understanding of the Innovation-Decision Process. In: VISHWANATH, A.; BARNETT, G. A. (Eds.). . **The Diffusion of Innovations:** a communication science perspective. New York: Peter Lang, 2011. p. 239.

VORMITTAG, M. P. A D. A. et al. **Avaliação dos Impactos na Saúde da Poluição Atmosférica no Estado de São Paulo**. São Paulo: Instituto Saúde e Sustentabilidade, 2013.

WANSART, J.; SCHNIEDER, E. Modeling market development of electric vehicles. **2010 IEEE International Systems Conference**, p. 371–376, 2010.

WB. **Mini/Micro LNG for commercialization of small volumes of associated gas**. Washington: World Bank, 2015.

WEI, K. C. Modeling the Impact of Incentives on Vehicle Sales Volume. PROCEEDINGS OF THE 2001 IEEE INTERNATIONAL. Mexico City: 2001

XIAN, H. et al. Diesel or compressed natural gas? A real options evaluation of the U.S. natural gas boom on fuel choice for trucking fleets. **Energy**, v. 90, p. 1342–1348, 2015.

YU, A. S. O. et al. The evolution of flex-fuel technology in Brazil: The Bosch case. **Technology Management for Global Economic Growth (PICMET), 2010 Proceedings of PICMET ’10:**, n. July, p. 1250–1260, 2010.

ZACHARIADIS, T.; SAMARAS, Z.; ZIEROCK, K. H. Dynamic modeling of vehicle populations: An engineering approach for emissions calculations. **Technological Forecasting and Social Change**, v. 50, n. 2, p. 135–149, 1995.

ZHU, Y.; TOKIMATSU, K.; MATSUMOTO, M. A Diffusion model for Natural Gas Vehicle : A case study in Japan. **Energy Procedia**, v. 75, p. 2987–2992, 2015.