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A fleet-based well-to-wheel model for policy support: the Brazilian socio-technical light-vehicles system transitions

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O presente trabalho em nível de doutorado foi avaliado e aprovado por banca examinadora composta pelos seguintes membros:

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Prof.ª Lucila Maria de Souza Campos, Dr.ª
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Dedico esta tese ao meu pai, Prof. Dr. Francisco das Chagas Marques, por ser um grande exemplo para minha vida e por me inspirar com sua própria trajetória acadêmica.

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“Compra a verdade, a sabedoria, a disciplina e a inteligência, e não as vendas por preço algum!”
(Salomão, Provérbios 23.23 – versão King James Atualizada)

“Buy the truth, and do not sell it,
Also wisdom and instruction and understanding.”
(Solomon, Proverbs 23.23 – New King James Version)

RESUMO

As transições para a sustentabilidade são processos de transformação de longo prazo que ocorrem entre um sistema sociotécnico para outro mais sustentável, envolvendo elementos como tecnológicos, regulamentos, políticas. O subsetor de transportes é responsável pela emissão de grande parte dos gases de efeito estufa (GEE) e outros poluentes. Esforços acelerados são necessários para atender à contribuição nacionalmente determinada (NDC) do Acordo de Paris, visando reduzir as emissões e limitar o aquecimento global. Nesse sentido, o Brasil é conhecido por sua trajetória ímpar de utilização de bioetanol como um de seus principais combustíveis. Além disso, sua rede elétrica predominantemente limpa indica o país como um lugar promissor para a difusão de veículos elétricos (VEs). Contudo, estas afirmações só podem ser confirmadas através de uma avaliação do ciclo de vida e, tão importante, ao considerar toda frota, da avaliação da necessidade de políticas para transições em longo prazo. Nesse contexto, esta tese visa responder às seguintes questões de pesquisa: Como diferentes estratégias podem mitigar as emissões de GEE da frota de veículos leves? Como os principais atores evoluíram historicamente em termos de suas posturas e saliências na transição dos veículos? Como contabilizar a eficácia de potenciais ações para sustentabilidade na frota de veículos para servir de suporte à política de longo prazo? O objetivo geral desta tese é propor um modelo do poço-à-roda (PAR) baseado-em-frota que estima o potencial impacto ambiental e de saúde humana da frota de veículos leves do Brasil no longo prazo para orientar e apoiar a tomada de decisão no sentido de acelerar as transições para a sustentabilidade. A metodologia envolveu abordagens qualitativa e quantitativa. Uma análise histórica da transição de 50 anos dos veículos no Brasil foi realizada, utilizando o *framework* da perspectiva multinível das teorias de transições, juntamente com a *multiple stream approach* das teorias de processo de política. Com isso, os principais atores foram avaliados com relação às suas posturas e saliências. Além disso, foi desenvolvido a ferramenta *Fleet-based Well-to-wheel Model for Policy Suppor*t (FWEMPS), programada em dinâmica de sistemas, capaz de estimar o potencial impacto ambiental e de saúde humana no longo prazo. O FWEMPS captura a inserção de novas tecnologias e combustíveis dos veículos e permite o teste de várias estratégias de mitigação. Os resultados revelam uma boa perspectiva de redução das emissões pelo aumento de biocombustíveis ou VEs, mas destacam que, a menos que avanços consideráveis na eficiência de combustível e difusão de VEs ocorram, há uma baixa perspectiva de atender aos padrões do Proconve L8. Ademais, eles enfatizam que se nenhuma ação de incentivo ocorrer, a baixa taxa de difusão dos VEs pode impedir o país de atingir seu potencial de mitigação para a NDC. Esta tese termina enfatizando a importância de políticas numa transição em longo prazo, de uma análise do ciclo de vida mais ampla quando avaliando o impacto de políticas, e do envolvimento dos atores em práticas inovadoras. Por fim, ela termina propondo um *framework* de formulação de políticas para acelerar transições e algumas recomendações para o Brasil.

Keywords: Transições para a sustentabilidade, frota de veículos leves, dinâmica de sistemas, análise do poço à roda, perspectiva multinível, abordagem de fluxo múltiplo, padrões de emissão.

RESUMO EXPANDIDO

Introdução

As transições para a sustentabilidade são processos de transformação de longo prazo que ocorrem entre um sistema sociotécnico para outro mais sustentável, envolvendo não apenas aspectos tecnológicos, mas também outros elementos como regulamentos, políticas, infraestrutura, práticas dos consumidores. O subsetor de transportes é um exemplo desse tipo de sistema e é responsável pela emissão de grande parte dos gases de efeito estufa (GEE) e outros poluentes. Esforços acelerados são necessários para atender à contribuição nacionalmente determinada (NDC) do Acordo de Paris, visando reduzir as emissões e limitar o aquecimento global. Nesse sentido, o Brasil é conhecido por sua trajetória ímpar de utilização de bioetanol como um de seus principais combustíveis. Além disso, sua rede elétrica predominantemente limpa indica o país como um lugar promissor para a difusão de veículos elétricos (VEs). Contudo, estas afirmações só podem ser confirmadas através da condução de uma avaliação do ciclo de vida e, tão importante, ao considerar toda frota, da avaliação da necessidade de políticas para transições em longo prazo.

Objetivos

Nesse contexto, esta tese visa responder às seguintes questões de pesquisa: Como diferentes estratégias podem mitigar as emissões de GEE da frota de veículos leves? Como os principais atores evoluíram historicamente em termos de suas posturas e saliências na transição dos veículos? Como contabilizar a eficácia de potenciais ações para sustentabilidade na frota de veículos para servir de suporte à política de longo prazo? O objetivo geral desta tese é propor um modelo do poço-à-roda (PAR) baseado-em-frota que estima o potencial impacto ambiental e de saúde humana da frota de veículos leves do Brasil no longo prazo para orientar e apoiar a tomada de decisão no sentido de acelerar as transições para a sustentabilidade.

Metodologia

A metodologia envolveu uma combinação de abordagens qualitativas e quantitativas. Utilizando uma abordagem qualitativa, uma análise histórica da transição de 50 anos dos veículos de passageiros no Brasil foi realizada, utilizando o *framework* da perspectiva multinível das teorias de transições, juntamente com a *multiple stream approach* das teorias de processo de política. Com isso, os principais atores foram avaliados com relação às suas posturas e saliências. Além disso, por meio de uma abordagem quantitativa, foi desenvolvido a ferramenta *Fleet-based Well-to-wheel Model for Policy Suppor*t (FWEMPS), programada em dinâmica de sistemas, capaz de estimar o potencial impacto ambiental e de saúde humana (DALY, ano de vida ajustado por incapacidade) advindo da frota no longo prazo (2020-2050). O FWEMPS captura a inserção de novas tecnologias e combustíveis dos veículos e permite o teste de várias estratégias de mitigação, como por exemplo: aumento da eficiência energética dos carros, viagens reduzidas, renovação da frota, alteração da taxa de biocombustível utilizada e cenários em que apenas vendas de VEs são permitidos.

Resultados e Discussão

Os resultados revelam a ocorrência de uma transição para a sustentabilidade 'fortuita' pela promulgação do Proálcool, originalmente não relacionado às preocupações com a sustentabilidade. Além disso, os resultados revelam que há uma boa perspectiva de redução das emissões tanto pelo aumento de biocombustíveis como com os VEs, mas destacam que, a menos que avanços consideráveis na eficiência de combustível e difusão de VEs ocorram, há uma baixa perspectiva de atender aos padrões do Proconve L8. Ademais, eles enfatizam que se nenhuma ação de incentivo ocorrer, a baixa taxa de difusão dos VEs pode impedir o país de atingir seu potencial de mitigação para o cumprimento da NDC.

Considerações Finais

Como considerações finais, esta tese termina enfatizando a importância de políticas, regulamentos e incentivos numa transição para a sustentabilidade no longo prazo, de uma análise do ciclo de vida mais ampla quando avaliando o impacto de políticas ao longo do tempo, e do envolvimento dos atores envolvidos no sistema sociotécnico em práticas inovadoras. Por fim, ela termina propondo um *framework* de formulação de políticas visando acelerar transições para a sustentabilidade e algumas recomendações para o Brasil.

Keywords: Transições para a sustentabilidade, frota de veículos leves, dinâmica de sistemas, análise do poço à roda, perspectiva multinível, abordagem de fluxo múltiplo, padrões de emissão.

ABSTRACT

Sustainability transitions are long-term transformational processes that occur from one socio-technical system to a more sustainable one, involving not only technological aspects, but also elements such as regulations, policies, infrastructure. The transportation subsector is an example of such system and is responsible for emitting large portion of greenhouse gas (GHG) and other pollutants. Accelerated efforts are needed to meet the national determined contribution (NDC) from Paris Agreement aiming at reducing GHG emission to limit global warming. In this regard, Brazil is known for its unique trajectory of using biofuel as one of its main fuel. Additionally, its mostly clean power grid also indicates the country as a promising place for electric vehicles (EVs). However, these assertions can only be affirmed by conducting a life cycle assessment and, as importantly, when considering the fleet perspective, by assessing the need of potential policies and strategies for aimed transitions with impact in the long term. In this context, this thesis aims to answer these research questions: How can different strategies mitigate GHG emissions of light-vehicles fleet? How have the main actors evolved in terms of their stances and salience in the historical vehicles transition? And, ultimately, how to account the effectiveness of potential sustainability actions in the vehicles fleet to serve as policy support in the long term? This thesis general objective is to propose a fleet-based well-to-wheel (WTW) model that estimates potential environment and human health impacts of the Brazilian light vehicles fleet in the long-term to guide and support decision making towards accelerating sustainability transitions. The methodology involved a combination of qualitative and quantitative approaches. A historical analysis of the 50-year transition experienced by Brazil's passenger vehicles was conducted, by using the multi-level perspective framework from transitions theories, together with the multiple stream approach from policy process theories. With this, the main actors changing nature regarding their stances and saliences was assessed, and a 'fortuitous' sustainability transitions was detected by the enactment of *Proálcool*, originally unrelated to sustainability concerns. Furthermore, this thesis provided the Fleet-based Well-to-wheel Model for Policy Support (FWEMPS) tool, designed in system dynamics, able to estimate the potential environment and human health impact of the fleet in the long-term (2020-2050). FWEMPS captures the vehicles' fuel-technology turnover through time and allows the testing of several mitigation strategies. Results reveal a good life cycle perspective of reducing GHG emissions by either the increase of biofuel or EVs but they highlight that unless considerable advances in fuel-efficiency and EVs diffusion take place, there is a low perspective in meeting Proconve L8 standard. Additionally, they emphasize that if no policy actions take place, the increasing rate of vehicles diffusion might prevent the country in achieving its fuller NDC mitigation potential. This thesis ends by stressing the importance of policies in a long-term transition, of a broader life cycle analysis when assessing policy impacts, and of actors' engagement in innovative practices. Finally, it ends by proposing a policymaking framework to accelerate transitions and some recommendations for Brazil.

Keywords: Sustainability transitions, light-vehicles fleet, system dynamics modelling, well-to-wheel analysis, multi-level perspective, multiple stream approach, emission standards.

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ABNT - Brazilian Association of Technical Standards

AEA - Automotive Engineering Association

ANFAVEA - National Association of Motor Vehicle Manufacturers

BEV - Battery Electric Vehicles

CETESB - Environmental Company of the State of São Paulo

CH_4 - Methane

CO – Carbon Monoxide

CO_2 – Carbon Dioxide

CONAMA - National Council of the Environment

COP - Conference of the Parties to the United Nations Convention

DALY - Disability Adjusted Life Years

FFV - Flexible Fuel Vehicles

FWEMPS - Fleet-based Well-to-wheel Model for Policy Support

GHG - Greenhouse Gas

HC - Hydrocarbons

IBAMA - Brazilian Institute of the Environment and Renewable Natural Resources

INMETRO - National Institute of Metrology, Quality and Technology

LCA - Life Cycle Assessment

MLP – Multi-level Perspective

MMA - Ministry of Environment

MSA – Multiple Stream Approach

N_2O - Nitrous Dioxide

NDC - Nationally Determined Contribution

NMHC-ETOH – Unburn Ethanol

NMOG - nonmethane organic gas

NOx - nitrogen oxides

PM - Fine Particulate Matter Formation

PM_{total} - Particulate Matter

POF - Photochemical Ozone Formation

PROÁLCOOL – Brazilian Ethanol Program

PROCONVE - Motor Vehicle Air Pollution Control Program

RCHO – Aldehyde

SD – System Dynamics

SIAN - National Archive Information System

SISNAMA - National Environment System

THC - Total hydrocarbons

TTW – Tank-to-Wheel

UFSC - Federal University of Santa Catarina

VKT - Vehicle Kilometre Travelled

WTT - Well-To-Tank

WTW – Well-to-Wheel

SUMMARY

CHAPTER I

1 INTRODUCTION

Sustainability concerns have been visibly increasing over the last decades as a result of several studies and reports about climate change and its negative potential impacts on natural and human systems (e.g. floods, droughts, and sea level rise) with the direct increased risks of illness, death, morbidity and food security issues threatening future generations (IPCC, 2014; 2018; MEADOWS; MEADOWS, 2007). The increasing level of greenhouse gas (GHG) emissions, in particular carbon dioxide (CO_2) emissions, has been highlighted as the main cause of climate change (IPCC, 2014). For this reason, many countries have gathered to establish measures seeking to act upon this matter of limiting global warming in a collaborative partnership way (UNFCCC, 2015). Worldwide, transportation is the subsector (within the energy sector) with more GHG emissions after the electricity/heating subsector, while in Latin America & the Caribbean region, this ranking order is reversed (WRI, 2018). Over the past decades, this subsector has witnessed faster emissions increase than any other sector (IPCC, 2018). Regardless of the region, these figures highlight the urgency for a shift from current mostly inefficient technologies to more efficient ones in the long-term (WINKLER *et al.*, 2014).

At the Conference of the Parties to the United Nations Convention (COP21), several countries established its intended nationally determined contribution, (i)NDC, commitment to the Paris Agreement aiming at reducing GHG emission to limit global warming to 1.5 to 2 degrees Celsius above pre-industrial levels, each according to its planned capacity. Brazil affirmed its iNDC to reduce GHG emissions in 37% by 2025 and 43% by 2030 (reference year: 2005), which later in 2017 it became official NDC[1], promulgated by decree (BRAZIL, 2017b). current. Since then, a national strategy has been articulated among federal, state and municipal governments along with relevant economy sectors and other interested groups (MMA, 2017).

In Brazil, the energy sector corresponds to the largest share of the country's total CO_2 emission (46%), the transportation subsector (within energy sector) accounts for 51% of that amount. The road transport the most responsible with 91% of that amount, where passenger vehicles are responsible for about one third of the road transport emissions (MCTI, 2021) (CETESB, 2019). Regarding the light-vehicles fleet, Brazil's initial proposal for achieving the

[1] Recently, the country updated its national inventories for the historical series following the 2006 IPCC Guidelines. This changed the net value emissions of historical emissions, and consequently the 2005 reference values (not the percentage). The country also stated an indicative long-term goal of reaching climate neutrality by 2060 (MCTI, 2021; UNFCCC, 2020).

NDC include some aim strategies such as the increase in biofuel use and electric vehicles (CCAC, 2018). In fact, the Intergovernmental Panel on Climate Change (IPCC) last special report on impacts of global warming has appointed that deep emissions reductions can be achieved by technology-focused measures such as energy efficiency and fuel-switching, and structural changes that impacts transport activity (IPCC, 2018, chapter 2). Examples of these strategies are mobility and social patterns behaviour such as car sharing mechanism (HJORTESET; BÖCKER, 2020), telecommuting (GUZMAN; ARELLANA; ALVAREZ, 2020; MENEZES; MAIA; DE CARVALHO, 2017), increasing vehicle occupancy (SHIRAKI *et al.*, 2020), increasing the use of public transportation (AZOLIN; RODRIGUES DA SILVA; PINTO, 2020), banning old cars and internal combustion engine vehicles (BENVENUTTI; URIONA-MALDONADO; CAMPOS, 2019; DEY; CAULFIELD; GHOSH, 2018). But the report also states that although electric vehicles sales (in much less pace in Brazil) and biofuel consumption has been increasing, projections indicate that in order to considerably reduce emissions it is required much more significant change from this sector (IPCC, 2018).

To tackle the foregoing issues and challenges, sustainability transitions theory can be a good frame for research especially as it involves describing a transition between one socio-technical system to a more sustainable one. More specifically, sustainability transitions can be defined as "[…] long-term, multi-dimensional, and fundamental transformation processes through which established socio-technical systems shift to more sustainable modes of production and consumption." (MARKARD; RAVEN; TRUFFER, 2012, 956). These transitions, therefore, involve deep change in a system that takes decades to occur and that requires the interaction among multiple actors (e.g. industry, government, users) immersed in a variety of innovations, technologies, policies and practices (GEELS; HEKKERT; JACOBSSON, 2008; GRIN; ROTMANS; SCHOT, 2010; ROTMANS; KEMP; VAN ASSELT, 2001). Among these characteristics, the presence of policies is one that is particularly highlighted since sustainability is considered a public good and thus policies' role becomes to shape the directionality of transitions through e.g. regulations, standards, subsidies. (IEA, 2020; KÖHLER *et al.*, 2019; STRN, 2017). Furthermore, public policies along with stakeholder's coalition can guide (sustainable) pathways by providing (or reducing) means to overcome transitions challenges towards a more sustainable production and consumption development (ROBERTS *et al.*, 2018). Policies can also have different points of intervention such as directly stimulating technological niches (e.g. R&D funding), destabilizing the regime (e.g. banning old technologies), or even ones that affect a broader landscape of international participation (e.g. Paris Agreement) (KANGER; SOVACOOL;

NOORKÕIV, 2020). In transport, policies have played a big role in stimulating the development and commercialisation of more efficient technologies (IEA, 2020).

In this context, some questions are inevitably raised. Using Brazil as example, how can different measures and/or policies mitigate GHG emissions of light-vehicles fleet, giving attention for potential setbacks in the long run? While aiming to enforce a policy, it is important to evaluate whether the desire goal is indeed likely to be achieved or not. For instance, higher fuel efficiency (lower fuel cost per distance) can lead to higher distanced travelled (higher fuel consumption) Freeman et al. (2016) (AUGUSTUS DE MELO; DE MARTINO JANNUZZI; DE MELLO SANTANA, 2018; FREEMAN; YEARWORTH; PREIST, 2016). These potentials particularities are critical when aiming to shift from one technology to another. By analysing system elements feedbacks dynamics, potential rebound-effect indications can be detected and thus further aid decision-making (STERMAN, 1994). A quantitative modelling approach able to capture these dynamics can provide a useful way of understanding the complex behaviours of societal system changes (KÖHLER; TURNHEIM; HODSON, 2018).

Furthermore, understanding the system peculiarities and characteristics is important since they too may impact future transition. The primary fuel-technology of the vehicles fleet in Brazil has changed three times over the last five decades, which brings up the question, how have the main actors evolved in terms of their stances and salience in the historical vehicles transition? As Köhler *et al.* (2019, p. 22) concluded in the agenda for sustainability transition research, “we tend to take sustainability for granted by looking at one dimension at a time, by not pausing to unpack it in various contexts, thereby missing potential conflicts and trade-off”. In the transition towards a low-carbon transportation subsector is no different. The main socio-technical system must be taken into consideration, by analysing the main actors’ interactions and dynamics, paying attention to the pressures and resistance they mostly experienced and/or expressed themselves.

And while socio-technical system analyses are directed for the recent past and present time, model-based scenarios provide a forward-looking perspective of transitions not to be used as exact predictions but rather to analyse the likely consequences of specific choices (GEELS; BERKHOUT; VAN VUUREN, 2016; MACHADO *et al.*, 2018; TURNHEIM *et al.*, 2015). In this sense, besides evaluating the potential impacts of emission mitigation strategies from the vehicles on the roads, the assessment scale must be expanded to include the analysis of potential impact from the fuel/power production phase as well and considering a long-term investigation. If no life cycle evaluation is properly conducted, it may be that a shift from one type of vehicles’ fuel-technology to another may generate equal or even more emissions, and the aim to mitigate emissions in the long term be put in jeopardy.

Among all countries in Latin America & the Caribbean region, Brazil is the largest manufacturer of passenger cars, being the 8th biggest producer worldwide (STATISTA, 2019). It is a strong and a well-established national market and thus one that cannot be disregarded. In recent years, fleet electrification has been put on emphasis. Several countries in Europe have even set phase-out dates for internal combustion engines vehicles sales, some by 2025 (e.g. Norway), although most of them by 2030 and 2040 (ICCT, 2020). But it is a common agreement between scholars that only with a clean electric grid can battery electric vehicles (BEV) reach their full potential in mitigating global warming and air pollutant emissions (NORDELÖF *et al.*, 2014; WINKLER *et al.*, 2014). If BEV are recharged from electricity produced from most of conventional technology power plants, they may provide equal or even more GHG emissions than conventional vehicles (PATIL *et al.*, 2016; POULLIKKAS, 2015).

Brazil has the advantage of comprising with a cleaner electric grid, with over 80% from renewable sources (BEN, 2019), which provides indications that a shift to electric and hybrids vehicles (EVs) could be worthwhile (COSTA *et al.*, 2017). Its diffusion, however, is in its very early stages, with predominantly imported vehicles, high costs and little uptake perspectives, with few incentives and not connected to a national program (BARAN; LEGEY, 2013; BENVENUTTI; RIBEIRO; URIONA, 2017). But the country has also a unique trajectory as the world lead in biofuel volume production per vehicle (HARVEY; BHARUCHA, 2016) and currently the second largest producer of ethanol (STATISTA, 2020). Considering that these socio-technical systems are often affected by international networks (FUENFSCHILLING; BINZ, 2018), this brings additional uncertainties to where this sector's pathway will head and where efforts, investments, incentives and actions should be concentrated. On top of that, even though in recent years there have been an increase in biofuel consumption and electric vehicles worldwide (in much slower pace in Brazil), IPCC's pathways projections indicate that in order to considerably reduce emissions, an unprecedented increased higher rate of technology efficiency experienced so far will be required (IPCC, 2018, chapter 2, p. 144).

Therefore, to tackle these issues, a combination of both qualitative and quantitative approaches can be of great benefit (GEELS; MCMEEKIN; PFLUGER, 2018; ROGGE; PFLUGER; GEELS, 2018; TURNHEIM *et al.*, 2015). The temporal aspect of sustainability has been also a current topic of discussion and emphasis when sustainability-oriented governance arrangements are involved (BORNEMANN; STRASSHEIM, 2019). By comparing different quantitative scenarios in the long term, possible results may be used as guidance and support to qualitative analysis of decision-making risks associated with future scenarios pathways (MACHADO *et al.*, 2018; PALTSEV, 2017). Within this context, this study final aim is to answer the following research question: how to account the effectiveness of potential sustainability actions in the vehicles fleet to serve as policy support in the long term?

1.1 OBJECTIVES

Considering the research problem along with the research questions presented, the general and specific objectives are presented below.

1.1.1 General objective

Propose a fleet-based well-to-wheel model that estimates potential environment and human health impacts of the light vehicles fleet in the long-term to guide and support decision making towards accelerating sustainability transitions.

1.1.2 Specific objectives

1. Evaluate potential policies towards passenger vehicles GHG emissions mitigation in the long-term;

2. Assess the main actors' response to the historical shift of fuel-technology experienced in the light-vehicles fleet since 1970;

3. Evaluate the environmental and human health impact from passenger vehicles in the long-term;

4. Assess the perspective of the vehicles in achieving the Proconve L7 and L8 emission standards.

1.2 JUSTIFICATION AND RELEVANCE

Sustainability transitions are long-term transformation processes of established industries, socio-technical systems and societies to more sustainable modes of production and consumption (STRN, 2010). As transportation affects communities in many spheres, it is thus important to study the interactions between industry, policymakers, consumers, and civil society (GEELS, 2012) and then make proper analysis and contribution towards a low-carbon system. Worldwide, transportation is the subsector much responsible to GHG emissions (WRI, 2018). And because of its importance on national economies, transportation has been the subsector most studied after electricity subsector among scholars in recent years (considering single sector investigations), but there has been a lack of these studies from developing regions, especially in modelling energy system, such as transport subsector systems, that considers their own characteristics, e.g. Africa and South America (as found in review paper by MACHADO *et al.*, 2018). Thus, considering that most of the growth in road transport energy consumption and GHG emissions in the future is expected to take place in developing countries, it makes this subsector worth deepening evaluations (EPE, 2016; HAO; GENG; SARKIS, 2016; IEA, 2020; OECD/ITF, 2017).

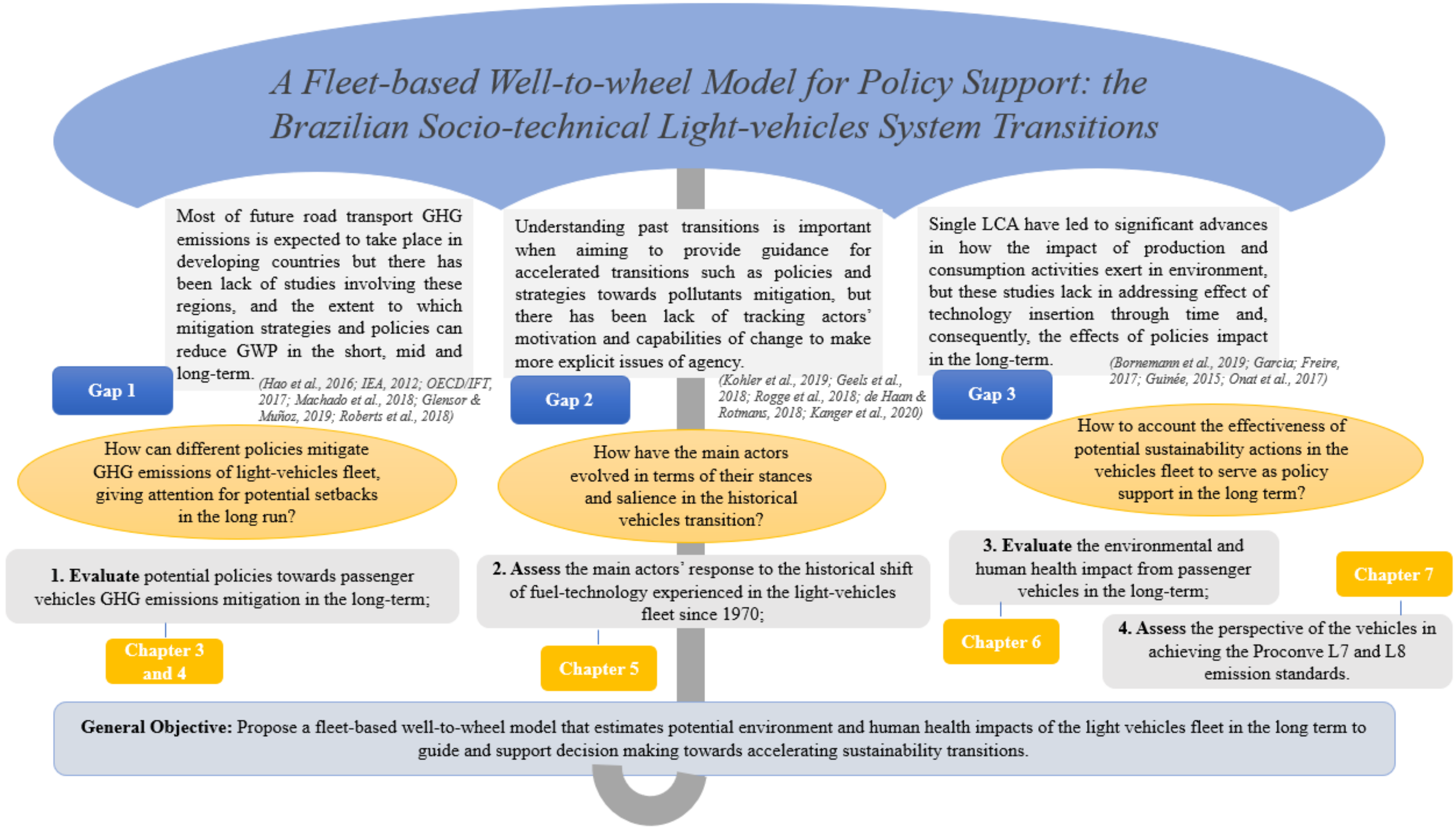
In terms of analytical tools for tackling sustainability transitions research and future directions, they "remains one of the main methodological frontiers for transitions research". (KÖHLER *et al.*, 2019, p. 20). The complexity in transitions and its multidisciplinary context call for a combination of tools and approaches able to capture the fuller picture of sociotechnical transitions. For this, scholars have been seeking to use a combination of analytical approaches, both qualitative and quantitative, by either bridging, combining or integrating them (HOLTZ *et al.*, 2015; KÖHLER; TURNHEIM; HODSON, 2020; MCDOWALL, 2014; TURNHEIM *et al.*, 2015).

In terms of evaluating environmental impact, designed to assess the potential environmental impacts over the life cycle of a product, the life cycle assessment (LCA) methodology has become increasingly widespread in the industrial and governmental sphere (GUINÉE, 2015; ISO, 2006). However, while single LCA studies have led to significant advances in how the impact of production and consumption activities exert in environment, these studies lack in addressing the effect of technology insertion through time and, consequently, the effects of policies in the long-term, important for future sustainability transitions (BORNEMANN; STRASSHEIM, 2019; GARCIA; FREIRE, 2017; GUINÉE, 2015; ONAT *et al.*, 2017). Additionally, there has been lack of consensus, comparability, and transparency regarding basic model assumptions, especially for biofuels, questioning the reliability of estimates of green technologies, creating confusions and debates amongst policymakers, affecting its LCA results acceptance in the policy context (PEREIRA *et al.*, 2019; SEABRA *et al.*, 2011).

It is in this context that this thesis stand, by deepening the analysis of the light-vehicles fleet fuel-technology transition by using a combination of both qualitative and quantitative approaches. The relevance of this thesis to the scientific development is twofold: theoretical and methodological. In terms of theory, this thesis contributes to fill the current gap in knowledge about the difference in environmental and human health impact of a fleet mostly driven by biofuel or by electric vehicles in the long-term, considering the country's production and fuel-technology characteristics. It also contributes to the literature by providing the potential impact extent that different pathways, strategies, and policies can have in mitigating emissions in the long term. Additionally, it also contributes to showing the emission perspective of the system if no measures are undertaken in the short to mid-term and presents a proposal of a conceptual framework for policymaking. In terms of methodological relevance, this thesis proposes a solution to overcome the limitations of existing single-focused LCA methods by developing a well-to-wheel model in a fleet-based perspective that simulates the fleet-turnover in a temporal perspective while using the LCA methodology rigor standard.

With this, the research outcome can serve as policy support towards more sustainable strategies. Also, it can serve as support to new research involving vehicles fleet and energy transition, and as support to new application of both the theoretical framework and quantitative model to other sectors or empirical boundaries. Finally, and in summary, this research is justified by: (i) current relevance of the theme (more sustainable transportation subsector), (ii) originality (contribution to the literature on both socio-technical transitions and on LCA literature), and (iii) contribution for the scientific community debate. Figure 1 presents an overall conceptual umbrella framework of this thesis, where the gaps, research questions and specific objectives are connected leading to the chapters result to fulfil general objective.

Figure 1 – Conceptual umbrella framework of the thesis.



Source: Elaborated by the author (2021).

1.3 DELIMITATIONS

For the completion of this thesis, some delimitations were considered. In terms of empirical focus, the delimitation of this thesis involves light-vehicles (passenger) fleet of the road transportation subsector of Brazil. Other modal transports such as commercial and freight vehicles, bus and trucks are not considered. Another delimitation is in regard to the life cycle assessment conduction. The chosen delimitation was in terms of well-to-wheel cycle assessment, in which two specific phases are considered: well-to-tank (WTT) and tank-to-wheel (TTW). Thus, no assessment of buildings construction for the production of fuel or vehicles, nor vehicles potential impact is considered (except the production of electrical batteries potential impact are considered as it stands more out between the vehicles).

In terms of literature review sources, this thesis used the database *Scopus* for all the papers. In the theoretical result paper (chapter 5), for the historical analysis of the past 50 years of Brazilian fuel-technology shift, other data sources were used such as the National Archive Information System (SIAN), books, legislation database, and the national newspaper *O Globo* (further descriptions are presented in its methods and data sources subsection).

1.4 STRUCTURE

The structure of this thesis is divided into nine chapters. The current chapter aimed was introducing the main subject of this thesis along with the central research questions that this thesis worked on. Besides the research context, the main and specific objectives of this study have been clearly stated, as well as the justification and relevance of this research and its delimitation.

Chapter 2 presents the research methods adopted in this thesis, which follows the guidelines of the Resolution 001/PPGEP/2018, of 07/11/2018 (PPGEP, 2018), that provides instructions for the option of preparing a master's dissertation or doctoral thesis in the form of collection of articles for the defense in the Postgraduate Program in Production Engineering (PPGEP / UFSC) from the Federal University of Santa Catarina (UFSC). Based on this format, this thesis consists in the collection of five articles, structured in a way to achieve the main objective of this work. In this chapter, the methodological framework is first presented, where each paper is classified according to the respective research question and specific objectives. Then, the methodological procedure is described, which aims to present the methods adopted in each paper and their connection to the context of the research. Regarding specific format aspects, some standards were adopted:

- All chapters are written in English (United Kingdom), except the papers from chapters 3 and 4 as they were previously published following English (US);

- The references and citations format style follow the Brazilian Association of Technical Standards (ABNT) format.

- The references, citations, figures, charts and tables format style follow the Brazilian Association of Technical Standards (ABNT) format style.

- All citation references of this thesis are presented on the references chapter, unless they were only cited inside a result chapter (chapters 3-7). In this case, their citation references are present at the end of their respective chapter.

Chapter 3 presents the first paper of this thesis collection, addressing the first specific objective. It is the first paper of the first methodological step that brings results of the potential impact that strategies aiming at mitigating GHG emission from vehicles on the road can provide in the long run. It also provides results of the power integrated strategies can have in the fleet and what would the Brazilian emission be like if the fleet were based on gasoline-powered based vehicles.

Chapter 4 presents the second paper of this thesis collection, still addressing the first specific objective. This is the second and last paper of the first methodological step that this thesis provides. It presents the preliminary fleet-based model of the thesis, brings results of similar and different mitigation strategies and policies to prior paper, and addresses potential undesirable result of policy rebound effect.

Chapter 5 presents the third paper of this thesis collection, addressing the second specific objective. This is the first and only paper of the second methodological step that this thesis provides. It contributes with a historical analysis of the 50-year transition experienced by Brazil's passenger vehicles, by using the combination of two well-known established frameworks, from transition and policy process theories, the multi-level perspective (MLP) and multiple stream approach (MSA), respectively. It provides discussion to the importance of policies in the long term and presents some add-in contribution to those frameworks to the socio-technical transitions literature.

Chapter 6 presents the fourth paper of this thesis collection, addressing the third specific objective. This is the first paper of the third and last methodological step that this thesis provides. It contributes by presenting the complete fleet-based model named Fleet-based Well-to-wheel Model for Policy Support (FWEMPS). It provides a life cycle assessment of the vehicles fleet in a well-to-wheel boundary, i.e. the fuel/power production phase (WTT) and tailpipe emissions (TTW). The evaluation present estimate of the fleet's potential environment and human health impact at midpoint and endpoint level in the long-term (2020-2050).

Chapter 7 presents the fifth and last paper of this thesis collection, addressing the fourth and last specific objective. This is the second and last paper of the third and last methodological step that this thesis provides. In it, FWEMPS is used to estimate the perspective of the average light-vehicles in meeting the new phases of PROCONVE (Motor Vehicle Air Pollution Control Program) emission standard by 2031 (L7 and L8). It also provides a comparative analysis of PROCONVE to the Euro (Europe) and Tier (US) emission standards, and ends with important discussions on the new phases of the emission standard.

Chapter 8 presents the discussion of this thesis. While every paper's result (chapters 3-7) included their own discussions, by adopting to present this doctoral thesis in the form of collection of articles, a general discussion of all the work is needed. In this chapter, as predicted in the resolution, the discussion is aligned with the objectives of the thesis and articulated according to the results documented in the articles. Three main points are emphasised in this chapter, which involve the strength policies and actions towards the mitigation of gases have in the long-term, the importance of analysing the broader life cycle when assessing the impacts of policy options in the long-term, and the importance of embracing innovative practices considering the energy transition that is taking place towards renewables sources. It ends with a subsection addressing policymaking implications and recommendations.

Finally, chapter 9 ends with the conclusion of this paper, by answering the proposed research questions and objectives of this thesis. This chapter also provides the limitations of this work and opportunities for future research.

CHAPTER II

2 RESEARCH METHODS

Following the Resolution 001/PPGEP/2018, of 07/11/2018 (PPGEP, 2018), that provides instructions for the option of preparing a master's dissertation or doctoral thesis in the form of collection of articles for the defense in the Postgraduate Program in Production Engineering (PPGEP/UFSC) from the Federal University of Santa Catarina (UFSC), this thesis is structured in the format of papers collection. This chapter presents the research methods of the thesis, being divided into two subsections (i) methodological framework, in which presents the connection of each paper with the methods adopted as well as the specific objectives and research questions and the (ii) methodological procedure, in which describes each step conducted for the completion of this thesis.

2.1 METHODOLOGICAL FRAMEWORK

This thesis is composed by three steps. One that addresses the first specific objective. The second address the second specific objective. The last answers the last two specific objectives. Chart 1 shows the summary of the methodological framework adopted:

Chart 1 - Methodological framework.

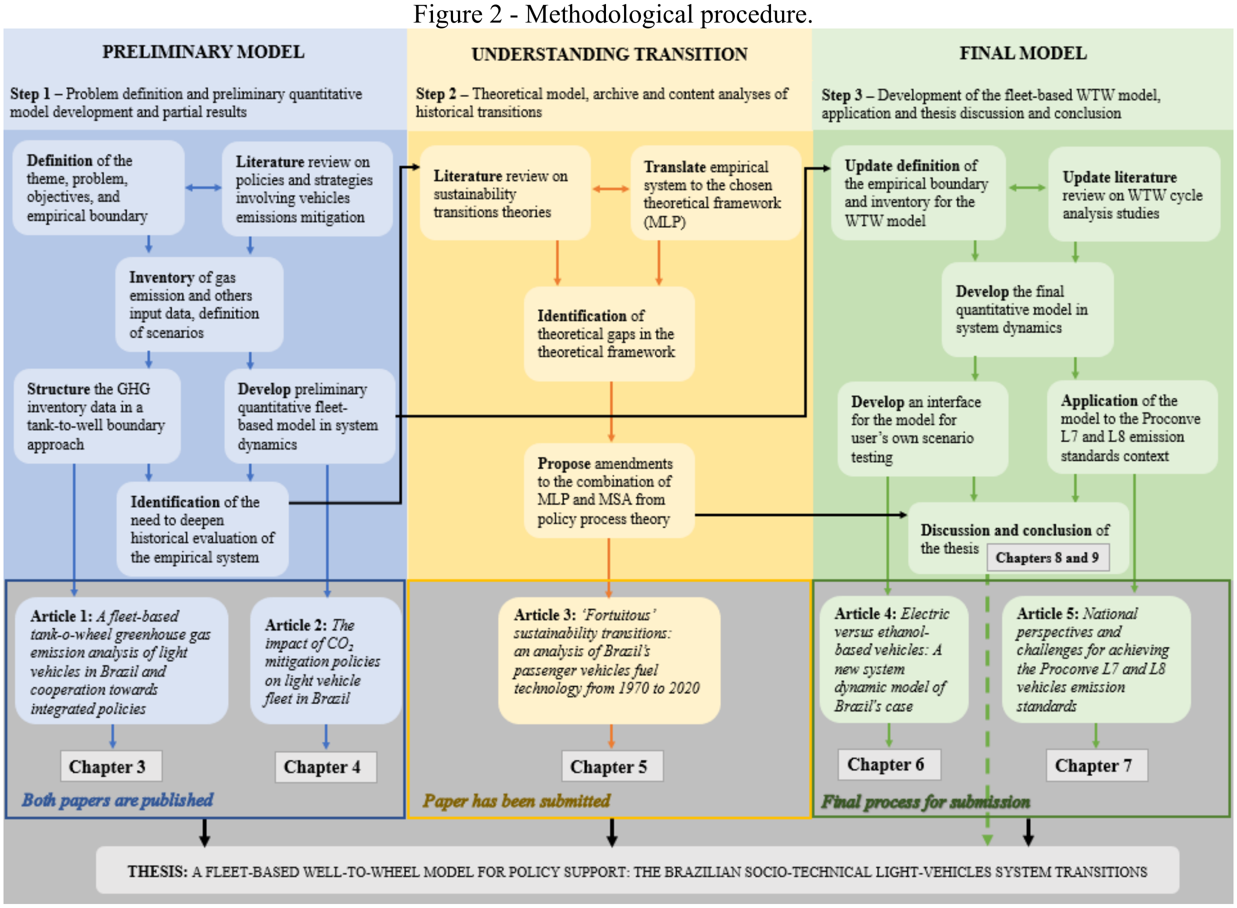
A FLEET-BASED WELL-TO-WHEEL MODEL FOR POLICY SUPPORT: THE BRAZILIAN SOCIO-TECHNICAL LIGHT-VEHICLES SYSTEM TRANSITIONS						
General objective	Propose a fleet-based well-to-wheel model that estimates potential environment and human health impacts of the light-vehicles fleet in the long-term to guide and support decision making towards accelerating sustainability transitions.					
Step	**Research question**	**Specific objective**	**Chapter**	**Methodology**	**Paper nº:**	**Main Results**
1	How can different policies mitigate GHG emissions of light-vehicles fleet, giving attention for potential setbacks in the long run?	**Evaluate** potential policies towards passenger vehicles GHG emissions mitigation in the long-term	**3**	TTW analysis on GHG emissions using a bottom-up approach	1	Benchmark emission target proposal Emission mitigation potential Integrated strategies impact results in the long-term
			4	Fleet-based model using a system dynamic modelling approach	2	Potential policies and strategies mitigation impact Identification of potential rebound effects in the long-term
2	How have the main actors evolved in terms of their stances and salience in the historical vehicles transition?	**Assess** the main actors' response to the historical shift of fuel-technology experienced in the light-vehicles fleet since 1970	**5**	Literature review Combination of the MLP and the MSA framework	3	Historical analysis of the 50-year transition experienced by Brazil's passenger vehicles Proposal of two amendments to the MLP+MSA combination Discussion of results
3	How to account the effectiveness of potential sustainability actions in the vehicles fleet to serve as policy support in the long term?	**Evaluate** the environmental and human health impact from passenger vehicles in the long-term	**6**	WTW fleet-based model using a system dynamic approach	4	FWEMPS introduction WTW emission comparison using extreme scenarios Scenarios/policies testing Discussion of results
		Assess the perspective of the vehicles in achieving the Proconve L7 and L8 emission standards	**7**	Analysis of PROCONVE, Euro 6 and Tier 3 Application of FWEMPS to local context	5	Comparative analysis between emission standards Perspective of the average new vehicles in reaching PROCONVE L7 and L8 emission targets by 2031 Discussion of results

- Source: Elaborated by the author (2021).

2.2 METHODOLOGICAL PROCEDURE

Figure 2 summarizes the methodological procedure employed in the conduction of this thesis. It is divided into three steps, reflecting Chart 1 structure. Each step leads to a completion of at least one paper. In the following, a description of each step conduction is presented, and further descriptions of them are described in the methods subsections of each paper.

Figure 2 - Methodological procedure.



Source: Elaborated by the author (2021).

2.2.1 Step 1 – Preliminary model

In this first step, the definition of the theme of research, problem and empirical boundary was established. This was conducted in concordance with the literature review analysis using the Scopus database. The literature review included the review of different policies, incentives and/or strategies most considered and applied in the transportation sector and in different regions towards a low-carbon society. A few of them were selected for scenario testing (see policies and scenarios descriptions in the papers of chapter 3 and 4). The choice of the empirical system was set: fuel-technology of light-vehicles fleet in Brazil. The system boundary was also set, and in this initial exploratory stage, in a fleet-based tank-to-wheel (TTW) GHG emission delimitation.

Subsequently, the inventory collection process was conducted. Because of the fleet-based boundary, the inventory selection included the historical tailpipe emissions from the different fuel-technology vehicles seen in Brazil. Other data were necessary such as the intensity of cars use, or vehicle kilometre travelled (VKT), vehicles licensing and fleet numbers, and the future projection of population. In this step, two papers were developed using different methodology tool approach.

In the first paper (chapter 3, published in the International Journal of Sustainable Transportation), the main objective was to evaluate potential policies, incentives and/or strategies towards the mitigation of GHG emissions in the selected empirical system, in the long-term. The methodology involved a fleet-based TTW analysis on the three main GHG from vehicles tailpipe emission (CO_2, methane, CH_4, and nitrous dioxide, N_2O) using the spreadsheet software Excel. The study used estimate from the literature for the historical vehicles licensing and fleet number and their projection. It proposed benchmarks emissions for Brazil to meet the NDC target, and tested a variety of mitigation strategies individually and in an integrated way.

The second paper (chapter 4, published in the Energy Policy journal) involved the development of a fleet-based model using the system dynamics (SD) modelling approach, with the aid of Stella Architect software. SD is fundamentally an interdisciplinary tool, grounded in the theory of nonlinear dynamics and feedback of human behaviour as well as physical and technical systems. The modelling process seeks to represent a system in a way that stock and flow structures along with time delays and feedback loops determine the dynamics of a system. The stock and flow diagrams emphasize the physical structure. The dynamics arise from the interaction between two types of feedback loops: positive (self-reinforcing) and negative (self-correcting or balancing). The positive loops tend to reinforce or amplify what is happening in the system, while the negative ones, the opposite (STERMAN, 2000).

The preliminary result was first presented at the IV Brazilian Symposium on Systems Dynamics held from 26-28 of October 2017 in Sao Paulo, Brazil. As in the first paper, the boundary evaluation was set at a tank-to-wheel phase, i.e. vehicles on the road emissions. And while in the first paper the three main GHG were assessed, in this second paper, the CO_2 emissions was the focus (in step 3 other pollutants will be included). Similarly to the first paper, a few policies and mitigation strategies were analysed. But by using the SD simulation tool, the objective of capturing the delay in fleet turnover was fulfilled (1980-2050 timeframe), as well as the inclusion of fleet renovation strategy testing. The design of this temporal aspect is important not only because technology insertion takes time to occur, but also since the vehicle's characteristics change over time (e.g. fuel economy). Thus, by accounting this turnover delay, the estimate impact calculation of the mitigation of gas emission could be improved. With this, some policies rebound effect were made possible to identify and, thus, possible trade-offs to the pursuit of a low-carbon sector could be highlighted to policymakers.

An example of a model designed in SD and used for strategic policy assessment in the transport and energy field is the ASTRA (ASsessment of TRAnsport Strategies) model (ASTRA, 2000). The model estimates the impact of long-term European transport policy strategies (involving over 27 countries). Since its conception (over 20 years ago), many extensions have been included and it has been used in several European projects. The model takes into account possible political, technical and socio-economic framework on, e.g. transportation, economy and environment. The development of the fleet-based well-to-wheel model to assess the potential environment and human health impact proposed in this thesis was inspired by this type of model (ASTRA), but in this case, to serve as support for decision-making policies in Brazil, which is absent to date.

The conduction of step 1 enabled the identification of the need to deepen theoretical study involving the empirical system in focus. This thesis departs from the standpoint that policies and incentives towards mitigating pollutants are important but understanding the system background and the historical developments is as essential to enhance probability of a successful sustainability transition. Modelling is a powerful tool, which can be most useful when the system characteristics are given account for. Thus, while step 1 followed a quantitative approach providing the development of the preliminary model, step 2 will involve a qualitative analysis approach aiming to deepen the understanding of past transition.

2.2.2 Step 2 – Understanding transition

In this second step, a theoretical qualitative approach involving archive and historical content analyses is conducted. Step 1 provided partial results to the main goal of proposing a "fleet-based well-to-wheel model that estimates potential environment and human health impacts of the light vehicles fleet in the long-term to guide and support decision making towards accelerating sustainability transitions”. A tank-to-wheel system boundary analysis is useful to tackle specific potential environmental issues that arise from the vehicles on the roads (e.g. city focused policy guidance). But to account their fuller impact, the life cycle of their fuels production must be taken into account. However, before extending the fleet-based model to include the well-to-wheel scope, the broader socio-technical system must be better comprehended to enable a more effective analysis and subsequent discussion of the region in focus.

Some scholars focus socio-technical system between the interdependency of humans and machines at the level of industrial workplace (TRIST; CENTRE, 1981) or of organizational fields from institutional theories (DIMAGGIO; POWELL, 1983). Others address the term in a broader context, encompassing more elements (e.g. user practices, culture, policies) in sector-levels such as the energy and transportation sectors (GEELS, 2005). In terms of the latter, the societal structure level includes several elements (social and technical) to produce functionality. Geels (2005, p. viii) defines socio-technical systems as “[…] consisting of technology, markets and user practices, public policies and regulations, infrastructure, symbolic meaning and scientific understanding.”

Therefore, this second step began with a literature review of sustainability transition theories. Among the main theoretical frameworks, the multi-level perspective (MLP) was selected for this thesis (see MARKARD; RAVEN; TRUFFER, 2012, for more information of other theoretical approaches commonly used in sustainability transition studies). The MLP framework was designed and introduced by Geels (2002), in which was built upon the studies of Rip and Kemp (1998) and Kemp; Rip and Schot (2001). The empirical socio-technical system was then translated into the MLP lens. The preliminary result was presented at the 10^{th} International Sustainability Transitions conference held from 23-26 June 2019 in Ottawa, Canada.

Subsequently, a further analysis and interpretation of the preliminary theoretical result presented at the conference was conducted. Considering the feedbacks received from experts of the field (e.g. researchers from the conference, doctorate qualification board, doctorate supervisors), it became clear that there was something missing in the qualitative work done so far and that, in fact, there were theoretical gaps that could be covered and addressed. The highlighted gaps were (i) the need to identify and monitor the actors’ role in a change, i.e. not only the main (lead, dominant, active) actors during a specific transition but also the secondary ones, and (ii) the need to look not only at their salience, but also at their stance towards a transition, i.e. whether they were more resistant, supportive, or even indifferent to a specific change.

The identification of these theoretical gaps and further study of the literature was deepened during the 6-month sandwich doctorate period, enabled by *CAPES-PrInt* scholarship, that took place in Canada (2019-2020) at the University of Ottawa, by the supervision of Professor Catherine Liston-Heyes from the Faculty of Social Science (currently at the University of Sussex, UK). During this period, the inclusion of another theoretical framework to the work was decided, in this case, from policy process theories and, more specifically, the Kingdon's multiple stream approach (MSA) (KINGDON, 1984). Finally, besides providing a historical analysis of the 50-year transition experienced by Brazil's passenger vehicles, this step ends with the proposal of those two amendments (actors' stance and salience) to the combination of an *actor-centred* MLP and the MSA framework, with some adaptations. This resulted in the third paper of the thesis (chapter 5), under journal submission.

2.2.3 Step 3 – Final model

By deepening the studies of the empirical socio-technical system, step 2 provided a proper transition to this final third step by elucidating the fuel-technology historical transitions involved, bringing direction to the different available fuelling for the WTT analysis, and enriching the subsequent final discussion of the thesis. In this step 3, the complete version of the fleet-based well-to-wheel model for policy support (FWEMPS) is developed. For this, an updated definition of the empirical boundary and inventory process was conducted.

The broadening of the life cycle analysis boundary occurred, from TTW to WTW. Thus, the inventory collection process was expanded to include fuel production impact phase of the hydrated and anhydrous ethanol production, the gasoline production (considering different anhydrous ethanol content), and electricity power production for the more recent diffusion of electric vehicles, including the battery as well. This was conducted with the use of the international database Ecoinvent 3.6 using OpenLCA software. Additionally, a broader scope of gases emissions evaluation was included. Besides the CO_2, CH_4, and N_2O, now it included the particulate matter (PM), aldehyde (RCHO), nitrogen oxides (NOx), nonmethane organic gas (NMOG), and monoxide carbon (CO). Therefore, the estimate of other midpoint impact categories besides the global warming potential (GWP) was included: photochemical ozone formation (POF) fine particulate matter formation (PM), stratospheric ozone depletion, ionizing Radiation, toxicity (cancer), and toxicity (non-cancer).

An update of the literature review on WTW studies was conducted to confirm the opportunity of research. With this, the endpoint impact category - human health (disability adjusted life years, DALY) - was also selected to be included in FWEMPS analysis. The outcome of these steps allowed the development of the final quantitative fleet-based model and the development of an interface[2], both using the Stella Architect software from Isee System.

The development of the model is the stage where a significant amount of time is spent. As with modelling in general (not necessarily only with system dynamics), translating the problem into the respective program language structure (in this case, in stocks and flows, including some arrays format), connecting the variables properly paying attention to the units, modelling the reference scenario, performing model validation, and modelling the strategies to be tested, requires an attentive and a thorough conduction. Furthermore, the inputs of the model must be clear and well documented for research replicability. With this, the fourth paper of the thesis was developed (chapter 6), where FWEMPS is introduced, described, and discussion to the main results are also provided. The paper is under final process for journal submission.

For the last part of this step 3, FWEMPS is applied to bring insight within the regional context of the national air pollution control program PROCONVE standard regulation. First, a historical background review of PROCONVE is conducted, along with the current (L6) and future emission limits phases proposal (L7 and L8). In addition, a review of the emission standards from Europe (Euro) and the United States (Tier) is also conducted to allow comparisons between them (all involving light-vehicles standard). At last, FWEMPS is used to simulate the perspective the future average vehicles have into reaching PROCONVE targets by 2031 (L8), and insights are given within this context. Results are presented in the last paper of the thesis result (chapter 7). The paper is under final process for submission (it first needs the publishing of the previous paper). Finally, the discussion and conclusion of the thesis was conducted, fulfilling the general objective of the thesis.

[2] The interface to be published online was developed, but a technical issue in the Stella Architect version 1.9.4 was found, making it impossible for the author to use the fuller functionalities available by the Isee System with this version. This technical issue was later fixed in newer Stella Architect versions, but since the perpetual student license does not come with support, the publishing of FWEMPS interface was compromise. Still, as it is commonly conducted within the SD community, FWEMPS Stella Data (.isdb) along with its inner interface (.stmx) and the model equations can be made available at request using the author's Research Gate profile page at: https://www.researchgate.net/profile/Livia-Moraes-Marques-Benvenutti or by email: lmmbenvenutti@gmail.com.

CHAPTER III

3 A FLEET-BASED TANK-TO-WHEEL GREENHOUSE GAS EMISSION ANALYSIS OF LIGHT VEHICLES IN BRAZIL AND COOPERATION TOWARDS INTEGRATED POLICIES

This chapter presents the first paper of this thesis, being the first result of step 1. It has been published in the International Journal of Sustainability Transportation. The original published paper[3] is available at https://doi.org/10.1080/15568318.2018.1542757.

Abstract

Transportation subsector has gained a relevant role being now the largest contributor to greenhouse gas (GHG) emissions from the energy sector, which is currently the largest sector contributor in Brazil. To analyze future scenarios and assist climate change mitigation policies, a bottom-up approach of a fleet-based tank-to-wheel (TTW) analysis on GHG emissions was conducted for light vehicles, in 2010-2040 timeframe. As the nationally determined contribution (NDC) does not define transportation targets specifically, we propose some benchmarks to serve as reference targets. Different intensity of three carbon mitigation strategies are considered: (i) fuel-efficiency improvements (such as those imposed by EU commission); (ii) biofuel increase (in 5 to 15% from the average use); and (iii) electric vehicles (EVs) diffusion (battery electric, hybrid and plug-in hybrid vehicles). The results indicate an overall accomplishment in meeting those benchmarks, but some were only achieved by the assumption that policies aiming to perform such scenarios would be introduced. Biofuel increase strategy, followed by fuel-efficiency increase, provided the most relevant GHG mitigation potential. EVs diffusion strategy needs additional incentives to achieve significant impact contribution, as its market share is only slowly increasing. Further emphasis is made to the importance of strengthening and integrating different policies and strategies along with some discussion and comparison with results from other countries.

Keywords: light vehicle fleet, tank-to-wheel analysis, greenhouse gas emission, alternative fuel vehicles, intended nationally determined contributions (INDC), sustainable transportation.

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[3] BENVENUTTI, L. M. M.; CAMPOS, L. M. S. A fleet-based tank-to-wheel greenhouse gas emission analysis of light vehicles in Brazil and cooperation towards integrated policies. **International Journal of Sustainable Transportation**, 14, n. 4, p. 255-269, 2019.

3.1 INTRODUCTION

Highlighted as the main cause of climate change, the increasing level of greenhouse gas (GHG) emissions has been rising environmental awareness. Worldwide, transportation is the subsector that most emits GHG after electricity/heating subsector (WRI, 2017). Decarbonizing it becomes essential to limit global warming. Thus, there is a relevant global substantial need of alternative vehicle/fuel technologies in the long-term (WINKLER *et al.*, 2014).

Researchers have been investigating different scenarios and pathways to reduce carbon emissions. Most of them aim at assessing an overall reduction in environmental impacts achieved by different fuel and/or vehicle technologies and different strategies. Through an analysis of two implementation plans, Kromer; Bandivadekar and Evans (2010) investigated four GHG mitigation strategies for the United States light-duty vehicle fleet in the 2010-2050 timeframe. These strategies included improvements in near-term vehicle technologies, low-carbon biofuels, de-carbonization of the electric grid and travel reduction initiatives. Its results emphasized the importance of focusing on parallel strategies pathways to reduce GHG emissions and petroleum consumption in the transportation sector.

Low-carbon scenarios measures have also been investigated for China's vehicle fleet. Some strategies included improving fuel efficiency of internal combustion engine vehicles (ICV), electric vehicles (EV) diffusion and increasing blending of biofuels on gasoline and diesel (GAMBHIR *et al.*, 2015; HUO *et al.*, 2012) by 2050. Highlights on the relevance of fuel-consumption improvement role was made (HUO *et al.*, 2012) and additional measures were incentivized to further reduce emissions (GAMBHIR *et al.*, 2015). Moreover, besides these strategies, Zheng *et al.* (2015) also assessed limiting car use intensity and emphasized the need of an integrated policy to effectively constrain China's GHG emissions peak by 2030. Through a carbon tax scenario analyses, Zhang; Chen and Huang (2016) conducted a bottom-up investigation for China and US transportation sectors, finding biofuel as the main carbon mitigation option to reduce the emissions in the near-term and EV in the long-term.

Using an Italian province as a case study, Nocera and Cavallaro (2016) compared the role of hydrogen and electricity in reducing carbon emissions, revealing the benefits from cooperation towards more sustainable transportation, rather than competition. Menezes; Maia and de Carvalho (2017) also evaluated low-carbon development strategies for the transport sector in the city of São

Paulo (Brazil) and highlighted biofuel increase as the highest potential strategy to reduce GHG emissions followed by strategies to increase the use of public transport.

Other strategies are outlined in studies of the impact of vehicle size class reduction (downsizing) and light material substitution (lightweighting) on energy consumption and carbon emissions (GONZÁLEZ PALENCIA; ARAKI; SHIGA, 2016; GONZÁLEZ PALENCIA *et al.*, 2017; GONZÁLEZ PALENCIA *et al.*, 2015; GUPTA *et al.*, 2016). By investigating the diffusion of different types of vehicles (conventional and electric) and size classes, González Palencia et al. (2015) showed the relevant potential lightweight vehicles have in tank-to-wheel energy consumption and CO_2 emissions reductions. While focusing on the impact of mini-sized and zero-emission vehicle diffusion, González Palencia; Araki and Shiga's (2016) results further indicated the relevance downsizing brings to lower energy, material consumption and CO_2 emissions, as also indicated by Gupta *et al.* (2016). Furthermore, these strategies can neutralize the cost implication trade-off for consumers buying EV (THIEL *et al.*, 2014). Also, if CO_2 savings are quantified and evaluated economically, they might even generate positive economy wide savings Nocera and Cavallaro (2016).

More policy instruments towards reducing carbon emissions have been strongly recommended (ALAM *et al.*, 2017a; GONZÁLEZ PALENCIA *et al.*, 2015; HAO; GENG; SARKIS, 2016; IANKOV; TAYLOR; SCRAFTON, 2017; ZENG *et al.*, 2016). Hao *et al.* (2016)'s global analysis on carbon footprint from passenger vehicles indicated the need for additional policies. Zeng *et al.* (2016) investigated GHG emissions from different motor vehicles of some Chinese cities considering different fuels and highlighted the urgency to develop and/or adjust low-carbon policies in the country. An integrated policy, rather than any single policy, seems to be a better way to constrain peak GHG emissions in China (ZHENG *et al.*, 2015). Free market forces have shown as insufficient to improve fuel efficiency of light vehicle fleet, suggesting that significant policies intervention should take place to accelerate the uptake of low or zero emitting vehicles in Australia (IANKOV; TAYLOR; SCRAFTON, 2017). Examining different vehicle technologies, Alam *et al.* (2017) emphasized the need of higher levels of technological intervention, biofuel use and implementation of EVs policies for the current state of vehicle penetration in Ireland. Additional policies such as modal shift, demand management and vehicle occupancy increase are also recommended to tackle the transportation emissions issue (GONZÁLEZ PALENCIA *et al.*, 2015).

Emission targets have been on the focus of other literature. Academics have assessed different carbon mitigation pathways and compared mid and long-term targets (DHAR; SHUKLA; PATHAK, 2017; GONZÁLEZ PALENCIA *et al.*, 2015a; LIU *et al.*, 2017; PATIL *et al.*, 2016; SORRENTINO; RIZZO; SORRENTINO, 2014; ZENG *et al.*, 2016). The Paris Agreement has mobilized several countries' development dynamics. Although it does not reference transport explicitly, given its great contribution on CO_2 emissions (the main GHG), this topic is comprehensively discussed in each country's (Intended) Nationally Determined Contributions, (I) NDC (OECD/ITF, 2017). In Japan's case, the target of 50% CO_2 emissions reduction by 2050 compared to the 1990 level may only be achieved with the diffusion of battery electric vehicle (BEV) and fuel cell hybrid electric vehicle (FCHEV) (GONZÁLEZ PALENCIA *et al.*, 2015). The necessity of further policies (or policy improvements) has been appointed as crucial to China and India in achieving their future GHG reduction targets (DHAR; SHUKLA; PATHAK, 2017; ZENG *et al.*, 2016).

Furthermore, the need for deep decarbonization of electric grids to meet emission targets (and a more sustainable mobility) has been emphasized in various studies (and regions) (LIU *et al.*, 2017; PATIL *et al.*, 2016; SORRENTINO; RIZZO; SORRENTINO, 2014; ZHANG; CHEN; HUANG, 2016). A common agreement between scholars is that only with a clean and fossil carbon emissions free in the global electricity production can EVs reach their full potential in mitigating global warming (NORDELÖF *et al.*, 2014). If EVs are recharged from electricity produced from most of conventional technology power plants, increased mobility may produce equal or even more GHG emissions than conventional vehicles (PATIL *et al.*, 2016; POULLIKKAS, 2015).

Brazil, however, is characterized for its clean electric grid, with over 80% from renewable sources (BEN, 2017). This is the main reason why EVs could today play a major role in transportation emission reduction and present higher positive impact on climate change mitigation than bioethanol as a fuel (when well-to-wheel, WTW, is considered) (COSTA *et al.*, 2017). However, although some countries have shown an outstanding diffusion increase (e.g., Norway with 29% market share of EVs, IEA, 2017), the high purchase costs and lack of infrastructure (aligned with the absent of payment regularities) have been major barriers providing a low uptake of electric vehicles in some countries, such as in Brazil Benvenutti; Ribeiro and Uriona (2017).

The literature shows, there is still considerable room to improve the efficiency of the light vehicle fleet in Brazil by introducing additional mandatory policies (AUGUSTUS DE MELO; DE MARTINO JANNUZZI; DE MELLO SANTANA, 2018). There is no GHG emission target for new vehicles sold in Brazilian market. Even in some other countries that do have targets, research has shown that the market penetration of some electric vehicles is not sufficient to accomplish their targets (SORRENTINO; RIZZO; SORRENTINO, 2014). Thus, considering that most of the growth in road transport energy consumption and GHG emissions in the future is expected to take place in developing countries (HAO; GENG; SARKIS, 2016; IEA, 2012; OECD/ITF, 2017), this study proposes some benchmark targets for the light vehicle fleet for 2025 and 2030 based on Brazil's NDC. At the Conference of the Parties to the United Nations Convention (COP22), Brazil reaffirmed its commitment to the Paris Agreement to reduce greenhouse gas emissions by 37% by 2025 and 43% by 2030 (reference year: 2005).

Through proposed benchmarks and scenario analysis, this study forecasts light vehicle emissions to assess Brazil's potential and progress towards more sustainable transportation. By presenting an outlook panorama of the fleet potential in reducing GHG emission, it tests similar practiced policies, such as the European mandatory emission reduction targets for new cars (EU, 2017), biofuel increase and EVs uptake increase. The importance of strengthening policies and strategies for both EVs diffusion as well as for other technologies is evidenced, and emphasis is on how different technologies should not be seen as competitors (NOCERA; CAVALLARO, 2016), but rather as mid-term action towards an integrated policy. Finally, this study highlights the relevance environmental policies bring and presents pathways to further induce carbon emission mitigation, contributing to international efforts aimed at reducing global climate change.

3.2 BACKGROUND

Worldwide road transportation sector accounts for 72.06% of total GHG emissions of the transportation sector (IPCC, 2014). In Brazil, in 2014, its impact was of 26.6% of all CO_2 emissions from all the main sectors in the country (i.e., energy, industrial processes, agricultural, changes in the use of land and forest and waste treatment sectors) (MCTIC, 2016).

The Brazilian government established a national policy about climate change (PNMC, abbreviation in Portuguese), law nº12.187/2009 (BRAZIL, 2009) that defines its voluntary commitment to adopt mitigation actions to reduce GHG emission between 36.1% to 38.9% of projected emissions for 2020. In accordance with the decree nº 7.390/2010 (BRAZIL, 2010) that regulates this law, the projection of GHG emission for 2020 is estimated in 3,236 Gt $CO_{2^{eq}}$. Hence, the aim is to reduce this emission to a maximum 2,068 million tons $CO_{2^{eq}}$ by 2020. The emission projection for 2020 from the energy sector is 868 million tons $CO_{2^{eq}}$. With the national commitment, the aim is to reduce this emission from this sector to 634 million tons $CO_{2^{eq}}$ (27% reduction).

Furthermore, at the Conference of the Parties to the United Nations Convention (COP22), Brazil's government has committed to the Paris Agreement to reduce greenhouse gas emissions by 37% by 2025 and 43% by 2030 (reference year: 2005), which account for 1,300 Mt $CO_{2^{eq}}$ (or 1.3 Gt $CO_{2^{eq}}$) in 2025 and 1,200 Mt $CO_{2^{eq}}$ in 2030. The figures from road transportation subsector represent a great potential for mitigating GHG emission in the country, providing actions are taken to achieve these targets.

In response to the commitments established in Paris Agreement, the Ministry of Science, Technology, Innovation and Communication (MCTIC, abbreviation in Portuguese) launched a project named "Mitigation Options of Greenhouse Gas Emissions in Key Sectors in Brazil" (MCT, 2016) with resources of the Global Environment Facility (GEF) and partnership of United Nation Environment Programme (UNEP), aiming to assist decision making about actions that can potentially reduce GHG emission from key-sectors of the Brazilian economy (MCT, 2016). In the transportation sector, three main measures of low carbon activities were highlighted to reduce these emissions in the country in the long term: (i) energy efficiency (from both incremental and advanced technologies); (ii) modal changes and (iii) the use of biofuels.

Incremental technologies (from energy efficiency measures) consist in reducing energy loss from vehicle operations. Advanced technologies include, for instance, the use of electric vehicles with renewable energy generation source as a key measure. Both incremental and advanced technologies measures can be achieved by public policies instruments such as the prohibition of inefficient new vehicles in the market, further incentives of more efficient technologies (target efficiency) and influencing local car manufacturers to gradually produce more efficient vehicles. Fiscal measurement can play a role by charging more those less efficient vehicles' consumers and/or rewarding the use of more efficient vehicles (MCT, 2016).

Modal changes include shifting from the individual to collective transportation, aiming at the transportation of passengers, and the transportation of cargo from highways (roads) to railways and waterways transportation. These activities will require restructuring urban mobility and infrastructure. Other low carbon policies include greater use of biofuel, promoting research and development and investments in logistics infrastructure.

However, there are considerable barriers to overcome for the implementation of advanced technologies. For the alternative fuel vehicles (AFV) diffusion, the main factors cited and studied in the literature can be classified as: financial, technical, institutional, public acceptability, regulatory, policy failures and physical barriers (BROWNE; O'MAHONY; CAULFIELD, 2012). In Brazil, the main barriers identified and associated with these technologies are: high costs, conventional auto industry lobby, lack of infrastructure, limited resources for new materials and possible environmental impact for the energy vector generation (hydrogen and electricity). On the other hand, that are potential economic, social and environmental gains with the occurrence of low carbon activities such as: energy safety, reduction of oil dependency, technological diffusion, cost reduction with public health, job generation, pollutants emission and noise reduction (local and global), among others (MCT, 2016).

In 1986, Air Pollution Control Program for Automotive Vehicles (PROCONVE, abbreviation in Portuguese) was created by the National Council for the Environment (CONAMA, abbreviation in Portuguese) (CONAMA, 1986), coordinated by IBAMA (Brazilian Institute of the Environment and Renewable Natural Resources), which defined emission limits for light vehicles. Since then, it has gone through different phases that involved mechanical improvements to meet emission limits targets. Although it establishes progressive emissions targets limits of carbon monoxide (CO), oxides of nitrogen (NOx), hydrocarbons (HC), particulate matter (PM), aldehydes (CHO) and sulfur oxides, it does not contemplate limits for CO_2 (there is only the need to inform it). Furthermore, the National Institute of Metrology, Quality and Technology has been releasing new vehicles energy efficiency since 2009 (INMETRO, 2017), making it possible to control average new cars emissions.

This paper is organized as follows: in section 3.3, we present the methodology adopted in this study, the inherent procedures as well as the different scenarios considered. In section 3.4, we present the results along with some discussion and at last, the paper ends with the main conclusions of this research in section 3.5.

3.3 METHODOLOGY

As thoroughly discussed in Garcia and Freire's (2017) review paper, a fleet-based life cycle approach is appropriate for evaluation of impacts when introducing a new technology. It follows a different approach to the function unit of a life cycle assessment (LCA) as it considers a set of units, rather than a single unit (FIELD; KIRCHAIN; CLARK, 2000). This approach has been mostly applied on the automotive sector as, for example, when assessing scenarios of evolution in the transport sector. In this sense, the analysis includes the development changes of mechanical aspects of the fleet (fuel efficiency improvements) as well as external influential aspects in a fleet such as biofuel rate use and the diffusion of EVs.

Thus, we conducted a fleet-based "tank-to-wheel" (TTW) analysis on GHG emission. For a better description, the methodology has been divided into three subsections. The first one (3.3.1) presents the forecast procedure of the average GHG emission rate per year from Brazilian passenger vehicles through time. In the following subsection (3.3.2), we present the steps undertaken to estimate appropriate emission rate benchmark targets for future passenger vehicles. Ultimately (3.3.3), the scenarios assumptions are defined and described.

3.3.1 Average GHG emission rate through time

The average operation phase emissions change through time as technology advances. The TTW impacts are calculated by using process data of the main three GHG for tailpipe emissions, i.e., carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), while burning either gasoline type C or bioethanol in vehicle operation.

A bottom-up approach is considered, which estimates the gases based on the (i) fleet (ii) vehicle kilometers travelled and (iii) emission rates (dependent on type of vehicle, GHG and fueling combustion) (CETESB, 2016). The estimated projection of the TTW emission from light vehicle fleet is conducted for 2010-2040 timeframe. The annual fleet GHG emissions (million tons of $CO_{2^{eq}}$) is calculated by equation [1]:

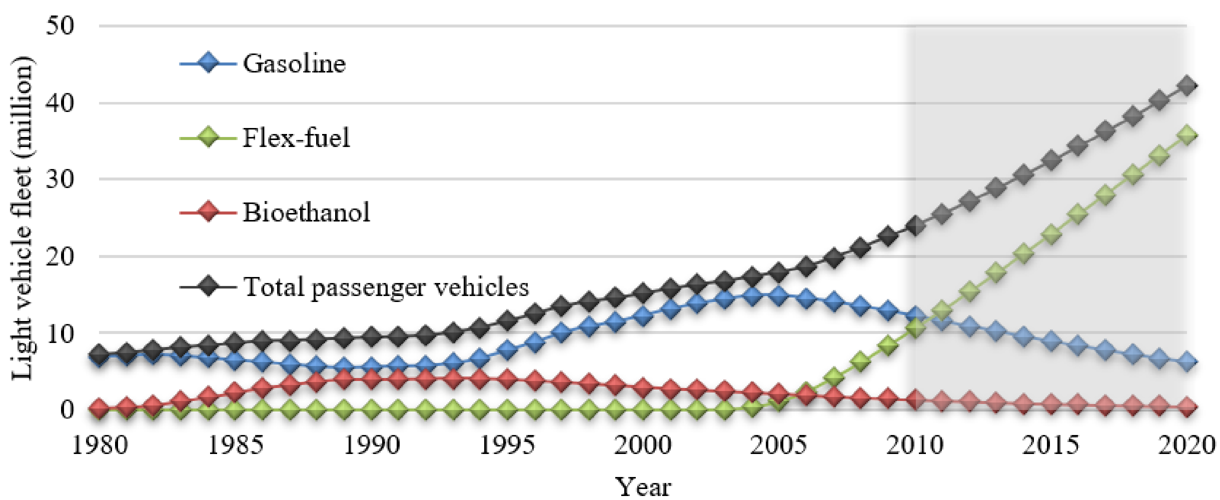
$$GHG_t^{TTW} = \sum_i \sum_j \sum_k CF_{ij} \times VKT \times ER_{i,j,k}^{(t-9)} \times GWP_k^{100\,year\ time\ horizon} \div 10^{12} \qquad [1]$$

where $i, j,$ k and t represent vehicle type (flex-fuel, bioethanol or gasoline type), fuel type (gasoline, anhydrous and bioethanol), GHG (CO_2, CH_4 and N_2O) and time, respectively. CF_{ij} represents the circulating fleet i (light vehicles) powered by fuel type j. VKT is the average vehicle kilometer travelled (km/year) of a 9-year old car (rationale behind explained in subsection 3.3.1.2). $ER_{i,j,k}^{(t-9)}$ is the average tailpipe emission rate (gram of a GHG/km) of the CF_{ij} and the respective GHG k with a 9-years lag. For this, we used the average exhaust emission rate of new cars sold determined in laboratory and published annually by Environmental Company of Sao Paulo (CETESB, 2016). $GWP_k^{100-year\ time\ horizon}$ is the global warming potential factor of the respective GHG k, provided by the Intergovernmental Panel on Climate Change (IPCC, 2014), which measures of how much heat a GHG traps in the atmosphere. Finally, the division by 10^{12} converts the unit, from grams of CO_{2eq} into million tons of CO_{2eq} Next, each variable is better depicted.

3.3.1.1 Circulating fleet

Car sales were first recorded in 1957 and were mainly powered by gasoline. Then, in the late 1980's and beginning of the 1990's, many bioethanol-powered cars were sold as a result of the "national alcohol program" (named "*Pró-alcool*" in Portuguese). However, their production was officially discontinued in 2007. Since 2003, flex-fuel car types became available, giving flexibility to consumers to use either petrol or bioethanol fueling. Figure 3 shows the estimative numbers of light vehicle fleet in Brazil,

Figure 3 - Historical light vehicle fleet estimative (1980-2010) and estimated projection (2010-2020, in gray shade) per car type in Brazil.

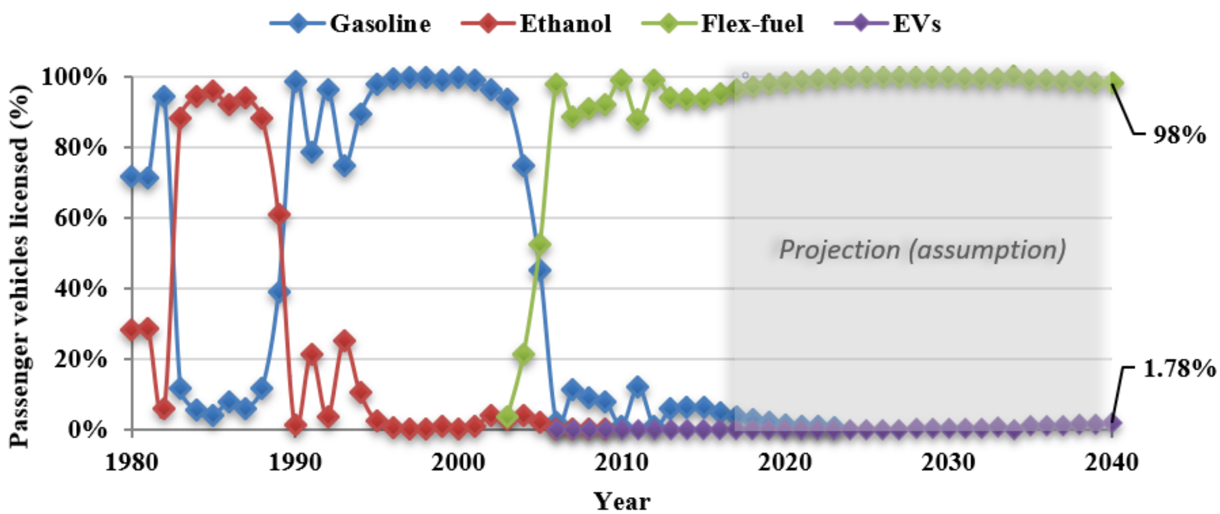


Source: Elaborated by the authors, historical values based on MMA (2011).

Today, flex-fuel vehicle sales represent 95% of total automotive vehicle sales in Brazil (ANFAVEA, 2017). Although flex-fuel vehicles may be classified as AFV in some studies, in this study we relate to them as part of the group of conventional cars (internal combustion engine cars) and only EVs in the category of AFV. Considering the flex-fuel vehicles historical licensing trend growth, by 2024, 100% of the conventional car market sales are expected to be flex-fuel vehicles.

For the circulating fleet projection (2010-2040), we based both the total number of vehicles in the fleet and the diffusion of EVs (see Appendix A for the fleet number per year) on a diffusion model developed in system dynamics modelling for Brazil in Benvenutti *et al.* (2017), which was based on the theory of Bass model (BASS; KRISHNAN; JAIN, 1994). Figure 4 presents the historical and estimated projection of the proportion of these cars licensing for the 1980-2040 time period.

Figure 4 - Historical (1980-2016) and estimated (2017-2040) proportion of light vehicles type licensing in Brazil.



Source: Elaborated by the authors, based on ANFAVEA (2017) and Base Case scenario from Benvenutti *et al.* (2017).

3.3.1.2 Vehicles kilometers travelled (VKT)

As for the VKT, there is data of car use intensity raised by a research center in USA (International Sustainable System Research Center) in partnership with CETESB for the city of Sao Paulo that the Ministry of the Environment (MMA, 2011) uses. These data indicated a correlation between the intensity of use with a vehicle's age and is expressed by kilometer per year (basically newer cars have the tendency to ride more than older ones, following a linear decrease pattern with vehicles' age).

For the past 15 years, Brazil has had a historical profile of car fleet age varying from 8 years and 4 months to 9 years and 5 months (SINDIPEÇAS, 2017). Thus, an average value of 14,600 km/year per car was adopted, which is the value for 9-year-old circulating vehicles. We are aware that this value might be overestimated since the city of Sao Paulo is a megacity, which may require longer trip distances than perhaps other cities. Still, for estimating purposes, we chose this average value.

3.3.1.3 Emission rate estimate

Emission rates differ for both the type of combustion fuel and the vehicle. For historical values, we used the process data of the average emission rates of new cars sold per year for the State of São Paulo (the most populous state with nearly 45 million people in 2017, approximately 22% of the country's population) (CETESB, 2016). Hence, to make an accurate estimation, the proportion of car types were considered. The emission rates are classified for each internal combustion vehicle type, namely, (i) gasoline type C (ii) bioethanol (iii) flex-fuel fueled with gasoline C and (iv) flex-fuel fueled with bioethanol (CETESB, 2016).

Table 1 presents the rate per year at which the average emission factors varied during the historical years 2003-2015. These rates are used for projecting the factors in the 2015-2040 period, reflecting the historical profile to be used as a business-as-usual (BAU) scenario emission profile. Before 2003, only emission rates from gasoline-powered vehicles are available.

Table 1 - Emission rates (gram of a GHG/kilometer) average variation (%) per year for internal combustion cars and per gas emission from historical years (between 2003-2015 period).

Internal combustion cars:	**Gasoline**	**Flex-fuel (bioethanol)**	**Flex-fuel (gasoline)**
CO_2	-0.3	-1.7	-1.8
CH_4	-34.2	-8.8	-61.6
N_2O	0	0	-1.58

Source: Estimated by the authors, based on CETESB (2016).

In addition to the different proportion of car types, the proportion of either gasoline or bioethanol used as fuel for flex-fuel vehicles was investigated. Based on Brazilian Energy Balance (BEN, 2017) and a GHG emission report (MCTI, 2015), during 2003 to 2016 the average use of bioethanol as vehicle fuel was approximately 45%. This number was used as the bioethanol/gasoline ratio for the BAU (later depicted in section 3.3.3).

Subsequently, the average CO_2, CH_4 and N_2O emission rates of the country's light vehicle fleet are estimated using all projection proposed, that is, the circulating fleet projection along with the country's estimate proportion of car types (and fueling preference) and their average GHG emission rates for each fuel combustion type per year (CETESB, 2016).

It is worth noting that the numbers presented in CETESB's report represents average emission rates of new cars released in the respective year, considering the combustion car type and the level of their sales. Thus, it is safe to affirm that if these rates from new cars are diminishing each year and the fleet's age has a profile to be around 9 years old, these new emission rates would take about this time to be the overall average of the fleet. Then, for appraisal's sake we considered this time lag for approximation, e.g., the emission rate average of new cars sold in 2010 would be achieved by the entire fleet in 2019.

Additionally, CO_2 emission rates from electric vehicles were considered based on (i) hybrid Toyota Prius for hybrid electric vehicle (HEV) and (ii) Mitsubishi Outlander for plug-in hybrid electric vehicles (PHEV). For BEV case, since there is zero exhaust CO_2 emission during vehicles operation, no reference was needed. For the HEV, since 2010, the CO_2 emission rate was 89 g/km and in 2017 it declined to 70 g/km (INMETRO, 2016; TOYOTA, 2014). For the PHEV, a 42 g/km CO_2 is considered from 2010 to 2017 (MITSUBISHI, 2017). In both cases, we consider that their emission rates face the same decline rate through time as the estimate for conventional cars during the same period. As for CH_4 and N_2O, due to unavailable data, we consider their emissions using the same proportional difference between CO_2 estimates for conventional cars and EVs.

3.3.2 GHG emissions benchmarks for passenger vehicles

The Brazilian NDC does not define road transportation subsector targets specifically, as the established decree nº 7.390/2010 (BRAZIL, 2010) targets for 2014 and 2020 also do not. The targets are for specific main sectors and do not include any targets for subsectors. From the decree, there is the GHG target emission for the energy sector. From the MCTIC (2017)'s work, there is the transportation sector potential reduction (evident in Table 4 in section 3.4.2). Thus, to provide comparable results for future passenger vehicles to the country's Paris Agreement targets, some assumptions are needed.

Table 2 presents the assumptions considered in this study for the proposal of GHG emissions benchmarks for light vehicles participation in Brazil. Proportions of CO_2 participation from light vehicle emissions from both the energy and transportation sector was estimated based on the country's own characteristics and trends.

Table 2 - Estimate fraction of GHG emission weight that the road (light vehicles) transportation sector have from other sectors (energy and transportation sector) in Brazil.

CO_2 participation (%)		**Fraction**	**Source**
Road transportation subsector emission proportion from Energy Sector		43.7%	Authors' own estimate based on MCTIC (2016) and MMA (2011)
Light vehicle emissions proportion from road transportation subsector (average projection for 2009-2020 period)		36%	
Light vehicle emissions proportion from:	Energy Sector	15.7%	
	Transportation Sector	33%	

Source: Elaborated by the authors, based on references shown in the 3rd column.

It is important to note that even though we use CO_2 to estimate the previous proportion (and not CO_{2eq}), for road transportation sector, CO_2 emissions represent over 95% of the CO_{2eq} weight (MCTIC, 2016).

3.3.3 Defining scenarios

Assuming policies intervention, we combine three GHG emission mitigation strategies using a light vehicle diffusion model output (Appendix A) to estimate future GHG emission reduction potential: (i) fuel-efficiency improvement (incremental technologies); (ii) increase in biofuel and (iii) electric vehicles (advanced technologies). Different intensity from these three mitigation strategies is tested in three scenarios. Also, besides the BAU scenario a fictitious scenario named "Hypothetical" scenario is also evaluated. Table 3 presents each scenario considered in this study along with their descriptions.

We first investigate fuel-efficiency improvement strategy, coming from more fuel-efficient vehicles in the fleet that spend less energy and fuel, thus emitting less GHG. For this, in our methodology we assumed that stricter policies, such as those imposed by EU commission (EU, 2017), would encourage the development and adoption of these vehicles (national program PROCONVE does establishes target limits for exhaust air pollutant emission, but not for GHG emissions). For the year 2015 the program had set a target of 130 grams of CO_2/km by all new cars (in which they achieved 118 grams of CO_2/km by 2016), and by 2021 the aim is 95 grams of CO_2 per kilometer. The cornerstone legislation for their strategy is to improve the fuel economy of cars sold on the European market.

Furthermore, it can be noted that cars' energy efficiency contemplates both incremental (reducing energy loss from vehicle operation) and advanced technologies (MCT, 2016). Thus, enhancing energy efficiency of a fleet not only can be achieved by improving mechanical aspects but also by the incorporation of more efficient vehicles such as electric and hybrid ones. However, since the trend has been increasing without incorporation of the latter (in 2016 their sales represented around 0.066% of the total vehicle licensing share in Brazil, ANFAVEA, 2017), we chose to study their potential influence separately.

Table 3 - Emission mitigation scenarios.

Description	Source/based on
BAU	
- No further CO_2 mitigation policies are assumed until 2040. The fleet average emissions level follows the projection estimated in our methodology.	ANFAVEA (2017), CETESB (2016)
- An average use of 45% bioethanol/gasoline ratio is considered in flex-fuel vehicles, assumed until 2040.	BEN (2017) and MCTI (2015)
- Electric vehicles diffusion occurs modestly following generalized Bass diffusion model (Bass et al., 1994) (assuming BEVs only).	Benvenutti *et al.* (2017)
Scenario 01	
(I) The same EU legislation mandatory CO_2 average emission reduction target for manufacturers for new car sold of 140g/km in 2010, but here we assume for 2020. Also, the same 2.2% average reduction rate per year achieved by them from 2000-2010, but here we assume for the 2020-2030 period. Afterwards the reduction rate is 2% per year.	IEA (2010), ANP (2014) and (EU, 2017)
(II) An average use of 45% bioethanol/gasoline ratio is considered in flex-fuel vehicles until 2019. From 2020 onwards, there is a 5% increase in this ratio.	Biofuel market boost assumption.
(III) Electric vehicles diffusion occurs aggressively following generalized Bass diffusion model (Bass et al., 1994).	Benvenutti *et al.* (2017)
Scenario 02	
(I) The same first assumption of previous scenario and 118g/km value achieved in 2015 (here we assume for 2025). For the following years, the same reduction rate as before.	IEA (2010), ANP (2014) and (EU, 2017)
(II) An average use of 45% bioethanol/gasoline ratio is considered in flex-fuel vehicles until 2019. From 2020 onwards, there is a 10% increase in this ratio.	Biofuel market boost assumption.
(III) From 2020 onwards, the EVs sales assumes 10% of total car market sales per year, the same average sales target from selected countries[1] for 2016-2020 period (here from 2020-2040).[2]	IEA (2016)
Scenario 03	
(I) The same first assumption of previous scenario and a 95g/km target by 2021 (in our case by 2031). For this, a 3.6% average reduction rate per year is applied from 2020-2031 period. For the following years, the same reduction rate as previous scenario.	IEA (2010), ANP (2014) and (EU, 2017)
(II) An average use of 45% bioethanol/gasoline ratio is considered in flex-fuel vehicles until 2019. From 2020 onwards, there is a 15% increase in this ratio.	Biofuel market boost assumption.
(III) From 2020 onwards, the EVs sales assumes 20% of total car market sales per year, the same average sales target from France for 2016-2020 period (here from 2020-2040).[2]	(IEA, 2016)
Hypothetical scenario	
The same assumption as the BAU, except the country's characteristics of the flexibility in fueling its cars with bioethanol. Thus, a fictitious BAU (BAU') is tested as if cars	Hypothetical assumption

could only be fueled with gasoline type C (the current country's gasoline with 27% of bioethanol). Moreover, the same (I) strategies from scenario 01-03 is tested.

Table observations
Each roman number is related to a GHG emissions mitigation strategy: (I) fuel-efficiency improvements (incremental technologies); (II) increase in biofuel and (III) electric vehicles diffusion (advanced technologies).
[1] Selected countries: Austria, China, Denmark, France, Germany, India, Ireland, Japan, Netherlands, Portugal, South Korea, Spain, United Kingdom and United States (IEA, 2016).
[2] In this EVs mitigation strategy, we first test only the uptake of BEVs. Moreover, we test what the outcome would be if HEVs and PHEVs diffusion should occur in place of the BEVs for scenario 02 and 03.

Source: Elaborated by the authors, based on references shown in the 2nd column.

For the second strategy, increased average rates of biofuel use in flex-fuel cars are tested. This strategy can be achieved by either increasing the bioethanol proportion inside gasoline blends or by stimulating more of its use. Here, we consider the latter option, an overall increase use of biofuel (bioethanol) by national consumers. The use of bioethanol as car fuel reduces significantly the amount of carbon emissions (biogenic process). The third strategy contemplates the incorporation of more electric vehicles in the fleet, where diffusion occurs following literature's perspective in scenario 01 and as a result of more stringent policies to achieve assumptions from scenario 02 and 03.

Under the BAU scenario, no further policies are implemented and no significant change in technology is considered other than current trends. Furthermore, under the hypothetical scenario, the fictitious BAU' is projected to make comparison in case the country did not rely on bioethanol as a combustion fuel, only on gasoline.

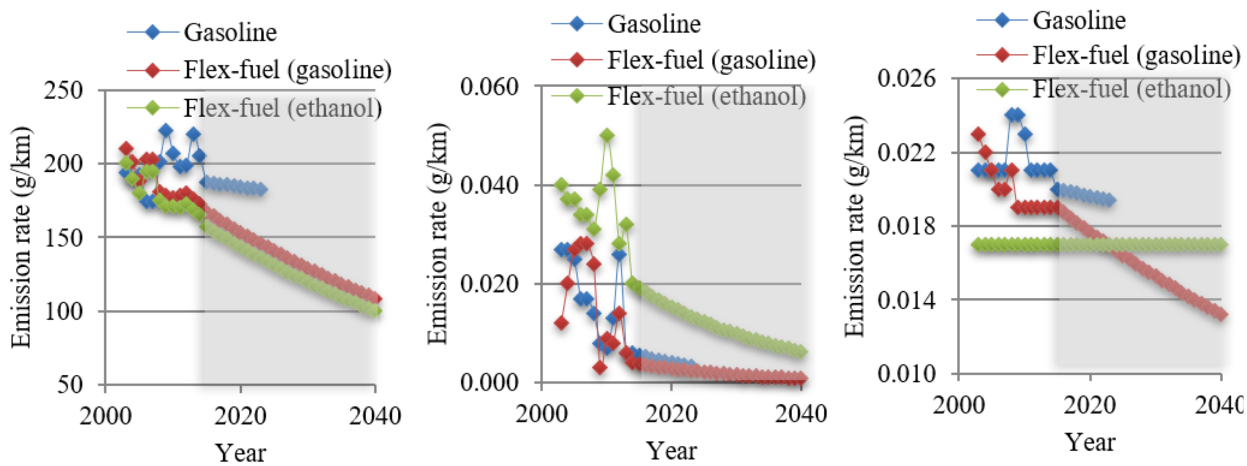
3.4 RESULTS AND DISCUSSION

To better present our results, we divide them into four categories, namely, (4.1) emission rate estimate results (4.2) proposed emissions benchmarks and (4.3) GHG emission mitigation potential.

3.4.1 Emission rate estimate results

Figure 5 presents the historical (2003-2015) and projected (2016-2040) average emission rate profile of new cars sold per year of each GHG considered in this study. As we can observe, vehicle emission rates have overall been historically declining through the years, except for nitrous oxide in flex-fuel cars (when powered by bioethanol). Note that there are no results beyond 2023 for cars powered by gasoline only due to our projection of their ending production.

Figure 5 - Historical (2003-2015) and projected (2016-2040, in gray shade) average emission rate of each greenhouse gas (a) CO_2 (b) CH_4 and (c) N_2O per type of internal combustion engine car sold per year.



(a) CO_2 (b) CH_4 (c) N_2O

Source: Elaborated by the authors.

Figure 6 presents the estimated average emission rate of the country's fleet for each GHG in the 2010-2040 period. In 2019 methane emission rate rises due to an increase of both flex-fuel licensing and its emission rate in the 9-year time lag considered for this rate (from 2010 emission rate of new cars sold, in this case). Figure 7 present the comparison between the CO_2 emission rate estimated in this study and the emission rate if only flex-fuel cars were fueled with gasoline.

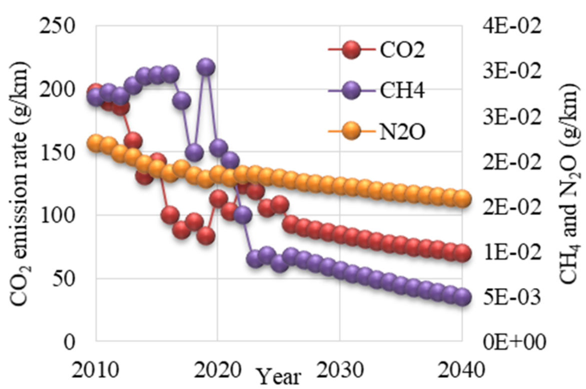


Figure 6 - Estimated average greenhouse gas emission rate (g/km) of Brazil's light vehicle fleet for the BAU scenario for 2010-2040 period

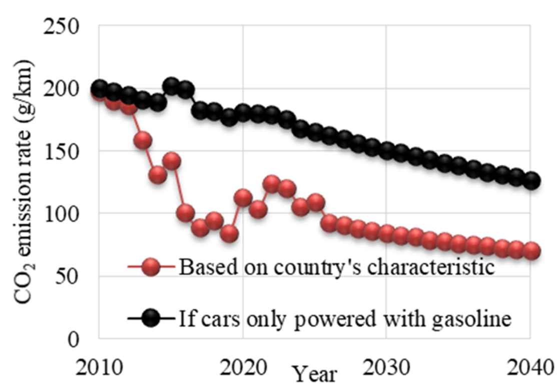
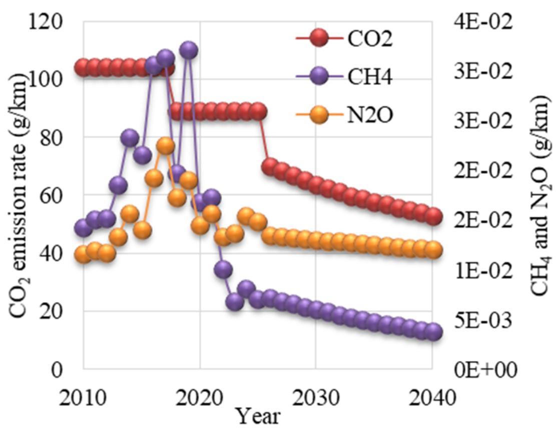


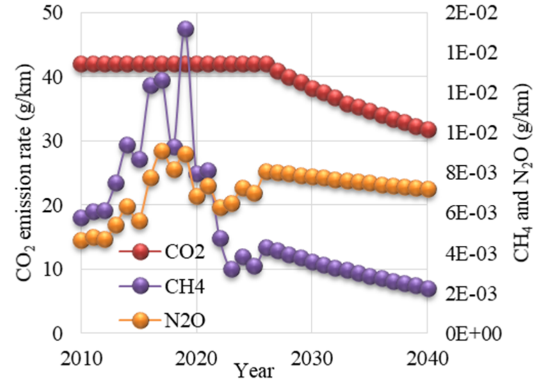
Figure 7 - Estimated CO2 emission rate used in BAU scenario (red) and, for comparison purposes, if the fleet was only powered by gasoline (black), BAU'.

Figure 8 presents the emission rate of each GHG emission for the HEV and PHEV in the 2010-2040 period.

Figure 8 - Estimated average greenhouse gas emission rate (g/km) of the country's fleet considered in this study for (a) HEV and (b) PHEV in the period 2010-2040.



(a)



(b)

Source: Elaborated by the authors.

3.4.2 Proposed emissions benchmarks

Table 4 presents the GHG emissions from the commitments established in the decree nº 7.390/2010 (BRAZIL, 2010) (for 2014 and 2020) for the energy sector and the results obtained by MCTIC's (2017) work for the transportation sector. Also, the proposed benchmarks for light vehicles share of GHG emissions in the country is presented (estimate based on assumption from Table 2).

Table 4 - Greenhouse gas emissions target (BRAZIL, 2010), reduction's potential (MCTIC, 2017) and authors' proposed benchmarks of GHG emissions (million tons of CO_{2eq}) for light vehicles fleet in the country.

Decree (BRAZIL, 2010)		**MCTIC (2017)**			
2014	**2020**	**2025**		**2030**	
		REF	BC0	REF	BC0
470	634	214.6	200.7	228.6	208.6
Authors proposed total GHG emissions benchmarks for the road (light vehicles) transportation sector:					
74	100	71	66	75	69

Source: Elaborated by the authors, based on references therein.

The nomenclature "REF" (Table 4) represents the MCTIC's (2017) reference scenario. In terms of transportation strategies they relied on the National Policy on Climate Change (PNMC, abbreviation in Portuguese) that relies on implementation action from the National Plan of transportation logistic (PNLT, abbreviation in Portuguese, in charge of strategic planning for the transportation sector in Brazil) (PNMC, 2008), in which projections for road transportation (which besides passenger vehicles includes commercial vehicles, motorcycle, buses, trucks) would drop from the 58% at that time to 33% in 15-20 years (around 2020). They assumed that this would be possible with the rise of railway and waterway use in as a more focused strategy as well as, but with less reliance on, pipeline and air modal use. In our study, we will use this REF to compare with our BAU as they did not consider, in this case, any efforts towards specifically changing the light vehicle fleet participation, but more on modally shifting freight.

The classification “BC0” represents a MCTIC low carbon scenario. In this case, they consider the use of enhanced technologies available to mitigate emissions. Regarding transportation sector, their focus was mainly on a rise in biofuel production (from sugarcane and soy in particular). The zero after the abbreviation represents the amount of rebate cost level, thus, in this case, there is no consideration of price (USD) per tons of CO_2. In their work, they considered other scenarios with different rebate cost levels. However, as we are not considering this aspect in our study, we use BC0 to compare with our other scenarios.

These estimated GHG emission benchmarks for light passenger vehicles are a guide for us to make reasonable comparisons. We are aware, though, that they are only references, since GHG emissions reduction from other sectors could compensate with higher mitigation rate, leading to a relief to other (sub)sectors, such as the one here, objective of our study. Still, we believe the country could take them into consideration given the amount of effort every sector will (and is) facing as we aim for a more sustainable society.

3.4.3 GHG emission mitigation potential

Figure 9 shows the year-by-year projected light vehicle fleet GHG emissions in 2010-2040 period for our four different scenarios (a) 01, (b) 02, (c) 03 and (d) hypothetical one. The results from scenario 01-03 present an expressive GHG emissions decrease between the years 2015 and 2020. This relates to the reflection of the flex-fuel vehicles diffusion in the fleet starting in 2003 (with an average of 45% bioethanol use as fuel). Our projection assumes flex-fuel vehicles will completely overcome conventional cars sales (powered by gasoline only) in 2024, however, due to the fleet number increase, GHG emissions start rising again. The upper result in each figure represent the BAU (business-as-usual) scenario, wherein the BAU from Figure 9d, BAU’, differs from the others as it assumes the hypothetical scenario (if all flex-fuel vehicles were only powered by gasoline). In the EVs diffusion strategies results, at this stage, all electric vehicles sold in each scenario is assumed to be replaced to battery electric vehicles (BEV).

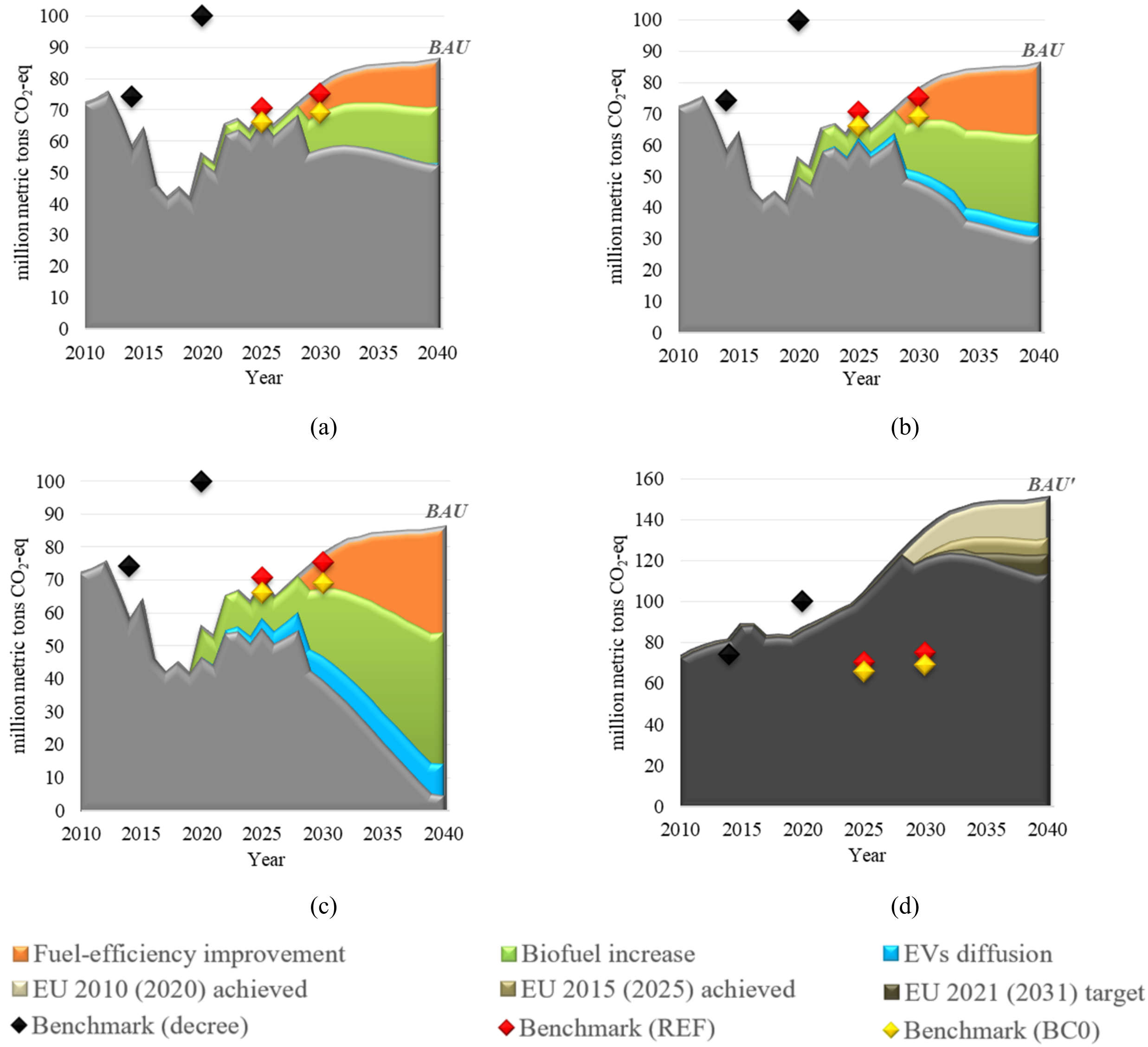
In each of the results (Figure 9) there are six bullets representing the proposed benchmark levels from the decree (for 2014 and 2020 in black) and from MCTIC's work (for 2025 and 2030 in red for 'REF" and in yellow for 'BC0'), from Table 4. Table 5 summarizes the scenarios results differences between the proposed target benchmarks. Examining them, the BAU scenario meets every target except the REF 2030, exceeding it by 3%. When considering the first set of policies (scenario 01), however, overcome it by far, mitigating by 24% the GHG emissions.

These scenarios (01-03), though, are more comparable with benchmarks estimated from the BC0 scenario as it includes mitigation strategies in it. In this case, scenario 01 does not achieve the aimed target, but only exceeds it by 0.3% the BC0 2025 (Table 5). It does, however, present an improvement of 17% by 2030. Thus, if the country undertakes similar EU fuel-efficiency consumption targets (specifically the EU 2010 achieved target) and even with the lag of 10 years as considered here (target for 2020), the fleet is able to meet the targets proposed here. If further efforts are made, such as increase of biofuel use and the occurrence of EVs diffusion, then by 2030 benchmarks are comfortably met. Moreover, the other scenarios are all able to achieve those targets exceedingly well and, overall, even though BAU and scenario 01 presented some setbacks, it does not seem concerning.

On the other hand, when comparing the targets with the hypothetical scenario, results differ significantly. From Figure 7d it is possible to note the fleet emission potential trend if all cars were powered by gasoline only (and the fuel implied here is the gasoline type C, which has an addition of 27% of bioethanol anhydrous since 2015). While BAU exceeds in 3% and 12% the REF 2030 and BC0 2030 targets, respectively, BAU' would exceed in 79% and in 96% from those benchmarks (Source: Elaborated by the authors.

Table 5). This represents an improvement in reaching GHG emission targets of approximately 80% through flex-fuel vehicles in the fleet. Obviously, if Brazilian fleet characteristics were different, the targets would be different as well. But the rationale is to show the significant impact flex-fuel cars bring into the fleet GHG emissions outcome.

Figure 9 - Estimated GHG emissions (million tons of CO_{2eq}) from Brazil's light vehicle fleet in the 2010-2040 period for the four different scenarios (a) 01, (b) 02, (c) 03 and (d) hypothetical case.



Source: Elaborated by the authors.

Table 5 - GHG emissions mitigation potential of each scenario compared with benchmarks proposed.

Compared with authors' benchmark (%) based on:	**Decree**		**REF**		**BC0**	
	2014	**2020**	**2025**	**2030**	**2025**	**2030**
BAU	23	45	2	(-)3	(-)5.2	(-)12
Scenario 01	23	47	6	24	(-)0,3	17
Scenario 02	23	50	14	37	8	31
Scenario 03	23	54	22	48	17	43
Hypothetical (BAU')	(-)10	14	(-)47	(-)79	(-)57	(-)96

Table 6 summarizes the avoided GHG emissions percentage compared with BAU scenario in 2040. With implementation of the reduction strategies, results reveal mitigation potential of 39%, 64 and 95% for scenario 01, 02 and 03, respectively. This represents a reduction in GHG emissions of 33, 55 and 81 million tons of CO_{2eq} in the year 2040. However, if compared to our hypothetical scenario, all cases exceed in the amount of target emissions. From the least emission exceeded level of 33% (EU 2021 target case) to the most with 75% in the BAU' case, representing an extra emission of 28 and 65 million tons of CO_{2eq} in 2040, respectively.

Figure 9 presents the GHG emission reduction potential from BAU scenario in 2040 of each strategy investigated in scenario 01-03. Table 7 summarizes their percentage impact. Biofuel increase strategy exhibited the highest overall mitigation potential, followed by fuel-efficiency improvement and EVs diffusion increase strategies.

Table 6 - Summary of GHG emission reduction potential in the year 2040 under each scenario and hypothetical scenarios compared to BAU.

Mitigation potential from BAU	**Scenario**			**Hypothetical scenario**			
	01	**02**	**03**	**BAU'**	**EU 2010 achieved (for 2020)**	**EU 2015 achieved (for 2025)**	**EU 2021 target (for 2031)**
(%)	39	64	95	(-)75	(-)53	(-)44	(-)33
Million tons of CO_{2eq}	33	55	81	(-)65	(-)45	(-)38	(-)28

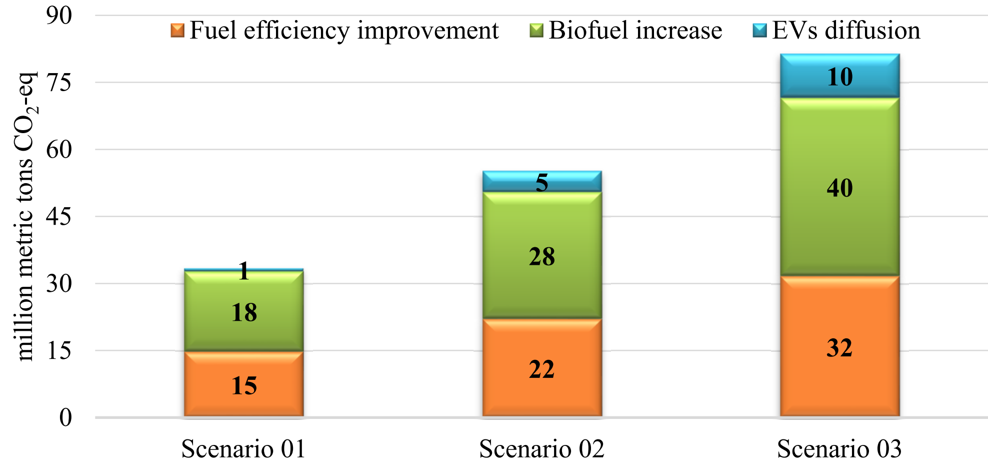
Source: Elaborated by the authors.

A different trend was found in Huo *et al.* (2012) for China. From their TTW analysis (low-car-growth scenario), fuel-economy improvement (implication comparable to our fuel-efficiency improvement strategy) presented the greatest potential for reducing GHG emissions by 2050 (with 34% from their BAU scenario), followed by electrification (with 26%) then fuel diversification (with 10%, which includes biofuel increase) and last dieselization strategy (with 5% potential). However, when compared with Brazil, there is a small proportion of biofuel use in their fuel blending, contributing to this lower biofuel strategy mitigation potential result as opposed to the results from this study (not to mention the absent of using biofuel straightly). Until 2012, in China, biofuel accounted for 2.5% of total gasoline consumption (ZHENG *et al.*, 2015), but researchers are aiming for an increase fuel blending ratio of 15% of total gasoline consumption by 2035 (ZHENG *et al.*, 2015) and of 30% by 2050 (HUO *et al.*, 2012). In Brazil, 27% of gasoline is blended with bioethanol since 2015 (since 1990's it always varied between 20-25%). Furthermore, the flex-fuel fleet characteristic collaborates with an average of a 45% bioethanol (that generates biogenic carbon) use as main engine power fuel. Thus, by increasing the average use in 5, 10 or 15% of the 45% (biofuel increase strategy), the mitigation potential reaches 18, 28 or 40 million tons of $CO_{2^{eq}}$ from BAU (related to scenario 01, 02 and 03, respectively) by 2040.

In Zhang et al. (2016)'s work for the China and US transportation sectors, although the authors found biofuel as the main carbon mitigation option to reduce emissions in the near-term, EVs were potentially found to be the best option in the long-term. The main reason was due to costs. So far, bioethanol production is cost-effective mainly in Brazil (AJANOVIC; HAAS, 2014). But once low carbon power generation options become economic competitive then EVs are potentially the best option in a long-term scenario (ZHANG; CHEN; HUANG, 2016). In Ireland's case, the results of CO_2 emissions reduction potential revealed a biofuel policy scenario as insufficient to achieve a significant reduction (ALAM *et al.*, 2017). While currently focusing their fleet on biofuel and EVs penetration, their current biofuel obligation is to increase it blending ratio from 6.4% to 8.7% in 2017, with optimistic assumptions from 12% in 2020 to 24% volume by 2035. However, to meet the country's 2020 target an unrealistic significant EVs growth rate would be necessary.

Kromer et al, (2010) found vehicle technologies improvement (e.g., improved gasoline and diesel vehicles, HEVs and PHEVs penetration, reduction in car weight) the strategy that most reduced GHG emissions (and petroleum use) in U.S. by 2050. Still, the authors identified the need for a large-scale adoption of low-GHG biofuel to contribute to the long-term reduction targets. In this study, if we combine our fuel-efficiency improvement with EVs diffusion strategy, only in scenario 03 would the result overcome the biofuel increase strategy (with 42 million tons of $CO_{2^{eq}}$ mitigation potential). While EVs diffusion assumptions in scenario 03 include a penetration rate similar to France's aim (IEA, 2016), that is unrealistic for Brazil, the assumption in biofuel increase strategy implies a 15% increase of bioethanol use from 2020 onwards (increasing from 45% to nearly 52% use).

Figure 10 - Avoided GHG emissions in 2040 in each strategy and scenario.



Source: Elaborated by the authors.

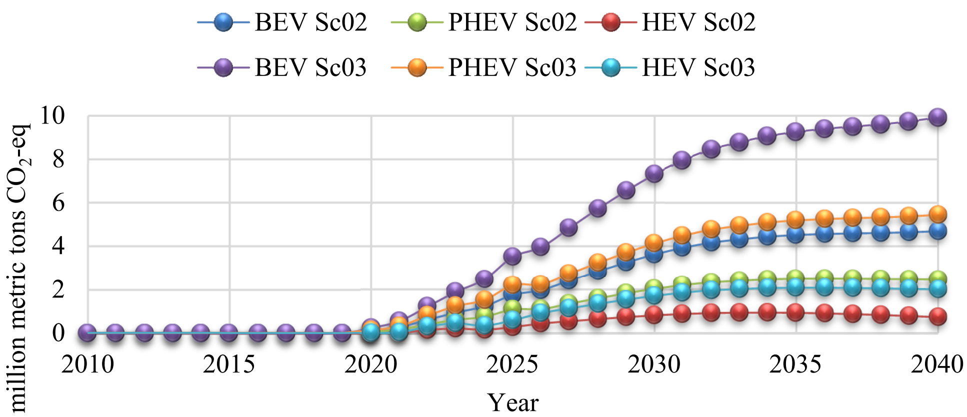
Table 7 - Summary of GHG emission mitigation potential percentage from BAU in 2040.

Mitigation strategy	**Scenario 01 (%)**	**Scenario 02 (%)**	**Scenario 03 (%)**
Fuel-efficiency improvement	17	26	37
Biofuel increase	21	33	47
EVs diffusion (BEVs)	1	5	12
Total	39	64	96

Source: Elaborated by the author.

Finally, Figure 11shows the GHG emissions mitigation potential from the EVs diffusion strategy for each scenario by different EVs (except from scenario 01 due to its very low result). Until this point, results from EVs diffusion strategies were entirely BEVs focused. Here, we estimate what the outcome would be if the whole EVs diffusion were made by PHEVs or HEVs. As expected, the 100% uptake from BEVs in our most aggressive scenario (03) would imply the highest-level mitigation potential (10 million tons of $CO_{2^{eq}}$, Figure 9). After this, the PHEVs diffusion (scenario 03) has the most reduction potential, before the BEVs diffusion strategy (scenario 02). Results suggest that EVs diffusion in Brazil is more of a longer-term mitigation potential.

Figure 11 - GHG emission mitigation potential of the strategy EVs diffusion in scenario 02 and 03 if there would only be BEVs, PHEVs or HEVs diffusion.



Source: Elaborated by the authors.

If WTW analysis is considered, only with a clean electricity production, in which Brazil benefits from it (COSTA *et al.*, 2017), can EVs reach their full potential in mitigating global warming (NORDELÖF *et al.*, 2014). Regarding biofuel production, depending on which life cycle impact assessment (LCIA) is considered, different results from life cycle environmental impacts can be achieved when compared with gasoline production in Brazil, mainly due to particulate emissions and land use impacts (CAVALETT *et al.*, 2013). These particularities are worth evaluating when ranking vehicles to better inform society (BATISTA; FREIRE; SILVA, 2015).

Results in this study showed the effect policies have in heading towards sustainable mobility. Due to different regional characteristics, there is no unique path for an optimal strategy. Appropriate pathways should include a set of strategies to impose a strong policy combination able to constrain national GHG emissions (ZHENG *et al.*, 2015), reduce road transportation emissions and, ultimately, mitigate global climate change. Each country's fleet characteristics will influence which is the best GHG mitigation potential strategy for a short, mid and long-term perspective.

While flex-fuel vehicles have been in the market for some years, their carbon mitigation potential (by the flexibility of using biofuel and further mechanical developments) should not be seen as competitors to transport electrification. Although mitigation pathways presented in this study seem to achieve targets fairly well, they would unlikely be achieved unless strong policies are in place (e.g., mandatory fuel economy, incentives on biofuel increase), considering that EVs are still in initial diffusion stages. Also, additional efforts must be thought through since studies have indicated a higher real-world car CO_2 emission (considering wind, rain, road grade) than when monitoring data in a laboratory-measured setting (FONTARAS; ZACHAROF; CIUFFO, 2017).

Knowing that vehicle/fuel choices are driven by economic and policy considerations, further strength to different types of policies should be conducted since free market competition does not offer significant emission mitigation potential (IANKOV; TAYLOR; SCRAFTON, 2017). There is a good indication that for the next decades, the appropriate pathway should include different strategies, each adding its strength to ultimately and significantly reduce road transportation emissions. Those potentially GHG emissions avoided from Figure 8 only present the amount in 2040. The mitigation potential is higher when we recognize the fact that if policy changes occur, they would accumulate over time. Thus, efforts to reduce transportation carbon emissions require policies to achieve benefits in the short, medium and long-term.

3.5 CONCLUSION

Through a bottom-up approach, a fleet-based tank-to-wheel analysis of greenhouse gas emissions for Brazil's light passenger vehicle fleet was conducted, and different mitigation strategies were considered. As the nationally determined contribution does not define transportation subsector targets specifically, emission benchmark targets were estimated and proposed. The highlight is that only by stimulating bioethanol proportion use in 5 to 15% (from the current approximately 45% since 2003, BEN, 2017; MCTI, 2015), a significant result is obtained (from 21 to 47% reduction potential by 2040). Emphasis on flex-fuel vehicles is even more pronounced when comparing results with a hypothetical scenario, i.e., if vehicles were only powered by gasoline solely. Also, if the country follows mandatory fuel-efficiency paths, such as those imposed by the EU commission, a relevant result in mitigating GHG emissions is also achieved (from 17 to 37% reduction potential by 2040). On the other hand, even if the country's average EVs sales reaches the same 20% target per year as France's intention from 2020 onwards, due to slow penetration volume compared with total fleet, the estimated reduction potential in Brazil is 12% by 2040.

Results from scenarios assessed seem to comfortably meet proposed benchmark targets. However, the benchmark considering emission reduction efforts (BC0), is only met if some policies are introduced, and actions are taken, so transportation can become more sustainable subsector. Just following a BAU scenario will not deliver a long-term goal, undermining future national and global targets. A greater extent of carbon emission reduction could relieve other sectors efforts and help achieving the NDC. At the end, targets and policies are only ways to further induce mitigation strategies. Local incentives and policies should be strengthened to collaborate with international efforts aiming at mitigating climate change globally. In other words, parallel strategies/incentives and policies are strongly recommended, especially in light of the increasing tendency of vehicle sharing.

While electric vehicles diffusion strategy results have not been the most highlighted in this study, this should not undermine further incentives for EVs as it should not undermine other strategies and techniques/technologies. Despite their emission mitigation potential, in Brazil these vehicles are still a minor fraction. While this market is under development, further incentives and policies are recommended for adoption for fleet replacement. An optimal use of energy resources should be in alignment with a set of strategies that impose together a strong policy combination (not relying on only one strategy). Thus, an appropriate pathway should include different mitigation strategies aiming to reduce adverse environmental impacts. From this study, a recommended pathway includes enhancing fuel-efficiency through mandatory carbon emission reduction targets for new cars, efforts in increasing biofuel use while at the same time promoting EVs diffusion.

A limitation of this study surrounds the estimates considered for both the VKT and the average emission rate of the fleet (gram of GHG/km). In both parameters we used the estimate of a 9-year-old car (or 9-year lag for the latter average parameter). We believe the estimate to be reasonable, as the average fleet's age has been in turn of 9 years old for the last 15 years. However, we do believe that this could be better managed if dynamically modeled, such as using system dynamic modeling to further facilitate the operation of these or other parameters, as well as for testing different policies.

Further studies can be carried out considering a longer vehicle life cycle. This study took into consideration the emissions during vehicle usage period (tank-to-wheel). A well-to-wheel analysis can be performed to this end, which would include the costs and impacts of generating gasoline, bioethanol and electricity power for EVs. At this stage, we completed a narrow investigation to make compatible mitigation strategies comparisons with GHG emissions reduction presented in the literature from other countries. Further research should include WTW analysis, as well as consideration of other environmental factors.

3.6 APPENDIX A

Table A 1. Light vehicle fleet and electric vehicles fleet estimate projection for Brazil in 2010-2040 period (based on Base Case and Aggressive scenario of Benvenutti et al. (2017) for BAU scenario and scenario 01, respectively.)

Year	Light vehicle fleet (Conventional + AFV)	AFV (BAU scenario)	AFV (scenario 01)
2010	24,002,300	56	56
2011	25,358,000	324	324
2012	26,604,400	731	731
2013	27,677,100	1,226	1,226
2014	28,425,900	1,838	1,838
2015	28,989,500	2,595	2,595
2016	29,475,800	3,523	3,523
2017	29,956,600	4,655	5,124
2018	30,455,900	6,031	7,221
2019	31,043,800	7,697	10,371
2020	31,812,900	9,710	14,600
2021	32,875,800	12,139	19,247
2022	34,349,000	15,067	25,157
2023	36,292,400	18,595	32,686
2024	38,760,800	22,845	42,270
2025	41,722,900	27,964	54,461
2026	45,066,000	34,123	69,953
2027	48,638,500	41,528	89,618
2028	52,330,000	50,417	114,549
2029	55,967,700	61,075	138,232
2030	59,453,200	73,831	166,453
2031	62,569,400	89,076	200,236
2032	65,280,100	110,799	244,434
2033	67,563,100	136,546	297,158
2034	69,502,400	166,971	359,958
2035	71,136,600	202,953	434,773
2036	72,609,400	245,530	523,897
2037	74,005,600	295,922	630,037
2038	75,453,400	355,559	756,384
2039	77,136,300	426,121	906,682
2040	79,124,500	509,568	1,085,300

Source: Elaborated by the authors, based on Base Case and Aggressive scenario of Benvenutti et al. (2017) for BAU scenario and scenario 01, respectively.

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CHAPTER IV

4 THE IMPACT OF CO_2 MITIGATION POLICIES ON LIGHT VEHICLE FLEET IN BRAZIL

This chapter presents the second paper of this thesis, being the second and last result of step 1. It has been published in the Energy Policy. The original published paper[4] is available at https://doi.org/10.1016/j.enpol.2018.11.014.

Abstract

Transportation is the largest contributor to greenhouse gas emissions in the energy sector, which, in turn, is the largest contributor in Brazil. The way different policies mitigate CO_2 emissions in the short, medium, and long-term is an ongoing research topic. Four potential policies for light vehicle fleet are investigated: (i) energy efficiency; (ii) modal change and regulatory management; (iii) renovation of the fleet; and (iv) biofuel increase. A system dynamics model is developed to estimate the delay in fleet turnover and its CO_2 emissions change during the 1980-2050 period. The results indicate a rebound effect in the long-term when an objective of renovating the fleet is realized. Only if more stringent terms are considered will this policy contribute to further mitigate CO_2 emissions in the long run. Results also demonstrate a longer-term perspective to energy efficiency and modal change policies, indicating the need for mandatory CO_2 emission targets, unseen in the country at the present time. A biofuel increase strategy provides CO_2 reduction in the short-term, and it is advisable this strategy be adopted alongside the other ones.

Keywords: Light vehicle fleet, CO_2 emissions, mitigation policies, system dynamics, long-term analysis, rebound effect.

4.1 INTRODUCTION

Concerns for our global environment have increased over the last decade, which has resulted in important international actions such as the Paris Agreement. The agreement's central aim is to strengthen the global response to the threat of climate change and the ability of countries to deal with its impacts (UNFCCC, 2017). Hence, several countries have been induced to create

[4] BENVENUTTI, L. M.; URIONA-MALDONADO, M.; CAMPOS, L. M. S. The impact of CO_2 mitigation policies on light vehicle fleet in Brazil. Energy Policy, 126, p. 370-379, 2019.

robust trajectory plans to reduce their emissions so they can achieve their country's nationally determined contributions (NDCs).

In 2016, Brazil assured its NDC commitment in the Paris Agreement convention. Within the energy sector greenhouse emissions (GHG) in Brazil, the transportation subsector has the largest share[5], with road transportation responsible for 91% of total carbon dioxide (CO_2) emissions (MCTIC, 2016). More specifically, the main GHG contributor and emitter is the nation's fleet of passenger vehicles (MMA, 2017).

Considering that CO_2 emission from fuel combustion represents over 95% of the $CO_{2\text{-eq}}$. (global warming potential metric) emission weight (MCTIC, 2016), how well can different types of policies mitigate CO_2 emissions? Furthermore, are there any setbacks that may arise in the long run? For this purpose, a system dynamics model is developed to assess the effects from policies aimed at mitigating CO_2 emissions.

System dynamics was first applied to industry-related issues by Jay Forrester and colleagues in the 1950s (FORRESTER, 1961). Later, it expanded to other areas, such as environmental policy, public policy, and energy policy (STERMAN, 2000). Within the applications in the transportation sector, Shepherd (2014) found 'strategic policy' (at urban, regional, and national levels) the most applied area by system dynamics modelers. Thus, several studies have analysed strategies and policies aiming at reducing traffic congestion, assessing different fuel types, and diffusing of alternative fuel vehicles. Other topics explored include an analysis of their impact on GHG mitigation and/or on energy consumption/demand.

With respect to policies aiming at reducing traffic congestion, several strategies were tested, including increasing vehicle occupancy (BISEN *et al.*, 2014), car sharing mechanisms (MENON; MAHANTY, 2015), incentivizing telecommuting jobs (BISEN *et al.*, 2014; MENEZES; MAIA; DE CARVALHO, 2017), driving restrictions (WEN; BAI, 2017), and increasing the use of public transportation (LIU *et al.*, 2015b; MENEZES; MAIA; DE CARVALHO, 2017; WEN; BAI, 2017). Moreover, banning old cars and internal combustion engine vehicles (MENON; MAHANTY, 2015; SHAFIEI *et al.*, 2017) has also been analysed. Economic implications for consumers have been evaluated, such as the rise of parking and fuelling payments (LIU *et al.*, 2015a), higher taxes for

[5] This has not always been the case. Before 2010, the main contributor sector was 'changes in the use of land and forest' MCTIC, 2016. Estimativas anuais de emissões de gases de efeito estufa no Brasil (Annual estimates of greenhouse gas emissions in Brazil). Ministério da Ciência, Tecnologia, Inovações e Comunicações.

higher CO_2 emitter vehicles (GUZMAN; DE LA HOZ; MONZON, 2016) or for fossil fuel use (BARISA *et al.*, 2015), and instituting a CO_2 emission tax (MENON; MAHANTY, 2015).

Other studies have focused on increasing the use of biofuel in the fleet, such as a proportional blend increase with the main fuel (BARISA *et al.*, 2015) or a pure biofuel use increase (MENEZES; MAIA; DE CARVALHO, 2017; SANCHES-PEREIRA; GÓMEZ, 2015). There is also research on biofuel implications on demand, market price, GHG emissions, and associated costs (SHAFIEI *et al.*, 2016). Besides biofuel, other fuels such as hydrogen (SHAFIEI *et al.*, 2017; VEZIROĞLU; MACÁRIO, 2014), natural gas (GUZMAN; ORJUELA, 2017), electricity for electric vehicles (ONAT; KUCUKVAR; TATARI, 2016; ONAT *et al.*, 2016; SHAFIEI *et al.*, 2017), or all previous fuels (SHAFIEI *et al.*, 2014) and electricity demand (MATTHEW *et al.*, 2017) have been subjects of investigation.

System dynamics enables the assessment of different aspects involving strategies and policies, and it is well suited to explore over a spectrum of several years. In this study, we base our circulating fleet model on the Bass model (BM) (BASS, 1969), which describes the S-shaped diffusion process of a product based on a pre-determined potential market. In our case, it is proportional to the population growth in the country.

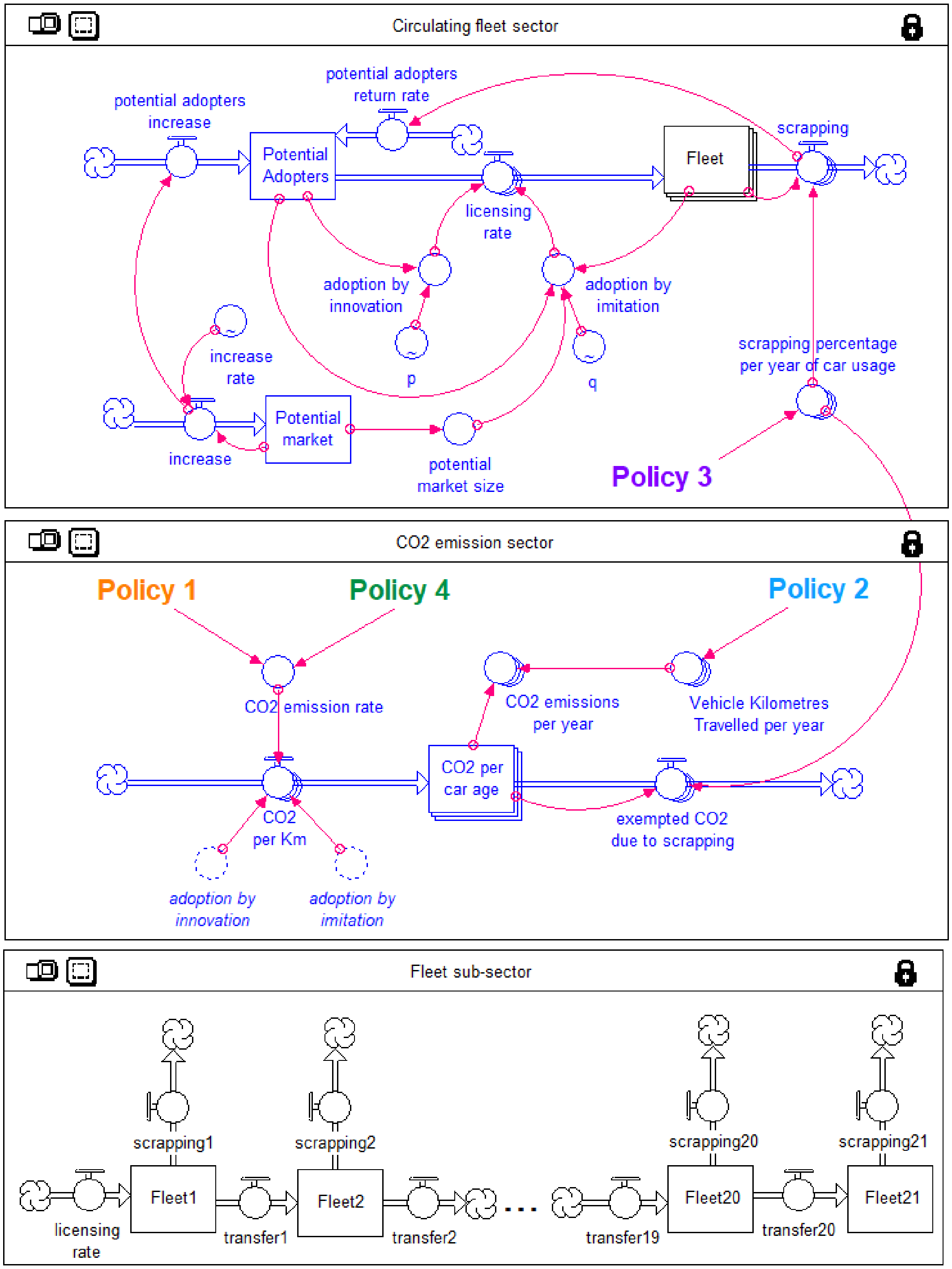
The paper is presented as follows: in section 4.2 we describe how the model was developed, bringing information on circulating fleet and CO_2 emission features along with its validation. In section 4.3 we describe the policies and scenarios assessed. In section 4.4 we present the results and discussion. Finally, the paper ends with the conclusions of this research in section 4.5.

4.2 MODEL DEVELOPMENT

In this study, we use the BM (BASS, 1969) for modelling the diffusion of light passenger vehicles in Brazil from 1980 to 2050. We used historical data on the circulating fleet for the period 1980-2014 and simulated its growth until 2050.

Figure 12 shows the system dynamics model for the Brazilian circulating fleet and CO_2 emissions rate sectors. The variables will be described in section 4.3. We used the Stella Software 9.0 to build the model and Microsoft Excel interface to generate the graphs for the results. Next, each sector of the model is depicted (subsection 4.2.1 and 4.2.2), as well as their parameters and assumptions, followed by the model validation (subsector 4.2.3).

Figure 12 - System dynamics model for the circulating light vehicles fleet and CO_2 emission sectors.



Source: Elaborated by the authors.

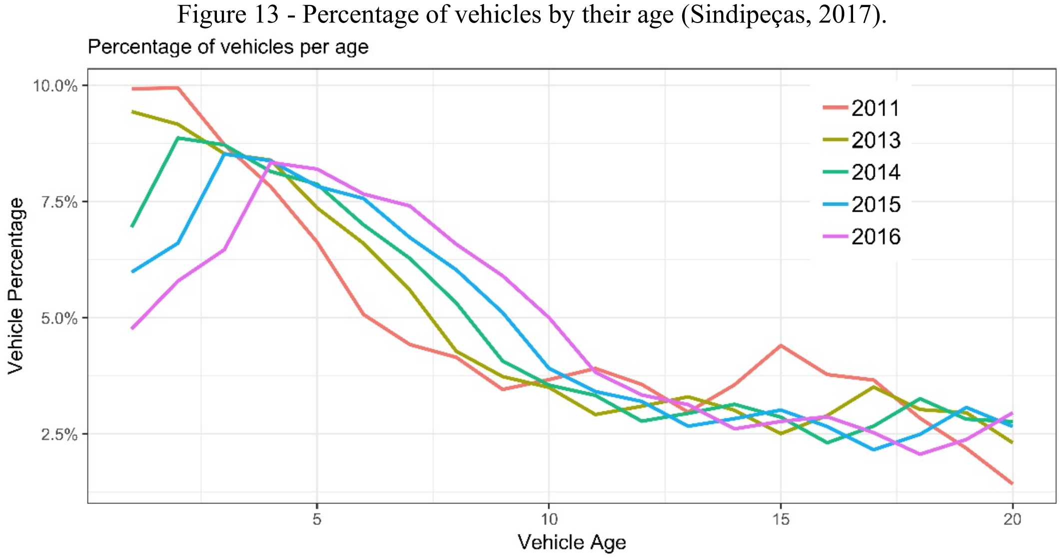
4.2.1 Circulating fleet sector

This sector models the growth of car adopters based on BM. Some extensions are the stock of '*potential market'* and the flow named '*potential adopters return rate'*. Historical fitting on both the '*fleet*' stock and '*licensing rate*' is conducted for validation.

An array function (a vector built-in function in Stella software) is used to estimate the number of vehicles by their age, enabling the use of the scrapping rate curve for light and commercial vehicles (MMA, 2011). This rate is a function of vehicle age and it considers a range of 40 years (100% discard rate at year 40). In our model, the fleet array structure assumes 20 stocks for the first 20 years of age and one last stock (21st) to allocate the older cars (following Little's Law for a period of 20 years).

To set the initial car units' value of each stock (for year 1980), we used the average from the last few years, elaborated by the National Union of the Automotive Component Industry (SINDIPEÇAS). Over the past 15 years, the fleet's age has varied from 8 years and 4 months to 9 years and 5 months (SINDIPEÇAS, 2017). Figure 13 presents the average vehicles' age profile of the fleet in recent years.

Figure 13 - Percentage of vehicles by their age (Sindipeças, 2017).



Source: Elaborated by the authors.

In this sector, there are two main feedback loops (Figure 12), one reinforcing (1) and the other a balancing loop (2) as follows (for more information, see Sterman, 2000):

(1) Fleet → (+) adoption by imitation → (+) licensing rate → (+) Fleet
(2) Potential adopters → (+) adoption by innovation → (+) licensing rate → (-) Potential adopters

The potential market accounts for the population at 20 to 80 years old (IBGE, 2017). The potential adopters vary according to the population increase, licensing rate, and potential adopters' return rate.

The total circulating fleet is the sum of all light vehicles being licensed per year (and the ones still circulating in the fleet), discarding the ones that leave the fleet from each corresponding vehicle stock year. Equations 1, 2, and 3 present the calculations involved in the '*Fleet*' array stock for new cars, for circulating cars, and for those with 21 years of age or more, respectively.

$$Fleet_1(t_j) = Fleet_1(t_{j-1}) + \int_{t_{j-1}}^{t_j} licensing\ rate(t) - [transfer_1(t) + scrap._1\,(t)]\ dt \qquad (1)$$

$$Fleet_k(t_j) = Fleet_k(t_{j-1}) + \int_{t_{j-1}}^{t_j} transfer_{k-1}(t) - [transfer_k(t) + scrap._k\,(t)]\ dt, \qquad 2 \le k \le 20 \qquad (2)$$

$$Fleet_{21}(t_j) = Fleet_{21}(t_{j-1}) + \int_{t_{j-1}}^{t_j} transfer_{20}(t) - scrap._{21}\,(t)\ dt \qquad (3)$$

where "j" represents the time in 1980-2050 period and "k" represents the age of the vehicle in the respective stock. The licensing rate is a sum of the adoption by innovation and adoption by imitation. Table 8 presents the key model parameters and assumptions.

Table 8 - Model parameters and descriptions – Circulating fleet sector.

Model parameters	**Descriptions**	**Values based on**
Increase rate	Increase rate of the potential market and consequently the potential adopters. It follows the historic and projected population increase rate.	(IBGE, 2017)
Discard per year	The proportion of adopters that leaves the fleet due to car scrapping (total loss by accident or for being too old). It computes a discard rate that depends on the car age.	(MMA, 2011)
"p" and "q"	The innovator factor 'p' and imitator factor 'q' from diffusion Bass model (Bass, 1969).	(Benvenutti *et al.*, 2017)

Source: Elaborated by the authors, based on referenced shown in the 3rd column.

4.2.2 CO_2 emissions sector

This sector computes the CO_2 emissions based on the number of cars in each age cohort. Since CO_2 emission varies from one vehicle to another and from year to year, some assumptions were made. The same array structure from the previous sector is used (and similar equations from the '*fleet*' stock; see Appendix A for equations). Therefore, the number of cars in each age cohort is multiplied by the CO_2 emission average rate of new cars from that year, in grams of CO_2 per kilometre per car (g CO_2/km), resulting in a stock of total gram of CO_2/km discriminated by age. Then, the total CO_2 emission of the circulating fleet is estimated by multiplying it by the vehicle kilometres travelled (VKT).

Used in national inventories (MMA, 2011), the VKT data was raised by ISSRC (International Sustainable System Research Centre) in partnership with CETESB (Environmental Company from the State of São Paulo), for the city of São Paulo. The VKT is a function of the car age, linearly decreasing with vehicle age. Table 9 presents the description of the parameters used in this sector.

Table 9 - Model parameters and descriptions – CO_2 emissions sector.

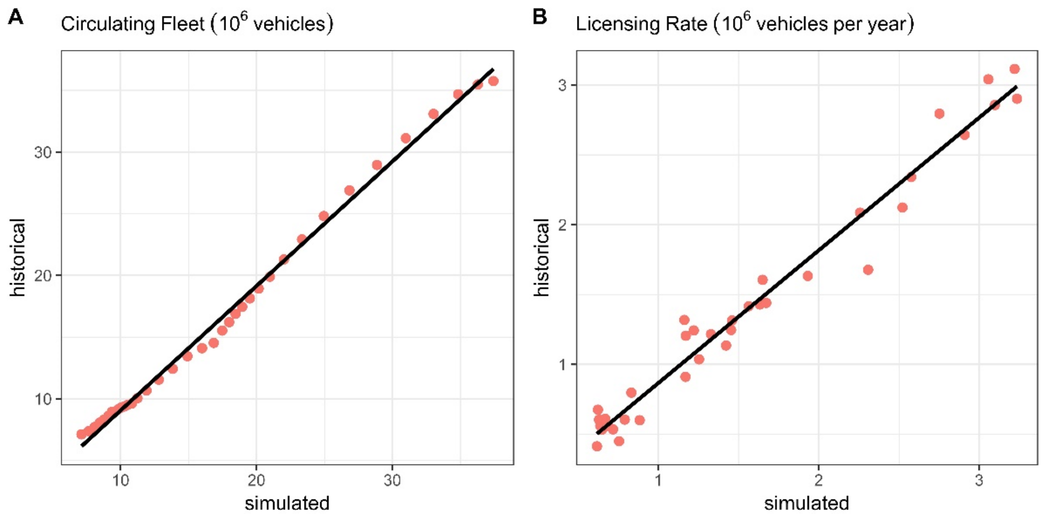
Model parameters	**Descriptions**
CO_2 emission rate	This is the CO_2 emission rate average of new cars per year. This parameter was estimated based on the CO_2 emission rate average presented in (CETESB, 2014) multiplied by the historical proportion of flex-fuel, gasoline, and ethanol-fueled cars (ANFAVEA, 2017) of each year. For future years, we assumed the same historical decrease or increase proportion rate of these cars (evidencing a projection of 100% flex-fuelled cars circulating in the fleet by 2021).
VKT	It is the VKT average according to its age. Based on a data raised by the ISSRC in partnership with CETESB for the correlation between car use and its age (MMA, 2011).

Source: Elaborated by the authors.

4.2.3 Model validation

Two variables are used to validate the model: one is the licensing of new cars per year and the other is the circulating fleet per year. The licensing number is a more reliable value as it has been registered since its diffusion (ANFAVEA, 2017). However, for the circulating fleet MMA (2011), estimates are required, since there may be some cars that are on the roads but not licensed. Also, the number of scrapped cars (through accident, robbery, or its old age) per year is not an exact known value. Therefore, some estimates are made and a scrapping curve is considered to estimate the circulation fleet of a country. Figure 14 presents the correlation of both variables with their respective historic values.

Figure 14 - Index correlation of the (a) circulating fleet and (b) licensing rate between the system dynamics model simulation results and historical values.



Source: Elaborated by the authors.

4.3 POLICIES AND SCENARIOS

Four different strategies are examined to mitigate CO_2, assuming policies implications. Each strategy differs in its approach and, ultimately, on the implications inside the model itself. The first one regards 'energy efficiency'. This type of policy is well discussed around the world; it has been a topic of great importance as its enhancements have a direct effect on the reduction of GHG emissions by the decreased use of fuel (IEA, 2010).

The second policy pertains to 'modal changes' and 'regulatory management'. The modal change consists in shifting the transportation pattern from mainly individual to a more collective one. This change brings the necessity of higher investments in infrastructure and different types of public transportation (buses, trams, subways, among others) (MCT, 2016). Furthermore, the promotion of telecommuting (i.e., working from home) has the potential of mitigating traffic congestion and CO_2 emissions (BISEN *et al.*, 2014; MENEZES; MAIA; DE CARVALHO, 2017). Since both policies could be summarized in reducing car use, they were combined into one.

The third policy tested regards enforcing the 'renovation of the fleet'. Although it is known that older vehicles emit more CO_2, individuals do not change to newer ones solely on environmental concerns. However, it has an impact on overall fleet's emission, which is worth investigating.

Our last policy relates to the increased use of biofuel, more particularly, bioethanol. Since its launch in 2003, the share of vehicles that have used bioethanol as fuel is presented in Table 10. Table 11 presents a brief summary description and implications for the four policies tested in our study.

Table 10 -The fraction of national flex-fuel vehicles that used bioethanol as fuel. Based on BEN (2015), BEN (2017), and MMA (2011).

Year	**Fraction**
2003	33%
2004	60%
2005	55%
2006	30%
2007	55%
2008	57%
2009	53%
2010	53%
2011[1]	43%
2012[1]	43%
2013	33%
2014	34%
2015	40%

[1]Estimated value, using the average between 2010 and 2013.

Source: Elaborated by the authors.

Table 11 -Policies aiming to mitigate CO_2 emissions tested in our model and its description and implications on the system dynamics model.

Policy	**Description**	**Implications on the system dynamics model**	**Scenario***
(1) Energy efficiency	Reduction of the CO_2 emissions rate average of new cars sold per year due to enhancement technologies	CO_2 emissions rate average, which in turn affects 'CO_2 per km' in equation A.1, Appendix A	PEeffic01 PEeffic02 PEeffic03
(2) Modal changes and Regulatory management	Shifting from individual to public transportation and teleworking (telecommuting)	VKT per year, affecting the 'CO_2 emission per year' when multiplied by 'CO_2 per car age' stock, from equations A.1, A.2, A.3, Appendix A	PTelewk01 PTelewk02 PTelewk03

(3) Renovation of the fleet	Policy prohibiting the circulation of older cars	Fleet circulation, changing the 'scrapping % per year of car usage' and consequently the 'scrap' variable from equations 1, 2, and 3	PFleet01 PFleet02 PFleet03
(4) Biofuel increase	Increase rate of anhydrous bioethanol into gasoline C and/or increase the use of hydro bioethanol in flex-fuel vehicles	Similar to policy 1, CO_2 emissions rate average, affecting 'CO_2 per km' in equation A.1, Appendix A	PBio01 PBio02 PBio03
*For scenarios description see Table 5			

Source: Elaborated by the authors.

4.3.1 Scenarios for individual policies

Table 12 describes the implications involved in each scenario. Each policy implies altering specific parameter values in the model: (i) CO_2 emissions rate; (ii) VKT of the fleet; (iii) fleet circulation, and (iv) bioethanol use ratio (see Figure 12). Note that both policy 1 and 4 change the 'CO_2 emission rate' parameter but in different ways, while policy 1 is focused on incremental and advanced technologies, and policy 4 is focused on a specific increase of biofuel use. Therefore, we can assess each CO_2 mitigation potential policy in a different manner and make reasonable comparisons between their implications.

Table 12 -Scenario description for each individual policy.

Policy	Scenarios' description
	BAU: The business-as-usual assumes the same CO_2 emissions rate decline from historic years. Also, from 2017 onwards, it assumes that 45% of the car owners fuel their flex-fuelled engines with bioethanol; therefore, the other 55% use petrol (as the average in 2003-2016 has been in turn of 45%, BEN, 2017; MCTI, 2015).
1	**PEeffic01:** From 2020 onwards, the country's fleet emission average rate declines to 140 g/km and reduces at a 2.2% rate per year until 2030 (after this moment reduction rate is 2% until 2050 – still a rate higher than the average decline rate in historical years of approximately 1.6% per year). This was Europe's average target for new cars sales achieved in 2010 and their average decline rate from 2000-2010.
	PEeffic02: From 2020 onwards, the country's fleet emission average rate declines to 140 g/km (as in the previous scenario), but it reduces at a 3.14% rate per year until 2030 to achieve a 118g CO_2/km. This

	was Europe's achieved efficiency for the average emission rate of new car sales in 2016. After this moment, reduction rate is 2.2% until 2030 and 2% until 2050.
	PEeffic03: From 2020 onwards, the country's fleet emission average rate declines to 140 g/km (as in the previous scenarios), but it reduces at a 3.8% rate per year until 2030 to achieve a 95g CO_2/km (after this, a reduction rate of 2% until 2050). This was Europe's in force efficiency policy for the average emission rate of new car sales for 2021, and here we assume it remains until 2030.
2	**PUrTranspTele01:** We assume a linear decline rate for the VKT (for all the circulating fleet) starting with 1% in 2020 and increasing until 10% in 2050.[1]
	PUrTranspTele02: The same implication as in the previous scenario except ending with 20% in 2050.[1]
	PUrTranspTele03: The same implication as in the previous scenario except ending with 30% in 2050.[1]
3	**PReFleet01:** No circulation of cars more than 20 years old from 2035 onwards. A linear reduction from Little's law period consideration of 20 years for cars with 21-40 years of age is considered for 2025-2030, as people would become aware of this policy direction and organize themselves to renew their vehicles.
	PReFleet02: No circulation of cars more than 20 years old from 2030 onwards (the same progressive reduction as PFleet01 is considered here).
	PReFleet03: No circulation of cars more than 15 years old from 2030 onwards (the same progressive reduction as PFleet01 is considered here).
4	**PBio01:** The historical use fraction and BAU of 45/55% of bioethanol/petrol used in flex-fuel vehicles from 2017-2020. Then, bioethanol/petrol rate of 50/50% from 2020 onwards.
	PBio02: The same implication as in the previous scenario except bioethanol/petrol rate of 60/40% from 2020 onwards.
	PBio03: The same implication as in the previous scenario except bioethanol/petrol rate of 70/30% from 2020 onwards.

[1] In scenario 2, we assume vehicle owners will use their cars less frequently due to increased public transportation and telecommuting jobs.

Source: Elaborated by the authors.

To assess each policy and their respective scenarios, we analyse:

- Total CO_2 emission of each scenario;
- Total circulating fleet for further investigation (if necessary);
- Total VKT of the fleet (if necessary);
- Total CO_2 mitigation potential compared with BAU for each scenario;
- Cumulative CO_2 emission mitigation potential.

4.3.2 Scenarios for integrated policies

Some combinations were compared to further investigate the results from the previous subsection. The reasons for these comparisons will be depicted in subsection 4.4.2. Table 13 classifies them by name. Each comparison is made for each level of intensity of the scenario proposed (i.e., level 01, 02 and 03).

Table 13 - Comparisons of different integrated policies.

Case	Contrast scenarios		
	Group 1		**Group 2**
A	P3 + P1		P1
B	P3 + P2		P2
C	P3 + P4		P4
D	P3 + P1 + P2	*versus*	P1 + P2
E	P3 + P1 + P4		P1 + P4
F	P3 + P2 + P4		P2 + P4
G	P3 + P1 + P2 + P4		P1 + P2 + P4
H	P1 + P2 + P3 + P4		P2 + P3 + P4

Source: Elaborated by the authors.

From these scenarios, a cumulative CO_2 emission difference between group 1 and 2 was assessed as well as their CO_2 emission rate average. In the next section, we present the main results obtained.

4.4 RESULTS AND DISCUSSIONS

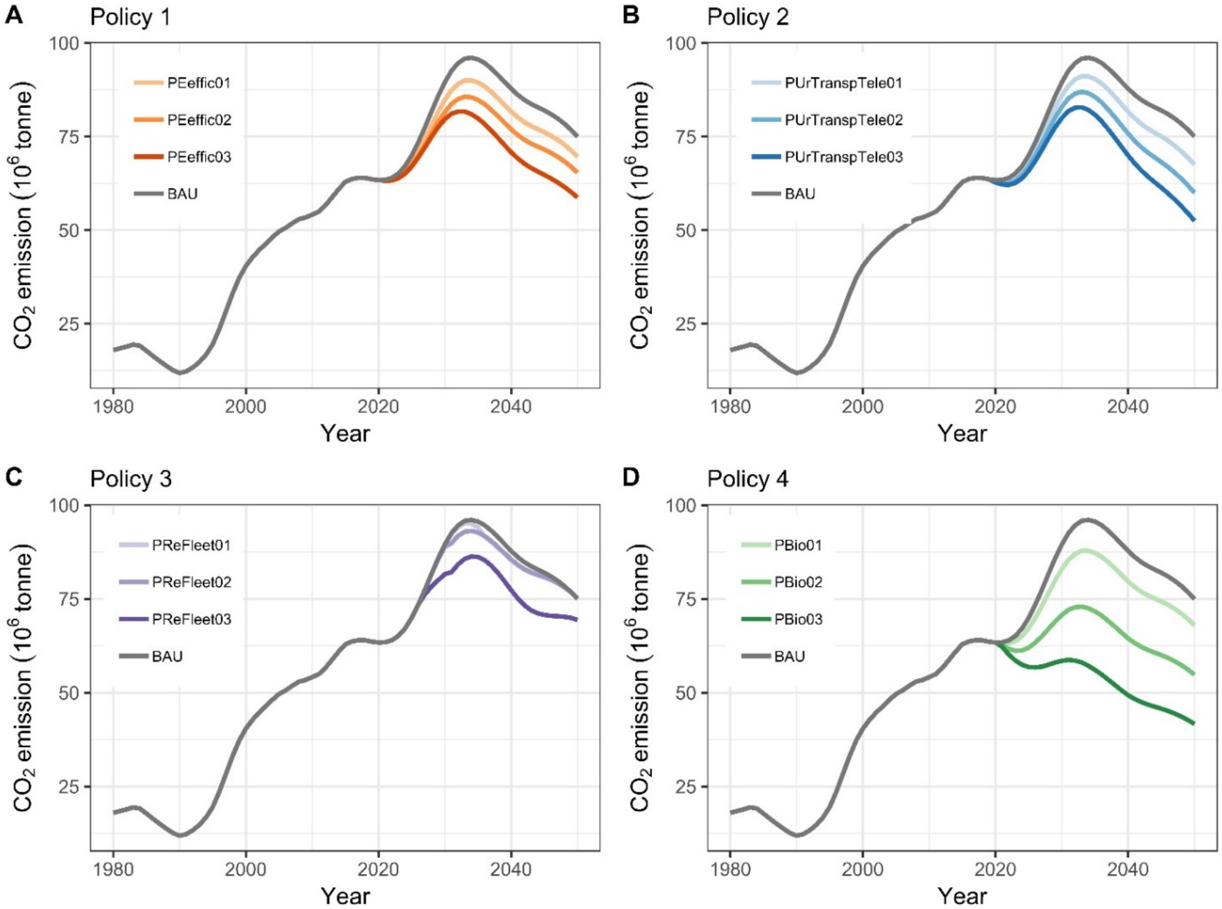
This section is divided into two subsections: 4.4.1 brings individual results from the policies and scenarios assumed in Table 12, and subsection 4.4.2 presents comparisons between scenarios assumed in the integration policies in Table 13.

4.4.1 Individual policies results

Figure 15 presents the results of total CO_2 emission for each policy compared with BAU. One important aspect to highlight is the lower CO_2 emission in the 1990s. This was due to the main sales of cars powered by bioethanol solely, enabled by the "National Alcohol Program" (named "*Pró-alcool*" in Portuguese) in the 1970s, which resulted in the large-scale production of bioethanol (EPE, 2008). Therefore, this trend is the direct result of this national program. However, it was compromised by the more economically viable sugar export and the oil barrel price decline at that time, enabling petrol fuel use to rise again and, therefore, CO_2 emissions to rise as well (besides the overall increase of fleet size). Although vehicles powered by bioethanol do emit CO_2, they are considered carbon-neutral and do not account in the global warming potential according to the guidelines compiled by agencies such as the Intergovernmental Panel on Climate Change (IPCC).

Note that the set of scenarios from policy 1 (Figure 15a), policy 2 (Figure 15b), and policy 4 (Figure 15d) obtained similar CO_2 reduction patterns but with different intensities. However, the set of scenarios from policy 3 (Figure 15c) differed from the others. Only the PReFleet03 scenario provided a modest CO_2 mitigation in the long run. In fact, by the end of 2050, the other scenarios (PReFleet01 and PReFleet02) turn out to be more CO_2 emitters than BAU, with approximately 75 million tonnes for both scenarios against 74 million tonnes in BAU scenario. These results indicate a potential rebound effect.

Figure 15 - Total historical (1980 – 2014) and projection (2014-2050) CO_2 emission profile for each scenario of policies (a) 1; (b) 2; (c) 3; and (d) 4 tested in the system dynamics model.

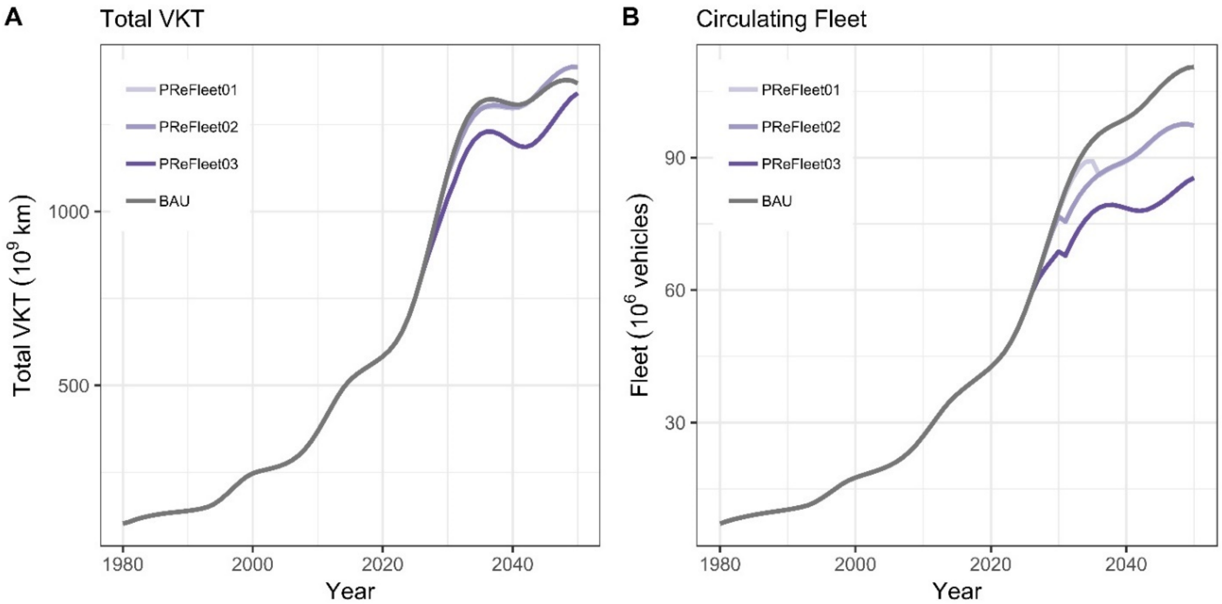


Source: Elaborated by the authors.

To further investigate these results, the numbers of total circulating and VKT of the fleet for policy 4 are assessed, as shown in Figure 16. The number of cars circulating in the fleet diminishes from 2025 onwards (Figure 16b), since older cars would be removed from the fleet. The policy's main feature is to promote the renewal (substitution) of older cars to more efficient ones. However, this change takes time to occur since the owners of older cars return to the '*potential vehicle adopters'* stock.

On the other hand, it generates a dynamic rebound effect on CO_2 emission. Although policy 4 is, at first, environmentally beneficial, it induces the rise in total VKT (Figure 16a). An extended use of newer cars is observed whether for commuting or leisure.

Figure 16 - Total VKT of the fleet (a) and total circulating fleet (b) of the set of scenarios from policy 3 compared with the BAU.

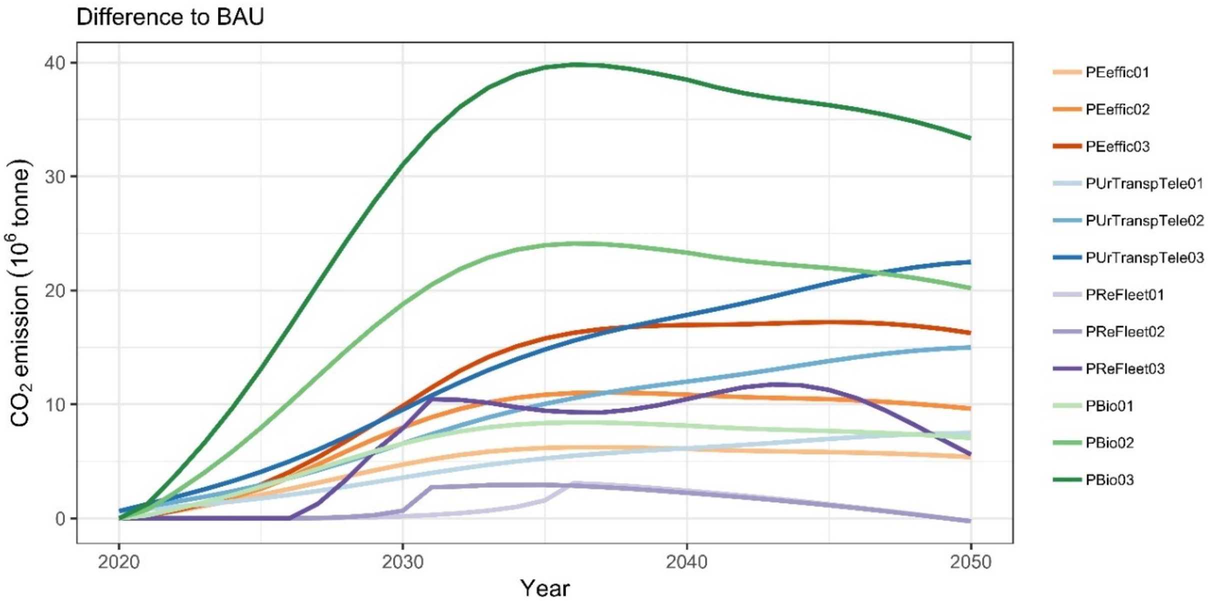


Source: Elaborated by the authors.

Some rebound effects have been researched in the literature. Freeman *et al.* (2016) utilized Jevons' paradox theory in their system dynamics model to assess this effect in UK private road transportation. The theory proposes that, paradoxically, technological efficiency can lead to an associated growth in resource use. Their work revealed the necessity of policies that further invest in energy efficiency, costlier travel, and a reduction in travel consumption.

In our case, this effect is reduced when a more stringent scenario is adopted. The PReFleet03 provides a better result than BAU. This is the case when vehicles over 14 years of age would be prohibited to circulate. Thus, a quantity of owners with cars that still presents a reasonable VKT per year would return to '*potential adopters*'. However, even with a positive mitigation result through the years, in the long-term, this difference starts decreasing (Figure 17).

Figure 17 - Total CO_2 emission mitigation potential of each scenario compared with the BAU scenario.



Source: Elaborated by the authors.

Each set of scenarios from the policies evaluated is evidenced by one colour with different intensity (policy 1: orange; policy 2: blue; policy 3: purple; and policy 4: green). Note that, while a positive outcome is present through PReFleet03, from 2045 onwards its mitigation potential tendency starts diminishing visibly. In these last years, the VKT tends to the BAU result (Figure 16a).

Policy 2 is the only one with an increased profile until 2050. Its potential is promising although quite challenging for a country like Brazil that covers such an extensive territory. The implications involved a progressive linear increase of this shift, because it takes time for the country to make the necessary investments in infrastructure to enable several modals of public transportation. Telecommuting would also contribute to a lesser use of the vehicles (Menezes et al., 2017). Even with its challenges, it should be a target in which to invest, especially if aimed for the long-term as it presents greater benefits over those years (also confirmed by Wen and Bai, 2017).

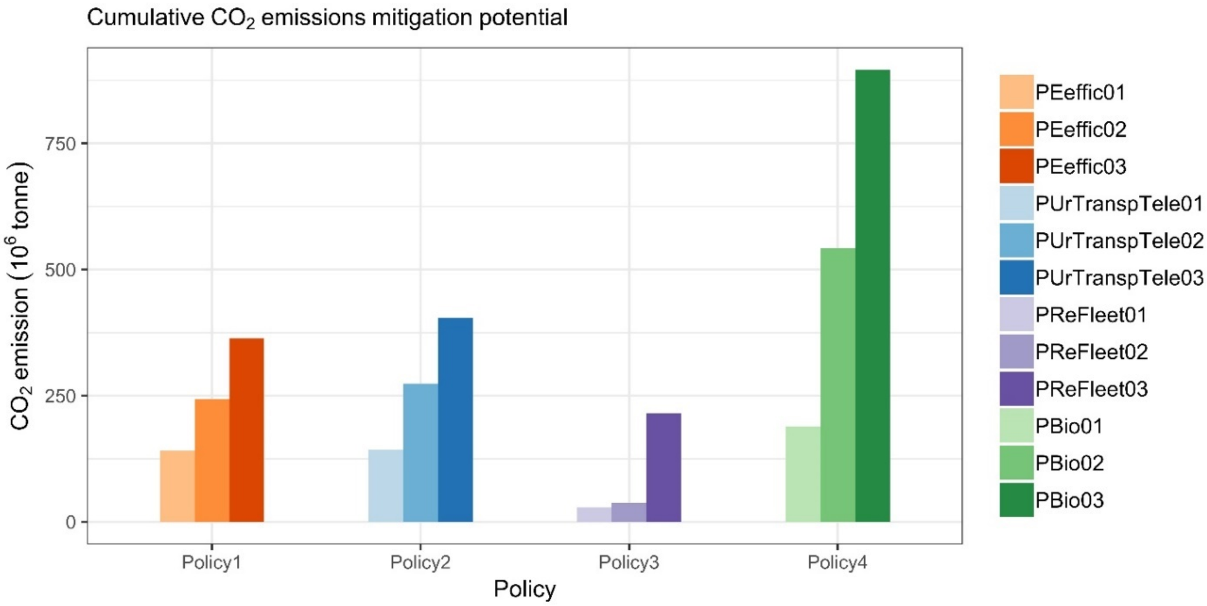
With policy 1, the scenarios present their highest mitigation delta with BAU around 2035-2040 period. In part, due to the changes in the model's parameter, a more stringent energy efficiency is set forth for car manufacturers from 2020 to 2030, then slowing its increase rate until 2050.

At last, the biofuel increase helps mitigate CO_2 emission in a relevant way. The pattern obtained is also similar to policy 1, where there is a strong increase at the beginning of the years, reaching its peak around 2036, then slightly decreasing until 2050 (also due to the implications involved). The PBio03 presented the highest mitigation potential from all scenarios tested. In this scenario, a fraction of 70/30% bioethanol/petrol for flex-fuel vehicles is considered. This may be seen as a little extreme. However, another source presents different figures from the ones we assumed in this study. According to MMA (2013), from 2003-2012, the average fraction of the flex-fuel vehicles that chose bioethanol as fuel resumed in approximately 68%. Thus, independently, if the historical average was 45% or 68%, we can infer that by increasing the use of biofuel by 25%, the present result should potentially take place.

The overall mitigation potential tendency (Figure 17) is valuable in assisting policymakers to design their strategies and implementation plan to overcome CO_2 emission excesses. While visualizing the potential of various policy reduction trends is important, analysing their full cumulative mitigation brings another responsibility factor into the decision-making process. One cannot refrain from investigating through a deeper analysis the potential strategies' impact.

Therefore, if we consider the cumulative aspect of CO_2 emission, mitigation results are even more evident (Figure 18). Since CO_2 remains for a while in the atmosphere, we may infer that this is the potential amount mitigated in each scenario, 2020-2050 period.

Figure 18 - Cumulative CO_2 emissions mitigation potential from BAU scenario for 2020-2050 period, for each policy and scenario.



Source: Elaborated by the authors.

In terms of potential average, if the country chooses to invest in these policies over the next three decades, an average of 250, 274, 94 and 543 million tonnes of CO_2 could potentially be mitigated by their adoption (Table 14). Both policy 1 and 2 have similar mitigation potential levels, with 46 and 50% from the highest mitigation potential average, respectively. The first two scenarios from policy 3, however, depict the least favourable result scenarios. On the other hand, although some rebound effects were detected, PReFleet03 presents a similar level result as PEeffic02, PUrTranspTele02, and PBio01.

While all previous results indicate their potential strength, it also reveals their readiness. By analysing them through time, policy 4 may be more strategic in a short to medium-term. It does not mean that its adoption will not generate a positive outcome in the long-term, or that it should not be aimed for a long-term perspective; it simply means that its results may be readily seen in fewer years. On the other hand, the reduction in the VKT average and energy efficiency enhancements demonstrate themselves as longer-term strategies. It takes time for their own beneficial characteristics to develop. Thus, although the fleet's emission is not promptly reactive to their change, in the long-run meaningful results are still attained.

Policy 3 mostly indicated it was unable to fulfil its purpose. While a low benefit could be observed from PReFleet01 and PReFleet02 scenarios (Figure 18), by 2050 they both end up emitting more than the BAU scenario (Figure 17). However, a better pattern was achieved in the PReFleet03 scenario, as it returned an outcome similar to other policies.

Table 14 - Cumulative CO_2 emissions mitigation potential average from policies from 2020-2050 period and its percentage from the highest score achieved.

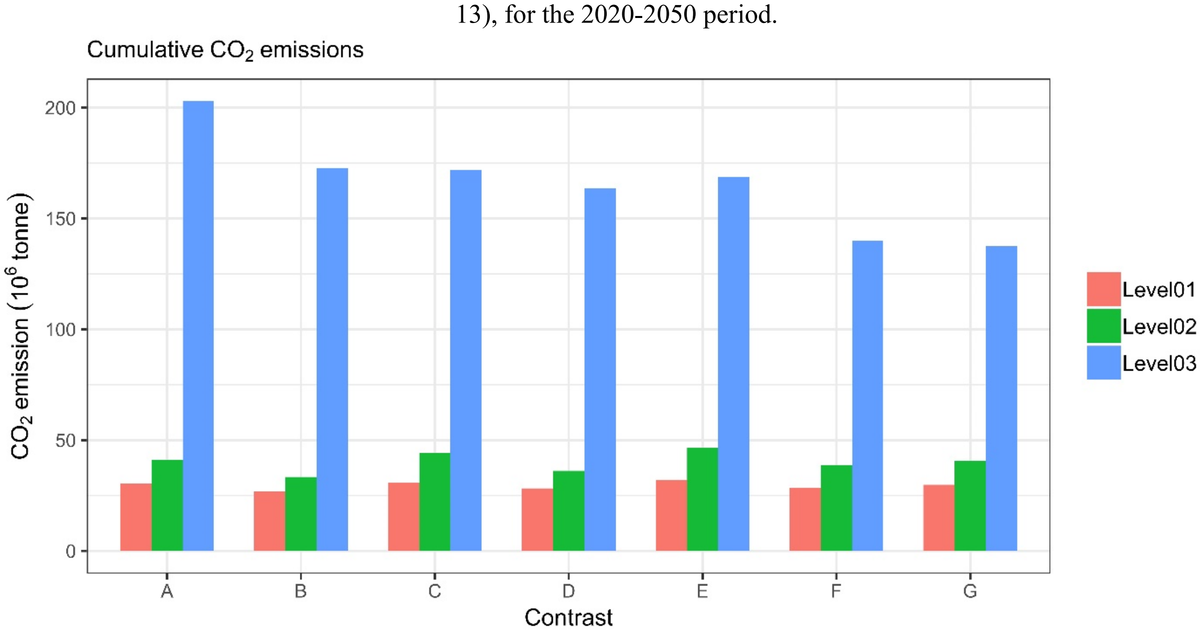
	Policy 1	**Policy 2**	**Policy 3**	**Policy 4**
Average (million tonnes of CO_2)	250	274	94	543
Percentage from the highest average (P4)	46%	50%	17%	100%

Source: Elaborated by the authors.

4.4.2 Integrated policies results

In the previous subsection (4.4.1), results were presented as if policies were conducted individually. Here, some integrated policies, classified in subsection 4.3.2, are considered for research purposes. Since policy 3 presented some setbacks, our aim is to check the possible outcome when integrating it with other policies. Thus, each contrast case scenario listed in Table 14 provides a comparison between one scenario involving policy 3 and one with its absence. Figure 19 presents cumulative CO_2 emission mitigation potential results, considering each level of intensity.

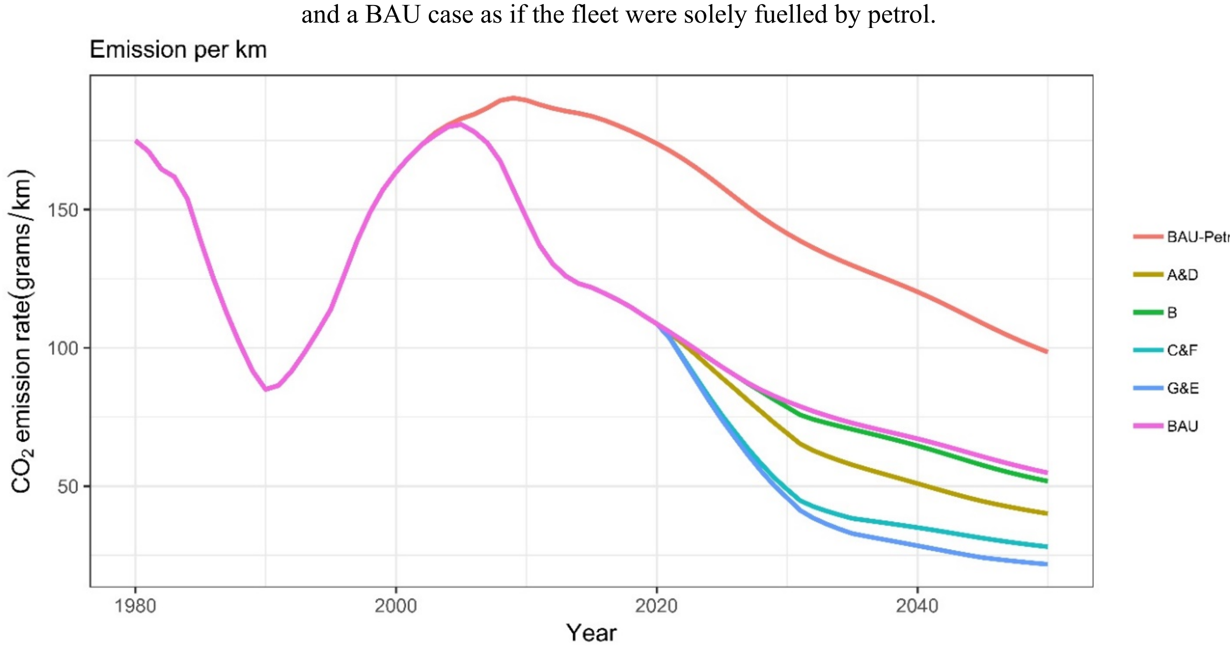
Figure 19 - Cumulative CO_2 emission mitigation potential of contrast scenarios from group 1 over group 2 (Table 13), for the 2020-2050 period.



In every contrast scenario, a very low importance of policy 3 is detectable when considering the first two intensity levels of stringency (01 and 02). This strengthens the result that this policy's purpose might be overshadowed by other effects that stimulate higher VKT, ending with similar emissions as BAU (Figure 16a). On the other hand, results obtained from the third level presented relevant cumulative CO_2 mitigation when policy 3 is involved. Note that as more policies are combined, these cumulative differences slightly decrease (from A to G). From a combination of two policies against one (A, B, and C), the integration of policy 3 with 1 presented its highest outcome (A). In the case of three policies against two (D, E, and F), the integration of policy 3 with 1 and 4 contributed the most. However, overall, these cumulative results achieved similar levels. It mostly demonstrates how more stringent criteria may be needed if renewing the fleet strategy should be pursued.

Finally, Figure 20 shows the average CO_2 emission per car profile of the fleet from integrated policies from group 1 and BAU. By 2050, both similar and different results can be observed. The combination B presents a little decrease from BAU result, due to policy 3. The combination A and D shows a similar result as C and F, as well as E and G, because the reduction on VKT from policy 2 implication does not change this rate.

Figure 20 - Average CO_2 emission rate per km of the fleet through time in scenarios of group 1 (Table 6), the BAU and a BAU case as if the fleet were solely fuelled by petrol.



Source: Elaborated by the authors.

The most prominent reduction in CO_2 rate per km achieved was in case E, G, C, and F (Figure 20). A fundamental characteristic of these scenarios is that they all include the integration of policy 4 (besides policy 3, the subject of the previous analysis). The Brazilian government has the advantage of producing bioethanol at a competitive price with gasoline (AJANOVIC; HAAS, 2014). However, an increased rate of bioethanol in the gasoline is a complex matter. Governmental regulations and other stakeholders are involved, and technological issues also complicate matters. This first-generation biofuel is worldwide viewed with some resistance because it competes with land use for international supply chain (as discussed in Espinoza *et al.*, 2017). Still, with the recent State policy named RenovaBio (MME, 2017), the government aims to increase bioethanol use from 28 to 54 billion litres by 2030 (AEA, 2017). It is expected that this policy should incentivize the use of bioethanol as a fuel to power the population's current flex-fuel vehicles.

4.5 CONCLUSIONS AND POLICY IMPLICATIONS

The paper investigates four potential policies to mitigate the impact of CO_2 emissions from light (passenger) vehicles. The model provides the assessment of different policies on (i) energy efficiency, (ii) modal changes and telecommuting increase, (iii) renovation of the fleet, and (iv) biofuel increase.

By analysing different levels of stringency of the policies and through a long-term perspective (1980-2050), some rebound effects were detected. While stimulating the removal of older vehicles from the fleet may seem as a prominent strategy, the simulations have shown otherwise. Although after policy implementation, fewer circulating vehicles were observed, the newer vehicles added (running more km on the roads) provided a higher cumulative VKT. Thus, in the long-term, some scenarios presented higher CO_2 emission than BAU. However, this setback may be overcome by applying more stringent policies, at least, in a mid-term perspective, where most of its positive influenced are achieved.

Furthermore, results have shown the contribution of renovating the fleet when integrated with other policies. Nevertheless, this integration is only advisable in more aggressive scenarios and if emissions from newer cars keep diminishing by either energy efficiency enhancement efforts or increased use of biofuel. A dynamic analysis provides meaningful insights to policymakers. It is important to analyse possible outcomes from different strategies beforehand. This provides valuable insights when investigating relevant issues such as those that reflect global climate change.

Based on our model result, energy efficiency and modal change policies are indicated as long-term strategies. In Brazil, there is no mandatory target for vehicle CO_2 emissions (only other types of emissions). Considering the economic and geographic challenges in improving public transportation, more incentives should be made to reduce this emission rate average from newer cars (such as those imposed in Europe, EU, 2018).

On the other hand, a strategy to increase biofuel usage is promising in the short to mid-term horizon. It mostly depends on regulations involved, since it partially depends on an increased level of biofuel in the main fuel blend. Moreover, incentives and strategies promoting bioethanol as the main fuel in the flex-fuel fleet can also contribute to this end; therefore, this strategy should be pursued, in parallel to others. Beneficial perspectives of regulation change are seen, as the new state policy RenovaBio has been recently released, which aims to boost biofuel production and cooperate to the NDC of the country.

Further work could include model additions that would allow the assessment of other emission types. We did not individually consider the mitigation potential from electric and hybrid vehicles; their impact is embedded in the implications of policy 1. To enhance the energy efficiency average of the new cars, besides incremental enhancements on their engines, advanced technologies such as these electric vehicles can further provide this. Considering a good use of renewable sources, more investigation in these technologies should be on any government's agenda.

Besides CO_2 emission evaluation, other environmental aspects, such as water use analysis, should be carried out alongside. Also, other sustainability aspects in the economic and social arenas should enhance transportation research. To this end, a life cycle sustainability assessment can be performed and is recommended for further research.

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4.6 APPENDIX A

$$CO_2 per\ car\ age(t_j) = CO_2\ per\ car\ age_1(t_{j-1}) + \int_{t_{j-1}}^{t_j} [CO_2\ per\ km(t) - exempted\ CO_{2_1}(t)]\ dt \quad \text{A.1}$$

$$CO_2 per\ car\ age_k(t_j) =$$

$$CO_2\ per\ car\ age_k(t_{j-1}) + \int_{t_{j-1}}^{t_j} CO_2\ transfer_{k-1}(t) - [CO_2\ transfer_k(t) + exempted\ CO_{2_k}(t)]\ dt, \quad 2 \leq \mathrm{k} \leq 20 \qquad \text{A.2}$$

$$CO_2\ per\ car\ age_{21}(t_j) =$$

$$CO_2\ per\ car\ age_{21}(t_{j-1}) + \int_{t_{j-1}}^{t_j} CO_2\ transfer_{20}(t) - exempted\ CO_{2_{21}}(t)\ dt \qquad \text{A.3}$$

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CHAPTER V

5 'FORTUITOUS' SUSTAINABILITY TRANSITIONS: AN ANALYSIS OF BRAZIL'S PASSENGER VEHICLES FUEL TECHNOLOGY FROM 1970 TO 2020

This chapter presents the third paper of this thesis, being the result of step 2. It is currently under journal submission[6].

Abstract

Sustainable socio-technical transitions refer to the multi-dimensional shifts societies undergo when they move from one socio-technical system to another that is perceived to be less damaging to the environment. Two well-known theoretical frameworks - the multi-level perspective (MLP) and the multiple stream approach (MSA) – have been used to investigate the factors that trigger or hamper these shifts. The complexity of sustainable transitions is such, however, that authors are increasingly combining these frameworks in an effort to capture a wider range of factors and contexts. This approach is used to investigate transformations in the fuel-technology used in Brazil's passenger vehicle fleet from 1970 to 2020. In addition to capturing this unusual story through the lens of social-technical transitions, our analyses highlight the changing role regime outsiders and dormant policies played throughout this period while emphasising the importance of 'fortuitous' windows of opportunity. In doing so, we complement the existing literature on sustainable socio-technical transitions by adding contextual factors that may be particularly salient for developing economies in their attempts to address persistent sustainability problems.

Keywords: Transitions; Multi-level perspective; Multiple stream approach; passenger vehicles; Brazil.

5.1 INTRODUCTION

Tackling climate change requires shifting our current socio-technical systems to more sustainable alternatives in a process that has become known as 'socio-technical sustainability transitions' (MARKARD; RAVEN; TRUFFER, 2012). Given their importance, many studies explore the complex dynamics that underpin these transitions (ELZEN *et al.*, 2004; GEELS, 2005; VAN SLUISVELD *et al.*, 2018). The bulk of these use either a multi-level perspective (MLP) (GEELS,

[6] BENVENUTTI, L. M. M.; CAMPOS, L. M. S.; VAZQUEZ-BRUST, D. A.; LISTON-HEYES, C. 'Fortuitous' Sustainability Transitions: An Analysis of Brazil's Passenger Vehicles Fuel Technology from 1970 to 2020. Working paper (Chapter 5 of this thesis), 2021.

2002) or a multiple streams' approach (MSA) (KINGDON, 1984) depending on the weight they assign to technological factors versus political and agency processes.

In recent years however, an increasing number of authors have combined these frameworks to capitalise on the different insights they offer (DERWORT; NEWIG; JAGER, 2018; ELZEN *et al.*, 2011; NORMANN, 2015, WALWYN, 2020). We do so here in an attempt to identify and narrate the events - and the mechanisms reinforcing these - pertaining to the fuel-technology transition of Brazil's passenger vehicle fleet between 1970 and 2020 (CORNELISSEN, 2017). In doing so, we find that there remains important opportunities for additional insights that have yet to be exploited by existing applications that combine the MLP and MSA frameworks. In particular, we argue that the role played by elements of resistance and secondary actors in the transition process have largely been ignored, as are the lingering effects national policies continue to exert on transitions after they have become inactive. Perhaps more importantly for developing economies like Brazil, are the potential for 'fortuitous' windows of opportunity for sustainability transitions. We argue that these findings enrich our understanding of sustainable socio-technical transitions, complement existing approaches based on the joint applications of the MLP and MSA frameworks, and ultimately facilitate the implementation of systems that address persistent sustainability problems.

The MLP framework distinguishes between three 'analytical' levels that need to interact for transitions to occur. These include (i) technological niches for radical innovations such as incubators, i.e. protected 'spaces', (ii) socio-technical regimes – i.e. the set of rules that maintain the socio-technical system, and (iii) the socio-technical landscape which refers to external factors that are largely outside the control of actors but influence their actions (e.g. oil prices) (GEELS, 2002). Proponents of MLP stipulate that radical innovation arise when a 'window of opportunity' emerges at the regime and landscape levels. While adept at capturing technological dynamics, critics of the MLP argue that it underrepresents the role of political and agency factors thereby reducing its explanatory power (DERWORT; NEWIG; JAGER, 2018; EDMONDSON; KERN; ROGGE, 2018).

Theories of the policy process, on the other hand, are more adept at conceptualising the role of power and institutions and explaining how solutions become attached to different problems, even 'wicked' ones involving substantial goal conflicts, technical disputes, and multiple actors (KERN; ROGGE, 2018; KÖHLER *et al.*, 2019; MARKARD; SUTER; INGOLD, 2016). Policy process theorists use theoretical devices that focus on understanding how policy-makers coalesce in their interpretation of contextual shocks in the process of policy changes (SABATIER, 2007). Kingdon's Multiple Stream Approach (MSA) synthesised these heuristic devices by differentiating between the three main streams of the policy process – i.e. policy, problem, and politics – thereby capturing the preoccupation of those interested in agency and how political processes promote policy changes (KINGDON, 1984).

In other words, the MLP provides a broader perspective which captures interactions between technologies, regime insiders and outside influences through time and in so doing, facilitates the identification of 'transition pathways' (GEELS *et al.*, 2016; GEELS; SCHOT, 2007). MSA complements these accounts by internalising the political factors that underpin these transitions (DERWORT; NEWIG; JAGER, 2018; KERN; ROGGE, 2018). Unsurprisingly, scholars investigating sustainable socio-technical transitions are increasingly combining the MLP and MSA frameworks in an effort to capitalise on their complementary insights (DERWORT; NEWIG; JAGER, 2018; ELZEN *et al.*, 2011; NORMANN, 2015).

We follow their lead by using both frameworks to 'process-narrate' the fuel-technology transitions of Brazil's passenger vehicle fleet since 1970 (CORNELISSEN, 2017). This fuel-technology changed three times over the past five decades, providing a rich and interesting setting in which to assess the explanatory power of the combined MLP and MSA frameworks, using an actor-centred focus and insights from stakeholder theory, institutional work and policy actors' position theories (MITCHELL; AGLE; WOOD, 1997; NEVILLE; MENGUC, 2006; RIAZ; BUCHANAN; BAPUJI, 2011; INGOLD *et al.*, 2020). Our application highlights four important gaps and tensions that emerge when using these heuristic devices. Firstly, the findings highlight the importance of tracking the changing salience of the multiple actors involved in the policy process through time. Secondly, they demonstrate the benefits of looking at actors' shifting political stances (supportive, neutral, resistant), demonstrating that these can be as important as technologies and policies in capturing the complexities of transitions. In this regard, our study responds to the call by Kanger, Sovacool and Noorkõiv (2020) for further research into the motivations and capabilities of actors effecting change during transitions. Thirdly, they show the influence national policies continue to exert on the transition process long after they have become officially 'inactive'. Finally, our narrative emphasises how sustainability transitions – particularly those involving developing countries - can be fortuitous, and not necessarily the outcome of deliberate and intentional measures sponsored by sustainability-oriented policies and organized action, and end with discussions of how both problem fitting solution and solution fitting problem approaches can aid the process of policymaking.

The latter is particularly important as it contradicts the dominant view that "sustainability transitions are the outcome of long term goals involving a broad range of actors working together in a coordinated and purposeful way" (MARKARD; RAVEN; TRUFFER, 2012, p. 956-957) see also (BERKELEY *et al.*, 2017; KERN; ROGGE, 2018; SMITH; STIRLING; BERKHOUT, 2005). More concretely, we find that 'fortuitous' sustainability transitions, i.e. those that materialise when an existing economic solution is paired with an emerging environmental problem, provide another conduit for sustainable socio-technical transitions (KERN; ROGGE, 2018). We argue that these may be particularly relevant in developing countries where economic concerns tend to be prioritised over environmental ones and are more resource-constrained (KÖHLER *et al.*, 2019; WALWYN, 2020). Capitalising on their potential requires agile, creative and pragmatic policy entrepreneurs that can recognise and act upon these opportunities.

The paper is structured as follows. Section 5.2 briefly reviews the MLP and MSA frameworks and documents past efforts to use them concurrently. Sections 5.3 describes the sources and methods used in the analysis of Brazil's passenger fuel-technology fleet from 1970 to 2020, while Section 5.4 presents the narrative and highlights its key findings. A discussion follows in Section 5.5 while brief conclusions appear in Section 5.6.

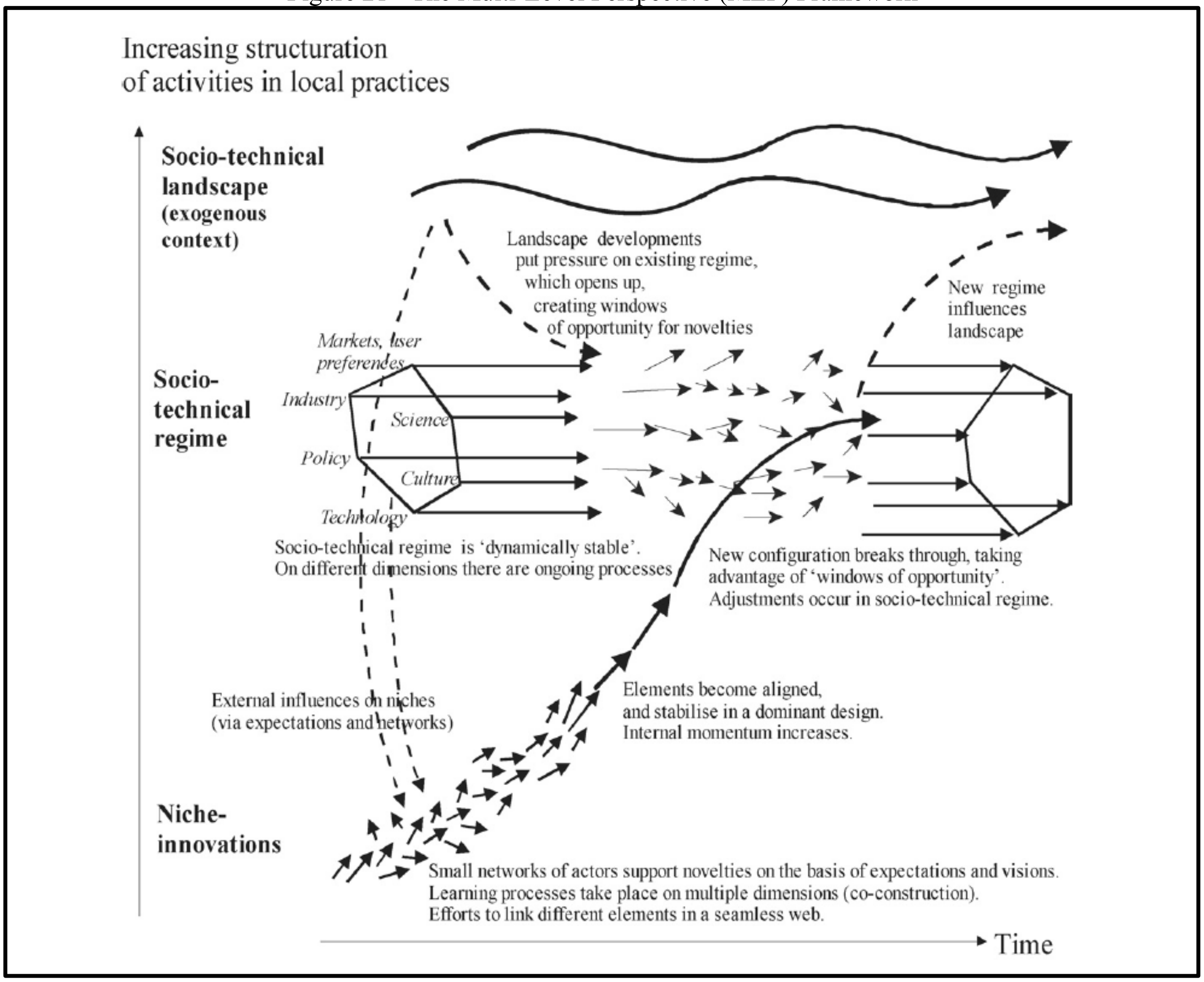
5.2 NARRATING SOCIO-TECHNICAL TRANSITIONS

Scholars investigating social-technical system transitions have developed simple heuristic devices that are meant to facilitate our understanding of the policy process in relation to what are essentially very complex phenomena. While these frameworks assemble insights from several disciplines, each tend to specialise on some particular aspect of transitions. However, as the pace and scale of large unforeseen environmental disasters increases, scholars are under pressure to enhance the relevance and applicability of their approaches. Accordingly, recent analyses of social-technical transitions rely on a diversity of frameworks in an attempt to capture a wider range of factors. What follows is a brief account of studies that combined two widely used social-technical system transition frameworks – i.e. the Multi-Level Perspective (MLP) and Multiple Streams Approach (MSA) – and a discussion of the challenges involved in doing so.

5.2.1 The Multi-Level Perspective (MLP)

As the name suggests, the MLP explores socio-technical transitions from three different perspectives - landscape, socio-technical regime and innovation niche - each framed by concepts adapted principally from sociology, evolutionary economics and institutional theory (ELZEN *et al.*, 2004). The MLP is particularly adept at identifying 'windows of opportunities' that can precipitate socio-technical changes and the transition pathways they engender (GEELS, 2002; GEELS; SCHOT, 2007). The framework has been used to identify transitions to solar electricity (ROSENBLOOM; BERTON; MEADOWCROFT, 2016), electric mobility (BERKELEY *et al.*, 2017; MAZUR *et al.*, 2015), teleworking (HYNES, 2016), bike sharing (Ó TUAMA, 2015) and agro-food systems (BUI *et al.*, 2016). Figure 21 and Chart 2 below provide original and simplified depiction of the MLP framework in which the three perspectives are independent and the landscape is exogenously determined. More recent contributions offer a range of more nuanced depictions that allow for interactions between actors, technology and institutions through the lens of endogenous enactment of transition pathways (GEELS *et al.*, 2016).

Figure 21 - The Multi-Level Perspective (MLP) Framework



Source: Geels and Schot (2007).

Chart 2 - MLP Transition Pathways.

Transition pathways	**Main scenario**	**Main outcome**
De and re-alignment	Intensive and sudden landscape change that weaken the regime	Rise of multiple niche-innovators
Technological substitution	Intensive landscape pressure combined with existing niche-innovation	Radical innovation substitute incumbent firms
Transformation	Niches already developed and adopted by the regime	'Add-on' to existing technologies with no major system architecture disruption
Reconfiguration	Niches already developed and adopted by the regime	Substantial change and disruption to the basic system architecture disruption

Source: Adapted from Geels (2002, 2005, 2006a, 2006b).

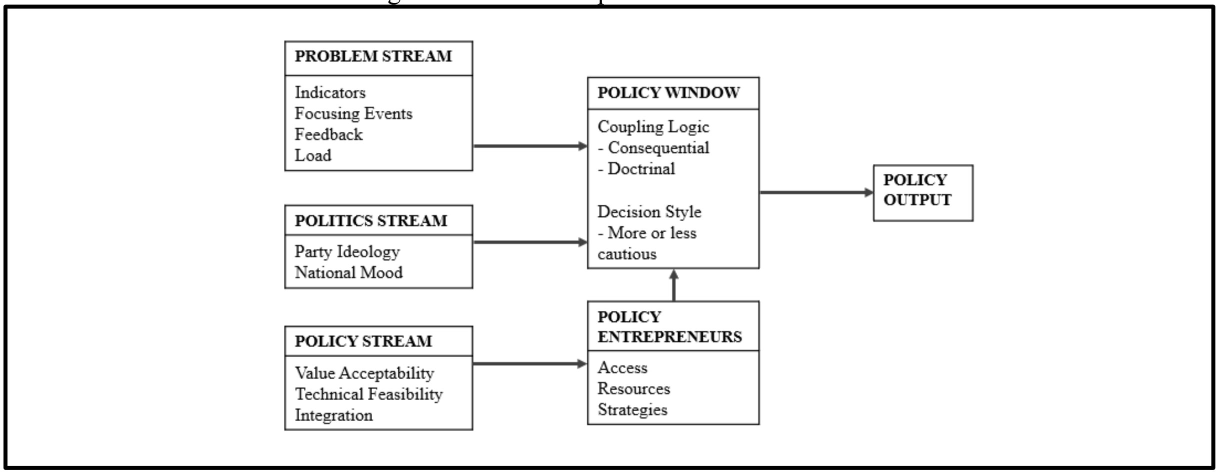
5.2.2 The Multiple Streams Approach (MSA)

The other major building block in the socio-technical system transition's tool box is the MSA. This analytical device focuses more explicitly on policymaking. In particular, it recognises that policymaking operates under conditions of ambiguity characterised by high actor turnover and unclear jurisdictions, not according to a rational and orderly process with clearly defined goals and accountabilities (KINGDON, 1984). It posits that policies are more likely to emerge when events in the three 'streams' – problem, politics and policy - converge within the same time frame, creating a window of opportunity for the enactment of change. The closer the alignment time-wise, the greater the probability that change will materialise.

Figure 22 provides a simple depiction of the MSA. The problem stream is assessed by indicators that measure the extent of a particular condition (e.g. CO_2 emission), focusing events that bring this condition to the attention of society (e.g. crisis, disaster), feedback which can be thought of as interventions that have worked in the past, and load which reflects competing pressures on policymakers. The politics stream consists of factors related to electoral, political parties, and/or pressure groups which together capture 'the broader environment within which policy is made' (ACKRILL; KAY; ZAHARIADIS, 2013, p. 873). Party ideology relates to the political stance of the administrators in power while the national mood represents wider public opinion in the country on a particular set of issues. Finally, the policy stream captures the range and nature of the solutions that are proposed to address identified problems, their acceptability to the public, their technical feasibility and the extent to which participants in the process interact with one another. Policy entrepreneurs facilitate the alignment of these three streams, articulate policy processes and ensure that policy outputs materialise (BAKIR, 2009; MINTROM, 1997; TIMMERMANS; VAN DER HEIDEN; BORN, 2014).

Of importance is that both the MLP and MSA recognise that windows of opportunities are temporary and may appear and close at any time.

Figure 22 - The Multiple Streams Framework.



Source: Adapted from Zahariadis (2007).

5.2.3 Combining the MLP and MSA

A number of authors used the MLP and MSA concurrently. For instance, in their study of pig husbandry, Elzen *et al.* (2011) redefined existing MSA streams to ‘fit’ dimensions of the MLP that were highly relevant to their study (e.g. market and technology) while emphasising the regulatory aspects of innovation and socio-technical regimes, rather than policy per se. Another example is Normann (2015) study of offshore wind politics in which the three MSA streams are maintained but interpreted sufficiently broadly to include technological niches within the policy stream. Derwort; Newig and Jager (2018) also uses the two frameworks in their study of energy transition. Although they make no attempt at integrating them, they discuss their respective strengths and weaknesses. In the context of a resource-constrained political system, Walwyn (2020) proposed an additional stream to the three main MSA streams, named techno-economic, for the analysis of decarbonization efforts in South Africa. Together these studies suggest that the MLP is particularly adept at representing the technological aspects from a historical perspective while the strength of the MSA resides in its ability to identify and map out the role of agency and power relations[7].

[7] We note that the technological innovation system (TIS) is another theoretical approach much used in transition studies. It is principally concerned with the emergence of new technologies and the interplay between institutional and organizational change, including identification of drivers and barriers to innovation. However, the TIS adopts a narrower and more inward-looking analysis that fails to embrace the wider system shift perspective we are more concerned about (MARKARD; RAVEN; TRUFFER, 2012; WALZ; KÖHLER; LERCH, 2016). See Andersen (2015) for a TIS application of Brazil’s sugarcane sector 1900-1973.

Process-narrating the fuel-technology transitions of light-vehicles fleet in Brazil is a tall order. Notwithstanding the usual challenges of categorising events, actors, and innovations into niche, regime, and landscape (MLP) or problem, politics, and policy (MSA), the transition we are investigating took place over half a century in a different geography to where most applications of social-technical systems transitions are based (DERWORT; NEWIG; JAGER, 2018; HANSEN; COENEN, 2015). While this allows for a richer and more complete account of the transition – i.e. one that captures feedback effects of policy outcomes on the process, it also increases the number of actors involved and multiplies the events to consider, heightening the power of the authors over the narration process (KÖHLER *et al.*, 2019). Acknowledging these caveats and recognising that no individual framework will be sufficient to capture the complexity of the phenomenon under study (KERN; ROGGE, 2018), we build on insights gathered from previous attempts at combining the MLP and MSA frameworks and provide additional developments. The analysis template we used consolidates technological, policy, political, and market forces and provides a consistent frame in which to narrate the several moving parts of this longer term transition.

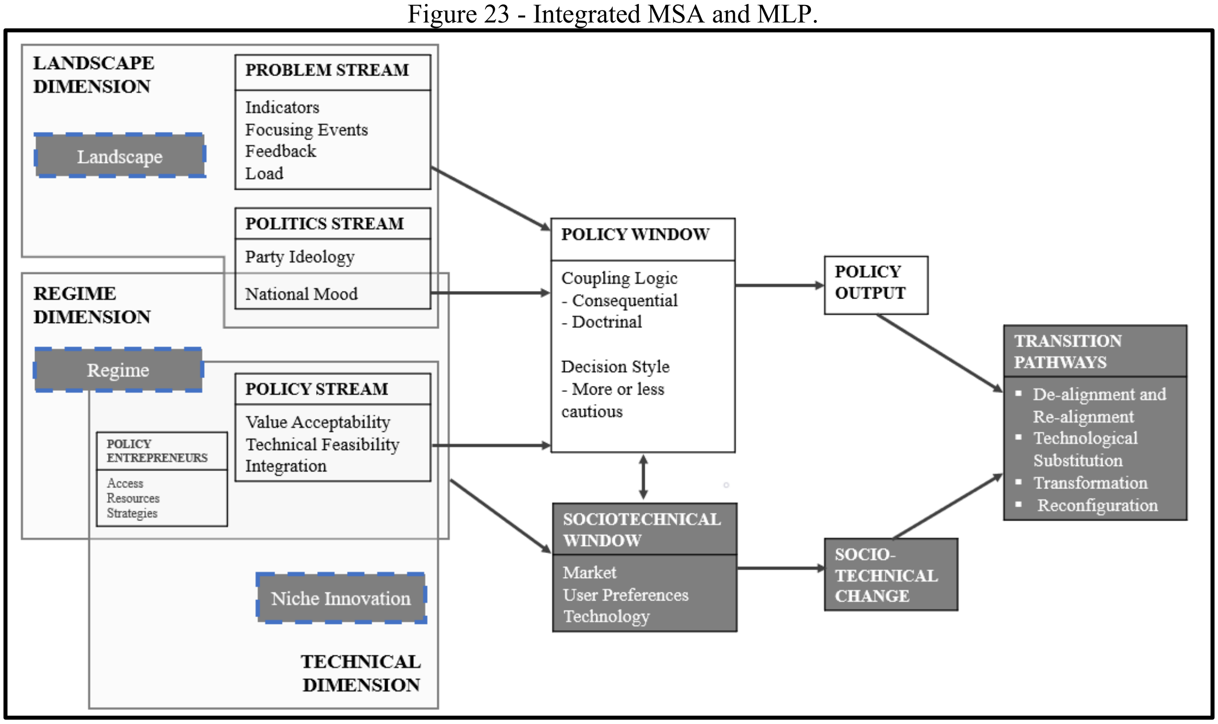
More concretely, we merged the problem and politics streams (MSA) with the MLP landscape level and labelled this the 'Landscape Dimension'. We also merged the politics and policy streams (MSA) with the regime level (MLP) and labelled this the 'Regime Dimension'. Finally we combined the policy stream (MSA) with the niche innovation level (MLP) and named this the 'Technical Dimension'. Dimension is a broader term that comprises concepts of levels and streams used in the MLP and MSA frameworks respectively. The dimensions remain faithful to the traditional MLP framework, but movement inside and between them are influenced by elements of the MSA that capture the dynamics of power and agency in transitions.

The Landscape Dimension captures exogenous pressures that are perceived by regime actors but lay largely beyond their influence. However, through time, the elements embedded in the problem and politics streams can coalesce and help shift the wider strictures of the landscape dimension. The Regime Dimension is the subject of political dynamics that are often considered to be exogenously determined within the time frame of the analysis. However – and given the extended time scale of our study - we argue that 'national moods' can become malleable and an instrument of regime change. We distinguish between 'insiders' and 'outsiders' national mood with the former capturing the regime incumbent's mood and the later referring to the general public's disposition towards an issue. Forces at play in the politics and policy streams can, with time, influence the national mood thereby altering regime parameters.

Finally, the Technical Dimension is only linked to agency elements through the policy stream. Policy stream are conceived as 'solutions' stream and naturally align with the standard interpretation of niche-innovation (NORMANN, 2015). Hence the Technical Dimension can be influenced by incumbent actors' as well as new entrants (GEELS *et al.*, 2016). By allowing the policy stream to straddle both the Regime and Technical Dimensions, we also recognise that policy actors can influence, with time, the regime level as well as the technological solutions. These assumptions implicitly recognise that policy may be enacted by governments but it is influenced by policy entrepreneurs, which can come from both the regime and technical dimensions. For simplicity, we do not categorise market and technology into separate MSA streams as proposed by Elzen et al. (2011) nor the techno-economic stream as proposed by Walwyn (2020) but retain the original 'market/user preferences' and 'technology' variables of the original MLP framework, and the original technical feasibility within the MSA policy stream.

Figure 23 summarises how we consolidated the MSA and MLP into a single template that was used to guide the process-narration of 50 years of events in Brazil's passenger fuel-technology fleet.

Figure 23 - Integrated MSA and MLP.



5.2.4 Stakeholder Theory, Institutional Work and Policy Actors' Position Theories

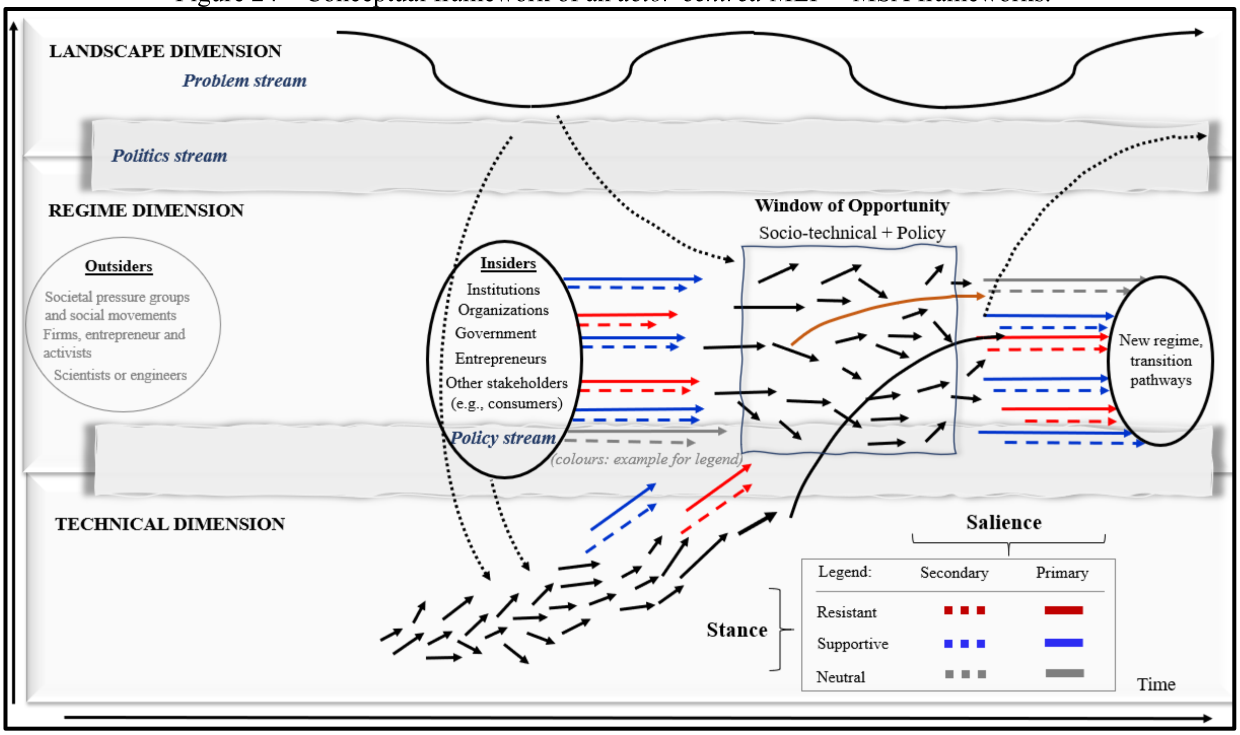
The combined MSA and MLP model of Figure 23 provides a more complete tool for the investigation of sustainable transitions. However, its ability to capture the agency of actors remains limited despite recent progress in developing the micro-foundations of social-technical transitions (KANGER, 2020). We build on Geels (2020) who emphasises the contextual nature of agency by incorporating insights from stakeholder theory, institutional work, and policy actors' position theories to address these gaps.

More concretely, we transferred Mitchell's et al. (1997) concept of 'stakeholder salience' - the degree to which managers prioritise competing stakeholder pressures - to the social-technical transitions context by re-interpreting it as 'actor salience' – the degree to which the social-transition system prioritises competing actor pressures. As in the stakeholder theory literature, salience is conceived as a function of power, legitimacy and urgency. This allows us to classify niche and regime actors as 'primary' or 'secondary' depending on their ability to exert pressures for change (their salience) during a given period.

We also follow Neville and Menguc's (2006, p. 387) suggestion to determine "which stakeholders are supportive of the organisation's activities and which are not..." by considering the direction, strength and synergies of actor pressures, or more generally their 'stance'. This is reminescent of Riaz, Buchanan & Bapuji (2011) who, anchored in an institutional work perspective, advocate examining actors' emerging positions in relation to policy, practices, and regulation, by categorizing them as 'status quo', 'neutral' and 'pro change'. Actor stance also relates to the concept of policy actors' positions –i.e. their beliefs, preferences, changing mood (SABATIER, 2007; INGOLD, 2011) which can be helpful in the study of socio-technical transitions. Accordingly, and in addition to actor salience, we introduce the notion of actor stance, which can be categorised as supportive, neutral or resistant to change in technology or in policy.

These features are added to the standard model in what we propose is an *actor-centred* MLP and MSA framework. Figure 24 highlights insider and outsider national actors' 'salience' using textured lines while their respective stance towards a social-technical system transition is represented by colours (red-resistant, blue-supportive, and grey-neutral). As in the original MLP template from Geels and Schot (2007) (see Figure 21), the long dotted arrows represent the strong influence of existing regimes and landscape on the niche-level, the short diverging arrows denote uncertainty and differences of opinion, the longer full black arrows represent ongoing incremental processes and the orange arrow[8] represents the incremental processes prompted by regime insiders.

Figure 24 – Conceptual framework of an *actor-centred* MLP + MSA frameworks.



Source: Based on the iconography of Geels and Schot (2007, p. 401), adapted to an *actor-centred* approach, with added MSA dimensions (ZAHARIADIS, 2007) and proposed actors' stance and salience.

5.3 METHODS AND DATA SOURCES

We follow a process-model theorizing approach (CORNELISSEN, 2017) to investigate the fuel-technology transition of Brazil's passenger vehicle fleet since 1970. Brazil provides an interesting case study given its history of investing in ethanol (National Alcohol Program, *Proálcool*) which, unbeknown to policy-makers at the time, proved to be a much greener alternative to other fuels and a more sustainable approach for the development of the sector. By integrating two existing process models (MLP and MSA), our approach is reminiscent of parallel process theorizing (CLOUTIER; LANGLEY, 2020). We argue that doing so enriches the narrative by empirically identifying elements that improve understanding of stage-level and cross-level dynamics and resulting process outcomes. More concretely, the structure and components of

[8] Note that in reference to Geels et al. (2016), the orange arrow was added to capture the incremental processes prompted by regime insiders.

Figure 23 guided how we gathered and extracted the information contained in the corpus of documents that collected through a systematic search of government, academic, practitioner and journalistic publications published over the past 50 years.

We used a three-pronged approach to our document search to ensure that we had adequate representation from experts, policy-makers, policy entrepreneurs and the wider public. Firstly, we collected documents that explicitly referred to the sugar-ethanol industry using *Proálcool* (and relevant variations[9]) in the Scopus platform. This exercise yielded 44 documents, most of which were of a historical nature and produced by scholars and industry experts discussing some aspect of the *Proálcool* investment program launched by the Brazilian government in 1975. Secondly, we used the same terms to search the National Archive Information System (SIAN) and legislations databases to gather government documents on the subject of ethanol. This produced 1,172 and 11 additional documents respectively. Finally, we used the same terms to search the archives of a popular and widely distributed national newspapers in Brazil, the *O Globo*. For consistency, we also examined the archives of two other popular national newspapers (*Folha de S. Paulo* and *O Estado de S. Paulo*). This produced an additional 2,612 documents. The original corpus of data was thus composed of 3,839 documents.

Since the initial search was likely to collect documents with little relevance to our research (e.g. adverts referring to ethanol, job listings, etc.), we searched document titles (and abstracts for documents listed in Scopus) and eliminated those that had little connections to the themes of this study. As expected, a large number of documents found in the SIAN and *O Globo* archives had no or little relevance to our research subject. After this time-consuming cull, the corpus of document was reduced to 102 documents. Table 15 provides additional details of our searches.

After establishing who the key actors were, we identified the key periods in the transition (1970-1980, 1980-1986, 1986-1990, 1990-2000, 2000 -2020). We then used the combined actor-centred MLP and MSA model (Figure 24) to track how the stance and salience of the actors evolved in each of these periods and the events that hampered or enhanced the transition. We also used the frameworks to guide our interpretation of the events on the socio-technical system and form an overall impression of whether the transition progressed, regressed or stagnated during the period under study.

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[9] *Proálcool* is short for “national alcohol program”. Other search terms included: ‘National ethanol program’, ‘Brazilian ethanol program’, ‘Brazil's alcohol program’.

Table 15 - Documents Per Source*, **

Source	Total	After selection	1970s	1980s	1990s	2000s	2010s	Total
Scopus (title, abstract, keywords) (https://www.scopus.com/)	44	30	0	10	2	6	12	44
Federal legislation (https://legislacao.presidencia.gov.br/#)	11	11	7	4	0	0	0	11
National Archives Information System*** (http://sian.an.gov.br/)	1172	15	2	10	2	1	0	1172
O Globo*** (https://acervo.oglobo.globo.com/)	2612	46	10	21	12	2	1	2612
Total	3839	102	19	45	16	9	13	3839

*Search terms for Scopus: 'Proálcool', 'National ethanol program', 'Brazilian ethanol program', 'Brazil's alcohol programme'.
*Search term for the rest: 'Proálcool'.
**Final date of access: 15 July 2020.
*** This search provided several results unrelated to the theme.

Source: Elaborated by the authors.

5.4 BRAZIL SOCIO-TECHNICAL FUEL-TECHNOLOGY TRANSITION

While we used Figure 24 to guide what information we extracted from the documents, we recognised that actors can lay inactive or be inconsequential for several periods before emerging or re-emerging as agents of change (JAWAHAR; MCLAUGHLIN, 2001). Hence, the application of our template required an initial reading of all the documents irrespective of publication date that would focus on identifying the elements (actors, events, policies) whose influence would persist in some way or the other throughout the 50 year period (BENNERTZ, 2014; MORAES, 2011; MORAES; ZILBERMAN, 2014; MOREIRA; GOLDEMBERG, 1999; OLIVEIRA, 2002; RICO; MERCEDES; SAUER, 2010; SANTOS, 1985). Once this identification was completed, we revisited each decade using documents produced by governments, experts, and newspapers to describe the elements at play during the specific period. What follows is a brief account of these findings.

5.4.1 Stage 1 – Transition triggers (1970-1980)

The first catalyst for Brazil's fuel-technology transition can be linked to the drastic change in the landscape that followed the 1973 oil crisis. At the time, Brazil was importing most of its oil (80%) such that the increase in the price of oil led to a 225% sudden rise in expenditures for Petrobras, Brazil's state-owned monopoly energy supplier (SANTOS, 1993). Brazil was also heavily involved in the export of sugarcane and its derivatives (including ethanol and sugar), activities that were heavily regulated by the Sugar and Ethanol Institute or IAA[10] (BRAZIL, 1933). Around the same period (mid-1975), the world supply of sugar increased leading to a substantial fall in the international price of sugar (SZMRECSÁNYI; MOREIRA, 1991).

The confluence of these two ‘landscape’ events (the sudden rise in oil price and fall in sugar price) created a window of opportunity for the ethanol industry to increase its production and led to the establishment of the National Ethanol Program (*Proálcool)* in 1975 (BRAZIL, 1975). The policy stream was thereby activated and regulation authorising a rise of anhydrous ethanol rate from 5% to 20% in the gasoline blend was enacted. These developments did not require major technological adaptions of car engines or filling stations infrastructure.

The national mood was mainly driven by Brazil’s military government (i.e. the executive power was controlled by the military but legislative authority was held by elected party members) and by sugar and ethanol producers who had sufficient clout to influence policy and policymakers (SIAN, 1988). Copersucar and Coperflu, two major sugarcane producer cooperatives, are on record as supporting the transformation policies with enthusiasm and even criticizing the low production targets set in the first phase of *Proálcool*. Other incumbents, including Petrobras and some automakers, were more indifferent or resistant to these changes. However, in the face of an economic collapse and with the population generally supportive of the ethanol policy and its promises of cheaper fuel and economic stability (OLIVEIRA, 2002), their complaints had relatively little impact, relegating them to the role of secondary actors in this particular period.

In addition to actors located within the political sphere, we note that there were also experts, academics and social groupings operating outside this network. At the time, these secondary actors had very little influence on the transition process but evidence suggests that they were generally in favour of a national strategy aimed at reducing Brazil’s dependency on oil by increasing its use of ethanol (CALMON, 1978).

This first phase is also characterised by low level incremental change – i.e. the technology did not require major disruptions - and ‘endogenous’ enactment by the government. It is strongly associated with the president of the time (Ernesto Geisel) and his Ministry of Industry and Commerce (MIC) who acted to prevent an impending economic crisis (SANTOS, 1993). Other insider actors were also instrumental in supporting ethanol-based fuels. While outsiders were less

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[10] The *Instituto do Açúcar e do Álcool* (IAA) in Portuguese.

influential at the time, evidence suggests that they too were in favour of these developments. The pre-existence of the sugarcane and automotive sectors meant that ethanol-based fuels were technically feasible and their use during the interwar years rendered them socially acceptable and marketable.

5.4.2 Stage 2 – System reconfiguration (1980-1986)

The second oil price shock of 1979 gave momentum to initiatives that would allow Brazil to further diversify itself away from petrol (SIAN, 1986). Headlines claiming that 'ethanol will substitute gasoline' became regular features of media outlets and support for *Proálcool* was widespread (GLOBO, 1980a; b). There were technological challenges however as the infrastructure required to accommodate the increased ethanol production and appropriate tanking and distribution facilities was lacking (MORAES; ZILBERMAN, 2014). Petrobras was not an incumbent ethanol producer but changed its stance and took on a leading role as a distributor. Universities, research centres, and private sector firms were also encouraged to collaborate and ethanol-based cars started appearing on the market (SIAN, 1986). The World Bank credit loan of US$250 million further increased international interest in the *Proálcool* program (SIAN, 1984).

Hence, by deepening economic and energy security concerns, the second oil crisis reinforced the window of opportunity for a socio-technical transition to ethanol-based fuels for passenger cars. The reorientation was only partial since several incumbents had started producing dual gasoline and ethanol-powered cars, but it nonetheless represented a higher level of incremental change. Regime actors were unilaterally in favour of the shift, and encouraged by government subsidies, they produced (i) higher volumes of hydrous ethanol, (ii) specialised tanking and distribution facilities, (iii) ethanol-fuelled vehicles, and (iv) equipment for filling stations.

Records indicate that the car industry was in favour of the program. It was hit very hard by the oil crisis (SIAN, 1988) and lobbied intensively to receive government incentives to facilitate the transition to ethanol-based fuels and the development of an export market (HIRA; DE OLIVEIRA, 2009). Encouraged by the National Association of Motor Vehicle Manufacturers (ANFAVEA), the government introduced consumer incentive schemes including (i) ethanol-fuel subsidies and 'weekend sales' events, (ii) lower highway tolls for ethanol-fuelled automobiles, and (iii) long-term financing schemes for ethanol-fuelled car purchases (GLOBO, 1982; MORAES; ZILBERMAN, 2014). Encouraged by these various incentive schemes, consumers embraced the new system wholeheartedly and by the end of 1983, the millionth ethanol car was sold. Events were held to celebrate was what deemed to be a spectacularly successful public-private partnership (GLOBO, 1983).

It is worth noting that agricultural producers in Brazil's northeast region were less favourable to the *Proálcool* program and had raised concerns about its impact on farming, referring to it as the 'food versus fuel' dilemma. The program addressed these concerns early on by accelerating the modernization of the agricultural sector to the extent that Brazil's production started increasing faster than its population growth (ROSILLO-CALLE; HALL, 1987). Changes were also made to the system architecture including the introduction of new pipelines, railroads, highways, and waterways. Tanks were also redesigned to accommodate the new fuels. Nonetheless, while impressive and substantial in terms of investments, these developments are considered to be 'add-ons' to an existing socio-technical system that was in the main managed by Petrobras. In other words, we argue that the sum total of these changes do not constitute a niche-driven substitution per se. This period is thus characterised by an active policy stream, stringent targets enacted by the government, supporting actors located inside and outside the political sphere and relatively little dissent. It constitutes a shift in the transition pathway towards reconfiguration.

5.4.3 Stage 3 – Transition stagnation (1986-1990)

The oil price suddenly fell in 1986, in what became known as the 'oil counter shock', marking the end of the expansion phase for *Proálcool* (SANTOS, 1993; SURREY, 1987). A concurrent rise in sugar prices encouraged sugarcane producers to sell their crops in export sugar markets away from the domestic ethanol market (ALVES; VOGEL, 1996; CHAGAS, 1997). The combined effect of these price changes contributed to a shift in the mood of national insiders by making them more resistant to the use of ethanol as a fuel. This reduced the overall appeal of *Proálcool* (GLOBO, 1986). Petrobras was hit particularly badly by this sudden reversal in price and mood, and was forced to scale down its oil exploration investments substantially (FOLHA, 1986; SIAN, 1986). Smaller ethanol producers were also affected and many local distilleries closed down (SANTOS, 1993). Car manufacturers were relatively less affected as they were able to adapt their cars to whatever fuel was in demand.

Theory predicts that due to path dependencies, when incentives revert as they did here, the system tends to returns to its old ways (ELZEN *et al.*, 2004). Hence with the price of oil plunging and the price of sugar rising, the trend away from fossil fuels stalled and by the end of 1989, the country was experiencing major ethanol-fuel distribution shortages. The program of transition to an ethanol-based regime became under serious threat (NOGUEIRA, 1989; SIAN, 1990), to the frustration of the 4.5 million consumers who purchased ethanol-only fuelled cars (CHACEL, 1989; ORDOÑEZ, 1989). The transition had more or less stopped and the system was in danger of reverting back to its original petrol-based state.

5.4.4 Stage 4 – Transition reversal (1990-2000)

In the 90s, Brazil underwent a major political shift, moving from a military to a democratic regime intent on market reforms and economic liberalization. The IAA was shut down and prices of sugar and anhydrous ethanol, hydrated ethanol, and gasoline were deregulated in 1997, 1998 and 1999 respectively. Petrobras' monopoly also ended in 1997 (BRAZIL, 1997) and several parts of the oil market – i.e. exploration, refining, transportation, import and export of petroleum and derivatives - were now operating in more competitive settings. New players, including a number of multinational companies entered the arena and incumbent actors were forced to adapt.

This period is characterised by a drastic change in the 'mood' of national actors, away from the ethanol program and back again. In the earlier years, consumer preferences for cheap and abundant petrol re-established the predominance of gasoline-powered vehicles. While automakers were generally content to accommodate these preferences, they also became subject to regulations linked to the new Program for Control of Air Pollution by Motor Vehicles (PROCONVE) introduced by the National Environment Council (CONAMA) in 1989 (CONAMA, 1989). This incentivised the industry to align with a minimum requirement of 22% anhydrous content. Nonetheless, there were clear signs that the transition was embarking on a reversal path.

As the decade progressed however, workers in the sugarcane industry became increasingly more organised and successful in publicising the devastating effects this reversal was having on their livelihood. Manifestations multiplied in size and scope and reverberated through the system, eventually refocusing the mood of national outsiders on employment and job security. An "employment pact" between the federal government, car producers and the sugar-alcohol sector was signed in 1999, reinstating incentives for the production and consumption of ethanol-fuel vehicles and subsidies for R&D in related technologies (CIOCCARI, 1999; MORAES; ZILBERMAN, 2014; OLMOS, 1999).

Hence, while the transition to ethanol fuels was in serious jeopardy following the fall in oil prices and the deregulation of fuel markets, pressures from national insiders (e.g. producers) and outsiders (e.g. commercial associations, shopkeepers) mitigated some of the effects of market liberalisation, reinstating incentives to producers and consumers to remain in the ethanol industry.

5.4.5 Stage 5 – Transition resurgence (2000-2020)

Interestingly, it is only at the start of the new millennium that *Proálcool* started to be viewed as a 'green' program. While automakers already had to comply with the basic PROCONVE emission regulations, new more stringent requirements were introduced for petrol-based vehicles (PROCONVE Phase L4). The realisation that ethanol is a more environmentally-friendly fuel gained momentum and policy initiatives were launched – such as 'Green Fleet' - that established a gradual substitution of the government official fleet to ethanol-powered alternatives on favourable terms (BRAZIL, 1998).

More concretely, gasoline-powered cars did made a comeback but resistance from sugarcane incumbents, societal pressure, and an emerging environmental movement created a window of opportunity for the introduction of the flexible fuel vehicle (FFV) (VOGEL, 2002). This was a genuinely new technology that would give consumers the flexibility of fuelling their cars with ethanol and/or gasoline to any extent they chose. Awareness and endorsement of FFV technology quickly grew amongst automakers, suppliers, academia and R&D institutes attracted by its potential to service consumers wanting to alternate between petrol and ethanol depending on their relative price and availability. FFV technology was also welcomed by governments as it would help them cater to demands from both the petrol and ethanol sectors. Accordingly, the development of FFV cars received widespread government support in the form of reduced car taxes, R&D subsidies to industry, and support to agricultural bodies in the development of more robust and abundant sugarcane crops (HIRA; DE OLIVEIRA, 2009). Finally, we note that existing system infrastructure was also conducive to the emergence and diffusion of FFV.

What is particularly striking about this period is the societal consensus that emerged around FFVs. Moreover, this consensus was principally enacted by incumbent actors (auto-parts industries, automakers, technology companies) and not by government insiders as was the case with the original *Proálcool* initiative. Unlike electric vehicles which were first commercialized in Brazil in 2006 but experienced a very slow diffusion, the market fully embraced FFVs. These now represent over 95% of new passenger car sales (ANFAVEA, 2018). The transformation pathway thus regained its strength along with technological substitution as incumbent actors reoriented themselves towards the new technology and FFVs successfully reinstated ethanol as a major fuel.

5.5 ANALYSIS AND DISCUSSION

In terms of characterising the nature of Brazil's fuel technology system transition, we argue that it shares features associated with the 'transformation' pathway. While some reconfigurations did take place over the 50 year period - i.e. those linked to ethanol fuel tanking and filling stations, most of the changes were add-ons to existing technologies and best described as 'symbiotic'. In more recent years however, the system experienced a major technological substitution in its primary fleet engine (FFV technology), and FFVs became the dominant type of passenger car in Brazil.

Brazil's fuel transition was undoubtedly spurred by the windows of opportunities the various oil and sugar price shocks created, and pressures exerted by insider enactment and regime incumbents. In Stage 1, the government (a military regime) was the main instigator of change thereby acting as its own 'endogenous enactor'. In Stage 2, the government supported and encouraged scientists and engineers' in their efforts to promote *Proálcool*. This national policy intervened in two points of the socio-technical system (Kanger et al., 2020): in the niche level, by accelerating the biofuel production, and in the regime level, by gathering strong efforts towards launching ethanol-based vehicles. Stages 3 and 4 are characterised by a lack of tangible progress in the transition as the system went through a reorganisation of regime actors. Attempts were made to shift the system towards ethanol-only vehicles (Stage 3) but these failed and it reverted to old petrol-based technologies (Stage 4). It is only in Stage 5 that regime insiders experienced strong pressures from outsiders which lead to the launch and widespread adoption of FFVs.

This narrative also highlights a number of interesting elements that were important to the transition but not fully captured by either the MLP or the MSA. Firstly, we note how actors' support (*stance*) for, and importance to (*salience*), the transition fluctuated through time depending on their interests and position in the regime, increasing the complexity of the process. In Stage 2 for instance, Petrobras migrated from an oil company intent on protecting the petrol-based system to an energy company that headed the transition to ethanol. By Stage 3, after suffering considerable losses, Petrobras changed its stance back to petrol and away from ethanol. It also lost much of its influence (salience) on the transition after the deregulation of the oil sector. Similarly, consumers alternated their stance towards ethanol and petrol-based cars depending on the respective price and availability of fuels and their salience on the transition increased through time. Hence, our analyses demonstrate that across periods, actors can change *salience* by acting as primary or secondary agents to the transition, and *stance*, by shifting between being supportive, resistant or neutral towards non-fossil fuel technologies or related policies.

Secondly, the narrative demonstrates how national policies enacted in earlier stages of the transition can have lingering effects decades later. While path dependencies linked to infrastructure developments are central features of the transition literature, policy 'residues' that can either enable or constrain transformations are less visible (MARKARD; SUTER; INGOLD, 2016). We argue that in Brazil's case, both infrastructure path dependencies and policy residues played a critical role in the diffusion of FFVs (BENNERTZ; RIP, 2018). We also showed how some periods saw no distinct progress but were nonetheless instrumental to the process as they allowed actors to consolidate, regroup and reposition themselves, thereby highlighting the potential for policy rebound effects.

Finally, our study demonstrates that sustainable transitions may occur 'fortuitously' when a pre-existing technology is given a sudden and unexpected advantage by new environmental research, consumer preferences and/or social concerns. In Brazil's case, the initial shift to biofuel was driven purely by energy security concerns, not environmental imperatives. Hence while *Proálcool* began as a program intent on reducing Brazil's dependence on oil, it morphed three decades later into one that addressed the nations' growing environmental preferences and objectives (BRILHANTE, 1997).

In other countries however, energy security concerns were combined with environmental preoccupations at a much earlier stage. For instance, greenhouse gas (GHG) reductions were a main driving force for the adoption of alternative fuels in Germany (HAKE *et al.*, 2015), Sweden (JOHNSON; SILVEIRA, 2014), Korea, Japan and California (EU, 2016). It is also the case that policies and strategies introduce specifically to encourage transitions to sustainable technologies can have a negative impact in the longer term (BENVENUTTI; URIONA-MALDONADO; CAMPOS, 2019).

As our analyses demonstrate, the diffusion of FFVs in Brazil is attributed to long standing policies for fuel security, support by car makers, and pressures from workers in the sugarcane industry, none of which were motivated by environmental concerns (GOLDEMBERG; COELHO; LUCON, 2004). Fortuitously however, the advent of FFVs coincided with a growing endorsement of environmental policies by Brazilians (e.g. PROCONVE L4). Moreover, FFVs provided Brazil with a significant comparative advantage in dealing with emerging international pressures to meet environmental targets (EU, 2016). Such developments strengthen the transition to biofuels by aligning it with a wider set of actors and national interests (BENVENUTTI; CAMPOS, 2019). The importance of these dynamics are exemplified by the new federal program (*Rota 2030*) which creates incentives to enhance R&D within the automotive chain (BRAZIL, 2018) and the new national biofuel policy (*Renovabio*) which helps Brazil meet its National Determined Contributions (NDCs) of the Paris Agreement (BRAZIL, 2017).

We posit that these fortuitous windows of opportunities are likely to become a more frequent feature of socio-technical sustainable transitions in developing countries where economic concerns often dominate environmental ones. Ongoing socio-technical transitions may yet to be perceived through sustainability lens but may gain momentum once they are positioned as solutions to both an economic and environmental problem (Kern & Rogge, 2018). Moreover as environmental events multiply and disrupt existing patterns of production, consumption and governance, synergies between sustainable and economic concerns will increasingly coalesce.

Moreover, the concept of 'fortuitous' windows of opportunities is relevant to discussions of problem-solution sequencing in the policymaking process (BÉLAND; HOWLETT, 2016). In Brazil's case, biofuel (i.e. the solution) existed before sustainability concerns (i.e. the problem) were considered important political and policy priorities. Our findings suggest that there may be merits in adopting hybrid approaches to policymaking that combine 'known problem and unknown solution' traditional sequencing with 'known solution and unknown problem' alternatives. This reversal in optic could encourage actors to visualise sustainability issues in more innovative and productive ways and help keep policies under greater scrutiny as they compete against a wider set of potential problem-solution combinations. We argue that doing so could ultimately accelerate the pace of sustainable transitions.

Figure A1 and Chart A1 use the proposed framework to process-narrate key developments in the fuel technology used in Brazil's passenger vehicles in the past 50 yrs. Together they highlight the different and changing stance of actors in each period of the socio-technical transition, and track their ability to influence policy and/or technological development and outcomes (i.e. their salience).

As with other such studies, our approach is subject to a number of caveats. In particular, considerable discretion was exerted in selecting the start and end of each stage, in identifying primary and secondary actors, and in determining their salience through time. Our narrative is also based on documents available through search engines. If earlier documents have not been picked up by these searches, our accounts are underrepresenting their content. Results should be interpreted accordingly.

5.6 CONCLUSION

This study contributes to the literature on socio-technical transitions in four important ways. Firstly, it provides an alternative and richer way of combining the MLP and MSA framework to process-narrate socio-technical transitions. In particular, it allows actors to be dominant in one period but secondary in another, thereby allowing them to exert different levels of pressures (or salience) at different stages of the transition. Our proposed amendments also allow actors to change their stance towards the transition in line with changing events. We argue that introducing actors' salience and stance to the MLP-MSA framework allows the narrator to capture a more dynamic version of the transition, one that reflects evolving power relations in a changing landscape.

Secondly, our amended framework emphasises the important long-term effects policies exert on socio-technical transitions even decades after they have become inactive. We argue that these lingering effects or 'policy residues' can potentially be as powerful as infrastructure developments in creating path dependencies, whether as enablers or constrainers of future sustainability transitions. This suggests that accounting for past national policies and investigating potential 'policy rebound effects' could improve our understanding of sustainable transitions.

Thirdly, our analysis highlights the importance of 'fortuitous' sustainability transitions and suggest that these can be particularly relevant to developing countries. We argue that sustainable transitions can become feasible even in situations where environmental concerns are not the primary driver of change. More concretely, certain technologies originally conceived and developed as solutions to economic or other problems may become more attractive when seen through the lens of mounting environmental pressures, as was the case with Brazil's fuel technology transition.

Our final contribution is in producing a process-narration of the 50-year socio-technical transition experienced by Brazil's passenger vehicles fuel-technology fleet. This adds another data point to the growing number of such analyses, eventually allowing others to meta-analyse the features of successful socio-technical sustainability transitions.

5.7 APPENDIX A

Figure A1 - Conceptual framework representation of the *actor-centred* MLP + MSA frameworks using Brazilian passenger vehicles case (1970-present).

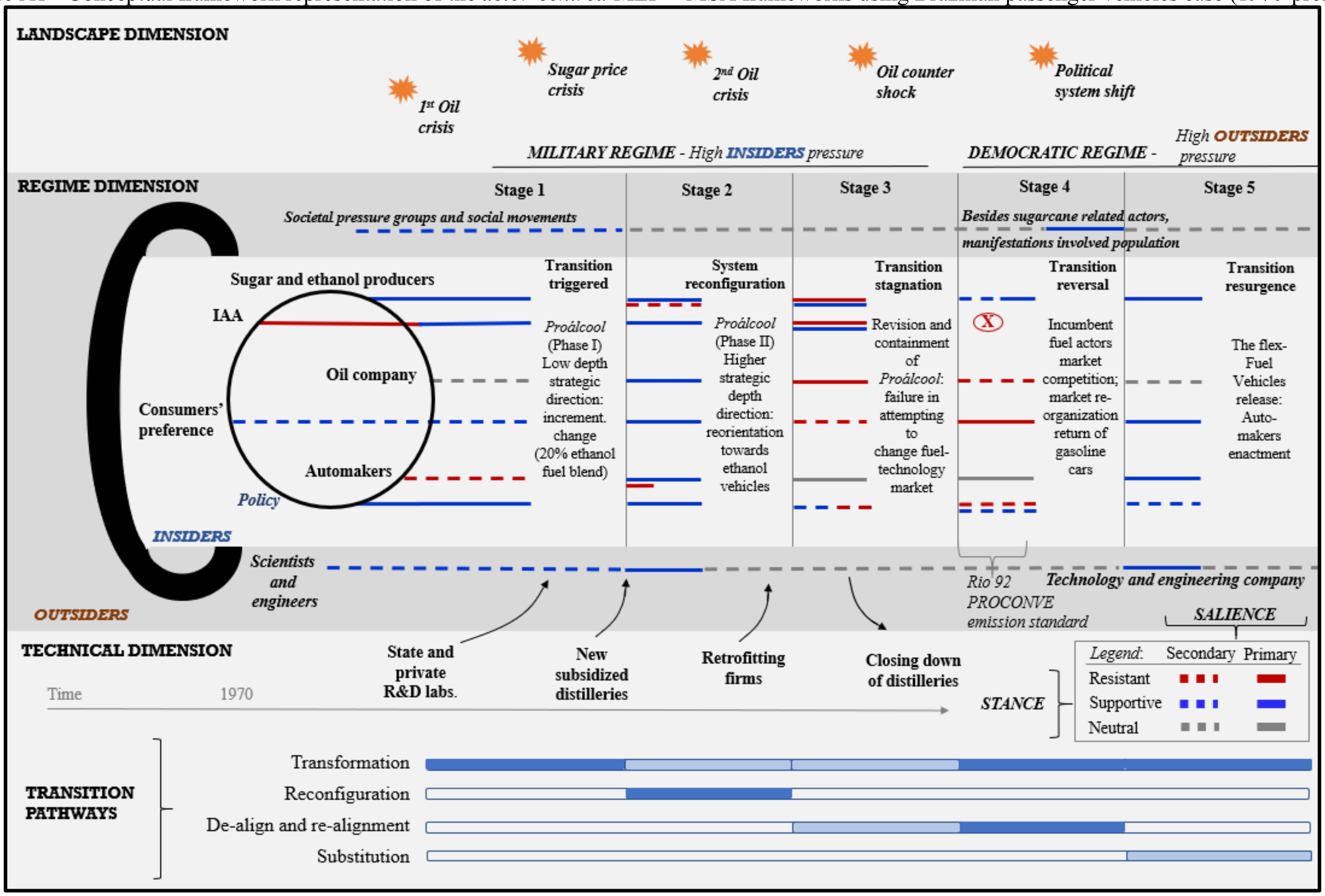

Chart A1 - MSA element classification for Brazil's sociotechnical fuel-technology fleet transition (1970-present).

Adapted MSA streams	**Stage 1**	**Stage 2**	**Stage 3**	**Stage 4**	**Stage 5**
Problem Stream					
Indicators	High oil prices Oil scarcity predictions Import oil dependency	Economic crisis Energy security concern Sugarcane surpluses	Oil prices dropped** Oil production rise** Sugar price rise**	Ethanol-car sales decline Petrobras' deficit rose	High oil prices Sugarcane industry crisis
Focusing events (landscape shocks)	1st Oil crisis Sugar crisis	2nd Oil crisis	Oil counter shock Sugar market rise	Political system shift Protests	Residue from prior stages
Feedback: path that worked before	Ethanol infrastructure and know-how	Ethanol previous use as fuel	Economic recovery plan working	Gasoline-powered vehicles return	Dual fuel infrastructure in place
Politics Stream					
Party Ideology	Military government	Military government	Military regime	Democracy	Democracy
National actors' stance (mood): **resistant** to change*	Automakers IAA (at first)	Automakers at first Northeast producers	Petrobras, IAA, ethanol producers, consumers	Policy (deregulations), consumers, Petrobras	
National actors' stance (mood): **supportive** to change*	Government, sugarcane sector, population in general	Government, sugarcane sector, consumers, oil company, scientists	IAA, ethanol producers, policy stream	Sugarcane industry, policy, societal groups	Overall acceptance from regime actors
National actors' stance (mood): **neutral**	Oil company	Outsiders	Automakers, outsiders	Automakers, outsiders	Outsiders, oil company
Policy Stream					
Value acceptability	Industrial development National security	Reduce oil dependency	Low: profitable oil and sugar	Environmental awareness growing	Industry recovery Environmental value
Technical feasibility	Higher ethanol rates previously used	Ethanol-powered vehicles able production	Shaken: ethanol-powered vehicles lost credibility	Minor action, know-how already in place	Common incentives type
Policy Output					
Fuel (ethanol content in gasoline blend)***	1-5% to 20%	15-22%	18%-22%	20-24%	20-27%
Technology, policy, infrastructure	*Proálcool* (phase I)	*Proálcool* (phase II) Ethanol-based vehicles Ethanol tanking, stations	*Proálcool* (still phase II)	Green Fleet, deregulations, PROCONVE L3	FFV, *Few initial tax incentives,* PROCONVE L4, L5, L6

* Change from less to more sustainable fuel/energy sources.
** The national energy strategy was jeopardized by the sudden changes in oil and sugar prices.
***Source: MAPA (2015).
Green: Landscape Dimension. Blue: Regime Dimension. Purple: Technical Dimension.

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CHAPTER VI

6 ELECTRIC VERSUS ETHANOL BASED VEHICLES: A NEW WELL-TO-WHEEL SYSTEM DYNAMIC MODEL OF BRAZIL'S CASE

This chapter presents the fourth paper of this thesis, being the first result of step 3. It is currently under final adjustments for journal submission[11].

Abstract

Modelling has become one of the key means to provide directions for policymakers towards a more sustainable transportation system. However, discrepancies in results are emerging questioning the reliability of estimates promoting the wide-scale adoption of green technologies, creating confusions and debates amongst policymakers. More holistic models that include well-to-wheel (WTW) system dynamic modelling with an embedded temporality perspective and built-in sensitivity tests for a wide range of assumptions can improve the robustness of model predictions and enhance their relevance for policy. Fleet-based Well-to-wheel Model for Policy Support (FWEMPS) tool offers these features. The application of our model suggests that technologies assumed to be environmentally friendly may not be such in certain life cycle context, and reaffirms that how we model things really matters. Amongst other things we find that the benefits of green technologies depend in important ways on the specific context of a country and that using endpoint life-cycle assessments weighs the results in favour of electrification for most countries. Importantly, we find that for Brazil, ethanol dominates under a wide variety of extreme scenarios, and depending on the assumption of land use change expansion, there may be negative well-to-tank emission by an increase of biofuel production. Results also highlights ambiguities, which provide relevant insight for policymakers for future sustainability transitions.

Keywords: Modelling; well-to-wheel; light-vehicles fleet; system dynamics; midpoint; endpoint.

6.1 INTRODUCTION

Transportation sector alone is responsible for the emission of nearly 16% of the world's greenhouse gas (GHG) emissions, where road transport accounts for about three

[11] BENVENUTTI, L. M. M.; CAMPOS, L. M. S.; VAZQUEZ-BRUST, D. A.; LISTON-HEYES, C. Electric versus ethanol-based vehicles: A new system dynamic model of Brazil's case. Working paper (Chapter 6 of this doctoral thesis), 2021.

quarters of that amount (WRI, 2016). Additionally, this sector consumes large proportion of energy (e.g. fossil fuel oil) and is a major source of urban air pollutants (e.g. particulate matter, carbon monoxide, nitrogen oxides) harmful to population health. Air pollution is estimated to cause 7.6% of deaths worldwide (WHO, 2016), and thus transitioning to a more sustainable and low-carbon transportation system includes at least two important spheres: environmental and human health.

Alternative fuel vehicles (AFV) have gained a spotlight on the task of reducing transportation emissions. Biofuel-based (e.g. flexible fuel vehicles, FFV) and electric vehicles (EV) are examples of AFV and are expected to provide lesser air pollutants compared to fossil fuel-based ones and thus contribute to global warming mitigation. GHG emissions from biofuel-powered vehicles are considered carbon neutral, but there are other emissions to account for, e.g. photochemical ozone formation, well-to-tank (WTT) emission such as from land use change (LUC). Battery electric vehicles (BEV) are completely emission free, but its WTT power generation emissions must be evaluated to affirm whether or not its well-to-wheel (WTW) emissions are indeed lower than other fuel-technology types. In this regard, life cycle assessment (LCA) is a useful tool to assess environment impacts of one or more technologies by comparing them with similar functional unit.

However, while single unit LCA have led to significant advances in how we account for the impact production and consumption activities exert on the environment, these studies lack in capturing impact effects of technology insertion through time and, consequently, policies effects in the long term (FIELD; KIRCHAIN; CLARK, 2000; GARCIA; FREIRE, 2017). The temporal aspect of sustainability is a current topic of discussion and relevant for actors involved in sustainability-oriented governance arrangements (BORNEMANN; STRASSHEIM, 2019). The urge to develop life cycle-based approaches to evaluate scenarios, to account for the transdisciplinary integration framework of models/methods, and deal with rebound effects and uncertainties have been encouraged for future LCA studies (GUINÉE, 2015; GUINÉE *et al.*, 2011; ZAMAGNI; PESONEN; SWARR, 2013).

To attend the abovementioned gaps and research calls, our paper introduces the Fleet-based Well-to-wheel Model for Policy Support (FWEMPS) and further applies it to the case of Brazil. The country provides an interesting case study given its unusual history as the world lead in biofuel volume production per vehicle (HARVEY; BHARUCHA, 2016), the second largest producer of ethanol (STATISTA, 2019), and its trajectory in the proportional size of its hybrid flexible fuel cars (see BENVENUTTI *et al.*, 2021, for an account of Brazil relationship with ethanol).

Our paper makes several contributions to the field of modelling sustainability impacts of transport. First, with FWEMPS we expand the ability of current LCA models to support policy by broadening the level of analysis from a single product to a system-oriented perspective, engaging with temporality in policy testing, and integrating different methods/techniques to assess sustainability impact (e.g. system dynamic modelling, LCIA, Bass diffusion model), as they have been encouraged within the LCA community (GUINÉE, 2015; GUINÉE *et al.*, 2011; HALOG; MANIK, 2011).

Secondly, we contribute to reduce ambiguity and define standards in our field of modelling. There has been lack of consensus, comparability, and transparency regarding basic model assumptions, especially for biofuels, which affects its LCA results acceptance in the policy context (see PEREIRA *et al.*, 2019, for a review on this issue). There are, therefore, still controversies in terms of the reliability of outcomes of policy-neutral assessments about the impacts these AFV have on the environment, and the extent to which they are better than other fuels. Thus, by clearly identifying, comparing, and discussing the assumptions of the model, the study provides an inventory of emerging conventions thereby serving as a useful benchmark upon which existing and future impacts can be assessed, adding transparency and clarity to the field while facilitating replicability. In doing so, we present sensitivity analysis of five different mitigation policy strategies (energy efficiency, reduced travel, renovation of the fleet, biofuel rate, and EV sales only), provide comparison of extreme scenarios, highlight the sensitivity of LUC emission impact, and address the power mix by comparing results with other countries mixes characteristics.

Finally, our study provides genuine and up-to-date policy guidance for Brazil regarding fuel-technology of passenger (light-vehicles) fleet. To the best of our knowledge, we are the first to use entirely representative emission data for the specific region of Brazil, with characterization factors recently added in the international database Ecoinvent 3.6 (see DONKE *et al.*, 2020, for LUC's integration on Ecoinvent database and effects in results), with updated values from EMBRAPA (2020), and some midpoint and endpoint impacts values using country specific data from Recipe (2016).

The rest of the papers is structured as follows. In section 6.2, the theoretical framework along with the methodology involved for the completion of this study is described. First, beginning with the description of FWEMPS, then providing the life cycle assumptions of the model. Section 6.3 involves the description of each set of scenario testing chosen for this study, namely: (i) sensitivity analysis, (ii) extreme scenarios, (iii) LUC scenarios, and (iv) power mix comparison. In section 6.4, the results of each group of scenario testing are presented, along with some discussion. Lastly, section 6.5 presents the conclusion of this research.

6.2 THEORETICAL FRAMEWORK AND METHODOLOGY

In the transportation sector, the term well-to-wheel (WTW) is commonly used to relate to two important phases of the vehicles' life cycle, i.e. well-to-tank (WTT) and tank-to-wheel (TTW) (JEC, 2014). The WTT phase may encompass the impacts of production, transport, and distribution of conventional and alternative road transportation fuels. The TTW phase includes the impacts during the vehicles' life in transit. WTW can be considered a simplified LCA, since it does not consider energy and/or emissions involved in building facilities, the vehicles themselves, or end of life factors (JEC, 2016; MORO; HELMERS, 2017).

The specific boundary of this study is defined considering a fleet-based WTW analysis approach. The term 'fleet-based', as it is not a life cycle analysis of a single product, but of a set of units (FIELD; KIRCHAIN; CLARK, 2000), in our case, the light-vehicles fleet. Additionally, fleet-based approach considers analysis in a temporal aspect, which is then capable of capturing the substitution of older products by new ones and, therefore, assess the effects of technology turnover over time. This approach is mostly appropriate for evaluation of impacts when introducing a new technology and specially applied on the transport studies to assess evolution scenarios (GARCIA; FREIRE, 2017).

In terms of modelling tool, a system dynamic (SD) approach is used to assess the WTW. SD models are designed to explore possible futures and ask 'what-if' questions (MEADOWS, 2009), which is then useful to tackle life cycle sustainability investigations (GUINÉE *et al.*, 2011). It is fundamentally an interdisciplinary tool, grounded in the theory of nonlinear dynamics and feedback of human behaviour as well as physical and technical systems. The modelling process seeks to represent a system in a way that stock and flow structures along with time delays and feedback loops determine the dynamics of a system (STERMAN, 1994). As it provides an analysis through time, it is able to capture potential policy strategies impact in the long-term (STERMAN, 2000), which aligns with main purpose of the model, i.e. to serve for policy support.

6.2.1 Fleet-based Well-to-wheel Model for Policy Support (FWEMPS) descriptions and assumptions

FWEMPS' vehicle fleet estimate is run by two interconnected diffusion subsections: one for the overall light-vehicles fleet diffusion using the original Bass Diffusion Model (BM), and the other for the EV's diffusion using the Generalized Bass Diffusion Model (GBM). These diffusion structures were based on the SD models published in Benvenutti; Ribeiro and Uriona (2017) and Benvenutti; Uriona-Maldonado and Campos (2019). The former focused on the effectiveness of tax incentive policies in the diffusion of electric and hybrid cars in Brazil using the GBM, while the later assessed the impact policies may have on the CO_2 TTW emission of passenger fleet. FWEMPS merges each of them, includes a few modifications and adaptations, and expands the scope of analysis in the following ways:

(i) includes several others air pollutants to account for TTW emission impacts;

(ii) broadens the level of life cycle analysis by including the WTT analysis of the fuel/power production impacts;

(iii) connects environmental impacts to human health impact;

(iv) provides an inner interface for the user to test a variety of policies (individually or combined) using a different range of inputs;

(v) includes historical fuel production data for history match validation (besides the licensing and vehicles fleet number).

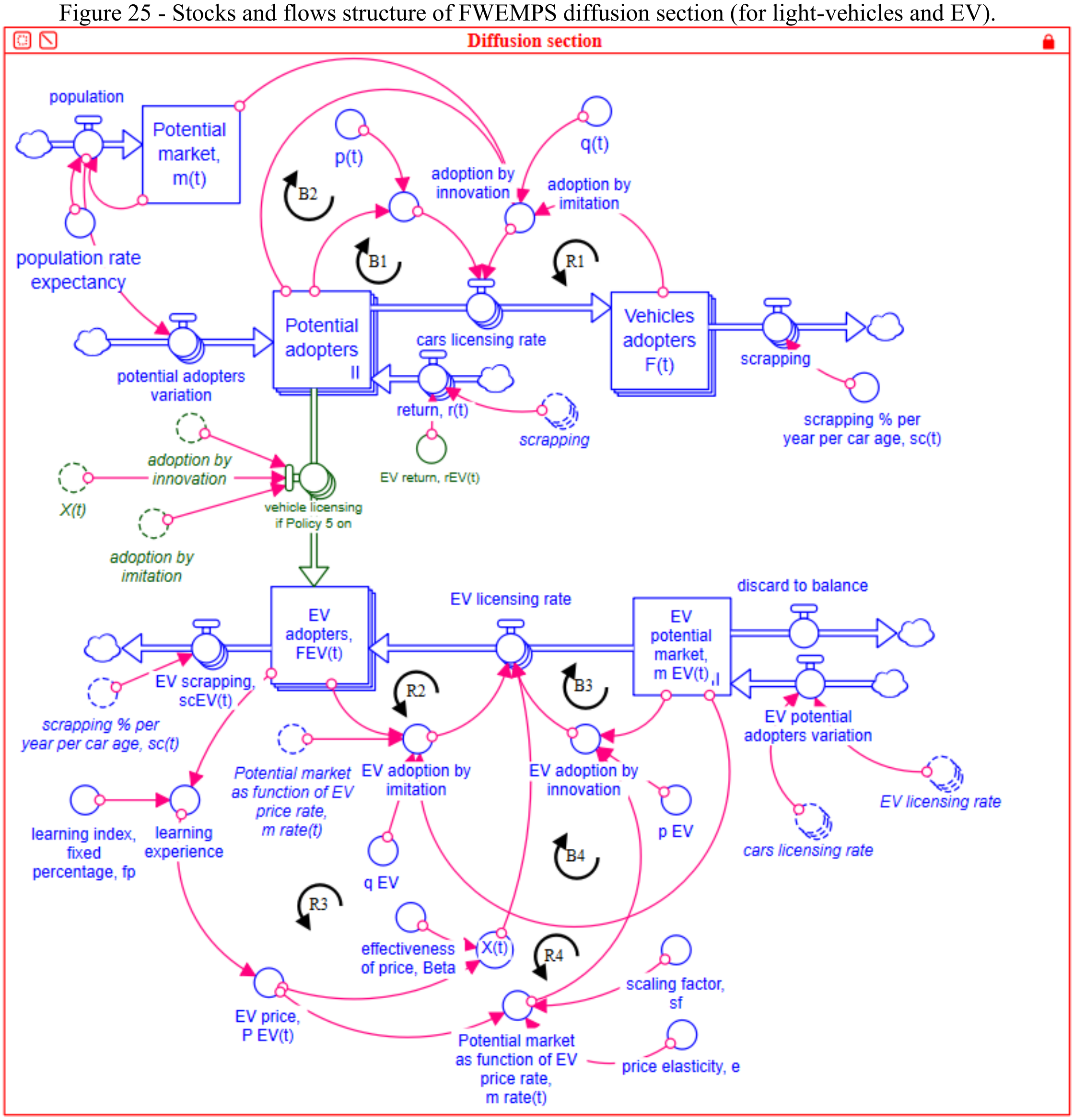
Figure 25 presents the basic stocks and flows of the main dynamics involved in the diffusion structure system. The main loops are highlighted by a loop identifier, i.e. either positive (reinforcing, R) or negative (balancing, B) loops. A reinforcing loop is when the feedback effect of a change in any of variables around the loop, *ceteris paribus*, reinforces the original change. In a balancing loop, it occurs the opposite (STERMAN, 2000). There are four balancing loops and four reinforcing loops, each number referring to the loop labels on Figure 25. Balancing loops:

1. Potential adopters → (+) adoption by innovation → (+) car licensing rate → (-) potential adopters
2. Potential adopters → (+) adoption by imitation → (+) car licensing rate → (-) potential adopters
3. EV potential market → (+) EV adoption by innovation → (+) EV licensing rate → (-) EV potential market
4. EV potential market → (+) EV adoption by imitation → (+) EV licensing rate → (-) EV potential market

Reinforcing loops:

1. Vehicle adopters → (+) adoption by imitation → (+) car licensing rate → (+) vehicle adopters
2. EV adopters → (+) EV adoption by imitation → (+) EV licensing rate → (+) EV adopters
3. EV adopters → (+) learning experience → (-) EV price → (-) X(t) → (+) EV licensing → (+) EV adopters
4. EV adopters → (+) learning experience → (-) EV price → (-) Potential market as function of EV price rate → (+) EV licensing → (+) EV adopters

Figure 25 - Stocks and flows structure of FWEMPS diffusion section (for light-vehicles and EV).



Source: Elaborated by the authors.

The BM (Bass, 1969) is essentially driven by the sum of two mechanisms, one from advertisement and the other from word-of-mouth forces, and they are dependent on the adoption by innovation (p) and by imitation (q) factors, respectively (eq. 1, used for the general light-vehicles diffusion upper part section, Figure 25). F(t) is the cumulative function of adopters at time t and potential market size, m. Potential adopters assume the result of: $m - F(t)$.

$$\frac{dF(t)}{dt} = p[m - F(t)] + \frac{q}{m}F(t)[m - F(t)], \qquad t \geq 0 \tag{1}$$

In our case, some adaptations and extensions are considered. First, market size varies through time, $m(t)$, exogenously following the historical (1980-2019) and projected (2020-2050) population between 20-80 years old (IBGE, 2018b). Furthermore, there is a scrapping rate per vehicles' age, $sc(t)$, that leaves from $F(t)$ (vehicles adopters' stock) and partially returns, $r(t)$, to the potential adopter's stock, eq. 2.

$$\frac{dF(t)}{dt} = p(t)[m(t) - F(t) + r(t)] + \frac{q(t)}{m(t)}F(t)[m(t) - F(t) + r(t)] - sc(t), \qquad t \geq 0 \tag{2}$$

Because the scrapping rate are assigned differently per vehicles' age (Table A1, Appendix A), a vector built-in function array is used to facilitate representing each group of vehicles (per age) as agents. This helps connecting each group with the subsequent section of the model on gases emissions average data that varies each year. See Benvenutti; Uriona-Maldonado and Campos (2019) for disaggregating representation of the $F(t)$ stock. Chart 3 presents the key parameters and assumptions of this section.

Chart 3 - FWEMPS' parameters and assumptions - light-vehicles fleet diffusion section.

Variable	**Value and description**	**Source**
$p(t)$ and $q(t)$	Adoption by innovation, $p(t)$, and by imitation, $q(t)$ factors from Bass diffusion model (BASS, 1969). Historical values per time in Table A2, Appendix A. Projection years: $p(t) = 0.002$ *and* $q(t) = 0.125$ (values approximate to the last historical year values found in BENVENUTTI; RIBEIRO; URIONA, 2017)	Adjusted/updated values from Benvenutti; Ribeiro and Uriona (2017)
$sc(t)$	Scrapping rate per vehicles' age. Based on Gompertz function, adopted by the Brazilian Automotive Industry Association (ANFAVEA) and by the National Union of the Components Industry for Motor Vehicles (SINDIPEÇAS), (Table A1, in Appendix A)	MCT (2006)
$m(t)$	Potential market. Exogenous value. Initial potential market is the population between 20-80 years old in 1980. Then it varies according with historical (1981-2019) and projection (2020-2050) changing rate of the same people group	IBGE (2018b)

$r(t)$	A return number, 6/7 of the sum of scrapping vehicles number (representing their previous owners) is considered to return to potential adopters' stock	Authors' own assumption

Source: Elaborated by the authors, based on the sources presented in the 3rd column.

For EV's diffusion part section, the GBM was used. It includes a mapping function, $X(t)$, to the general BM, related to decision variables such as price and advertising (BASS; KRISHNAN; JAIN, 1994) (eq. 3). In our case, the EV's average price was chosen as decision variable, where $P(t)$ is the average EV price at time t, and β the effectiveness of price over the time (eq. 4). Moreover, assuming that any EV cost reduction are fully passed into their average price, the effect of learning (ARGOTE; EPPLE, 1990) assumes the function of equation 5. The fp represents a fixed percentage by which the EV price falls with every doubling of experience (cumulative adopters), and $P(0)$ and $F(0)$ are the initial price and initial number of EV adopters (cumulative experience) at time 2013, respectively (see STERMAN, 2000, p. 338, for further explanations on modelling learning curves). The initial time for the EV diffusion section simulation was set at 2013 as is a middle time between the first EV sold in 2006 and currently, providing enough initial data (adopters) for model diffusion simulation.

Furthermore, in this study, the EV potential market, $m^{EV}(t)$, is assumed to be dependent of the size of total vehicles adopters, $F(t)$, i.e. we assume that the maximum EV potential market size are the number of people who owns cars[12] (vehicles adopters, which varies per year). However, and additionally, $m^{EV}(t)$ is also impacted by the EV average price, $P^{EV}(t)$, in comparison to the popular conventional cars (CC) average price, $P^{CC}(t)$, which represents customers that are willing to buy at a certain price. For this, we use the same demand function commonly adopted in economics but to the relation between potential market and price (eq. 6), where sf is a scaling factor and e is the coefficient of elasticity for price (a relation of this type have been previously used by BOEHNER; GOLD, 2012; JAIN; RAO, 1990; NARASIMHAN; GHOSH; MENDEZ, 1993).

Thus, taking the reference 2013 year, a potential market rate relation, $m^{rate}(t) = \frac{sf\ P^{EV}(t)^{-e}}{sf\ P^{CC}(2013)^{-e}}$ is considered for the calculation of $m(t)^{EV}$. This means that as $P^{EV}(t)$ decreases by the effect of the learning curve (eq. 5), its potential market rises (or the exact opposite). The

[12] This assumption is subject to change if a policy related to internal combustion engine (ICE) sales ban would be launched (where the green part of Figure 25 would be activated, more on this on policies description).

maximum number for $m^{EV}(t)$, i.e. $F(t)$, is only reached if this rate equals 1, when $P^{EV}(t)$ drops at the same level as popular conventional cars (CC) average price, $P^{CC}(t)$ – all prices considering 2013 levels. In FWEMPS, this second rationale consideration (potential market relation to the price) is inherent calculated within adoption by innovation and imitation parameters, the stock $m^{EV}(t)$ assumes the first implication $F(t)$ size variation (as Figure 25 depicts, programmed to maintain $F(t)$ size).

$$\frac{dF(t)}{dt} = \left(p[m - F(t)] + \frac{q}{m}F(t)[m - F(t)]\right)X(t), \qquad t \geq 0 \tag{3}$$

$$X(t) = 1 + \beta\,\frac{P(t) - P(t-1)}{P(t-1)} \tag{4}$$

$$P(t) = P(0)\left(\frac{F(t)}{F(0)}\right)^{log_2(1-f_p)} \tag{5}$$

$$m(t) = sf\ P(t)^{-e} \tag{6}$$

Finally, by considering these hypotheses and combining equations 3, 4, 5, and 6, equation 7 presents the function for the EV adopters, $F^{EV}(t)$, diffusion section. Inputs of the parameters are shown in Chart 4.

$$\frac{dF^{EV}(t)}{dt} = \left(p^{EV}(\mathrm{t})[m^{EV}(t) - F^{EV}(t) + r^{EV}(t)] * \frac{sf\ P^{EV}(t)^{-e}}{sf\ P^{CC}(2013)^{-e}} + \frac{q^{\,EV}(t)}{\left(F(t) * \frac{sf\ P^{EV}(t)^{-e}}{sf\ P^{CC}(2013)^{-e}}\right)} F^{EV}(t)[m^{EV}(t) - F^{EV}(t) + r^{EV}(t)] * \frac{sf\ P^{EV}(t)^{-e}}{sf\ P^{CC}(2013)^{-e}} \right) * \left(1 + \beta\,\frac{P^{EV}(2013)\left(\frac{F^{EV}(t)}{F^{EV}(2013)}\right)^{log_2(1-f_p)} - P^{EV}(2013)\left(\frac{F^{EV}(t-1)}{F^{EV}(2013)}\right)^{log_2(1-f_p)}}{P^{EV}(2013)\left(\frac{F^{EV}(t-1)}{F^{EV}(2013)}\right)^{log_2(1-f_p)}} \right) - sc^{EV}(t) \tag{7}$$

Chart 4 - FWEMPS' parameters and assumptions – electric vehicles' diffusion section.

Variable	**Value and description**	**Source**
$P^{EV}(t)$	Average EV commercial price. Initial price $P^{EV}(2013)$ = 250 thousand BRL	UOL (2019)
$P^{CC}(t)$	Average popular conventional cars. $P^{CC}(2020)$= R$ 46,466. Considering average inflation of 5.88% since 2013, thus $P^{CC}(2013)$ estimate of: 31.148 thousand BRL	NoticiasAutomotivas (2020) Inflation (2020)
β	Effectiveness of price: -1.1521	Park; Kim and Lee (2011)

fp	Fixed percentage by which the average EV price falls with every doubling of EV adopters: 8%	Weiss *et al.* (2012)
p^{EV}(t)	The result of the function: $m^{rate}(t)$* $p(t)$ + [1-$m^{rate}(t)$]*p^{EV}, where $p^{EV} = 0.000026$, which is the value found in Massiani and Gohs (2015) for a potential market of 5 million passenger cars, and chosen due to the 5.32 million EV potential market estimated in FWEMPS for 2013	Authors' own assumption and Massiani and Gohs (2015)
$q^{EV}(t)$	The result of the function: $m^{rate}(t)$* $q(t)$ + [1-$m^{rate}(t)$]*q^{EV}], where $q^{EV} = 0.748$, value calculated using Stella Optimization feature, using sum of squares error (SSE) of both licensing vehicles and historical fleet with model's output*	Authors' own assumption and estimate
$m^{EV}(t)$	EV potential market. Endogenous value according to vehicles adopters, $F(t)$. It also varies according with the Eq. 6, although this consideration calculation takes place inside EV adoption by imitation and innovation	Authors' own assumption
sf	Estimated scaling factor from Eq. 6 using 2013 year as reference point, sf = $\frac{m^{EV}(2013)}{P^{CC}(2013)^{-e}}$ =11.4E+15, where $m^{EV}(2013) = F(2013)$, i.e. 33,091,814 (historical vehicle fleet number), e = 1,9 (price elasticity), and $P^{CC}(2013)$= 31.148 thousand BRL (estimated average price estimated based on 2020 values, considering annual average inflation 2013-2019 of 5.88%)	Authors' own estimation based on (ANFAVEA, 2020; INFLATION, 2020; NOTICIASAUTOMOTIVAS, 2020)
e	Coefficient of elasticity for price: 1,9	Nicolay and Jesus (2019)
$sc^{EV}(t)$ and $r^{EV}(t)$	The same rationale as presented in Chart 3	MCT (2006) and authors' own estimate

Source: Elaborated by the authors, based on the sources presented in the third column.

6.2.1.1 Fuel/power usage and vehicle kilometre travelled (VKT)

The amount of gasoline and ethanol fuel estimation per year is calculated using the cars fuel economy (kilometre per litre). We used data that are released by the Environmental Company of Sao Paulo (CETESB) for the state of Sao Paulo, as proxy for the country. This assumption is supported by the fact that Sao Paulo is responsible for 33% of the national vehicles fleet (IBGE, 2018a). The data classifies the average fuel economy of the cars sold in a specific year considering vehicle (gasoline-powered, ethanol-powered, and flexible fuel vehicles) and fuelling type (gasoline or ethanol) (CETESB, 2019) (Table A2, Appendix A).

Also, as CETESB's data are currently results from laboratories, we considered a correction factor of 23.4% to the efficiency of fuel economy to reflect the real use of vehicles (as they use more fuel than what appears in their labels). This is the average correction factor from the Inmetro (2020) reports considering vehicles use on urban and highways roads.

For BEVs, we used the fuel economy of Jaguar I-Pace of 0.72 MJ/km (0.2 kWh/km) commercialized in Brazil (INMETRO, 2020). For the hybrids, we use the fuel economy of the Corolla Altis Hybrid, the first version of a flex-fuel hybrid powered (MERCOPRESS, 2019). We considered the average between driving in urban and highway roads of 10.4 km/litre and 15.4 km/litre, if fuelled by gasoline or ethanol, respectively (INMETRO, 2020). For PHEV, we use the fuel economy of Mitsubishi Outlander being sold in the country of 45 kWh/100miles (0.28 kWh/km) (MITSUBISHI, 2020). In this study, we assume that the EVs diffusion involves 7.5% BEVs, 7.5% PHEV and 85% hybrids.

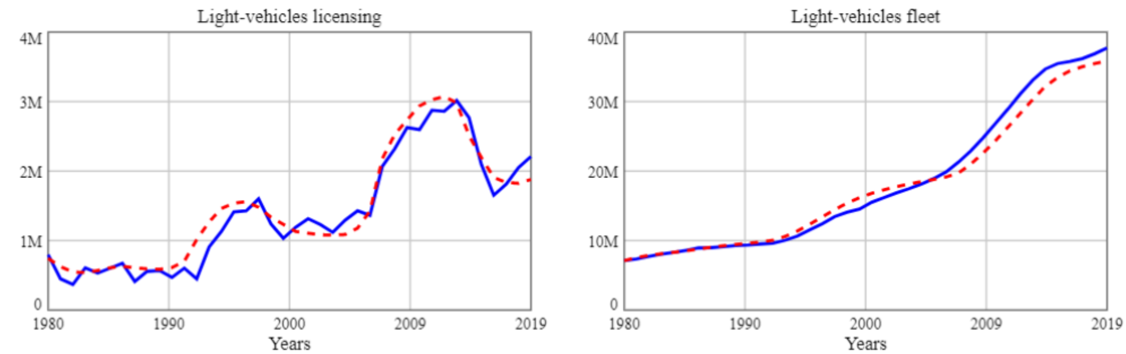
As for VKT, we use data from a study by International Sustainable System Research Centre (USA) in partnership with CETESB (ISSRC, 2004; MMA, 2011). The study was conducted in 2004 and correlates intensity of use (km) with vehicle's age (Table A1, Appendix A).

6.2.1.2 Model validation and history match

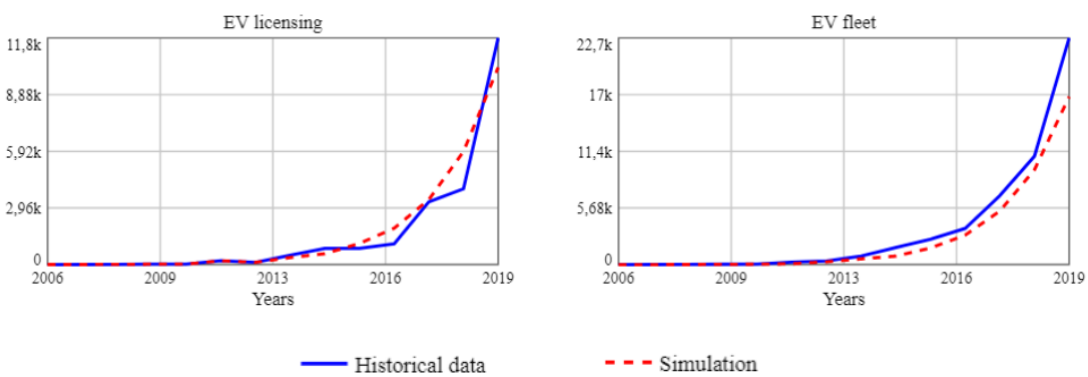
Four variables are used to validate FWEMPS, the licensing rate and circulating fleet for both total vehicles and EV, and gasoline and ethanol fuel use volume (ANFAVEA, 2020; BEN, 2020). The licensing rate and the circulating fleet are the main validation indicators to the fleet diffusion section (at first for passenger vehicles in general, then to EV). The fuels volume, to the WTT fuel estimation section.

First, the parameters $p(t)$ and $q(t)$ are adjusted for history match using values from Benvenutti; Ribeiro and Uriona (2017), updated until 2019 (Table A2, Appendix A). Then, since the premise is that EV potential market is dependent on total vehicles adopters (and average price), $m^{EV}(t) = F(t) * \frac{sf\ P^{EV}(t)^{-e}}{sf\ P^{CC}(2013)^{-e}}$, the fixed value q^{EV} – within $q^{EV}(t)$ –was subsequently calibrated using Stella optimization function for the EV diffusion section. The choice of calibrating the imitator factor over the innovator factor is due the fact that its diffusion strength is greatly felt over the years. The innovation factor diffusion strength is relevant mostly at the very beginning of the adoption period, leading us to use a value from the literature (Chart 4). Figure 26 presents the history match of both diffusion section parts.

Figure 26 - History match of licensing and fleet numbers for (a) light-vehicles (1980-2019) and (b) electric vehicles (2006-2019).



(a)



(b)

Source: Elaborated by the authors, based on historical data source, ANFAVEA (2020) and MMA (2011).

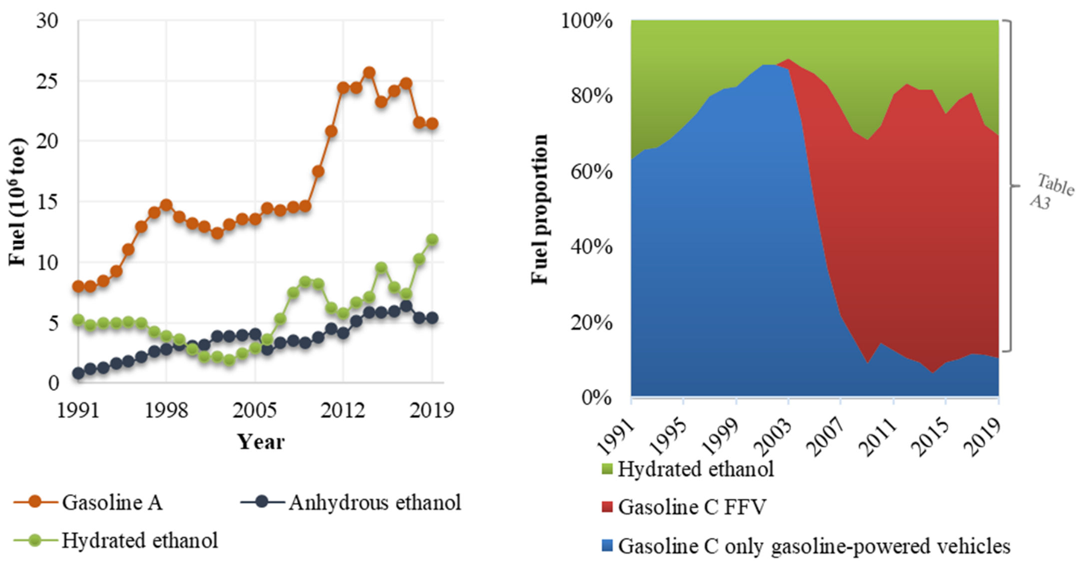
For the history match of gasoline and ethanol use volume, some estimations are needed. Gasoline type C ($GasC$) is a blend of gasoline type A ($GasA$) with anhydrous ethanol ($Etha^{Anhy}$, content varying from 15% in 1990 to 27% currently). Historical data (1991-2019) of fuel consumed are provided in 10^3 tonne of oil equivalent (toe) for $GasA$, $Etha^{Anhy}$ and hydrated ethanol ($Etha^{hyd}$) (BEN, 2020), Figure 27a, so gasoline C volume can be easily calculated. However, there is no data of the fuel proportion used by FFV from 2003 onward ($GasC^{\%FVV}$ and $Eth^{\%FFV}$), which can be fuelled by both $GasC$ and $Etha^{Hyd}$, at any rate. For $GasC$, we removed from total volume a portion related with gasoline-powered vehicles only, based on their production proportion (ANFAVEA, 2020), following equation 8. For $Etha^{Hyd}$, equation 9, we considered all ethanol volume directed to FFV, ignoring the low volume used in low circulating fleet of ethanol-powered vehicles since 2003, which were eventually discontinued in 2007. Figure 27b visually presents this fuel proportion considered for FFV (estimated values in Table A3, Appendix A). This estimate is required for WTW emissions calculation (dependent on the fuel-technology type) and for the subsequent historical fuels volume estimate.

$$GasC^{\%FVV} = \frac{\frac{GasA + Eth^{Anhy}}{GasA + Eth^{Anhy} + Eth^{Hyd}} * \left(1 - \frac{Gas^{light} + Gas^{Comm}}{Gas^{light} + Gas^{Comm} + FFV^{light} + FFV^{Comm}}\right)}{\left[\frac{GasA + Eth^{Anhy}}{GasA + Eth^{Anhy} + Eth^{Hyd}} * \left(1 - \frac{Gas^{light} + Gas^{Comm}}{Gas^{light} + Gas^{Comm} + FFV^{light} + FFV^{Comm}}\right)\right] + \frac{Eth^{Hyd}}{GasA + Eth^{Anhy} + Eth^{Hyd}}} \quad (8)$$

$$Eth^{\%FFV} = 1 - GasC^{\%FVV} \quad (9)$$

where Gas^{light}, FFV^{light}, Gas^{Comm} and FFV^{Comm} are the number of vehicles licensed per fuel type, the first two light-vehicles (gasoline and flexible), and the latter commercial vehicles (gasoline and flexible) (ANFAVEA, 2020, p. 54).

Figure 27 - Historical fuel volume (a) consumed by road transport, and (b) fuel proportion estimate for gasoline-powered vehicles and FFV (gasoline or hydrated ethanol).



(a) (b)

Source: Based on (BEN, 2020) and on ANFAVEA (2020, p. 54), and equations 8 and 9.

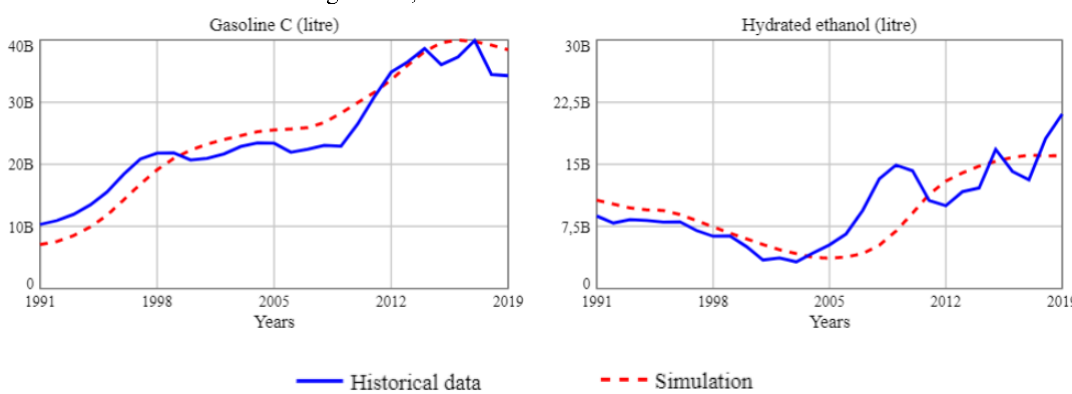
Furthermore, gasoline C is not only used in light-vehicles and FFV, but in commercial and flexible fuel commercial vehicles as well (not the subject of this study). Thus, for historical gasoline and ethanol ($Gas\ C^{light\&FFV}$ and $Eth^{hyd(light\&FFV)}$, in litres) we considered a volume excluding a portion of fuel related with commercial and commercial FFV, also based on their licensing proportion (ANFAVEA, 2020, p. 54), following equation 10 and 11.

$$Gas^{light\&FFV} = \left[\left(\frac{GasA}{0.77}\right) + \left(\frac{Eth^{Anhy}}{0.534}\right)\right] * \left(\frac{Gas^{light} + (GasC^{\%FVV} * FFV^{light})}{Gas^{light} + Gas^{Comm} + [GasC^{\%FVV} * (FFV^{light} + FFV^{Comm})]}\right) * 10^6 \quad (10)$$

$$Eth^{hyd(light\&FFV)} = \left(\frac{Eth^{Hyd}}{0.51}\right) * \frac{Eth^{Hyd(light)} + (Eth^{\%FFV} * FFV^{light})}{Eth^{Hyd(light)} + Eth^{Hyd(comm)} + [Eth^{\%FFV} * (FFV^{light} + FFV^{Comm})]} * 10^6 \quad (11)$$

where $GasA$, Eth^{Anhy}, and Eth^{Hyd} are given in 10^3 toe. $Eth^{Hyd(light)}$ and $Eth^{Hyd(comm)}$ are the number of light and commercial ethanol-powered vehicles licensed, respectively. 0.77, 0.534, and 0.51 are conversion factors from toe to meter cubic (m^3) (BEN, 2020). Figure 28 presents the history match of fuel production.

Figure 28 - Authors' own estimate of historical gasoline C and hydrated ethanol consumed in light-vehicles and light FFV, and FWEMPS simulation results.



Source: Elaborated by the authors, based on historical values from BEN (2020) and ANFAVEA (2020).

6.2.2 Life cycle assumptions

The fleet-model diffusion section can be characterized as the engine for the WTT and TTW calculation for its output are required for their inputs. Figure 29 and Figure 30 presents the stock and flows of TTW gas emission and WTT fuel estimate sections, respectively. See equations B1-8 (Table B1 and Table B2, Appendix B) for the disaggregated calculation of the stocks, following similar agent array structure as in the fleet diffusion section.

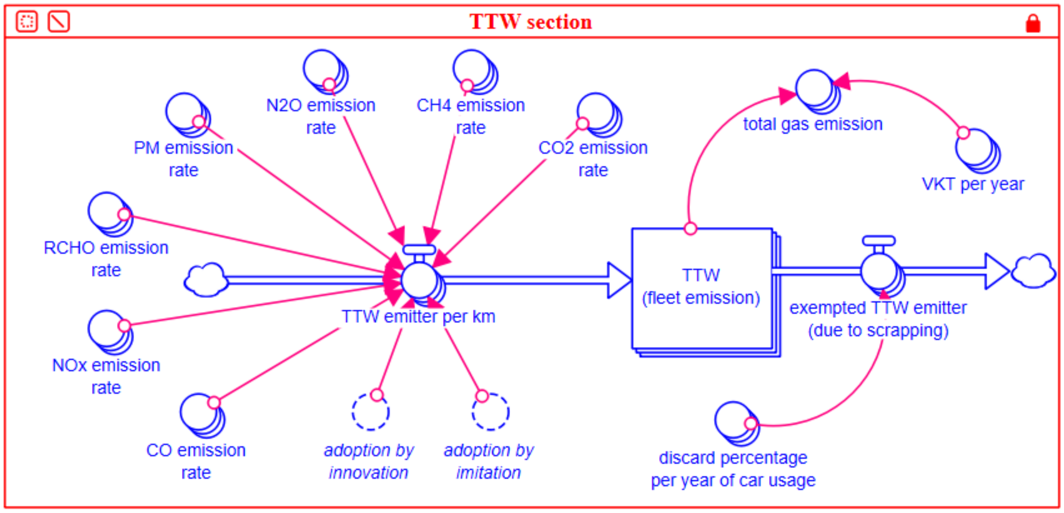


Figure 29 - FWEMPS TTW stock and flows section.

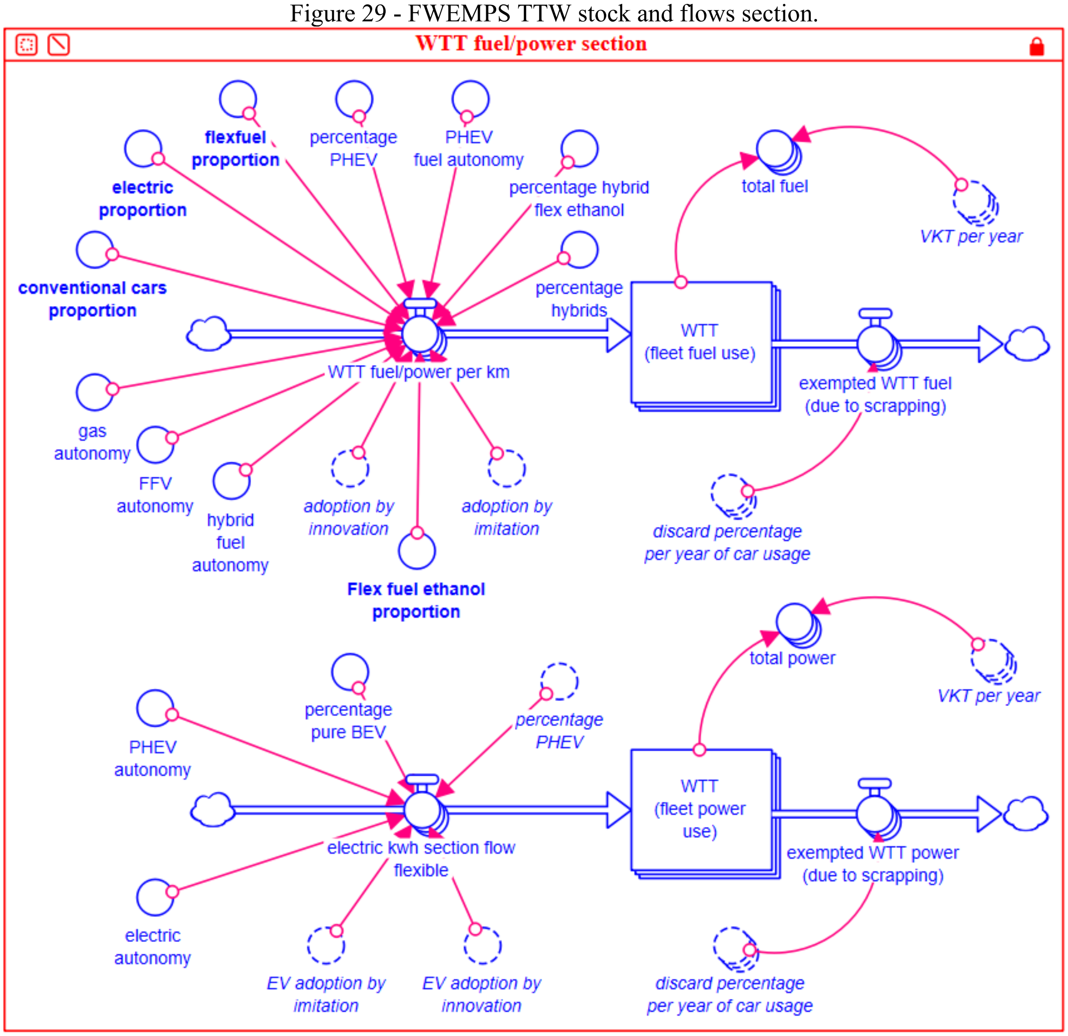


Figure 30 - FWEMPS WTT stock and flows section for fuel (either gasoline or ethanol) and power.

In terms of life cycle procedures, there are four main steps in a LCA methodology: (i) goal and scope definition, (ii) inventory analysis, (iii) impact assessment and (iv) interpretation (ISO, 2006). The impact assessment step takes all elementary flows (from inventory step) and uses a LCA (characterization) method to translate them into indicator results. There are several existing characterization methods (e.g. CML 2002, Eco-indicator 99, ReCiPe, TRACI) that works on either both or one of the impact categories: midpoint and endpoint levels (HAUSCHILD *et al.*, 2013). The midpoint level captures an impact earlier in the cause-effect chain (e.g. climate change), whereas the endpoint level reflects to the end of the chain, normally divided into three impact categories: human health, natural environment (ecosystem quality) and natural resources (resource scarcity). Endpoint indicators are known for its higher relevance compared to midpoint indicators, but are also known for its lower certainty (BARE *et al.*, 2000).

With a focus on socio-ecological investigation, FWEMPS ultimately estimates the endpoint human health (disability adjusted life years, DALY) for the light-vehicles fleet in Brazil in 2020-2050 timeframe, using the following impact midpoint categories (see RECIPE, 2016 for further categories descriptions):

- Global warming potential (GWP)
- Fine particulate matter formation (PM)
- Photochemical ozone formation (POF)
- Stratospheric ozone depletion
- Ionizing Radiation
- Toxicity (cancer)
- Toxicity (non-cancer)

For the WTT phase, FWEMPS considers all the above. For TTW phase, only the first three (GWP, PM and POF), as described hereafter.

6.2.2.1 Well-to-tank (WTT) emissions

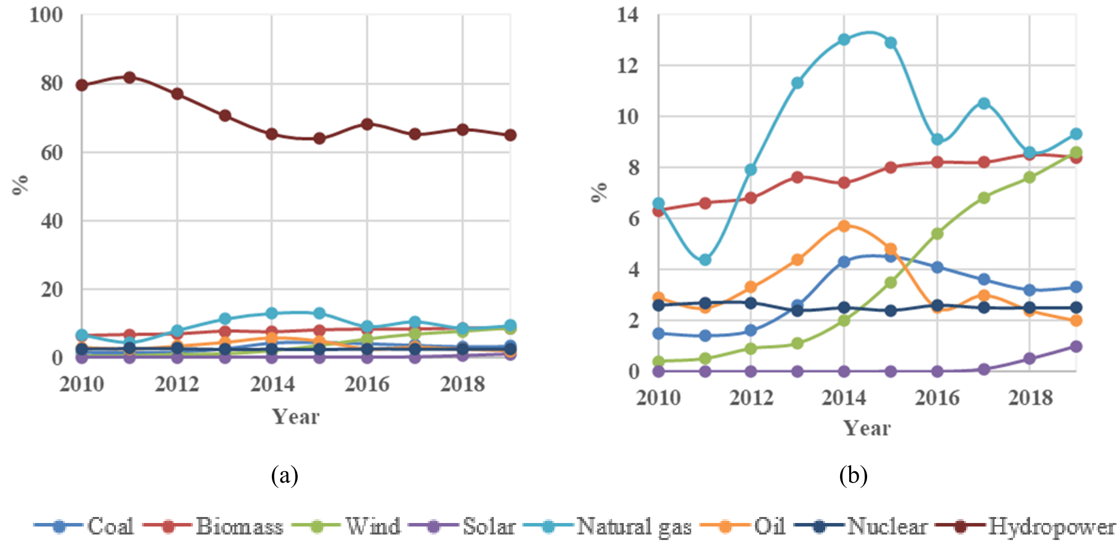
In the WTT phase, we used the OpenLCA software to generate midpoint characterization factors of fuel production using the Ecoinvent 3.6 database version and the LCIA Hierarchic method Recipe (2016). One interesting fact is that the 3.6 version from Ecoinvent database is so far the latest version released (end of 2019) and it has brought together many characterization factors from the specific-site regions, many of them from Brazil. This enhances the investigation here presented as it avoids using estimation from other regions (as in CHOMA; UGAYA, 2017; DE SOUZA *et al.*, 2018; and GLENSOR; MUÑOZ B., 2019). Especially when it comes for ethanol production, Brazil has a unique production process, mostly from sugarcane, and to the best of our knowledge for the first-time specific WTT characterization factor for the region is being used.

For the WTT gasoline blend production, a combination of two processes is considered, one from petrol production and another from anhydrous ethanol (99,7%) solution state. Ethanol content in the gasoline has varied along the years (from 15% in 1990 to 27% currently). Since 2015, it has risen from 25 to 27%, which is how is modelled in the fleet-model. The petrol production characterization factors consider the operation in oil production (both onshore and offshore), transportation and the oil refinery process. The anhydrous ethanol (97%) production factors consider the impact from sugarcane processing in modern annexed plant.

As for WTT hydrous ethanol (95%), the impact factors consider the whole market of ethanol, i.e. the proportion sugarcane processing practice in the country (unseen for anhydrous ethanol), whether by traditional and/or modern annexed and/or autonomous plant. For both ethanol production, besides ethanol processing the characterization factors include impacts from sugarcane harvesting, production, and transportation to the fabric/mill. All these factors are presented per kilo of fuel used (Table A4, Appendix A). For litre-kilo conversion, we use the densities 0.753, 0.754 and 0.755 kilo/litre for gasoline (22% until 2007, 25% until 2015 and then 27% of anhydrous ethanol, respectively), and 0.809 kilo/litre for hydrated ethanol (BEN, 2020).

For WTT electricity impact, FWEMPS starts capturing the historical power source mix since 2006, when EV were first introduced. Historically, hydropower has been the major source of Brazil's electricity supply (around 80% before 2010), now other sources are gaining market share, with highlights to wind power source (BEN, 2020) (Figure 31, historical values in Table A7, Appendix A). Midpoint characterization factors from each source are presented in Table A8 (Appendix A). Additionally, a grid-battery electricity efficiency of 86% and a 1.5 batteries per EV in a lifetime is considered, following similar assumptions as in Krause *et al.* (2020) and Glensor and Muñoz B. (2019). FWEMPS simulation default considers the last historical power mix (2019) until 2050, but it also allows the testing of different power sources proportion (2020-2050).

Figure 31 - Brazilian power mix (2010-2019) considering (a) all source types, and (b) without hydropower.



Source: BEN (2020).

6.2.2.2 *Tank-to-wheel (TTW) emissions*

For FFV, gasoline and ethanol-based vehicles, seven exhaust pipe gases emissions are accounted: dioxide carbon (CO_2), methane (CH_4), nitrous dioxide (N_2O), particulate matter[13] (PM_{total}), aldehyde (RCHO), nonmethane organic gas (NMOG), nitrogen oxides (NO_x), and monoxide carbon (CO). Historical TTW emission factors figures were taken from CETESB (2019) database. There is no similar range of information available for hybrid and PHEV cars (except a few CO_2 emission rates). Thus, similar rationale as in Benvenutti and Campos (2019) was adopted for all gases, where emission rates are estimated considering the same proportional difference between CO_2 estimates for FFV and for them. In the case of BEV, there are no exhaust emissions. Table 16 shows the average decrease rate that TTW emissions experienced over a 16-year period (2003-2019).

Table 16 - Emission average rate change per year (%) for each gas per vehicle type in 2003-2019 timeframe.

Vehicle	**CO_2**	**CH_4**	**N_2O**	**PM**	**RCHO**	**NO_x**	**CO**
Gasoline	-0.32	-5.56	-0.32	0	-5.83	-6.11	-3.78
FFV gasoline	-1.73	-4.17	-1.45	0	-5	-4.67	-3.29
FFV ethanol	-1.69	-2.66	0	0	-4.43	-6.1	-2.25

Source: Based on data from CETESB (2019).

[13] The total amount of PM ($PM_{2.5}$ + PM_{10}) was multiplied by 60% as an estimate of fine particulate matter ($PM_{2.5}$)

By tracking these gas emissions, three midpoint impact groups are assessed, the GWP (with CO_2, CH_4 and N_2O), the PM (with PM) and the POF (with RCHO, NMOG, NO_x and CO). All midpoint impact factors are presented in Table A5, and endpoint factors in Table A6, Appendix A.

6.2.2.3 Land use change (LUC) area and emissions

A direct LUC emission estimate is considered for 2020-2050 timespan. According to Intergovernmental Panel on Climate Change's glossary, land use refers "to the total of arrangements, activities and inputs undertaken in a certain land cover type", and LUC "involves a change from one land use category to another" (IPCC, 2018, p. 553). In our case, it is associated with the direct expansion of biofuel feedstock production, i.e. ethanol from sugarcane[14]. In recent years, LUC impacts have been included in LCA studies of biofuel for its important implications in CO_2 emissions (SCARLAT; DALLEMAND, 2019). It therefore cannot be ignored since ethanol plays a relevant role in Brazilian fleet composition.

The last available database Ecoinvent version (3.6) incorporated several datasets of LUC from Brazilian products in state, regional and national level (DONKE *et al.*, 2020). The factors therein are a result of a method named BRLUC that estimates historical LUC and its GWP ($CO_{2\text{-eq}}$) emissions associated to agriculture in Brazil, developed by Novaes *et al.* (2017) for 64 croplands (e.g. sugarcane, soybean, maize, timber, beef, and mango) and available at EMBRAPA (2020). Comparing with the prior version (Ecoinvent 3.5), the GWP emission for sugarcane LUC dropped 75%, from 8.4 tCO_{2eq} $ha^{-1}year^{-1}$ to 2,1 tCO_{2eq} $ha^{-1}year^{-1}$ (BRLUC version 1.3, considering their *proportional* scenario). Some of the reasons attributed to this difference were the consideration of carbon stock of sugarcane and its pattern of expansion, which related to the use of state-level LUC modelling with national official data (see DONKE *et al.*, 2020, for further descriptions).

The rate 2,1 tCO_{2eq} $ha^{-1}year^{-1}$ is the amortized result (*proportional*) of the 20-year period 1999-2018, and a result of the category of land use of arable annual crops (7%), arable permanent crops (3%), pastureland, man-made (29%), unspecified, natural (14%), and the rest (47%) in pre-existent areas arable sugarcane. In 2009, the sugarcane Agroecological Zoning (AEZ) was established by law, delimiting potential land use expansion for a sustainable

[14] Due to its expressiveness and for simplicity we focused on ethanol from sugarcane, although ethanol production from corn has been recently increasing.

production of the crop in the Brazilian territory, giving preference to already occupied pasturelands (BRAZIL, 2009; EMBRAPA, 2021). More recently, the new national biofuel policy (RenovaBio) imposed stricter land use management along with a regulation determining that only biomasses from non-native vegetation are eligible for expansion (ANP, 2017, article 24; BRAZIL, 2017).

Given these regulations, to consider the same expansion pattern observed from 1999-2018 for future years would not be appropriate. We thus assume that the expansion of sugarcane from 2020 to 2050 will occur over pasturelands, which has been the main source of sugarcane (and other crops) area expansion for the past years and in future projection (BORDONAL *et al.*, 2018; ADAMI *et al.*, 2012; DE ANDRADE JUNIOR *et al.*, 2019).

It is worth noting that there are other relevant challenges regarding LUC for biofuel production such as land-use conflicts with its relationship between food production (SOUZA *et al.*, 2015; WRI, 2015). In this regard, literature has shown that there has been an overall increase in food crops yield and livestock intensification (e.g. over pastureland) that have enabled decrease in land competition between food and sugarcane (see BORDONAL *et al.*, 2018, and the references therein).

Therefore, to estimate the GWP emission per hectare ($tCO_{2-eq.}$/hectare) from LUC expansion over a certain category of land to be considered in 2020-2050 simulation timeframe, we consider the following data:

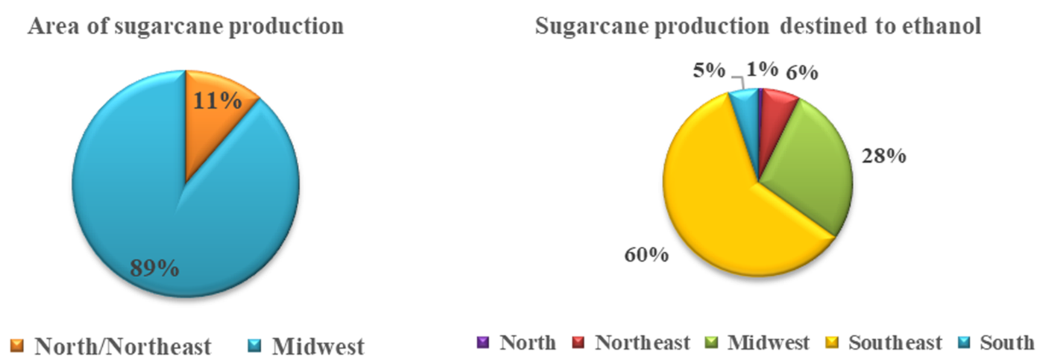
(i) the state-level carbon stock data provided by Novaes *et al.* (2017, in their Appendix S1, pro.C Stocks Summary);
(ii) the historical sugarcane production destined to ethanol per state provided in CONAB (2020) reports.

In terms of region, the majority of its production has taken place in the state of Sao Paulo, and mostly been conducted in pasturelands (WALTER *et al.*, 2011) (for concentration area map see Figure A3, Appendix C). Over the past few years, the great majority of sugarcane plantation area and destination to ethanol production has occurred in the Midwest and South/Southeast region (Figure 32a-b) (CONAB, 2020). From the produced sugarcane destined to ethanol, we calculated the average produced by state from 2012 to 2020 ($SugAve_i^{\%}$, see values in Table A9, Appendix A), and multiply with the state-level carbon stock, considering a stock change factor (from C to CO_2) of 44/12 recommended by IPCC (2019), following equation 12,

$$LUC_{GWP\ per\ hectare}^{L} = \left(\frac{44}{12}\right) * \sum_{i=1}^{n} (C\ Stock_i^L - C\ Stock_i^{Sugarcane}) * SugAve_i^{\%} \quad (12)$$

where “n” is the number of states considered, “i” is an index that references the states, “L” is the category of land over which the LUC is being expanded to, $C\ Stock_i^L$ is the carbon stock of a land “L” in the state “i", $C\ Stock_i^{Sugarcane}$ is the carbon stock of sugarcane in the state “i", and $LUC_{GWP\ per\ hectare}^{L}$ is the GWP per hectare of the LUC expansion over land “L” considered for 2020-2050. In the case of our business-as-usual (BAU) scenario, L is considered pastureland, resulting in $LUC_{GWP\ per\ hectare}^{pastureland}$= 8.8 tCO_2/ha (the respective LUC GWP emission single factor per hectare per year is provided in Table A 11, Appendix A). In section 6.3.3 other categories of L are considered.

Figure 32 - Average of the (a) area of sugarcane plantation, and (b) sugarcane production destined for ethanol, per region in Brazil from 2012 to 2020.



(a) (b)

Source: Based on reports from CONAB (2020).

In terms of land use area projection for 2020-2050 simulation, we use the impact category ‘land use’ from Recipe (2016), named as ‘agricultural land occupation potential’ (LOP) (HUIJBREGTS *et al.*, 2017). LUC emissions are only assigned to the expanding lands during a certain period, FWEPMS calculates the land-use expansion variation (delta) required for ethanol production (hydrous and anhydrous), from one year to another, and subsequently multiplies to the factor from eq. 12. To this regard, the SD modelling approach is advantageous since it dynamically captures the LUC impact variation through time, adapting itself according to the policies/strategies or scenario tested (see Table A4, Appendix A, for land use impact factors per fuel type). If a delta returns negative – such as a case of less need of land use –

FWEMPS is programmed to return zero LUC emissions[15]. However, negative emissions – as in the case of Carbon Fixation testing scenario – is accounted (more on this on LUC scenarios subsection).

Furthermore, over the last eight years (2012-2020), land use area for sugarcane has varied around 8.4-9.05 million hectares, in which an average of 57% of the harvest was attributed to ethanol production (CONAB, 2020). Thus, we used a multiplier factor of 2.68 to the land use area simulation results to match with the approximate average 4.9 million hectares destined to ethanol production in historical data. Lastly, we assume a biofuel yield increase of 0.535% per annum, an efficiency which is transferred to the land use size (the same as in GLENSOR; MUÑOZ B., 2019, based on the carbon reduction target projection by RenovaBio).

6.3 SCENARIOS

As the name FWEMPS proposes, the model is primally designed to be a tool and provide guidance for policymakers. Its inner interface brings flexibility features to enable individual or integrated strategies testing results. Prediction of future impact values are not the end goal, but rather the possible projections, and potential system behaviour according to actions adopted towards sustainability transitions.

In this context, and for the purpose of this study, four main sets of scenario testing are chosen: (i) sensitivity analysis of FWEMPS' main features, (ii) extreme scenarios, (iii) LUC scenarios, and (iv) power mix comparison. Each of them provides evaluation involving different aspects of the fleet system. Sensitivity analysis provides mitigation potential results of different sustainability policies and/or strategies. The extreme scenarios focus on hypothetical fleet projections and deal with not only the environment and human health impact between different vehicles fuel-technologies, but also the temporal aspect inherent in a fleet turnover in the long term. The LUC scenarios testing allows the impact assessment of different category of land use projection. Finally, the power mix comparison deals with the testing of different electricity grid profile in the long term by comparing the extreme electric scenario under different power mixes, similar to other countries. Each set of analysis is described hereafter.

[15] Future work considering indirect LUC could include estimate of possible other crops projections over the diminished sugarcane land use (as in would be the case of an electric vehicles increase scenario).

6.3.1 Sensitivity analysis

Sensitivity analysis is the process of learning from simulation runs by varying a specific variable and assessing its impact on the model responses. FWEMPS provides the testing of five policies/strategies: (i) energy efficiency; (ii) reduced VKT, (iii) renovation of the fleet, (iv) biofuel use from FFV, and (v) EVs only. There is the flexibility for the user to test them (independently or combined) through a range of values[16]. Chart 5 describes their main implications.

Chart 5 - FWEMPS' description and testing range of policies/strategies.

Policies/Strategies (P)		Description and implication	Input range for the user testing
P1:	Energy efficiency	Gas emission efficiency has been improving (Table 16). TTW exhaust mitigation reduction of new car sold per year, affecting future gas emission estimates (2021-2050)	One input: emission efficiency per year (range: 0-6%, default is the 2019 emission factor from each gas)
P2:	Reduced VKT	Change of the average VKT considered (MMA, 2011). This may come through modal shifts, remote working encouragement (e.g. experienced in Covid-19 pandemic)	Three inputs: (i) start year of the policy, (ii) VKT variation percentage (range: -100-100%), (iii) period the policy is in vogue
P3:	Renovation of the fleet	Prohibition of older cars circulation. The scrapping rate is affected	Three inputs: (i) start year of the policy, (ii) car from and older than what age, (iii) period the policy is in vogue
P4:	Biofuel use from FFV	FFV can be fuelled by either gasoline or hydrated ethanol (estimated historical values in Table A3). For future simulation, different rates can be tested	One input: ethanol proportion in percentage from 2020 onward (range: 0-100%)
P5:	Electric vehicles only	If similar policy as few EU countries are proposing, to ban internal combustion engine, selling only BEV (EU, 2017)	One input: start year of such policy
Covid-19, ON?		The Covid-19 pandemic impacted mobility pattern in 2020. It reduced the use of public modal to increase health security issues (virus spread), generating higher use of individual transport. However, the isolation and the increase of remote working also affected VKT.	One input: VKT variation percentage (range: -100-100%),

Source: Elaborated by the authors.

To assess their mitigation power, some scenarios are tested. Table 17 presents the selected inputs per mitigation strategy in three levels of stringency (A, B and C). It also presents three integrated policies groups (1, 2 and 3) for sensitivity analysis. In P2, even though there is

[16] As it is commonly conducted within the SD community, FWEMPS Stella Data (.isdb) along with its inner interface (.stmx) can be made available at request using the first author's Research Gate page at: https://www.researchgate.net/profile/Livia-Moraes-Marques-Benvenutti or by email: lmmbenvenutti@gmail.com

the possibility of testing it during a specific period, for this analysis it was chosen during all simulation years (2020-2050) to capture the potential mitigation impact by 2050 and compare with the others (P3 in this case is a more aggressive policy, so a shorter period for it was chosen).

Table 17. Sensitivity analysis scenarios inputs.

Mitigation strategy	**Level A**	**Level B**	**Level C**
PS1	2%,	3%	4%
PS2	2021, 5%, all years	2021, 10%, all years	2021, 15%, all years
PS3	2035, 20 years, 2 years	2030, 20 years, 3 years	2030, 15 years, 4 years
PS4	50%	60%	70%
PS5	2045	2040	2035
Integrated scenarios:	All level A, Group 1	All level B, Group 2	All level C, Group 3

* all sensitivity analysis scenarios consider *Covid-19, ON?* Checked with 10% of VKT decrease in 2020. Percentage selected based on the report of 84% reduction in the overall VKT in Brazil in the month of March alone (WINGS, 2020).

Source: Elaborated by the authors.

6.3.2 Extreme scenarios

Besides the BAU scenario, three other scenarios are tested. One where every new vehicle sold would be fuelled only by gasoline (Extreme gasoline), another by ethanol (Extreme ethanol), and another by power (BEV, Extreme electric), from 2020 onward. The vehicles sold before 2020 remain with their own fuel-technology characteristics behaviour, but the new ones would be forced to be driven by one of the three power/fuels possibilities. These are hypothetical scenarios, relevant to drawn important insights for future transition. No enforcement of any policy/strategy implications (2020-2050) is considered in these scenarios' analysis, except 1% of energy efficiency per year for all including the BAU scenario (the same assumption as in EPE, 2016).

6.3.3 LUC scenarios

Considering that LUC emissions are highly relevant but also carries a lot of uncertainties, and that it is dependent on method/model used and site-specific data assumptions (REINHARD, 2017), we assess GWP and DALY impact result of the extreme scenarios with two other LUC projection patterns named: (i) Carbon Fixation and (ii) Illegal Expansion. In the Carbon Fixation scenario, the considered land use expansion is also over pastureland (as in the BAU scenario), but it includes a portion of land over severely degraded pastureland and over cropland. In turn, the Illegal Expansion receives such name as it considers part of its expansion over native vegetation, which is beyond the AEZ established by law and unpermitted by

RenovaBio policy and regulations (ANP, 2017; BRAZIL, 2009; 2017). For the latter, we based our expansion assumption on one scenario projection from de Andrade Junior *et al.* (2019) for 2010-2030, in which the authors used a land-use competition model named GLOBIOM-Brazil (SOTERRONI *et al.*, 2018) and considered a scenario of imperfect or partial illegal deforestation control in the Amazon and the Cerrado biomes. The category of land use considered in each of these scenarios and its proportion are shown in Chart 6.

Chart 6 – LUC expansion projections scenarios descriptions.

LUC scenario	Descriptions	Based on
Carbon Fixation	- 40% pastureland - 30% pastureland severely degraded - 30% cropland	CONAB (2020), EMBRAPA (2020), and Novaes *et al.* (2017)
Illegal Expansion	- 4,1% Other crops (cropland) - 0,7% Planted forest (Forest intensive – which is in reference to eucalyptus and pine) - 4,8% Native vegetation (Forest Natural) - 18,8% Non-productive land (30% Pasture Severely degraded, 30% Grassland natural, and 40% of unspecified land) - 71,7% Pasture (Pastureland, man-made)	CONAB (2020), EMBRAPA (2020), Novaes *et al.* (2017), and the same evolution of land use considered in de Andrade Junior *et al.* (2019) in their "*RFO-FFO*" column from Table 7.

* de Andrade Junior *et al.* (2019, p. 9) mention that "large areas of unproductive degraded pasture are also included under the label non productive land"

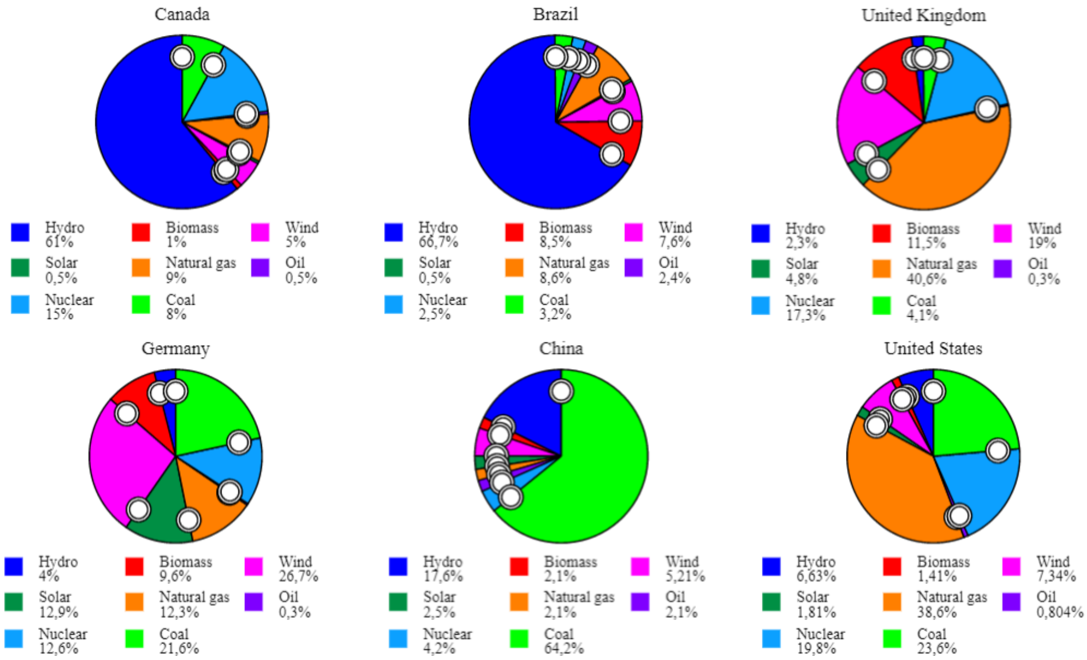
Source: Elaborated by the authors.

Considering the premisses shown in Chart 6 and using equation 12, in the Carbon Fixation scenario, the LUC GWP emission factor for Carbon Fixation scenario -15.6 tCO_2/ha, and under Illegal Expansion is 48.4 tCO_2/ha (for single factor per hectare per year, see Table A 11, Appendix A).

6.3.4 Power mix comparison

A comparison with other five countries' power mix balance is tested. These countries are: Canada, United Kingdom, Germany, China and United States (Figure 33). All emission factors from each type of power source remain the same for the specific region of Brazil (Table A8, Appendix A), and not varying in the 2020-2050 timeframe. Additionally, similar comparison to prior subsection analysis assuming different LUC emission factor is conducted.

Figure 33 - Different country's current power mix balance considered for GWP and DALY result comparison.



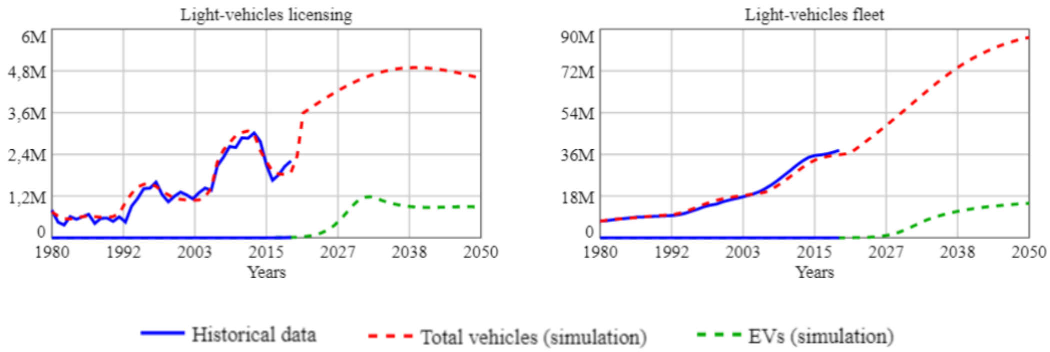
Source: CER (2019), BEN (2020), Energy-charts (2020), CEC (2018) and EIA (2019).

6.4 RESULTS AND DISCUSSION

6.4.1 Simulation projection and interface

Considering the assumptions adopted in this study, Figure 34 presents the simulation results (see Table A10, Appendix A, for their numbers). By 2030, the number of light-vehicles are expected to reach 55.9 million, which is close to the 53 million considered in the Ten-Year Energy Expansion Plan by EPE 2030 (2021). By 2050, the number of light-vehicles are expected to reach 86.5 million. This value is lesser than the around 130 million projected in EPE (2016) scenarios (although their study includes commercial vehicles, which is outside the scope of this study), and closer to the 73 million considered in Glensor and Muñoz B. (2019), as well as to the expected to reach of 17,2% of EVs by 2050 in the fleet (in which their consideration was 18%). A sensitivity analysis on the q(t), which mostly impact fleet number, and Fp that mostly impact the pace of decrease rate in the average EVs price – and consequently their diffusion numbers - can be found in Figure A2, Appendix A.

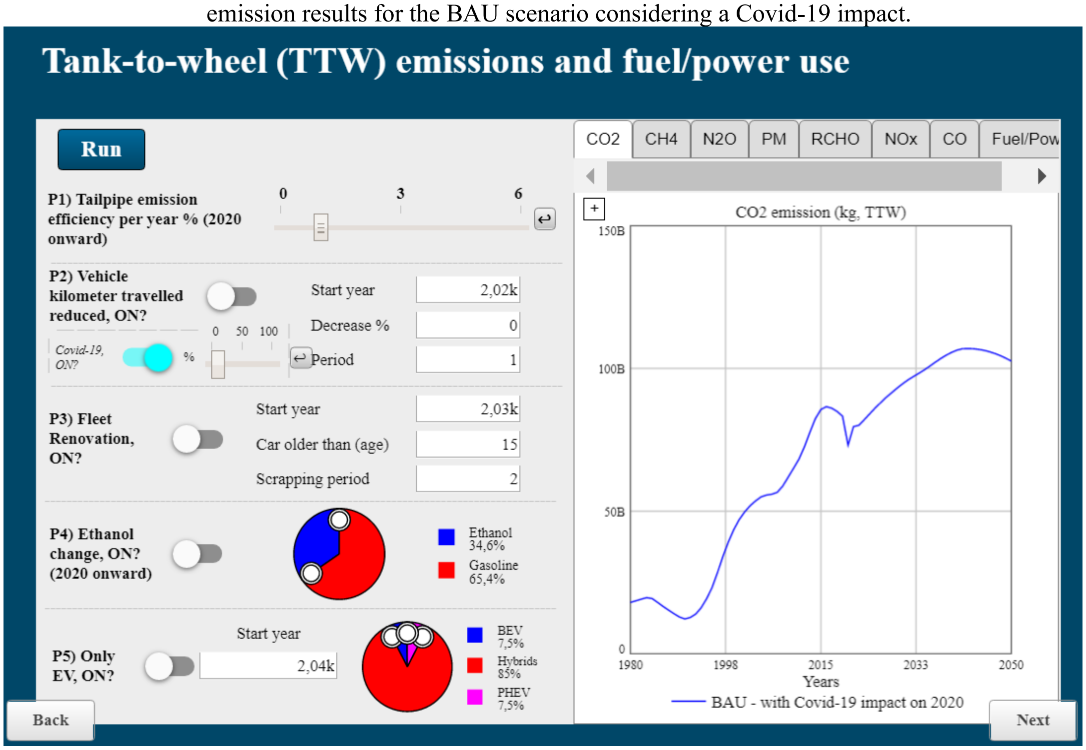
Figure 34 - Total and EVs light-vehicles fleet projection (values in Table A10, Appendix A).



Source: Historical values based on ANFAVEA (2020).

Figure 35 shows the first set of results from the interface, the TTW emissions and fuel/power use results (different graph tabs). The left part is the policies/strategies section for the user selection testing, and on the right, the graphs results. The downward pick in 2020 is a reflection of an average of 10% travel decrease in 2020 due to Covid-19 pandemic (this premise is only present in sensitivity analysis results). Similar interface design is found for other results such as midpoint and extreme scenarios results.

Figure 35 - Example of FWEMPS inner interface (policy selection space on the left), showing TTW CO_2 emission results for the BAU scenario considering a Covid-19 impact.



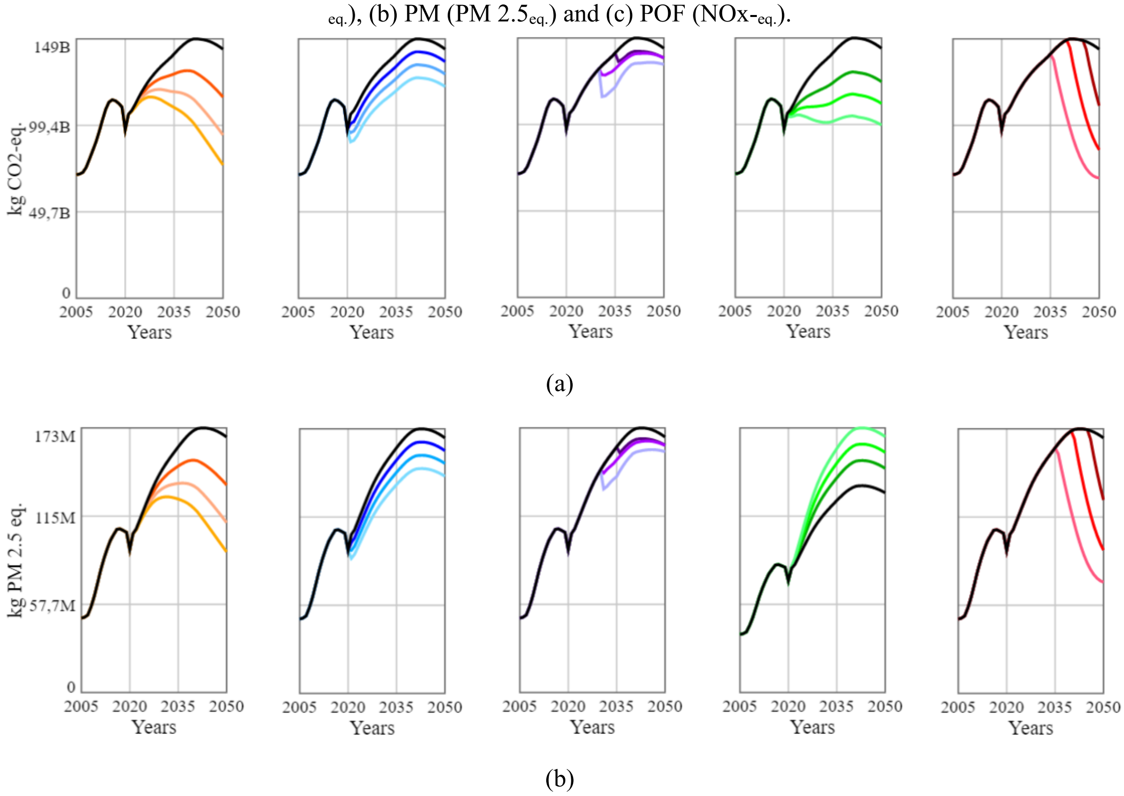
Source: FWEMPS' inner interface.

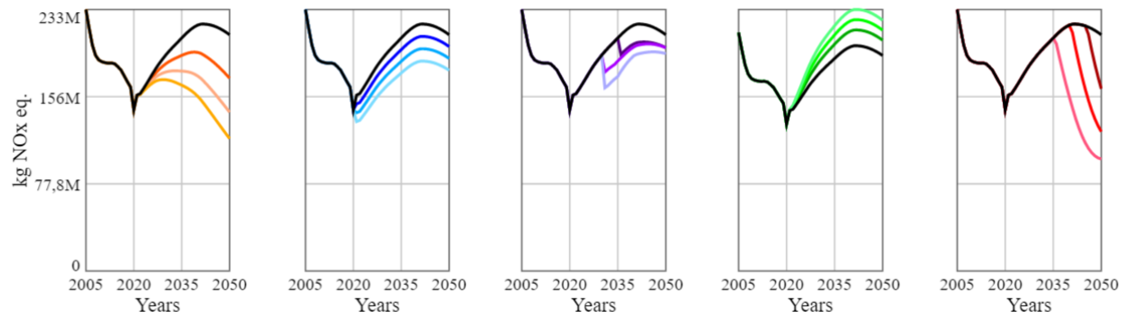
6.4.2 Sensitivity analysis and integrated results

Figure 36 presents sensitivity results from different level of policy stringency (Table 17) for GWP, PM and POF WTW midpoint impact analysis (Figure 36a-b-c, respectively). Naturally, hypothesis/assumptions tested play an important role in the intensity result. Energy efficiency (P1A/B/C) does impact $CO_{2\text{-eq.}}$ emission, but not $PM_{2.5\text{-eq.}}$ (e.g. PM are not accounted in FFV driven with ethanol), and little $NO_{xeq.}$ As their emission rates are already low. By reducing VKT (PS2A/B/C), results show impact in the long term in all midpoint category types. However, if renovating the fleet is proposed (P3A/B/C), a long-term result may not necessary be achieved by a more stringent policy (see level 1 and 2). While banning older cars from circulating may seem strategic to reduce exhaust fleet emission (because of their higher tailpipe emission per km), by inducing their renovation, it potentially increase the average intensity of car use (new cars are driven more), and consequently rising fleet emission (BENVENUTTI; URIONA-MALDONADO; CAMPOS, 2019).

Biofuel increase provides interesting results (P4A/B/C). While an increase use of ethanol rate helps decrease GHG emissions, it does the opposite to PM and POF (Figure 36b-c, fourth column). This is due the WTT phase, Figure 37. By increasing the biofuel use, it increases the necessity of bioethanol production, which ends up increasing their emission in total WTW analysis. Although vehicles on the roads emit less PM, its final emission is compensated by the production phase. And although ethanol fuel provides higher aldehyde emission, when combined with NMOG, CO and NOx impact, it results in very little POF midpoint impact in TTW phase (Figure 37b). At last, the EV sales mitigation policy provides the greatest impact. In terms of TTW, this would be expected as they are emitter free or less emitter (hybrids). In terms of the WTT phase, a good mitigation outcome is achieved possibly due to the power mix characteristic, a reflection to Brazil's high renewable source power system (more discussion on Power mix analysis subsection), but also as conventional cars are not sold, diminishing the fleet in the short to mid-term.

Figure 36 - Sensitivity analysis WTW results of each five policy/strategy tested (Table 17) for (a) GWP ($CO_{2\text{-}eq.}$), (b) PM ($PM\ 2.5_{eq.}$) and (c) POF ($NOx\text{-}_{eq.}$).

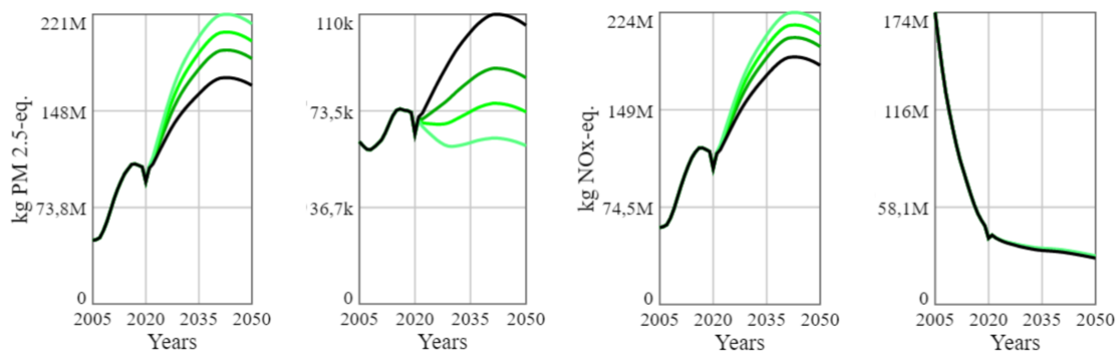




(c)

Source: Based on FWEMPS results.

Figure 37 - Disaggregated results of the sensitivity analysis of policy 4 for PM and POF.

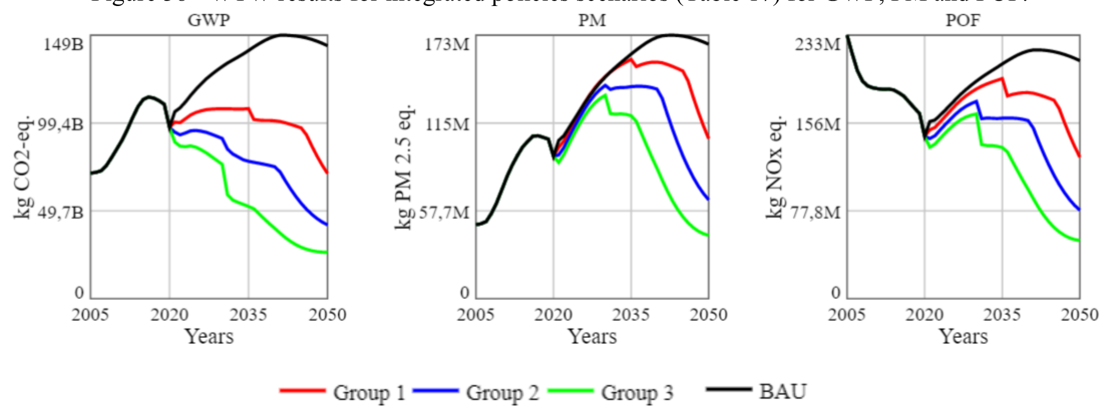


(a) (b)

Source: Based on FWEMPS results.

In terms of integrated analysis, Figure 38 provides these results for GWP, PM and POF midpoint category (group description in Table 17). As expected, by increasing the level of rigor, mitigation results are achieved faster and with more intense results. But it is noticeable a delay in the mitigation impact in both PM and POF cases This is the reflection of the pronounced increased impact due to higher ethanol production necessity, as observed in Figure 36.

Figure 38 - WTW results for integrated policies scenarios (Table 17) for GWP, PM and POF.



Source: Based on FWEMPS results.

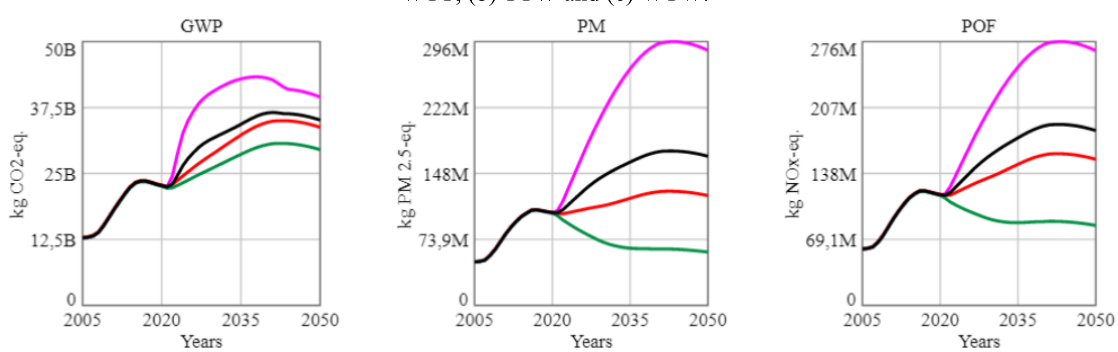
6.4.3 Extreme scenarios (Midpoint and Endpoint results)

Figure 39 presents the WTT, TTW and WTW midpoint impact for extremes scenarios. In terms of GWP, as expected, it is evident the opposite WTW tendency between a fleet driven by the fossil fuel gasoline against a fleet by either ethanol or power. Although in extreme gasoline the GWP of the WTT is lower that BAU, this is not enough to significantly mitigate its whole life cycle, as observed in Figure 39c. In terms of ethanol versus electric fleet, the result indicates a little more impactful mitigation WTW result by a fleet fuelled by BEV in the long-term (although FWEMPS BAU considers hybrids and PHEV, extreme results are solely for BEV). While the TTW emissions they are quite similar (Figure 39b, GWP), the extreme ethanol surpasses all other scenarios in the WTT stage, emitting the most (Figure 39a, GWP). Still, both are able to mitigate GHG emission considerably (Figure 39c, GWP). This tendency result differs from a recent projection made for the Brazilian fleet in Glensor and Muñoz B. (2019), where their biofuel scenario resulted in even more CO_2 emission than their BAU scenario. Usually when this happens, the reason stands on the assumptions considered in both studies. Discrepancies between LCA results have been addressed before, which main reason has been attributed to different LCA tools/models and consideration of different region-specific information (PEREIRA *et al.*, 2019). This will be further addressed in the following subsection, LUC analysis.

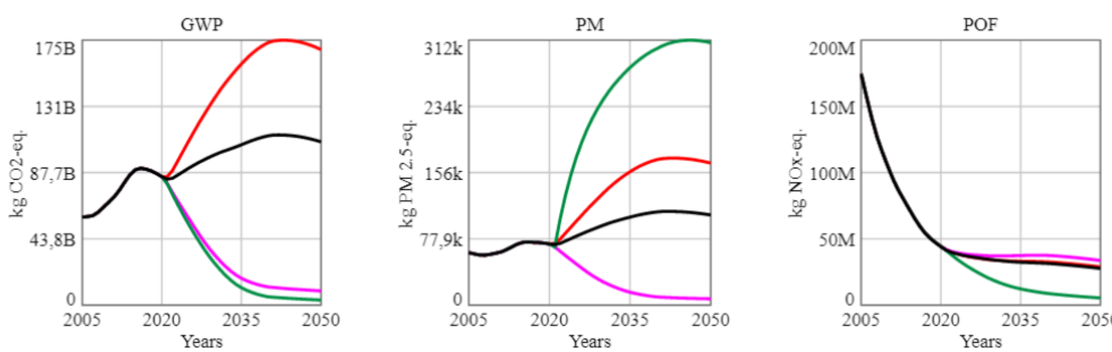
Furthermore, as expected, the extreme ethanol scenario provides a higher WTW emission for both PM and POF (as Figure 36 showed). But as Figure 39 shows, this high emission arises from the WTT stage, not from vehicles on the roads. Using the contribution tree from OpenLCA software, 78.65% of $PM_{2.5\text{-eq.}}$ emission from ethanol production is attributed to market for sugarcane itself (planting, harvesting, loading, transport), the rest comes from other manufacture market of chemicals and products, and processes involved. For POF, this number is 63.15%, also from the own market of sugarcane. Additionally, it is clearly noticeable the sharp TTW decrease over the years from $NO_{x\text{-eq.}}$ emission (Figure 39b, POF). The Program for Control of Air Pollution by Motor Vehicles (PROCONVE) was instituted in 1986. Since then, many target phases have been established, allowing the decrease of many pollutants.

In terms of either higher or lower impact, these results are in line with Cavalett *et al.* (2013) study involving a comparison between ethanol and gasoline midpoint and endpoint impacts using different LCIA methods. Their results also presented lower impact from ethanol to GWP category, but higher impact for ethanol for both PM and POF category also using the LCIA Recipe (2016) method.

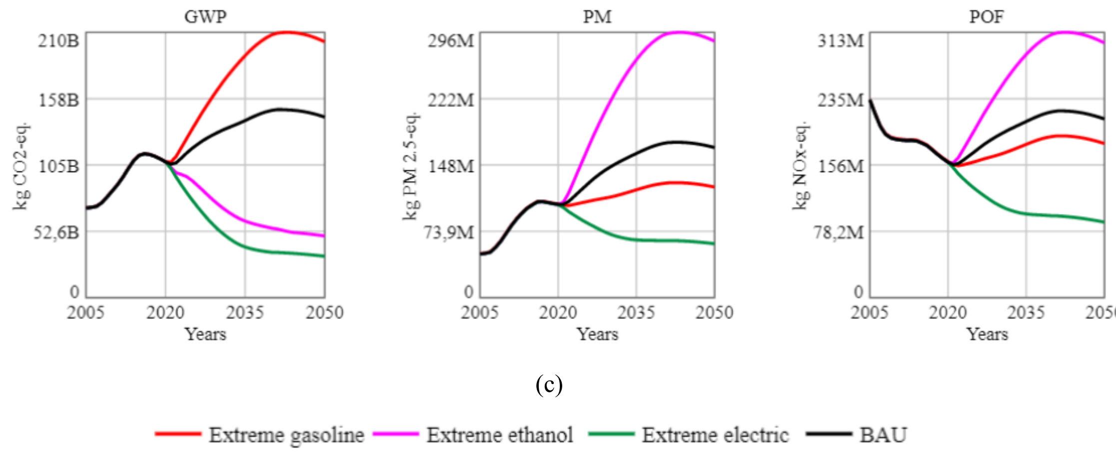
Figure 39 - Midpoint impact results of BAU and extreme scenarios of GWP, PM and POF for the stages (a) WTT, (b) TTW and (c) WTW.



(a)



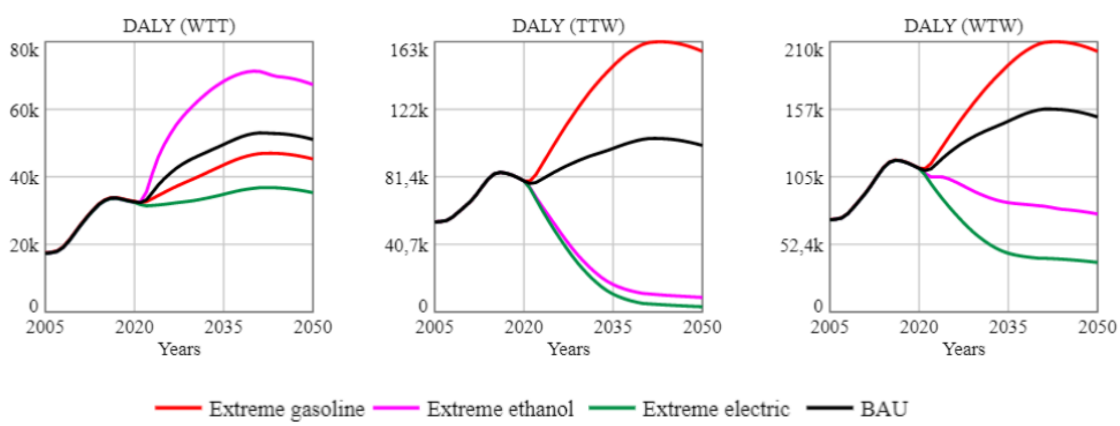
(b)



Source: Based on FWEMPS results.

In terms of human health endpoint impact DALY, Figure 40 presents results for each life cycle stage and total one. We can see how the production phase of ethanol is potentially more damaging of all. On the other hand, when combining with DALY values from TTW phase, the mitigation power of DALY even with an extreme ethanol scenario in the long-term is much lower than the extreme gasoline or BAU. Note that this pattern (WTW) is similar to that of GWP (Figure 39c), indicating $CO_{2\text{-eq.}}$ emission as at least one of the most relevant midpoint categories for DALY impact. In the case of DALY, however, there is a larger difference between the mitigation power of electric and ethanol scenarios, with extreme electric presenting more promising results.

Figure 40 - Endpoint impact results of BAU and extreme scenarios of DALY for the stages WTT, TTW and WTW.

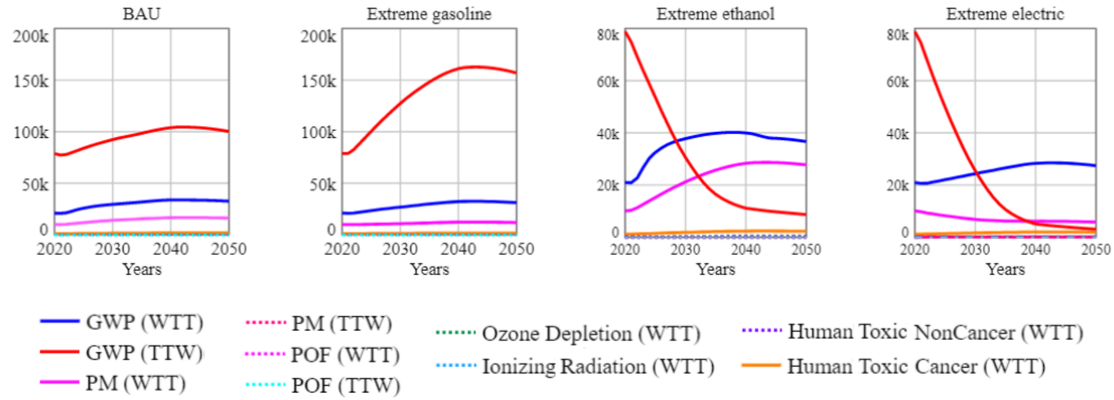


Source: Based on FWEMPS result.

When the DALY result is discriminated by each midpoint categories and life cycle phases (Figure 41, 2020-2050), we can see that for both BAU and gasoline extreme scenarios the majority weight of the total estimated DALY comes from the vehicles on the road GWP-TTW phase. The second and third most influential accounts for the production phase, GWP-WTT, and PM-WTT, respectively. After that, the other categories present an extremely low impact on the total DALY ('Human toxic Cancer' has a little weight on the BAU, extreme ethanol and electric scenarios). For ethanol and electric extreme scenarios, the pattern is similar except after about 2030, GWP-TTW reaches lower impact values than the GWP-WTT in production phase, and after 2032 (ethanol) and 2039 (electric) lower than PM-WTT.

In fact, GWP has the most influential weight on DALY (either through WTT or TTW). The LCIA method ReCiPe considers the endpoint GWP-DALY as "years of life lost and disabled related to increased malaria, diarrhoea, malnutrition and natural disasters due to increased global mean temperature" (HUIJBREGTS *et al.*, 2017, p. 143). Therefore, by either increasing the use of bioethanol or electric vehicles the DALY result in the long-term is potentially reduced. Assuming the second or third place (depending on time and scenario), the PM from fuel/power production is another relevant midpoint category source for DALY impact. The fine particles can penetrate deep into the respiratory tract and thus cause severe health damage, its impact is attributed as "years of life lost related to an increase in cardiopulmonary and lung cancer caused by exposure to primary and secondary aerosols" (HUIJBREGTS *et al.*, 2017, p. 143). The PM emission from WTT phase is relevant (Figure 39), which indicates that people involved in fuel/power production sites (but especially in ethanol production) are more susceptible of having respiratory symptoms, risk of cardiopulmonary or lung cancer. It is outside the scope of this study to go deeper into this subject, but there have been some studies that can corroborate with this result (ARBEX *et al.*, 2007; CECCATO *et al.*, 2014). Also, it should be noted that the DALY result should be different if heavy-vehicles were the focus of studies, as they are known for their higher tailpipe emissions.

Figure 41 - Endpoint impact DALY discriminated by source of category and process (WTT or TTW) for the (a) BAU, and extreme (b) gasoline, (c) ethanol, and (d) electric scenarios.



Source: Based on FWEMPS result.

6.4.4 LUC analysis

Figure 42a shows the variation of the land use (in m^2)[17] for the BAU and extreme scenarios. As expected, the use of land for ethanol production in the electric and gasoline extreme scenarios is reduced through time, the latter in a smaller proportion because of the anhydrous ethanol inside gasoline blend. Also, it is interesting to note that by 2042 the land use area begins to diminish for both the BAU and extreme ethanol scenario. This is a reflection of the stabilization of vehicles turnover aligned with the progressively increased biofuel yield increase (land efficiency) and fuel economy efficiency considered in the model.

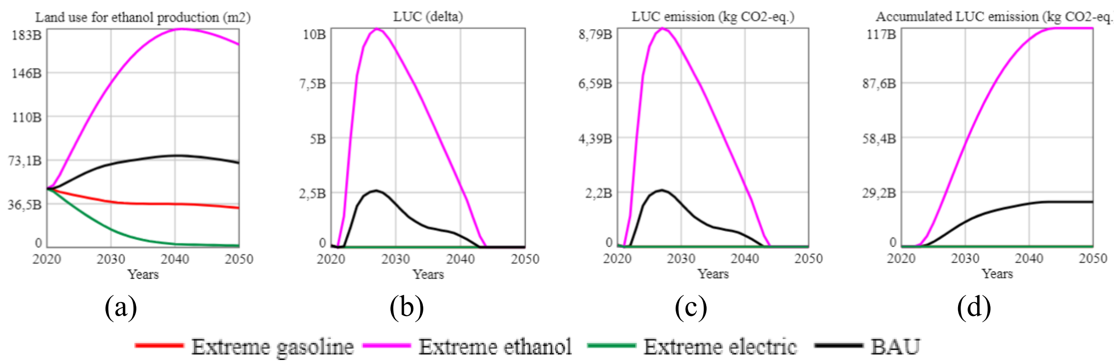
By 2030, the projection of sugarcane expansion from the Ministry of Agriculture, Livestock and Supply (MAPA, 2020) is to reach 11 Mha (million hectares), and from de Andrade Junior *et al.* (2019) to reach 11.3 Mha. Considering the 57% average rate of sugarcane destined to ethanol production (2012-2020), this would be 6.3 Mha and 6.4 Mha, respectively, which corroborate with our BAU projection for 2030 of 6.96 Mha (Figure 42a). Regarding the extreme scenario, because of the aggressive assumption of a complete turnover of the fleet, results are much higher with an increase projection of 8.8 Mha and 12 Mha from 2020 levels to 2030 and 2050, respectively.

Figure 42b shows the variation of the land use between one year to another. The delta does not increase continuously, and that is the reason LUC emission presents the pattern from

[17] Starting 49 billion m^2 in 2020, which represents 4.9 million hectares, the size estimated for ethanol production considering an average of and 8.6 million hectares of sugarcane and 57% of land use for ethanol over the past 8 years (2021-2020) (CONAB, 2020).

Figure 42c. Sometimes the increase in land-use is more accentuated than other times (function of the derivative from Figure 42a). This is also one reason that LUC emissions are annualized (amortized), to simplify the LUC impacts of a particular carbon stock loss over a period of usually 20 or 30 years (MATTILA *et al.*, 2011). This annualization is not present in the results as the model captures land variation dynamically per year, but the respective LUC GWP emission single factor per hectare per year is provided in Table A 11, Appendix A. Figure 42d presents the accumulated stock of $CO_{2\text{-eq.}}$ emission from LUC by 2050, with BAU potentially emitting 24 billion of kg $CO_{2\text{-eq.}}$ (or megatonnes, Mt) and extreme scenario 117 Mt.

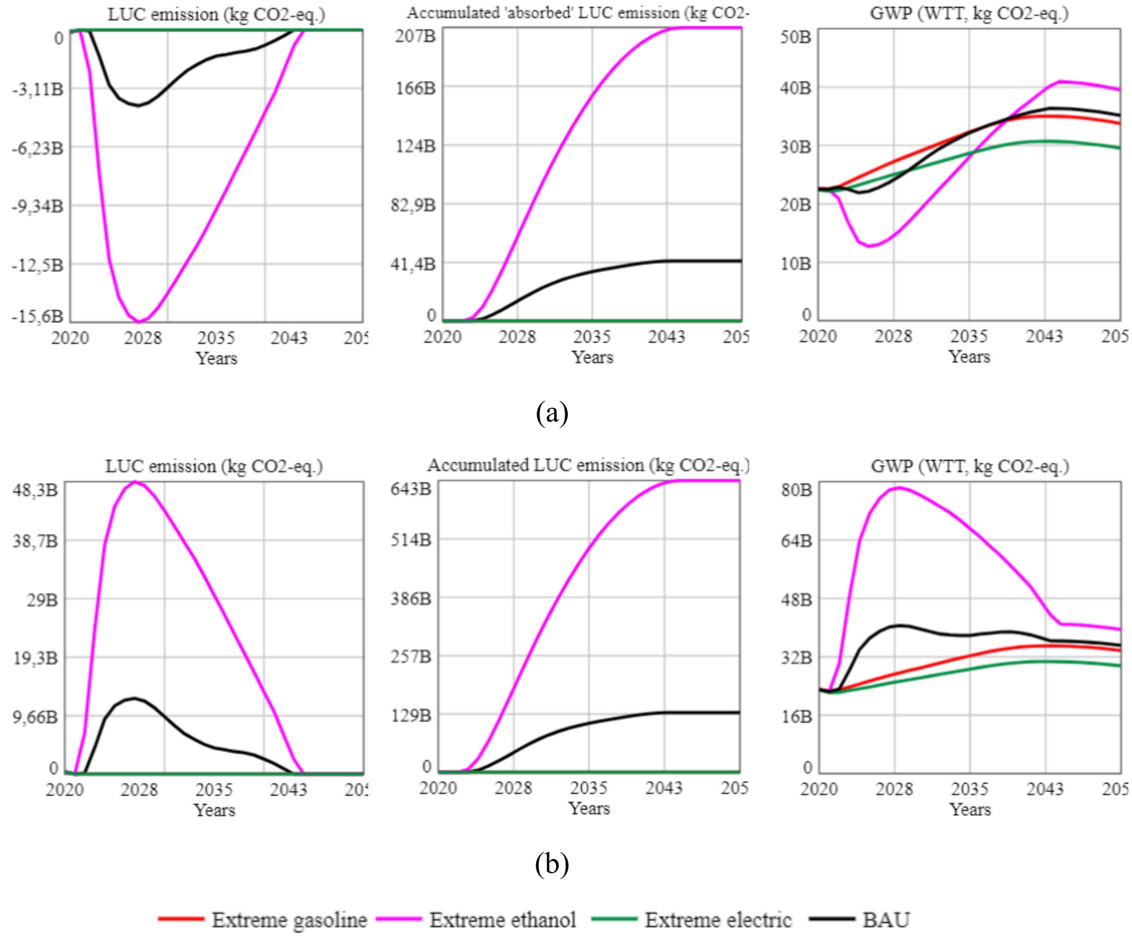
Figure 42 - Land use (a) area, (b) delta (change from one year to another), (c) change emission, and (d) accumulated emission for BAU and extreme scenarios.



Source: Based on FWEMPS result.

When other LUC expansion pattern scenarios are considered, Figure 43, different direct LUC emission result is observed. By 2050, the Carbon Fixation scenario is able to not only prevent emission, but to intake (absorb) 42.6 or even 207 billion kg $CO_{2\text{-eq.}}$ in the BAU and extreme ethanol scenarios, respectively. Considering that the model captures these emissions per year, the result on GWP for the production of the fuel adopts a different pattern, where in the production phase the extreme ethanol scenario is able to mitigate more $CO_{2\text{-eq.}}$ than the other scenarios until 2039 (Figure 43a). On the other hand, if an illegal expansion takes place, the Illegal Expansion scenario might result emitting an accumulated 643 billion by 2050, Figure 43b, and its respective GWP under extreme ethanol scenario would be higher than the other scenarios all the years, with a pick in 2028.

Figure 43 - LUC GWP emission, accumulated (absorbed) emission, and GWP (WTW) for (a) Carbon Fixation and (b) Illegal Expansion scenarios.

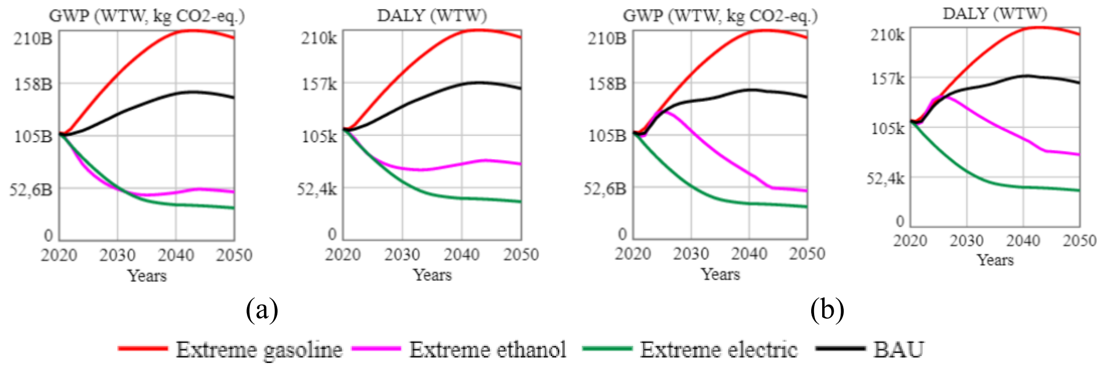


Source: Based on FWEMPS result.

While this higher LUC emission factor provides an also higher and increased $CO_{2\text{-eq.}}$ emission in the initial years, it is interesting to observe the dynamics of this emission through time. As mentioned, LUC area necessity for ethanol production in extreme ethanol scenario does not increase constantly and considering production (sugarcane and fuel) efficiency, it can eventually reduce or stabilized (Figure 42). The outcome of both these LUC scenarios within the WTW boundary is shown in Figure 44.

Extreme gasoline shows the same results regardless of the GWP emission since an extreme scenario as such - despite the need of anhydrous ethanol -would require less ethanol production than a BAU scenario (and FWEMPS does not account for negative emission due to less need of land use). The extreme electric is also unimpacted by LUC variations. As for BAU and extreme ethanol scenarios, as seen they are more impacted, and Figure 44 shows that there is mitigation power under either one of LUC scenarios with the increase of biofuel in the long term.

Figure 44 - GWP and DALY results for BAU and extreme scenarios considering the LUC scenarios (a) Carbon Fixation and (b) Illegal Expansion.



Source: Based on FWEMPS result.

It is worth noting that no indirect LUC emission is being accounted in this study, which could change results in either one of these four scenarios. By assuming an expansion mostly over pasturelands, if there is no increase of cattle ranching efficiency, then indirect LUC impact could be substantial. In this regard, Brazil has been experiencing support increase in higher cattle stoking rate, and the tendency is to continue this increase over the next decades (ADAMI *et al.*, 2012; BORDONAL *et al.*, 2018; DE ANDRADE JUNIOR *et al.*, 2019).

In terms of GWP (WTW) impact, our results corroborate with found in the literature for vehicles fleet case, but only if comparable category of LUC expansion is considered (GLENSOR; MUÑOZ B., 2019, see the difference between their main LCA result to the sensitivity analysis #1 result). Different result tendency is detected if LUC assumption differs substantially. All this also reinforces that discrepancy in LCA results may be seen depending on the assumption considered, and comparison between them is specially aggravated when there is lack of clarity of assumption, as it has been discussed in the literature (PEREIRA *et al.*, 2019; SEABRA *et al.*, 2011). This reveals how important is the way the model is conducted and the need to careful interpretation when considering different results.

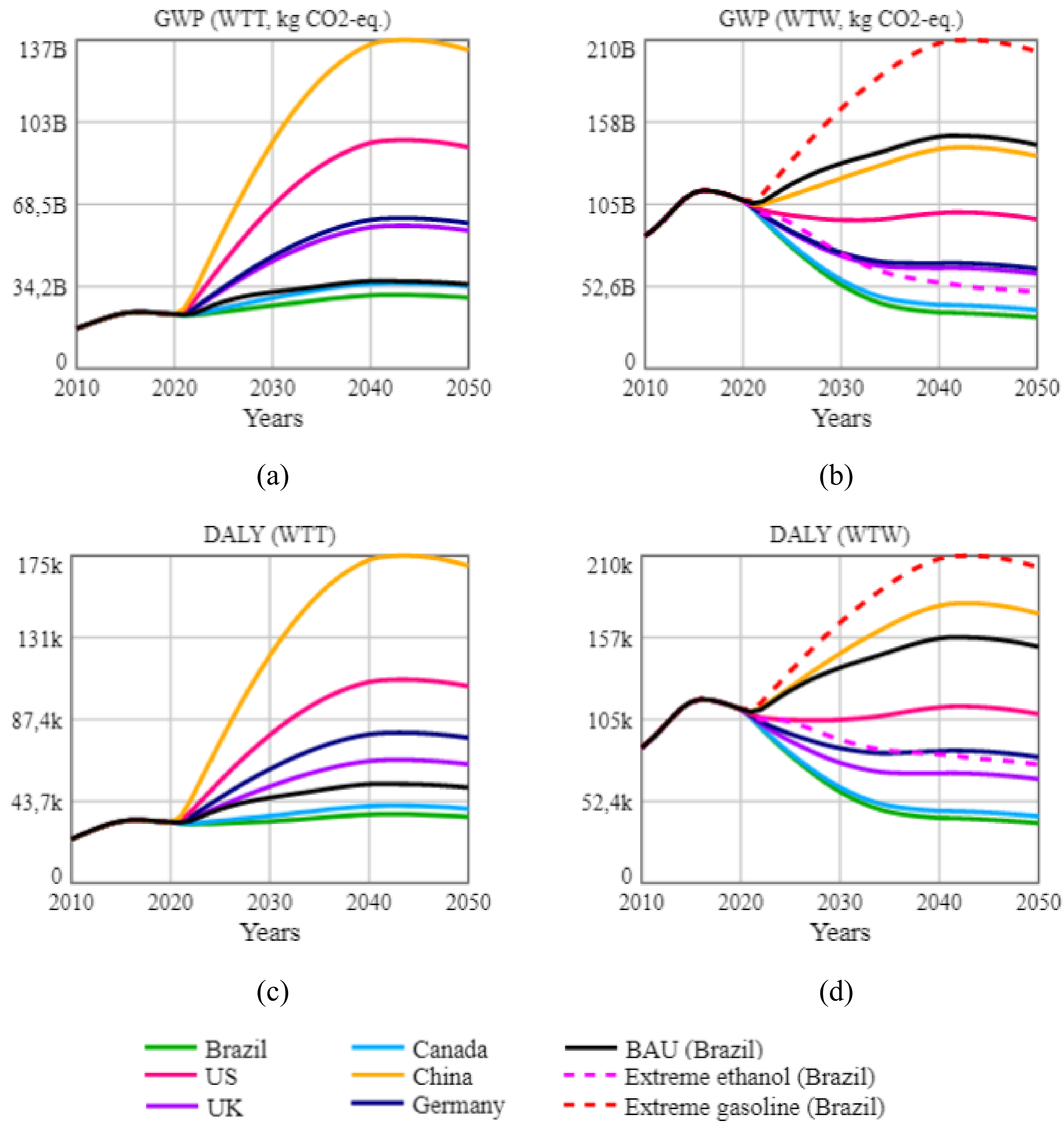
6.4.5 Power mix analysis

Figure 45 presents the final comparison analysis of both GWP and DALY assuming different power mix (from other five countries) and LUC emission factor. Results are for extreme scenarios except the BAU and, for perspective purposes, the extreme ethanol and gasoline scenarios (dotted lines). Both Canada and Brazil use a high (over 60%) percentage of hydropower (Figure 33), and similarity in GWP and human health impact are seen in results. In UK and Germany's case, although their power mix is quite different, two of their main sources are similar, i.e. wind and nuclear (with natural gas and coal being another power source they use the most, respectively). By assuming their power mixes, electric extreme scenario would potentially reach similar results and still considerable mitigation impact in both GWP and DALY, differing a bit in DALY as they differ in PM emission, also considerable responsible for this result (compare factors values in Table A4 and Table A8). In the case of DALY (Figure 45b), an electric scenario assuming Germany's current electricity share would present nearly similar impact as an extreme ethanol.

In the case of similar US power mix, by comparing with the BAU, although in a slower pace than the previous mentioned country scenarios, results show mitigation potential in the long-term. As for China' power mix, because of their most reliance on coal (although a good percentage of the renewable hydropower use), results show similar GHG emissions and higher DALY impact result than the BAU scenario. Thus, in this case (if power mix were similar to China's), if a decision strategy were to be made, it would be reasonable choice to just maintain the BAU fleet characteristic, improving with some other strategies/policies through time (such as biofuel increase), instead of shifting efforts to an extreme electric scenario.

Finally, it is worth noting that, all these results are based on current power mix data. Energy efficiency are being sought worldwide, so results would change if this indeed occurred. Results shown are hypothetical, for the purpose of comparison and thus this should be taken into consideration.

Figure 45 - GWP and DALY result for BAU, extreme scenarios and extreme electric scenarios considering other country's power mix.



Source: Based on FWEMPS results.

6.5 CONCLUSION

In this study, a fleet-based well-to-wheel model for policy support (FWEMPS) was introduced, which is able to assess the well-to-wheel life cycle of light-vehicles fleet, and enables a variety of policies/strategies testing in the long-term (2020-2050). By using Brazil's passenger fleet as empirical case, FWEMPS brings three key modelling features relevant for enhancing LCA analysis and decision making for the transportation community.

Firstly, FWEMPS broadens the level of analysis from product to a system-based using the fleet-based model approach. This enables capturing fuel-technology turnover and its impact on the overall system. Secondly, it engages with temporality in policy testing by the aid of the system dynamic modelling. The model picks the effect of the fleet behaviour shifts such as reduced travel intensity (even a potential Covid-19 impact in 2020 specifically), fleet renovation, tailpipe emission efficiency, ethanol increase/decrease and the testing of EVs sales only (in which different shares of BEV, hybrids and PHEV can be simulated). This enables the testing of various scenarios. Thirdly, the model connects midpoint impacts (e.g. GWP, PM and POF) to the endpoint impact of the human health category, DALY. The human health impact is essential to increase our understanding of how pollutant emissions can affect human health, enhancing awareness of our day-to-day lives potential impact.

Whether wanted or not, uncertainties play a relevant part in modelling. It cannot be neglected and, therefore, different potential outcome is addressed in this study. One of the key purposes of modelling - and not absent within the system dynamics approach - is to provide potential results for 'what if' questions. 'What if' questions are hypothetical questions for the sake of providing as much insight as possible for future decision making. Results presented on extreme scenarios are perfect examples of this use. By assessing those scenarios, it is possible to check whether a fleet mostly driven by EV (or ethanol-based) are indeed more sustainable than another type, the time lag for this to happen - especially when fleet turnover is concerned - and to which extent it differs from another type.

This comparison contrast between these fuels (more specifically, ethanol and electricity) is brought to attention since ethanol production already plays an important role in the country's fuelling system with its current majority flexible-fuel vehicles. Meanwhile, a fleet electrification is a recent ongoing topic worldwide, which enhances the pressure to shift the main fuel-technology, affecting this sector's strategic planning. When considering a WTW perspective, the country's power mix characteristics puts electric vehicles in a good territorial place to be spread, but their mostly associated high cost has been hindering its attractiveness among potential buyers. On the other hand, the country's know-how with its sugarcane production also puts biofuel increase on the spot. By adopting and keeping the best management practices in place - such as keeping the boundaries of agro-ecological zoning land expansion within the RenovaBio policy regulations - Brazil's perspective to invest in either direction is overall promising in respect to environment and human health impact.

Finally, this study has reinforced the sensitivity of the results according to the assumptions considered and the importance of clarity among them all. By assuming a different parameter within a simulation, vehicles diffusion number can easily vary which would subsequently impact the environmental and human health results in the long term. The same could be mentioned to land use projection assumption. Depending on the assumption on the category of land use, a scenario may end up intaking (absorbing – negative emission) or emitting CO_2-eq. in the WTT phase. Although in the overall WTW cycle, both additional LUC scenarios tested showed potential GWP mitigation impact in the long term, this may not be the case if other land use assumption is considered. In this regard, special attention must be made when considering the LUC expansion projection, both in terms of land category considered – as recent law has established eligible expansion only on non-native vegetation - and in terms of LUC emission methodology conduction.

Regarding future improvements, we suggest that the model can include the possibility of varying some other parameters through time, such as the power mix shares, and the inclusion of other modal transport. Also, an inclusion of indirect LUC assessment impact could be another future research analysis. Besides this, and while the model structure uses Brazil's data, it could also be adapted elsewhere.

6.6 APPENDIX A

Table A1 - Intensity of use of vehicles and scrapping rate based on the vehicles' age.

Year of use (1st, 2nd and so on)	**VKT (km/year)**	**Scrapping rate (%)**
1	10000	0.0037
2	19400	0.0065
3	18800	0.0102
4	18200	0.0150
5	17600	0.0207
6	17000	0.0272
7	16400	0.0342
8	15800	0.0415
9	15200	0.0489
10	14600	0.0561
11	14000	0.0631
12	13400	0.0697
13	12800	0.0759
14	12200	0.0816
15	11600	0.0868
16	11000	0.0915

17	10400	0.0957
18	9800	0.0995
19	9200	0.1029
20	8600	0.1060
20 plus*	3064	1/20

* for vehicles with 20 years of use and more (average estimate considered here).

Source: intensity of use, MMA (2011), and scrapping rate, MCT (2006).

Table A2 - Estimated innovation and imitator factors, and historical fuel economy (km/litre of fuel) of the average of cars sold in the state of Sao Paulo per vehicle type.

Year	**P(t)**	**q(t)**	**Gasoline fuel economy**	**Ethanol fuel economy**	**Flex fuel petrol**	**Flex fuel ethanol**
1980	0.009405	0.0368	8.90	7.10	0	0
1981	0.008860	0.0197	8.90	7.10	0	0
1982	0.008316	0.0105	8.90	7.10	0	0
1983	0.007772	0.0118	9.65	7.90	0	0
1984	0.007214	0.0184	10.19	8.25	0	0
1985	0.006642	0.0263	10.39	8.54	0	0
1986	0.006071	0.0316	10.42	8.46	0	0
1987	0.0055	0.0316	10.64	8.52	0	0
1988	0.005358	0.0289	10.86	8.58	0	0
1989	0.005217	0.0276	11.07	8.65	0	0
1990	0.005075	0.0303	11.82	8.65	0	0
1991	0.004895	0.0408	11.82	8.65	0	0
1992	0.004675	0.0763	10.98	8.01	0	0
1993	0.004455	0.1013	10.98	8.54	0	0
1994	0.004235	0.1158	10.04	7.54	0	0
1995	0.003882	0.1171	10.40	7.54	0	0
1996	0.003529	0.1132	11.04	7.17	0	0
1997	0.003176	0.1013	11.04	7.17	0	0
1998	0.003011	0.0855	11.82	7.41	0	0
1999	0.003034	0.0737	11.82	8.01	0	0
2000	0.003057	0.0632	11.89	6.96	0	0
2001	0.00308	0.0592	11.97	6.96	0	0
2002	0.002954	0.0566	10.9	7.2	0	0
2003	0.002828	0.0553	11.2	7.5	10.3	6.9
2004	0.002702	0.0553	11.4	8.6	10.8	7.3
2005	0.002608	0.0605	11.3	8.6	11.5	7.7
2006	0.002545	0.075	11.3	6.9	11.7	7.8
2007	0.002482	0.1197	11.3	0	11.7	7.8
2008	0.00242	0.1342	9.6	0	11.4	7.7
2009	0.002341	0.1382	9.9	0	11.5	7.8
2010	0.002262	0.1408	10.9	0	12.3	8.5
2011	0.002184	0.1368	11.2	0	12.2	8.6
2012	0.002137	0.1316	11.1	0	12.1	8.5
2013	0.002121	0.1211	11.2	0	12.4	8.6
2014	0.002105	0.0961	11.5	0	12.7	8.8
2015	0.00209	0.0803	12.0	0	13.2	9.2
2016	0.00209	0.0671	12.5	0	13.8	9.6

2017	0.00209	0.0632	13.1	0	14.3	9.8
2018	0.00209	0.0618	13.4	0	14.2	9.8
2019	0.00209	0.0632	12.1	0	14.5	10

Source: updated factors values from Benvenutti; Ribeiro and Uriona (2017), and fuel economy from CETESB (2019).

Table A3 - Historical estimated proportion of the fuel used in flexible fuel vehicles (both light and commercial), and historical estimated fuel volume used in light-vehicles fleet only.

Year	**Gasoline C (%)**	**Hydrated ethanol (%)**	**Gasoline C (litre)**	**Hydrated ethanol (litre)**
1991	-	-	7,080,685,078	10,669,323,549
1992	-	-	7,565,634,543	10,194,228,572
1993	-	-	8,514,752,337	9,731,524,281
1994	-	-	9,914,645,099	9,497,615,953
1995	-	-	11,782,292,734	9,423,076,120
1996	-	-	14,278,451,585	8,932,113,090
1997	-	-	16,813,081,065	8,206,994,975
1998	-	-	19,105,046,360	7,443,885,698
1999	-	-	20,947,026,524	6,697,721,361
2000	-	-	22,280,987,381	6,003,483,402
2001	-	-	23,239,670,697	5,312,750,596
2002	-	-	23,975,715,699	4,686,125,560
2003	0,21	0,79	24,605,612,877	4,218,521,343
2004	0,54	0,46	25,237,981,341	3,765,820,569
2005	0,71	0,29	25,527,310,743	3,656,427,402
2006	0,74	0,26	25,666,841,879	3,806,020,368
2007	0,70	0,30	25,901,079,227	4,220,266,459
2008	0,65	0,35	26,704,348,565	5,230,572,297
2009	0,65	0,35	28,221,503,099	6,934,332,313
2010	0,67	0,33	29,922,565,781	9,108,987,655
2011	0,77	0,23	31,563,047,162	11,374,967,963
2012	0,81	0,19	33,588,369,008	12,968,119,137
2013	0,79	0,21	35,951,980,029	13,959,433,398
2014	0,80	0,20	38,130,615,316	14,768,784,850
2015	0,73	0,27	39,543,976,203	15,359,436,514
2016	0,77	0,23	39,981,028,354	15,828,548,820
2017	0,78	0,22	39,725,607,784	16,095,693,649
2018	0,69	0,31	39,174,695,050	16,022,662,421
2019	0,65	0,35	38,420,757,545	16,033,742,251

Source: authors' own estimation of the ratio of fuel following equations 8-11, based on volume consumption in road transport in reports from BEN (2020) and vehicle production per fuel type from ANFAVEA (2020).

Table A4 - Characterization factors (per kilo of fuel) at the midpoint level for gasoline and ethanol WTT phase.

▪ Impact category (midpoint)	**Gasoline***		**Ethanol****
	Petrol	**Ethanol 99.7%**	**Ethanol 95%**
Global Warming (GWP)	0,623634774	0,494277681	0,453776363
Fine particulate matter formation (PM)	0,001522394	0,00377653	0,00331007
Photochemical ozone formation (POF), human health	0,002290666	0,003657742	0,003082752
Stratospheric ozone depletion	1,00173E-06	7,36384E-06	6,73548E-06
Ionizing Radiation	0,031548152	0,004328329	0,003948755
Toxicity (cancer)	0,009582062	0,008368715	0,007900955

Toxicity (non-cancer)	0,194172533	0,387541606	0,365662256
Land use (m2a crop eq.)	0.000457378	0.918001652	0.869645416

* A combination of the product systems: (i) petrol production, unleaded, petroleum refinery operation | petrol, unleaded | Cutoff, U – BR; and (ii) sugarcane processing, modern annexed plant | ethanol, without water, in 99.7% solution state, from fermentation | Cutoff, U – BR (22% of anhydrous ethanol until 2007, 25% until 2015 and 27% rest of simulation).
** Market for ethanol, without water, in 95% solution state, from fermentation | ethanol, without water, in 95% solution state, from fermentation | Cutoff, U – BR.

Source: Ecoinvent 3.6 database using the LCIA Hierarchic method ReCiPe (2016).

Table A5 - Midpoint impact factors (Hierarchic) for TTW gas emissions.

Midpoint group	**Gas emission**	**Impact factors**	**Unit**
GWP	CO_2	1	kg $CO_{2\text{-}eq}$/ kg GHG
	CH_4	34	
	N_2O	298	
PM	PM*	0.2257	kg$PM_{2.5\text{-}eq.}$/kg
POF	RCHO	0.2	Kg $NO_{x\text{-}eq.}$/kg
	CO**	0.0456	
	NO_x*	0.83	
	NMOG(NMVOC)	0.03	Kg $NO_{x\text{-}eq.}$/kg

* Country-specific factors (Brazil)
** Factor from ReCiPe year 2014.

Source: Recipe (2016).

Table A6 - Endpoint impact factors (Hierarchic).

Midpoint to Endpoint converters	**Impact factors**	**Unit**
Global Warming (GWP)	9,28E-07	DALY/kg CO2 eq.
Fine particulate matter formation (PM)*	9,70E-05	DALY/kg PM2.5 eq.
Photochemical ozone formation (POF), human health*	4,50E-07	DALY/kg NOx eq.
Stratospheric ozone depletion	5,31E-04	DALY/kg CFC11 eq.
Ionizing Radiation	8,50E-09	DALY/kBq Co-60 emitted to air eq.
Toxicity (cancer)	3,32E-06	DALY/kg 1,4-DCB emitted to urban air eq.
Toxicity (non-cancer)	2,28E-07	DALY/kg 1,4-DCB emitted to urban air eq.

* Country-specific factors (Brazil)

Source: Recipe (2016).

Table A7 - Historical percentage of energy power source in Brazil.

Year	**Hydro***	**Biomass***	**Wind**	**Solar**	**Gas natural**	**Oil derivative**	**Nuclear**	**Coal**
2006	83.80	6.1	0.10	0.00	3.20	2.80	2.60	1.40
2007	83.80	6.1	0.10	0.00	3.20	2.80	2.60	1.40
2008	83.80	6.1	0.10	0.00	3.20	2.80	2.60	1.40
2009	83.38	7.02	0.20	0.00	2.60	2.90	2.50	1.30
2010	79.60	6.30	0.40	0.00	6.60	2.90	2.60	1.50
2011	81.90	6.60	0.50	0.00	4.40	2.50	2.70	1.40
2012	76.90	6.80	0.90	0.00	7.90	3.30	2.70	1.60
2013	70.60	7.60	1.10	0.00	11.30	4.40	2.40	2.60
2014	65.20	7.40	2.00	0.00	13.00	5.70	2.50	4.30
2015	64.00	8.00	3.50	0.01	12.90	4.80	2.40	4.50

2016	68.10	8.20	5.40	0.00	9.10	2.50	2.60	4.10
2017	65.20	8.20	6.80	0.10	10.50	3.00	2.50	3.60
2018	66.60	8.50	7.60	0.50	8.60	2.40	2.50	3.20

* 80% of (renewable) imported power has been attributed to hydropower and 20% to biomass source between 2006-2009.

Source: Brazilian energy balance (BEN, 2020).

Table A8 - Characterization factors (per 1 kWh) at the midpoint level for Brazil's power mix WTT phase and battery lithium emission rates.

Impact category (midpoint)	Hydro[1]	Biomass[2]	Wind[3]	Solar[4]	Natural gas[5]	Oil[6]	Nuclear[7]	Coal[8]	Battery[9]
Global Warming (GWP)	0.053	0.031	0.014	0.076	0.565	1.064	0.012	0.963	7.955
Fine particulate matter formation (PM)	1.10E-05	1.55E-03	3.45E-05	1.93E-04	1.31E-04	2.85E-03	4.17E-05	1.83E-03	0.043
Photochemical ozone formation (POF), human health	1.92E-05	2.05E-03	4.35E-05	2.01E-04	5.65E-04	3.38E-03	3.98E-05	2.45E-03	0.031
Stratospheric ozone depletion	3.11E-09	6.24E-07	6.22E-09	3.60E-08	1.45E-07	7.40E-07	3.75E-08	1.76E-07	6E-06
Ionizing Radiation	2.80E-04	4.84E-04	6.86E-04	5.89E-03	7.11E-04	0.011	0.699	1.67E-03	0.586
Toxicity (cancer)	7.64E-04	1.86E-03	5.31E-03	7.88E-03	9.35E-04	5.51E-03	1.69E-03	0.048	1.262
Toxicity (non-cancer)	0.005	0.462	0.050	0.335	0.021	0.076	0.024	0.531	126.141

Product systems (1-6 Ecoinvent 3.5 and 7 Ecoinvent 3.6):
1 electricity production, hydro, reservoir, tropical region | electricity, high voltage | Cutoff, S
2 treatment of bagasse, from sugarcane, in heat and power co-generation unit, 6400kW thermal | electricity, high voltage | Cutoff, S
3 electricity production, wind, 1-3MW turbine, onshore | electricity, high voltage | Cutoff, S
4 electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si, panel, mounted | electricity, low voltage | Cutoff, S
5 electricity production, natural gas, conventional power plant | electricity, high voltage | Cutoff, S
6 electricity production, oil | electricity, high voltage | Cutoff, S
7 electricity production, nuclear, pressure water reactor | electricity, high voltage | Cutoff, S
8 electricity production, hard coal | electricity, high voltage | Cutoff, S
9 market for battery, Li-ion, rechargeable, prismatic | battery, Li-ion, rechargeable, prismatic | Cutoff, U GLO

Source: Ecoinvent 3.5 and 3.6 database using the LCIA Hierarchic method ReCiPe (2016).

Table A9 – From the produced sugarcane destined to ethanol, the average produced by state from 2012 to 2020.

State (or region)	Percentage (%)
North	**1**
AM (Amazonas)	0.028
PA (Pará)	0.154
TO (Tocantins)	0.599
Northeast	**6**
MA (Maranhão)	0.594
PI (Piauí)	0.123
RN (Rio Grande do Norte)	0.339
PB (Paraíba)	1.002
PE (Pernambuco)	1.282
AL (Alagoas)	1.582
SE (Sergipe)	0.677

BA (Bahia)	0.656
Midwest	**28**
MT (Mato Grosso)	3.861
MS (Mato Grosso do Sul)	9.323
GO (Goiás)	14.429
Southeast	**60**
MG (Minas Gerais)	9.586
ES (Espírito Santo)	0.550
RJ (Rio de Janeiro)	0.296
SP (São Paulo)	49.646
South	**5**
PR (Paraná)	5.023
RS (Rio Grande do Sul)	0.013
Brazil	**100**

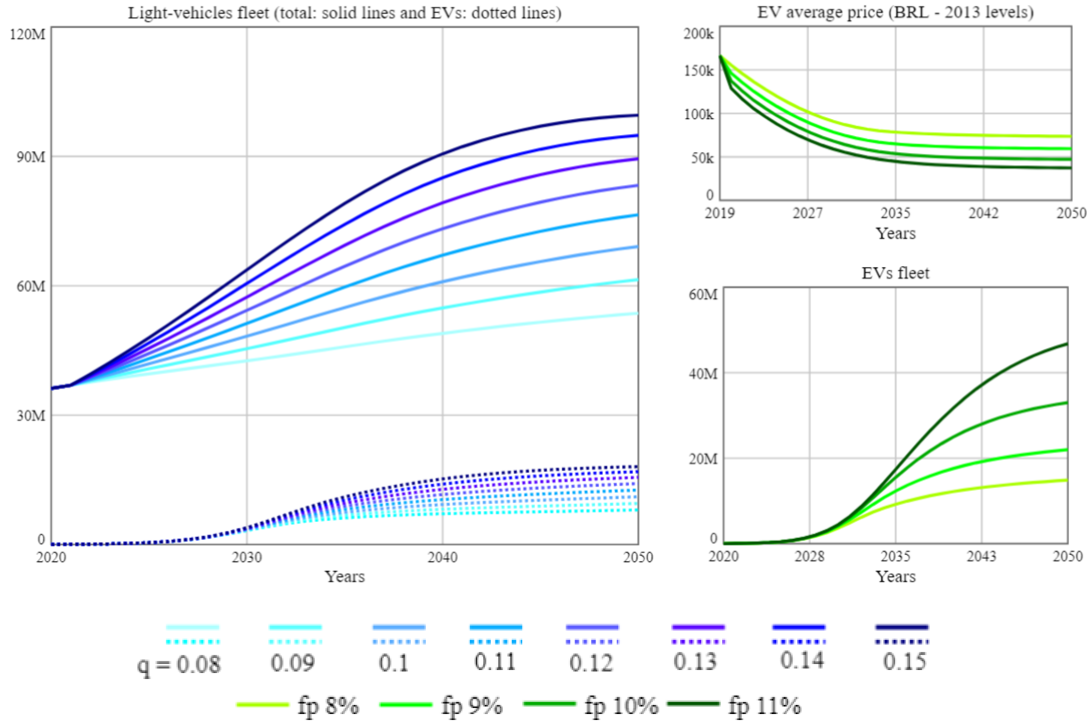
Source: Based on reports from CONAB (2020).

Table A10 - FWEMPS result of licensing and vehicles fleet number.

		q(t) fixed at 0.125		
Year	**Licensing vehicles**	**Total fleet**	**Licensing EVs**	**Total fleet EVs**
2020	2,343,680	36,196,776	18,560	24,133
2021	3,589,696	36,939,454	32,215	42,490
2022	3,711,076	38,857,229	55,278	74,343
2023	3,829,059	40,826,704	93,587	128,981
2024	3,943,860	42,847,130	155,695	221,446
2025	4,055,075	44,916,819	253,078	375,187
2026	4,162,260	47,031,855	398,903	624,899
2027	4,264,313	49,187,136	603,771	1,018,078
2028	4,359,808	51,376,987	867,072	1,612,262
2029	4,449,136	53,601,410	1,165,489	2,463,591
2030	4,531,611	55,850,982	1,446,580	3,603,846
2031	4,605,972	58,112,073	1,640,949	5,011,127
2032	4,672,441	60,369,660	1,697,392	6,592,867
2033	4,730,526	62,607,346	1,617,765	8,204,223
2034	4,779,467	64,808,626	1,455,803	9,701,536
2035	4,820,160	66,955,227	1,278,908	10,994,733
2036	4,853,176	69,024,759	1,131,977	12,061,517
2037	4,875,618	71,000,885	1,030,580	12,925,353
2038	4,888,727	72,867,190	971,149	13,626,604
2039	4,895,278	74,614,379	943,743	14,203,779
2040	4,894,034	76,238,317	938,339	14,687,396
2041	4,885,646	77,735,927	946,599	15,099,964
2042	4,870,763	79,112,818	963,051	15,457,553
2043	4,849,989	80,389,052	985,125	15,772,400
2044	4,823,797	81,562,965	1,008,421	16,055,474
2045	4,792,771	82,633,656	1,029,912	16,314,289
2046	4,757,445	83,601,079	1,047,582	16,553,982
2047	4,718,150	84,465,951	1,060,106	16,778,111
2048	4,675,296	85,229,510	1,066,592	16,989,220
2049	4,631,631	85,893,533	1,066,451	17,189,167
2050	4,587,543	86,462,611	1,059,614	17,379,200

Source: FWEMPS results.

Figure A2 - Sensitivity analysis on the imitation factor, q(t), and on the fixed percentage, fp, by which the EV price falls with every doubling of experience.



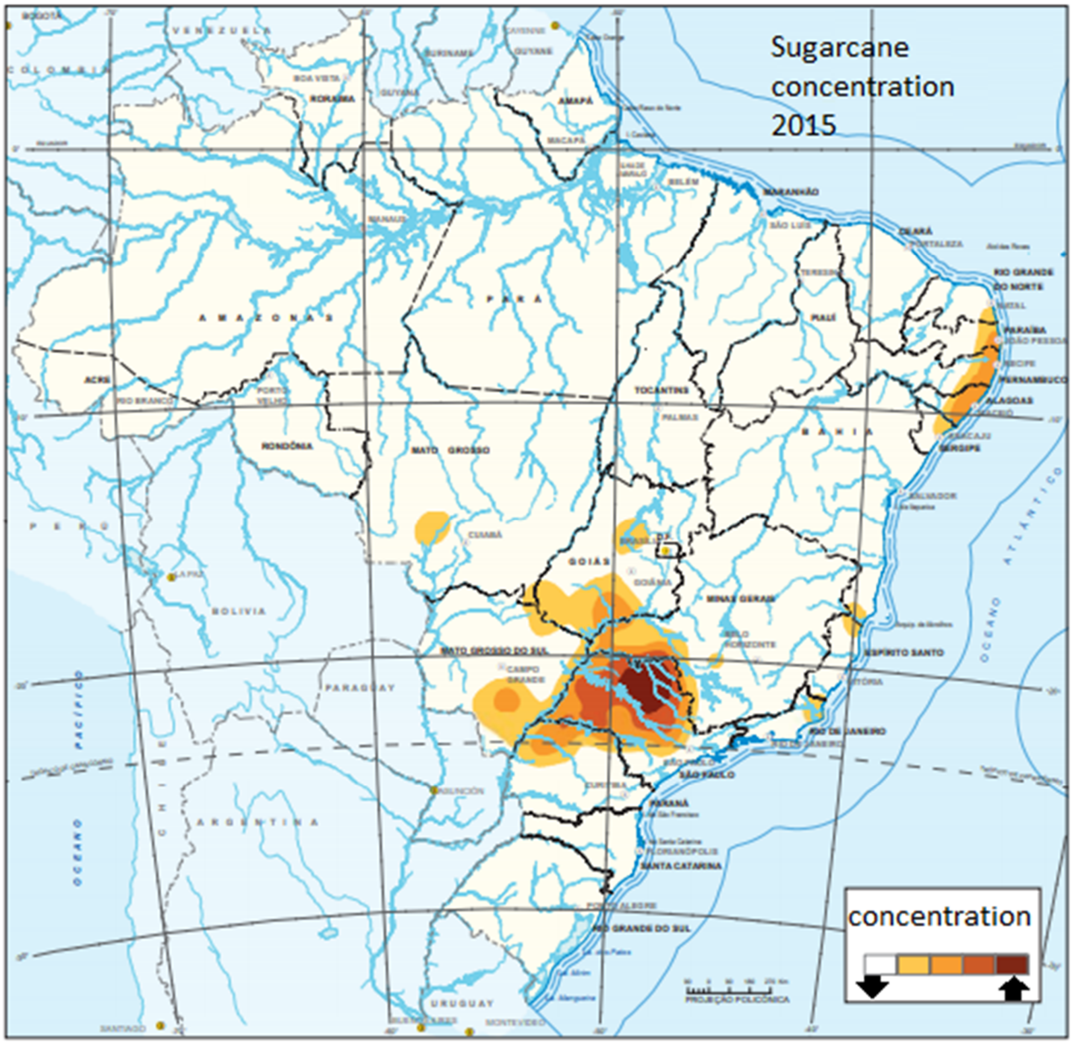
Source: Based on FWEMPS result.

Table A 11 – The respective LUC GWP emissions of the scenarios adopted in this study, considering different amortized period for the simulation 2020-2050 timeframe.

LUC scenario	**20-years** (tCO_2/ha.yr)	**30-years** (tCO_2/ha.yr)
BAU (8.8 tCO_2/ha)	0.44	0.29
Carbon Fixation (-15.6 tCO_2/ha)	-0.78	-0.52
Illegal Expansion (48.4 tCO_2/ha)	2.42	1.61

Source: Based on the assumptions and authors described for equation 12 and subsection 6.3.3.

Figure A3 - Concentration map of sugarcane production.



Source: IBGE (2017).

6.7 APPENDIX B

Table B1. WTT disaggregated calculation of the stock from Figure 30.

$$WTT_1^{fuel}(t_j) = WTT_1^{fuel}(t_{j-1}) + \int_{t_{j-1}}^{t_j} WTT^{fuel} per\ km(t) - [WTT^{fuel} transfer_1(t) + exempted\ WTT_1^{fuel}(t)]\ dt \quad \text{B1}$$

$$WTT_k^{fuel}(t_j) = WTT_k^{fuel}(t_{j-1}) + \int_{t_{j-1}}^{t_j} WTT^{fuel} per\ km_{k-1}(t) - [WTT^{fuel} transfer_k(t) + exempted\ WTT_k^{fuel}(t)]\ dt, \quad 2 \le k \le 20 \quad \text{B2}$$

$$WTT_{21}^{fuel}(t_j) = WTT_{21}^{fuel}(t_{j-1}) + \int_{t_{j-1}}^{t_j} WTT^{fuel} per\ km_{20}\ (t) - exempted\ WTT_{21}^{fuel}(t)\ dt \quad \text{B3}$$

$$WTT_{total}^{fuel}(t_j) = (WTT_1^{fuel}(t_j) * VKT_1) + (WTT_k^{fuel}(t_j) * VKT_k) + (WTT_{21}^{fuel}(t_j) * VKT_{21}) \quad \text{B4}$$

where "j" represents the time in 1980-2050 period and "k" represents the age of the vehicle in the respective stock. Where $WTT^{fuel} per\ km(t) = (adoption\ by\ innovation + imitation) * \frac{(CAR\ proportion)}{CAR\ autonomy}$, and in the case of EV is $WTT^{power} per\ km(t) = (adoption\ by\ innovation + imitation) * EV\ proportion * EV\ autonomy$

Table B2. TTW disaggregated calculation of the stock from Figure 29.

$$TTW_1^{emitter}(t_j) = TTW_1^{emitter}(t_{j-1}) + \int_{t_{j-1}}^{t_j} TTW^{emitter} per\ km(t) - [TTW^{emitter} transfer_1(t) + exempted\ TTW_1^{emitter}(t)]\ dt \quad \text{B5}$$

$$TTW_k^{emitter}(t_j) = TTW_k^{emitter}(t_{j-1}) + \int_{t_{j-1}}^{t_j} TTW^{emitter} per\ km_{k-1}\ (t) - [TTW^{emitter} transfer_k(t) + exempted\ TTW_k^{emitter}(t)]\ dt, \qquad 2 \le k \le 20 \quad \text{B6}$$

$$TTW_{21}^{emitter}(t_j) = TTW_{21}^{emitter}(t_{j-1}) + \int_{t_{j-1}}^{t_j} TTW^{emitter} per\ km_{20}\ (t) - exempted\ TTW_{21}^{emitter}(t)\ dt \quad \text{B7}$$

$$TTW^{emitter}(t_j) = (TTW_1^{emitter}(t_j) * VKT_1) + (TTW_k^{emitter}(t_j) * VKT_k) + (TTW_{21}^{emitter}(t_j) * VKT_{21}) \quad \text{B8}$$

where $TTW^{emitter} per\ km(t) = gas\ emission\ rate * (\ adoption\ by\ innovation + imitation)$.

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CHAPTER VII

7 NATIONAL PERSPECTIVES AND CHALLENGES FOR ACHIEVING THE PROCONVE L7 AND L8 VEHICLES EMISSION STANDARDS

This chapter presents the fifth paper of this thesis, being the last result of step 3 and of this doctoral work.

Abstract

The next two phases of PROCONVE emission standards have been proposed for light-vehicles. The L7, starting in 2022, and the L8 starting in 2025, which gradually attains more rigorous limits until 2031. Although with a certain time lag, the regulation will lead the country closer to the standards adopted by other international regions such as Tier (US) and Euro (Europe). One of the main differences to prior PROCONVE phase (L6), and now similar to US emission standard (Tier), is the inclusion of the combine NMOG (nonmethane organic gas) and NOx (nitrogen oxides) standards into one NMOG+NOx standard, responsible for ozone and smog formation. However, due to its characteristics, flexible fuel vehicles fuelled with ethanol have much more difficulty in reaching those limits, putting not only these vehicles but also ethanol in a contradictory disadvantage position. Car manufacturers now face this particular challenge in addition to other requirements of the regulation and to the global Covid-19 pandemic, which has contributed even more to financial difficulties. In this study, we use the fleet-based model FWEMPS to simulate the perspective of the average new vehicles in reaching PROCONVE L7 and L8 emission targets by 2031. The main aim is to verify whether or not there is tangible challenge towards meeting any of air pollution limits and the extent of this gap. We also test different scenarios that can aid the mitigation of gas emissions. Results indicate that although there is a good perspective of the vehicles meeting most of the air pollutant limits, automakers will need to accelerate and increase efforts to meet the new NMOG+NOx emission limit by 2029 and 2031 (L8). While the past recent years they were able to increase the fuel-economy by an average of 2.65%, if no increase uptake of less emitter technologies such as electric and hybrid vehicles occurs, car manufacturers are expected to improve vehicles' fuel-efficiency by at least 5% each year to meet the new standard. Finally, this study also provides insights on the regulation in comparison to international ones and bring important discussion on PROCONVE L7 and L8.

Keywords: Emission standards; Proconve, light-vehicles, system dynamics.

7.1 INTRODUCTION

Over the last decades, concerns for the global environment have increased and with this, regional and national standards have emerged to, among other reasons, induce industries into adopting more efficient and sustainable practices. In this context, the transportation sector has a relevant part to play since they are one of the main sectors responsible for air pollution, in which is estimated to cause 7.6% of deaths worldwide (WHO, 2016). Air emission standards and regulation policies helps limiting vehicles' emission and thus contribute to the transition to a lower pollutant emitter sector (ICCT, 2017).

In Brazil, the Air Pollution Control Program by Motor Vehicles (PROCONVE) was established in 1986 by the National Council of the Environment (CONAMA) (CONAMA, 1986). Since then, the automakers have been subject to six progressive phases (light-vehicles) of emission limits. Recently, two other phases were set, one for 2022 (PROCONVE L7), and another for 2025 (PROCONVE L8). The L8 phase starts in 2025 but gradually becomes more rigours by 2031 (CONAMA, 2018). Although temporarily behind, PROCONVE's regulation for light-vehicles has mostly resembled the legislation from the US and the heavy-vehicles to the European emission standards (Euro) (CETESB, 2018).

Since 2003, flexible fuel vehicles (FFV) have penetrated the Brazilian vehicles market, currently reaching over 95% of the sales annually (ANFAVEA, 2020). This type of engine allows the use of both gasoline and ethanol as a fuel at any given rate. However, while FFV contributes to a lower emission of greenhouse gas (GHG) because of the use of biofuel, it is not exempt of other gases emission responsible for air pollutant such as gases responsible for the formation of ozone and smog. The photochemical ozone formation (POF) is formed as a result of reactions of NOx and nonmethane organic gas (NMOG) in the presence of sunlight (RECIPE, 2016). Ozone intake is harmful to humans due to its capacity to cause respiratory related diseases (HUIJBREGTS *et al.*, 2017). Vehicles fuelled by ethanol are particular stricken with this type of formation as it emits a higher portion of these compounds and also unburn ethanol (NMHC-ETOH), which can account for a significant fraction of total organic gas compounds (ICCT, 2017).

Regarding the unburn ethanol emission, until current regulation (L6), car manufacturers have been exempted of limiting its emission. The main reason is attributed to the difficulty the flexible engines had in meeting the targets considering the occurrence of ethanol emission during ignition in cold (Branco *et al.*, 2014). To support the FFV diffusion, the Brazilian Institute of the Environment and Renewable Natural Resources (IBAMA) then authorized the discount of this emission until new technologies to reduce them were seen (IBAMA, 2004). More recently, this aspect has been brought up by specialists of the field (IBAMA, 2018; ICCT, 2017). For instance, in the public consultation for the new phases of PROCONVE and PROMOT (related to motorcycles), among other issues, the ozone formation matter was one of the main subjects referred by the experts. They pointed out the need to control the emission of organic compounds more efficiently such as hydrocarbon, unburn ethanol and aldehydes by flex engines because of its POF potential. Overall, this point was accepted by IBAMA and now the next PROCONVE L7 phase stipulates that unburn ethanol will not be discounted and has established a more stringent limit for NMOG+NOx emission (in similar fashion as the Tier 3). Another point emphasised by the experts was the need to not only monitor the emission of CO_2, but to include limits to it. In this case, this point has not been adopted so far, and IBAMA's response was that CO_2 emission would be subject of another CONAMA's resolution (IBAMA, 2018).

However, besides the regular challenges involved in improving technologies to meet more rigours standards, PROCONVE's new phases imposed an intriguing issue for the automakers: the bioethanol potential disadvantage under this scenario (Kutney, 2019). The aim to significantly reduce the ozone formation potential was reflected in L8 phase by the progressive increasingly more stringent limits for NMOG+NOx standard starting in 2025 until 2031. When fuelled by ethanol, however, FFV will have more challenge in attending it, which may put this fuel-technology into jeopardy (Ortiz, 2019; Siqueira, 2019; UDOP, 2019). The limit has even been referred to a result of a potential conceptual error (Cardamone, 2020). On top of that, the Covid-19 pandemic only posed more challenges to the automakers engineering development in meeting the new PROCONVE's phases (Toume, 2020). With all this, the National Association of Motor Vehicle Manufacturers (ANFAVEA) have been requesting a postponement of PROCONVE L7 and P8 (Kutney, 2020a; b; Terra, 2020).

In this context, by using the Fleet-based Well-to-wheel Model for Policy Support (FWEMPS) (Benvenutti; Campos; Vazquez-Brust; Liston-Heyes, 2021), this study simulates the perspective the future average vehicles have into reaching PROCONVE targets by 2031 (with the gases: particulate matter, PM, carbon monoxide, CO, aldehyde, RCHO, NMOG + NOx, and CO_2). By doing so, it will be possible to estimate the extent of the gap the automakers are expected to work with. Additionally, a few scenarios involving the testing of different fuel content, fuel-efficiency improvement, and electric and hybrid vehicles (EVs) increase are also simulated to check their mitigation potential impact on those emission rates and their strength to reach the standards. This study also brings a comparison analysis between PROCONVE emission limits to other international standards, such as Euro 6 and Tier 3.

This paper is presented as follows: in Section 2, a brief history background of the legislation PROCONVE is provided along with current and future phase proposal (L7 and L8). In section 3, the methodology undertaken to conduct the perspective of light-vehicles meeting future targets is presented. In Section 4, the results of the analysis are presented with first a comparative analysis between PROCONVE and emission data from the Environmental Company of the State of São Paulo (CETESB) of vehicles since 2014 (L6), and then to the Euro 6 and Tier 3 standards. The last subsection of this section contains the simulation results, which includes some important insights to both the regulation and the auto industry. Finally, this study ends with the conclusion of this research analysis.

7.2 BRAZILIAN LEGISLATION CONTEXT ON AIR POLLUTANTS – PROCONVE

7.2.1 Brief historical facts

The history of the Brazilian legislation related to atmospheric pollution dates back to 1975 (BRAZIL, 1975), which deals with the control of environmental pollution caused by industrial activities. This decree states that industries must promote the necessary measures to prevent or correct the inconveniences and losses caused by pollution and contamination of the environment. In this stage, however, it does not specify any rules and targets. It states that appropriate measures must be defined by the competent federal agencies, in the interests of the well-being, health and safety of the population.

Six years later, the National Environment Policy was created, with the objective of "preserving, improving and recovering the environmental quality conducive to life, aiming to ensure, in the Country, conditions for socio-economic development, national security interests and the protection of the dignity of human life." (BRAZIL, 1981) In this law, the National Environment System (SISNAMA) is also created, constituted by the bodies and entities of the

Union, the States, the Federal District, the Municipalities, as well as the National Council of the Environment (CONAMA), which is SISNAMA's regulatory, advisory and deliberative body whose function, among others, is "to establish, exclusively, national norms and standards for the control of pollution by motor vehicles, aircraft and vessels, upon hearing from the competent Ministries."

In 1986, the Air Pollution Control Program by Motor Vehicles (PROCONVE) is instituted by CONAMA (1986), with the following objectives: "to reduce the levels of emission of pollutants by vehicles motor vehicles aimed at meeting air quality standards, especially in urban centres; promote national technological development, both in automotive engineering, as well as in methods and equipment for testing and measuring pollutant emissions; create inspection and maintenance programs for motor vehicles in use; promote public awareness of the issue of air pollution by motor vehicles; establish conditions for evaluating the results achieved; promote the improvement of the technical characteristics of liquid fuels, made available to the national fleet of motor vehicles, aiming at the reduction of polluting emissions to the atmosphere". From this moment forward, the maximum limits of air pollutants emission began to be established for new engines and motor vehicles.

As a historical context, it is worth mentioning the first rules established for light vehicles with Otto cycle engines: "For the new light motor vehicle configurations launched and marketed from June 19, 1988, the emission of exhaust gases should not exceed the following values: carbon monoxide (CO): 24.0 grams per kilometre; hydrocarbons (HC): 2.1 grams per kilometre; nitrogen oxides (NOx): 2.0 grams per kilometre; carbon monoxide content at idle: 3.0 percent." (CONAMA, 1986). Since then, a number of standards and targets were established via legislation, varying for different vehicle categories. In the case of light passenger vehicles (automobiles), there are 8 phases; L1 and L2 (CONAMA, 1986), L3 (CONAMA, 1995), L4 and L5 (CONAMA, 2002), L6 (CONAMA, 2009), L7 and L8 (CONAMA, 2018).

7.2.2 Present and future targets

Currently, Brazil's automakers are subject to PROCONVE L6 phase. In this stage, the following maximum emission limits rules have come into force in 2014 (2015 for some models) and must be met by new passenger light motor vehicles:

• Carbon monoxide (CO): 1.30 g/km;

• Total hydrocarbons (THC), only for natural gas vehicles: 0.30 g/km;

• Non-methane hydrocarbons (NMHC): 0.05 g/km;

• Nitrogen oxides (NOx): 0.08 g/km;

• Aldehydes (CHO) for Otto cycle: 0.02 g/km;

• Particulate matter (MP) for the Diesel cycle: 0.025 g/km;

• Carbon monoxide idling for the Otto cycle: 0.2% by volume.

The above regulation is valid until December 31, 2021, and then PROCONVE L7 will begin. In L7 phase, some important rules change is established for calculating tailpipe emissions. Among them, the following stands out: (i) the sum of NMOG and NOx as a single factor; (ii) the portion of unburned ethanol will be accounted; (iii) it must be proven that the maximum pollutant emission limits are met for 160,000 km, or ten years of use, whichever comes first, and for that deterioration factor tests will be used. The maximum emission limits for new light passenger vehicles will be:

• NMOG + NOx: 80 mg/km;

• MP: 6 mg/km;

• CO: 1 g/km;

• CHO: 15 mg/km.

The L8 phase will take effect on January 1, 2025. In this phase, in addition to the previous phase measures rules, each new light passenger vehicle will be certified in a certain level (bin), according to Table 18 (e.g. if the vehicle receives a certification of level 80, it means that the vehicle must have at least one gas emitter that its higher than the level-70 but below or in the maximum equal to level-80):

Table 18 - PROCONVE L8 vehicles emission standard levels (or bin), in similar fashion to the US Tier standards.

Level (bin)	**NMOG + NOx** mg/km	**MP** mg/km	**CO** g/km	**Aldehydes** mg/km	**NH_3** ppm	**Evaporative** g/test	**Fuelling emission** mg/L
80	80	6	1	15	10	0.5	50
70	70	4	0.6	10			
60	60	4	0.6	10			
50	50	4	0.6	10			
40	40	4	0.5	10			
30	30	3	0.5	8			
20	20	2	0.4	8			
0	0	Null	Null	Null			

Source: CONAMA (2018).

In addition, there will be maximum limits for the emission of pollutants in a corporate manner. The corporate emission limit, in the category of light passenger vehicles, will be verified by calculating the annual average of the levels of all new vehicles sold by the automaker, weighted by the respective annual quantities of vehicles registered (sold) in each level. In this stage, each automaker must meet a corporate level according to Table 19. Note that there is no change in the corporate level from 2029 to 2031 for these vehicles' category. In 2031, changes will occur only in the category of light commercial vehicles, which is outside the scope of this study, but shown in the table for comparison purposes.

Table 19 - PROCONVE L8 maximum corporate (automakers' fleet-wide average car sold) pollutant emission limits for light-vehicles.

Date	**Corporate level for light commercial vehicles**	**Corporate level for light passenger vehicles**
01/01/2025	140	50
01/01/2027	110	40
01/01/2029	50	30
01/01/2031	30	30

Source: CONAMA (2018).

7.3 METHODOLOGY

The methodology adopted in this study involves two main steps. First, a comparison analysis between the national light-vehicles emission limits established by PROCONVE with the average vehicles' emissions published annually by CETESB database, and then PROCONVE standard comparison with the limits provided by the European union standards (Euro 6) and the US (Tier). Second, a simulation of the new vehicles using a fleet-based model (FWEMPS) (BENVENUTTI *et al.*, 2021) and their estimate emissions by 2031. Next, each step is described.

7.3.1 Regulation comparison analysis

Besides the air emission limits, there are many other aspects involved in a regulation (e.g. laboratory measurements requirement). In this study, the comparison focus was on gases emission of light-vehicles. The source used to verify PROCONVE emission standards historically and currently established by CONAMA is found in the online database of the Ministry of Environment (MMA, 2021). For the information of the average emission of new vehicles sold annually since the beginning of PROCONVE L6, the CETESB online database is used (CETESB, 2019).

It is important to note that the National Institute of Metrology, Quality and Technology (INMETRO) has also been annually publishing vehicles emission rates and fuel-economy as part of the Brazilian program of labelling (INMETRO, 2020). But while INMETRO publishes the data per each vehicle type, CETESB provides historical data of the laboratory measurements of emissions from the average vehicles sold in the state. This facilitates comparison analysis of this study since it aims to present the perspective of the fleet-wide average vehicles that will be sold each year in achieving the targets. Furthermore, passenger vehicles from the state of Sao Paulo corresponds to 33% of the total national fleet (IBGE, 2018), a considerable number to make such comparison. Furthermore, the emission limits from the Euro and Tier are taken from the online database (EUR-LEX, 2020) and (EPA, 2021), respectively.

7.3.2 Simulation procedure

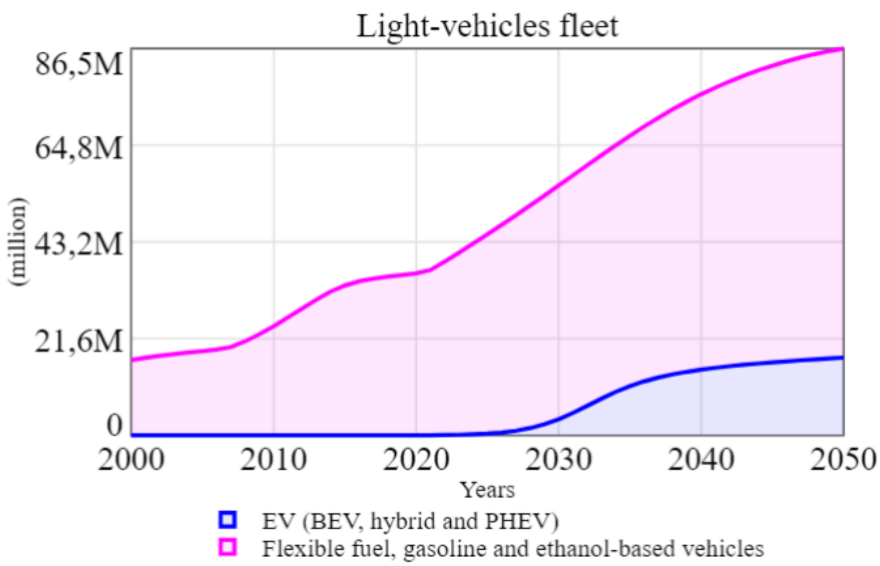
7.3.2.1 System dynamic model for the national fleet

In this study, we use FWEMPS from to conduct the simulations. Designed in system dynamic modelling, this model simulates the diffusion of light-vehicles in Brazil in two interdependent parts, one for all the fleet (since 1980) and the other for EVs only (since 2006, when the EVs was first sold). It also allows the testing of different strategies/policies intended to mitigate environmental emission at midpoint level (the main ones are GWP, PM and POF) and endpoint level (DALY) impact in a temporal perspective (2020-2050).

We take FWEMPS to simulate the Brazilian fleet-wide average vehicles licensed and their emission factor for each of the following gases: NMOG + NOx (we combine them just as the new resolution proposes), CO_2, CO, PM and RCHO. The vehicles are expected to meet specific emission limits from each of these gases, except CO_2, in which the resolution only establishes the need to monitor and declare. So here we compare it with the CO_2 targets established by the European Commission. For 2015, the EU fleet-wide average emission of new passenger cars had set a target of 130g of CO_2/km for 2015, and 95 g CO_2/km for 2021 (EU, 2017).

The historical period of analysis begins in 2003, when the first FFV is sold, and future estimate starts 2020 and goes until 2031, when the last emission limit is proposed by PROCONVE L8. The fleet-wide average emission rates are based on the proportion of vehicles sold per year, using the numbers of FWEMPS business-as-usual (BAU) scenario. Figure 46 shows the number in terms of fleet (total and the respective EVs share). From 2024 onward it is assumed that no more solely gasoline-fuelled vehicles will be commercialized, only FFV or EVs (which includes battery electric vehicles, BEV, hybrids and plug-in electric vehicles, PHEV) being sold. In this scenario, by 2030, EVs represents a share of 6.4% of the fleet (3.6 million out of 55.9 million vehicles), and by 2050, 20.1% of the total fleet (17.4 million out of 86.5 million vehicles, similar to the 18% considered in GLENSOR; MUÑOZ B., 2019).

Figure 46 - Brazil national fleet number (million), historical (2000-2019) and future estimate (2020-2050).



Source: Based on BAU scenario of Benvenutti *et al.* (2021).

7.3.2.2 Defining scenarios

To further examine the potential light-vehicles have in reaching PROCONVE L7 and L8 standards, three different future assumptions aspects are tested: (i) percentage use of ethanol and gasoline in FFV, (ii) fuel efficiency increase per year, and (iii) the fixed percentage (Fp) by which the average EVs price falls with every doubling of EV adopters (for more information of the inherent assumption of the model, please check BENVENUTTI *et al.*, 2021). For each of these criteria, two levels are tested, totalising in seven scenarios altogether when considering the BAU scenario.

Each of these scenarios are tested and emission rate results per gas emitter are compared to PROCONVE limits for 2025 and 2029/2031, L7 and L8 phases, respectively. For all scenarios (except for Fp 9% and Fp 11% scenarios), the EVs diffusion numbers assumption considers the following proportion from the EVs sales: 7.5% BEV, 7.5% PHEV and 85% Hybrids. Chart 7 presents the scenarios descriptions.

Chart 7 - Scenarios descriptions for 2020-2031 simulation.

Name of the scenario	Assumption category	Description
BAU	Ethanol/gasoline rate for FFV vehicles	50%/50%
	Fuel efficiency rate increase per year	1% improve in fuel efficiency is considered from 2020 onward.
	Fixed percentage on EV price with every doubling of adopters	Considers a fixed percentage (Fp) of 8%, value based on Weiss *et al.* (2012)
Flex if 100% bioethanol	Ethanol/gasoline rate for FFV*	100%/0%
Flex if 100% gasoline		0%/100%
Effic. 3%	Fuel efficiency rate increase per year*	3%
Effic. 5%		5%
Fp 9%	Fixed percentage on EV price *	9% and EV shares: 25% BEV, 25% PHEV, 50% hybrids
Fp 11%		11% and EV shares: 1/3 BEV, 1/3 PHEV and 1/3 hybrids

* Except the assumptions adopted in each scenario, the other assumptions remain similar to the BAU scenario description. For further information on the inherent assumptions of the model, please check Benvenutti *et al.* (2021).

Source: Elaborated by the authors.

7.4 RESULTS AND DISCUSSION

7.4.1 Comparative analysis between the current data measured by CETESB and the PROCONVE phases L7 and L8 requirements

Table 20 presents the gases emission rates from the average light-vehicles licenced published in CETESB, since PROCONVE L6 phase implementation in 2014. Excluding the NOx rate, FFV provides the highest emission rates compared to vehicles powered by gasoline solely. Because of its dual fuel flexibility capacity engine use, FFV are known for not being as efficient as a vehicle driven by one fuel type only. In the case of NOx, the historical data varies more, making the comparison difficult. Also, it is important to note that although CO_2 emission by FFV driven by bioethanol is declared, their emission is considered neutral due to its biogenic source, sugarcane.

Table 20 - Average emission factors of new light vehicles sold in Sao Paulo state since PROCONVE L6 (2014).

Year	Fuel type	CO (g/km)	Total (g/km)	NMHC (g/km)	CH_4 (g/km)	NMHC-ETOH (g/km)	NOx (g/km)	RCHO (g/km)	MP (g/km)	CO_2 (g/km)
2014	Gasoline C	0.211	0.021	0.015	0.006	nd	0.015	0.0013	0.001	197
	Flex-Gas. C	0.228	0.024	0.020	0.004	nd	0.019	0.0015	0.001	173
	Flex-Bioethanol	0.398	0.073	0.053	0.020	0.021	0.018	0.0083	nd	165

2015	Gasoline C	0.155	0.016	0.012	0.004	nd	0.025	0.0010	0.001	186
	Flex-Gas. C	0.217	0.021	0.018	0.003	nd	0.015	0.0012	0.001	166
	Flex-Bioethanol	0.360	0.073	0.058	0.015	0.019	0.016	0.0078	nd	158
2016	Gasoline C	0.114	0.016	0.010	0.006	nd	0.022	0.0010	0.0010	176
	Flex-Gas. C	0.251	0.022	0.018	0.004	nd	0.012	0.0009	0.0010	159
	Flex-Bioethanol	0.363	0.075	0.047	0.028	0.020	0.013	0.0065	nd	151
2017	Gasoline C	0.141	0.015	0.011	0.004	nd	0.013	0.0008	0.001	175
	Flex-Gas. C	0.229	0.022	0.018	0.004	nd	0.011	0.0010	0.001	154
	Flex-Bioethanol	0.340	0.069	0.046	0.023	0.020	0.012	0.0064	nd	147
2018	Gasoline C	0.173	0.016	0.012	0.004	nd	0.010	0.0005	0.0010	177
	Flex-Gas. C	0.253	0.023	0.019	0.004	nd	0.012	0.0010	0.0010	154
	Flex-Bioethanol	0.338	0.070	0.047	0.023	0.019	0.012	0.0067	nd	147
2019	Gasoline C	0.166	0.014	0.011	0.003	nd	0.014	0.0006	0.001	184
	Flex-Gas. C	0.275	0.024	0.020	0.004	nd	0.011	0.0010	0.001	152
	Flex-Bioethanol	0.339	0.069	0.045	0.023	0.020	0.010	0.0067	nd	146

Source: CETESB (2019).

Considering only the PM, CO and RCHO pollutants, on average, the vehicles licensed after 2014 already met the limits of PROCONVE L7 phase (which starts in 2022). In addition, they would also fall within the level 20 (Table 18) of phase L8 (which starts in 2025). This means that no further improvement in PM, CO and aldehyde emissions rates would be required in the short-term.

However, the case of NMOG + NOx, which now includes the share of unburned ethanol, the average situation is different. Table 21 presents these values (column "NMHC + NMHC-ETOH + NOx"). Note that, on average, the cars licensed since 2014 (L6 phase) already met the requirement of 80 mg/km of the L7 phase (which starts in 2022). In terms of L8 phase (which starts in 2025), gasoline-powered vehicles licensed from 2017 fits into the level 30 (Table 1) of 2029/2031 (L8). On the other hand, the FFV fit, on average, between L7 levels 60 and 80 (Table 18). Hence, it seems that further improvements on these vehicles such as fuel efficiency will be required. An important value of reference is to evaluate the historical evolution of these vehicles fuel-economy. Table 21 shows the fuel economy and the efficiency improvement experience in the past years.

Table 21 - Calculated NMOG + NOx emissions of new light vehicles, their average for flexible fuel vehicles, fuel-economy and estimate average fuel efficiency rate change.

Year	Fuel type	Phase	NMHC + NMHC-ETOH + NOx (g/km)	Average flex fuel*	Fuel-economy (km/L)	Fuel efficiency rate change (%)
2014	Gasoline C	L5/L6	0.03		11.5	-
	Flex-Gas. C		0.039		12.7	-
	Flex-Bioethanol		0.092	0.065	8.8	-
2015	Gasoline C	L6	0.037		12.0	4.35
	Flex-Gas. C		0.033		13.2	3.95
	Flex-Bioethanol		0.093	0.063	9.2	4.55
2016	Gasoline C	L6	0.032		12.5	4.15
	Flex-Gas. C		0.03		13.8	4.55
	Flex-Bioethanol		0.08	0.05	9.6	4.35
2017	Gasoline C	L6	0.024		13.1	4.8
	Flex-Gas. C		0.029		14.3	3.6
	Flex-Bioethanol		0.078	0.053	9.8	2
2018	Gasoline C	L6	0.022		13.4	2.3
	Flex-Gas. C		0.031		14.2	-0.7
	Flex-Bioethanol		0.078	0.054	9.8	0
2019	Gasoline C		0.025		12.1	-9.7
	Flex-Gas. C		0.031		14.5	2.10
	Flex-Bioethanol		0.075	0.053	10.0	2.05

* This column was included facilitate comparison the limits established for L7 and L8, since the methodology for FFV involves the average of the vehicles fuelled by ethanol and by gasoline.

Source: Based on CETESB (2019).

7.4.2 Comparison with the European and the USA legislation

The European emissions standard (Euro) is a set of standards that regulate emissions from new vehicles sold in the European Union. Their regulatory evolution stages have started with Euro 1 and is currently on Euro 6 for light-vehicles. More specifically, Euro 6 (EUR-LEX, 2020) has the following limits (positive ignition vehicles):

- NOx: 0.06 g/km;
- MP: 0.0045 g/km;
- CO: 1 g/km;
- NMHC: 0.068 g/km;
- THC (total HC): 0.1 g/km.

As for the US, it is the Environmental Protection Agency (EPA) that establishes the emission standards for vehicles (EPA, 2021). Since 2017, automakers have been under the Tier 3 standards, which brings similarity to the California LEV III standards, as presented in Table 22.

Table 22 - Tier 3 emission standard levels (bin) for light-vehicles. To facilitate comparison, values presented in this table have been converted per kilometre. Original values are presented per miles.

Level (bin)	**NMOG + NOx mg/km**	**MP mg/km**	**CO g/km**	**Aldehydes mg/km**
160	99.4	1.9	2.6	2.5
125	77.6	1.9	1.3	2.5
70	43.5	1.9	1	2.5
50	31	1.9	1	2.5
30	18.6	1.9	0.6	2.5
20	12.4	1.9	0.6	2.5
0	0	0	0	0

Source: EPA (2021).

Furthermore, Tier 3 emission standard also predicts that the manufacturers must meet a fleet-wide average emission standard, meeting the corporate limits, as shown in Table 23 by 2025. As mentioned, PROCONVE emission standards for light-vehicles have mostly resembled the legislation from the US. More recently, with phases L7 and L8, it has taken a step further in similarity to the way vehicles are first classified in a level (bin) and then the average fleet-wide vehicles (sold) are given a certification, where automakers have to meet specific corporate levels.

Table 23 - Tier 3 standard for NMOG + NOx emission (from automakers' fleet-wide average car sold). Values presented in this table have been converted from mg/mi to mh/km.

Date	**Corporate level for light passenger vehicles (mg/km)**
2017	53.4
2018	49
2019	44.7
2020	40.4
2021	36
2022	31.7
2023	27.3
2024	23
2025	18.6

Source: EPA (2021).

Comparing these limits to the average emissions published by CETESB (Table 20), since the L6 phase the fleet-wide vehicles have been, on average, meeting the requirements from Euro 6 standard. Differently than the Tier standard, in Euro 6 the pollutants NMOG and NOx are accounted separately. If their sum is considered, in this case NMHC and NOx, the value would be 128 mg/km. This number is similar to the current PROCONVE L6 standard, considering the sum of NMHC and NOx (as it returns the value of 130 mg/km), but much less rigorous when compared with the new limits proposed for L7 and L8. As for Tier 3 limits, by

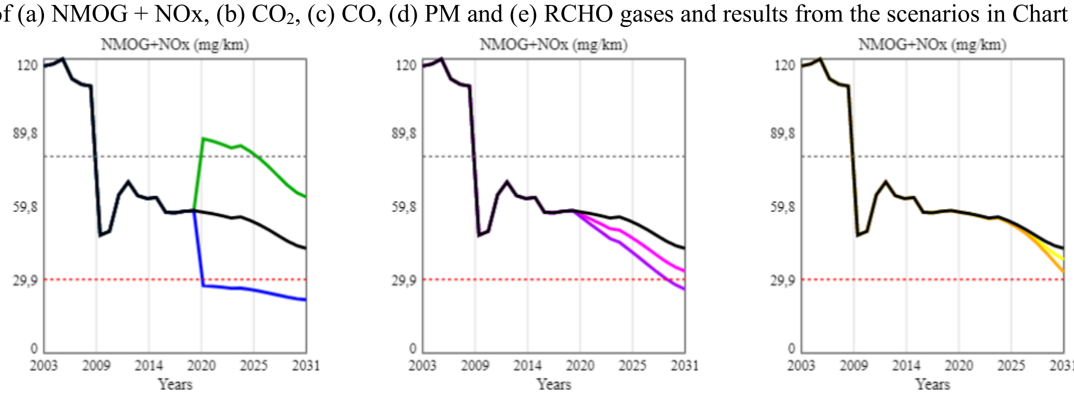
2025, automakers must meet a maximum fleet-wide average certification bin of 18.6 mg/km for NMOG+NOx (Table 23). In this case, Tier 3 standard presents considerably more stringent limits when compared to PROCONVE L8 phase target of 30mg/km by 2029 (Table 18 and Table 19).

The comparison analysis presented here does not aim to conclude that new Brazilian light-vehicles are within Euro 6 standards. It is worth noting that these emission standards are not restricted to tailpipe emissions limits only. In these regulations there are several other criteria (that are not being addressed here) such as: (i) emission limits when fuelling; (ii) noise limits; (iii) minimum standards for installed emission control systems; (iv) testing and measurement procedures, and others. Emission limits of Tier standard, especially in regard to NMOG+NOx, are in fact much stricter. But it is worth mentioning that each region has its own peculiarities in terms of their main vehicles fuel-technology. This kind of characteristics should be taken into consideration.

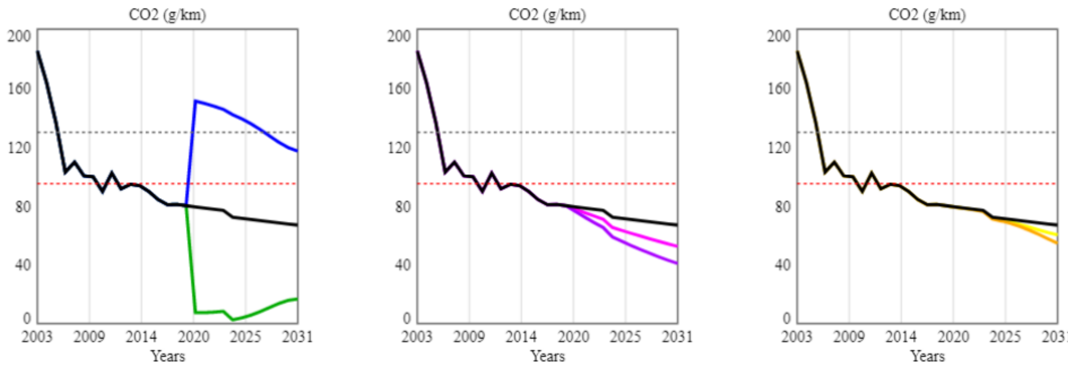
7.4.3 Simulation results

Figure 47 presents the progress of the average of vehicles' emissions since 2003 and the future perspective rate emission per gas emitter type and scenario (2020-2031). The historical high picks evidenced in CO in 2009 (Figure 47c) and in RCHO in 2006 (Figure 47e) are a reflection of their pick experienced during those periods (see Table 20). Besides this, an average decrease in emissions rate is seen in historical years.

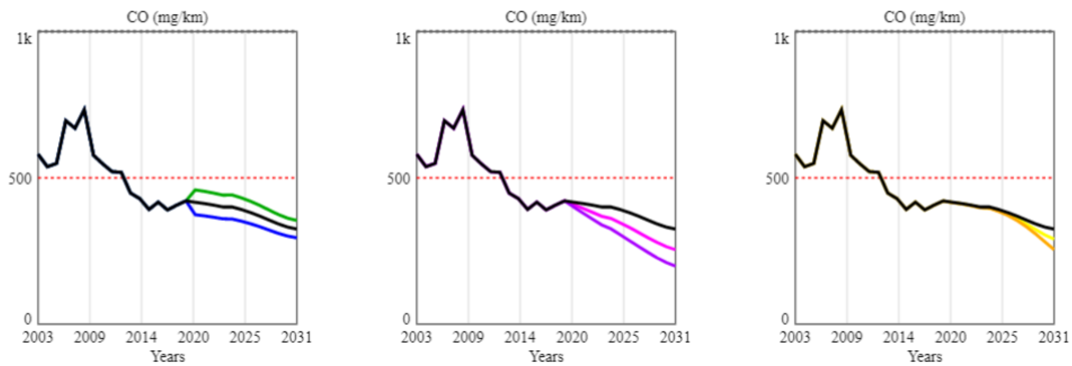
Figure 47 - Historical (2003-2019) and estimate (2020-2031) of the Brazilian new car sold average emission rate of (a) NMOG + NOx, (b) CO_2, (c) CO, (d) PM and (e) RCHO gases and results from the scenarios in Chart 7.



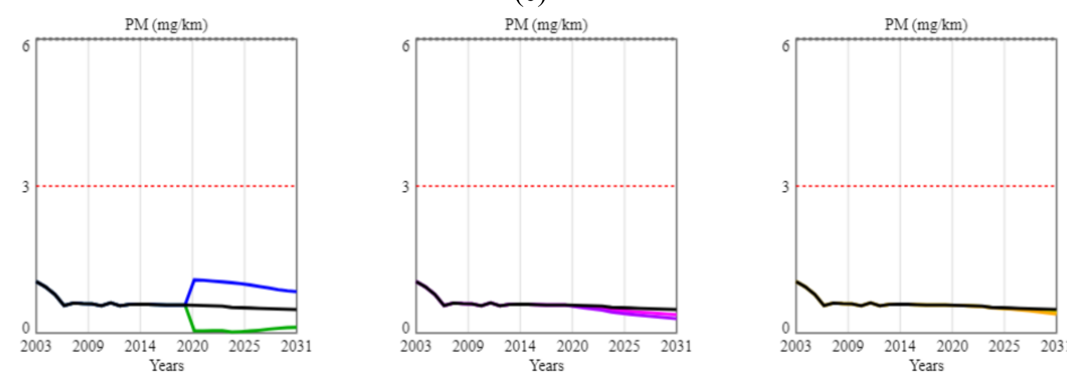
(a)


CO2 (g/km)
CO2 (g/km)
CO2 (g/km)
200
160
120
80
40
0
2003
2009
2014
2020
2025
2031
Years

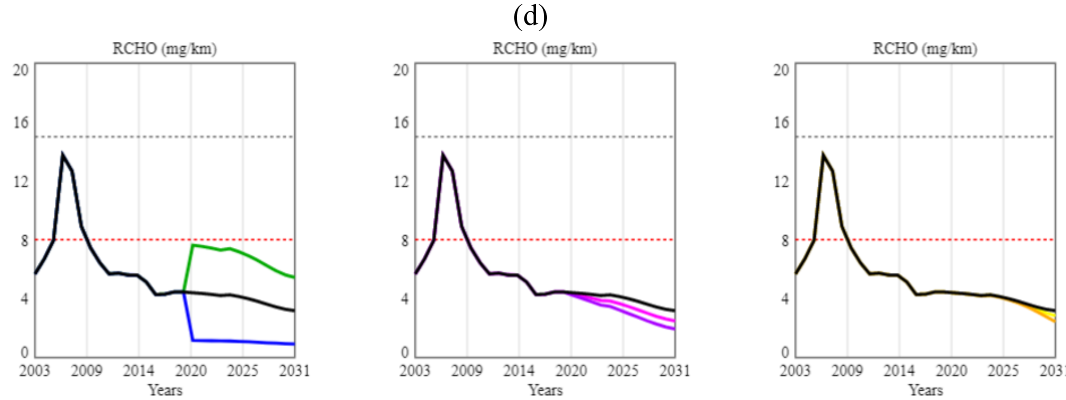
(b)


CO (mg/km)
CO (mg/km)
CO (mg/km)
1k
500
0
2003
2009
2014
2020
2025
2031
Years

(c)


PM (mg/km)
PM (mg/km)
PM (mg/km)
6
3
0
2003
2009
2014
2020
2025
2031
Years

(d)


RCHO (mg/km)
RCHO (mg/km)
RCHO (mg/km)
20
16
12
8
4
0
2003
2009
2014
2020
2025
2031
Years

(e)

Source: Simulation conducted by the authors, based on FWEMPS model from Benvenutti *et al.* (2021).

In terms of meeting PROCONVE L7 (in grey) and L8 (in red) targets, Figure 47 results corroborate with what was previously detected in the comparison analysis subsections. The potential perspective of the automakers (in a general sense) in meeting those targets are high for all gases except for the NMOG + NOx standard. By 2031, Figure 47a shows the BAU scenario reaching values between the L7 and L8 limits, about 60mg/km by 2031 (twice the limit target). To meet a maximum of 30mg/km by 2029 (both 2029 and 2031 limit targets are the same for light-vehicles), further and accelerated actions must take place. The fleet-wide vehicles will have to either increase the use of gasoline as a fuel, or considerably improve their average fuel-efficiency each year.

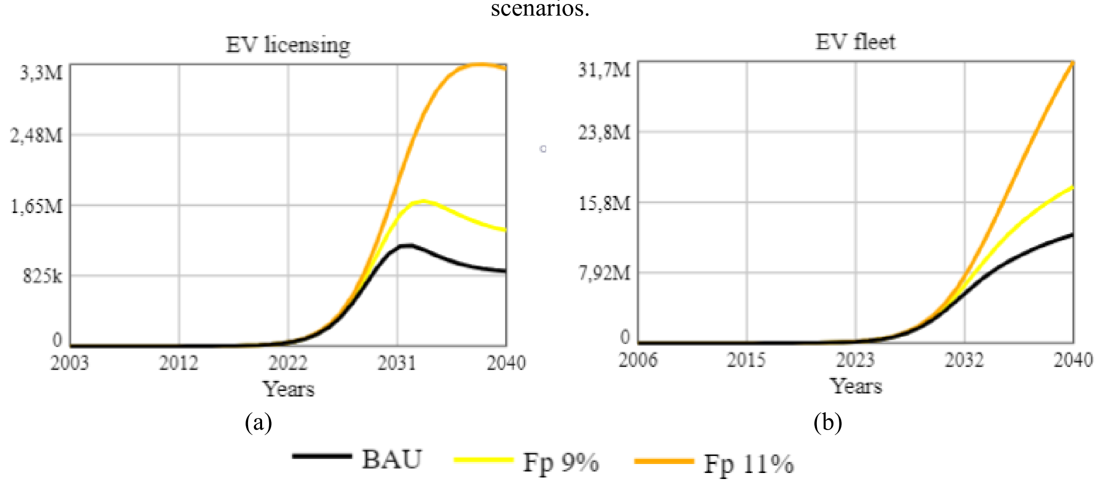
In terms of fuel content, since the homologation procedure (when each vehicle receives a qualification level/bin, Table 18) for FFV is conducted considering the average emission result of them being fuelled by ethanol and by gasoline, this puts FFV in an unexpected and unfavourable position (Ortiz, 2019; Siqueira, 2019), and consequently ethanol as fuel, as discussed by executives from Automotive Engineering Association (AEA) (Kutney, 2019). From Figure 47, the FFV fuelled by gasoline have the potential of meeting every limit level by 2029/2031 (considering that no CO_2 emission limits are established). However, since getting back to gasoline-powered vehicles would not be a proper solution, this leaves the industry with significant additional challenges.

In terms of fuel-efficiency improvements, this can be done in two main ways. The first option, by investing in the mechanics of the vehicles themselves such as in catalyst conversion efficiency, sensors, lighter materials, fuel system monitoring (ICCT, 2017). The second option, by boosting the production and/or availability (aiming to increase their sales) of lesser emitter technologies such as electric and hybrids vehicles. Regarding the first way, as shown, since the PROCONVE L6 phase, the FFV fuel-efficiency improvement per year has been approximately 2.65%. Results show that if nothing else is done, the fuel-efficiency of the average vehicles must reach 5% of improvement per year to meet the NMOG+NOx emission limit by 2031 (when achieves 29.9g/km by 2031). However, even with the 5% rate, they are on the verge of not meeting the 2029 limit target (the same as 2031), when it reaches 30.2 mg/km. This reveals that relying on the current average vehicles' portfolio solely will not be enough, which leads to the second strategy.

Results in Figure 47 show the improvement in reaching the NMOG+NOx standard by accelerating the introduction of EVs. If the learning curve of EVs production accelerate (with the consequent of price decrease), then the average vehicles is expected to move closer to the 2031 limit (with 32.9 mg/km). It does not, however, reach the 2029 limit.

Figure 48 (2003-2040) shows the respective outcome in terms of EVs licensing and fleet numbers. The increase followed by a decrease in the licensing rate numbers (Figure 48a) is a reflection to the Bass diffusion model adopted in FWEMPS. The diffusion model predicts that the number of adopters follows an S-shape increase (Figure 48b), so there is a more pronounced licensing rate initially, and as potential adopters' numbers diminishes (as they become adopters-consumers), the diffusion strength eventually decreases over time (the derivative of the S-shape). Considering the BAU scenario assumptions, by 2031 the EVs fleet is expected to reach 4.92 million vehicles within the total of 58.1 million vehicles fleet estimated by FWEMPS. This means that to meet the NMOG+NOx limits, EVs boost uptake will have to result in more than the 6.39 million vehicles shown in Fp 11% scenario. Figure 48 indicates is that an EVs diffusion boost is mostly experienced after 2032 because of its low diffusion numbers seen so far.

Figure 48 - EVs licensing (a) and fleet (b) numbers expected to reach by 2040 of the BAU, Fp 9% and Fp 11% scenarios.



Source: Based on Benvenutti et al. (2021).

All these results reveal the significant challenges the car manufacturers have ahead in the near to mid-term future. In terms of limits, the new resolution does predict that the IBAMA may propose to CONAMA a revision of the corporate values presented in Table 19 for the years 2029 and 2031 (L8) (article 4, paragraph 1) (CONAMA, 2018). According to the regulation, this decision will be based on (i) the automakers' corporate average value (level/bin), (ii) available technologies and (iii) international experience. In one of IBAMA's response to the public consultation they did state that they predict a decrease in 10mg/km of NMHC+NOx every two years from 2025 onward with an increase uptake of EVs. However, as Figure 47a shows, even considering an accelerated learning curve (Fp 11% scenario), this would only be possible with a more increase EV uptake and additional energy efficiency help, since an EVs diffusion boost impact is felt mostly after 2032. Unless combined efforts involving improving FFV (or vehicles in general) fuel-efficiency in the short-term in addition to efforts towards EVs diffusion take place, the NMOG+NOx emission limit may not be reached, and a revision of the corporate values might be needed.

It is worth mentioning that the Brazilian fleet are unique due to its high percentage of FFV that has been annually sold since its launch (2003). In US, although after Brazil their fleet is the second largest of FFV, compared to other cars that are sold, their uptake (and consequently their fleet) numbers are very low (EIA, 2017). Also, their E85 fuel carries less ethanol than the Brazilian one (around 95%), with a gasoline-ethanol blend containing 51% to 83% ethanol. Since ethanol as fuel is the one that increases the challenge regarding the NMOG+NOx emission limit, a different methodology to the way these FFV are certified may be needed in order to avoid putting both ethanol and FFV in a contradictory place. Ultimately, however, efforts must be made to lower emissions, but this characteristics differences must be taken into account into the transition pace.

Another point emphasised by the experts in the public consultation, was the need to not only monitor the emission of CO_2, but to include limits to it. In this case, this point has not been adopted so far, and in one IBAMA's response was that CO_2 emission would be subject of another CONAMA's resolution (IBAMA, 2018). If similar homologation methodology is adopted for CO_2 (in terms of the average emission value between FFV fuelled by ethanol and by gasoline), assuming CO_2 emission from ethanol combustion is disregarded due to biogenic source, and considering the same European Commission CO_2 target limits, then results indicate that the average vehicles sold is already meeting European standard targets (Figure 47b).

7.5 CONCLUSION

This study presents an analysis of the perspective of the average light-vehicles in meeting the new phases of PROCONVE emission standard by 2031 (L7 and L8). It contributes to the literature and to the community involved in the transport sector in three main ways. First, it provides a comparative analysis of PROCONVE to the current standards adopted in Europe (Euro 6) and in US (Tier 3). The compilation of the main gas emission limits provides an easy access to practitioners of the field to visualize and contrast them. The future L7 and L8 phases take a step forward into reaching similar limits required internationally, which besides contributing to the environment it helps increase automakers' international competitiveness.

Second, the analysis highlights the contradictory disadvantage of ethanol as fuel, and consequently FFV in general, under the new posed regulation. Although the perspectives in meeting L7 and L8 standards are high for most of the pollutants, for the case of NMOG+NOx they are indeed quite low. The challenges involved in this issue will required greater investment efforts from the automakers. These efforts should include a higher pace of improving vehicles' fuel-efficiency in general and accelerated boost of lesser emitter technologies such as EVs. Unless these effort takes place, it may happen that flexible fuel vehicles will not reach enough standard and thus prevent them to be sold.

Third, the study emphasizes the potential need to reviewing the corporate level limits established for L8 phase. As the regulation predicts, CONAMA may propose a revision of those limits according to the progression of the automakers' corporate average value. While more stringent limits are in line with more sustainable actions and thus beneficial to air quality, the different characteristics of the region must be taken into consideration. A careful revision to the methodology involved in grading FFV should occur in order to prevent putting them in jeopardy and ethanol in a contradictory environmental position.

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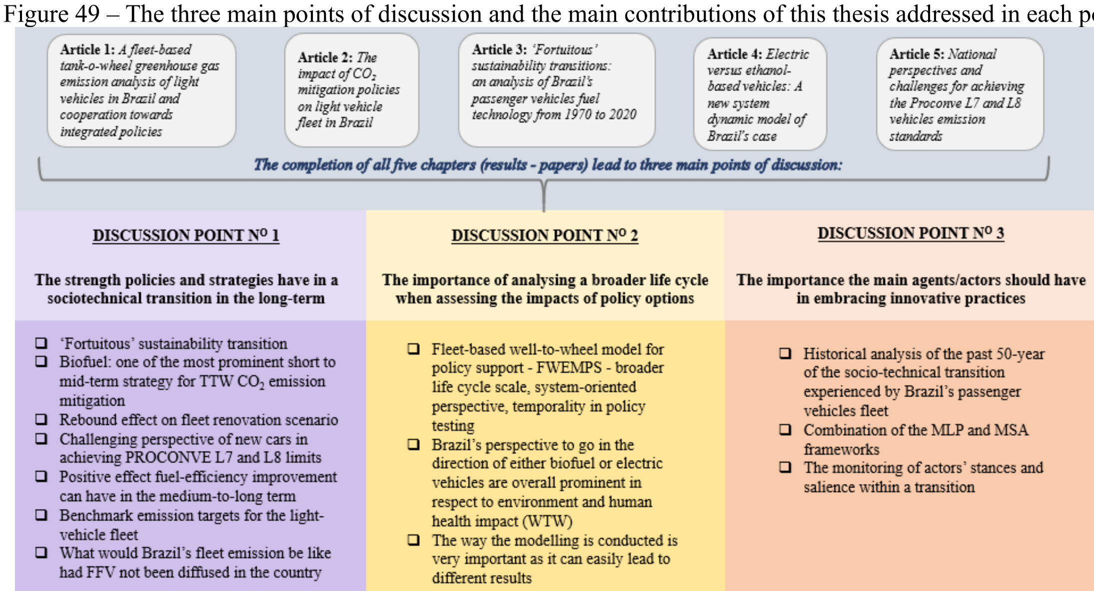
CHAPTER VIII

8 DISCUSSION

The completion of this thesis has led to some important contributions to the literature. This chapter brings their discussion along with relevant insights to sustainability transitions. In summary, three main points can be withdrawn from the results (chapters 3, 4, 5, 6 and 7): (i) the strength policies and incentives/strategies have in a sociotechnical transition in the long-term, (ii) the importance of analysing a broader life cycle when assessing the impacts of policy options, and (iii) the importance the main agents/actors should have in embracing innovative practices in light of the current energy transition towards renewables sources (Figure 49).

Figure 49 – The three main points of discussion and the main contributions of this thesis addressed in each point.



Source: Elaborated by the author (2021).

Firstly, regarding the relevance policies and incentives have in the long-term of socio-technical transition, in terms of their effects, policies are referred to as being enablers of change or constrainers when they avoid the creation of novel technology paths (MARKARD; SUTER; INGOLD, 2016). This thesis has shown that the Brazilian fuel-technology system was deeply affected by the national policy *Proálcool* of the 1970s. Even when not active anymore, this policy left enough system residues that ended up allowing and accelerating the fleet transition to FFV (2003 onward). While sustainability transitions are mostly referred to "involving a broad range of actors working together in a coordinated and purposeful way" (MARKARD; RAVEN; TRUFFER, 2012, p. 956-957), one contribution of this thesis was detecting that 'fortuitous' sustainability transitions may also happen. While the enforcement of *Proálcool* policy stimulated the use of the renewable biofuel in a greater measure, the original reason for its enactment was not towards a more sustainable regime, but a driving effort to prevent further national financial and energy security issues.

Proálcool can be categorized as a policy that mostly intervened in at least two socio-technical points: at the niche and the regime levels (KANGER; SOVACOOL; NOORKÕIV, 2020). At first, this policy was responsible to accelerate the niche - in this case biofuel - by establishing a higher amount of biofuel use in the gasoline blend and incentives for research centres in the task of producing ethanol-based vehicles. Then, in a later period, due to aggravated economic figures, it attempted to destabilize the regime by gathering efforts towards accelerated ethanol-based vehicles availability on the market. The 'accidental' sustainability path that Brazil undertook during the past 50 years, involved transformation, de-alignment and re-alignment, attempts of reconfiguration and incipient technological substitution (flexible fuel engines) features. It eventually contributed and led to a more sustainable sociotechnical system in the long-term (1970-present). Its lingering effects only enabled and accelerated FFV diffusion and now most of the fleet can be fuelled by both gasoline and bioethanol at any rate. This 'fortuitous' occurrence reveals an aspect of transitions that can, in fact, aid the process of policy making connected with the discussions of problem and solution, and which comes first (BÉLAND; HOWLETT, 2016) (more on this in the final subsection of this discussion: Framework for policy-making and recommendations for Brazil).

In terms of potential impact of strategies based directly on the fuel-technology fleet, by testing different policies and levels of stringency, their future mitigation potential can be compared. For instance, while some studies showed limited GHG mitigation result by their biofuel strategy scenario (ALAM *et al.*, 2017; HUO *et al.*, 2012; KROMER; BANDIVADEKAR; EVANS, 2010), the result of this thesis indicates biofuel as one of the prominent best short to mid-term strategy for mitigating tank-to-wheel CO_2 emission. The main reason attributed to this difference stands on the country's fleet characteristics with its peculiar trajectory with the current main FFV fleet. Additionally, this result is emphasized by an additional contribution, of showing what would Brazil's fleet emission be like had FFV not been diffused in the country.

Naturally, having the possibility of using biofuel does not make it certain that a consumer will choose bioethanol over gasoline. There are other factors involved such as fuel price, availability and consumers own preferences. In this sense, incentives and policy enactment can be of great aid to induce higher consumers use rate of biofuel. An example of a policy output that has taken place over the years is the increase of bioethanol rate in the gasoline blend. From 1-5% in the 1970s to current 27% (since 2015) (MAPA, 2021). Thus, even when consumers use gasoline to fuel their cars, a considerable percentage rate of ethanol is already being used as well. In many countries, however, that is not the case, with biofuel policy research testing involving, for instance, an ethanol addition increase from 2.5% to 15% (ZHENG *et al.*, 2015) or to 30% (HUO *et al.*, 2012) by 2050 in China, or from 6.4% to 24% by 2035 in Ireland (ALAM *et al.*, 2017).

In addition, there are also policy rebound effect possibility to be aware, and this thesis contributes to reinforce the importance of attentive evaluations. While most well intended mitigation policies and strategies potentially provide positive results, if testing and analysis are not conducted closely, some may generate the opposite in the long term (FREEMAN; YEARWORTH; PREIST, 2016). This was the case detected to the fleet renovation scenario case, where in the long term, although the older and more pollutants cars would be removed from the fleet, an increase use from the newer cars would end up providing a setback in the goal of mitigating CO_2 emission (or other pollutant) in the long-term. Similar rebound effect result have been detected in strategies related to fuel-efficiency improvement, where higher use of the cars ends up occurring in face of lower need of fuel (AUGUSTUS DE MELO; DE MARTINO JANNUZZI; DE MELLO SANTANA, 2018). Although this has been attributed to occurring at a low risk (SMALL; VAN DENDER, 2007; WEST *et al.*, 2015), the reality of rebound effects must be taken into consideration to avoid unnecessary investments or wasteful actions, and to direct other strategies to aid and enhance intended mitigation goals.

In this context, the establishment of emission standards can further improve fleet emission. For instance, vehicles average fuel economy has been improved over the past years by PROCONVE standards requirements. Since 1986, car manufacturers have been under different phases of PROCONVE regulation, which stablishes limits to tailpipe emission on various pollutants. And although its limits lag temporarily behind the US and Europe emission standards, it seems to be heading towards similar targets with the recent established phase L7 (2022) and L8 by 2025-2031 (CONAMA, 2018).

In this regard, this thesis has contributed to presenting the challenging perspective of new cars in achieving PROCONVE L7 and L8 emission limits. More specifically, in respect to the emission limit of NMOG + NOx (nonmethane organic gas and nitrogen oxides, respectively, responsible for ozone and smog formation) by the FFV due to its higher emission when fuelled by ethanol. Results reinforced the challenges the automakers face into reaching the near to mid-term targets by bringing to light a possible inadequacy to this limit established by CONAMA. This has also been pointed out by automotive experts (CARDAMONE, 2020), and further concerns has been heard by automakers executives from the National Association of Motor Vehicle Manufacturers (ANFAVEA) and from the AEA (KUTNEY, 2019; 2020; ORTIZ, 2019; TOUME, 2020). With the aid of the developed fleet-based model tool, this concern has been confirmed. Unless significant boost from lesser emitter technologies such as EVs take place, an increase pace of the vehicles' fuel-efficiency improvement beyond what has been reached over the past years will be require.

The new resolution does predict that the IBAMA may propose to CONAMA a revision of the limits for the years 2029 and 2031 (L8) (article 4, paragraph 1) (CONAMA, 2018). In fact, results reveal that this may be the case, but more than that, a revision to the methodology of homologating FFV may be required. The methodology for light-vehicles resembles the one used in the US emission standards (Tier). However, the characteristics of the country regarding the use of ethanol as a main fuel must be considered. Ultimately, the goal should not be to ease emission limits, otherwise - besides the environmental aspects aggravation - the national vehicles may lose international competitiveness, but to carefully consider appropriate method calculations to the level/bin these FFV receives (homologation) to avoid putting them at risk and the increase return of gasoline-powered vehicles.

Furthermore, in terms of fuel-economy, this thesis has contributed to showing the positive effect fuel-efficiency improvement can have in the medium-to-long term of the national fleet's emission. Also, when integrating with other actions such as rising the ethanol fuel use, it can attain even further mitigation potential. And while emission limits to automakers have been established by PROCONVE, this thesis has contributed to providing benchmarks emission targets for the light-vehicle fleet, which is absent to date. This can assist policy makers into newer kinds of policies aiming at the fleet as a whole, and to aid the country's achievement towards the NDC targets agreed in COP 21, Paris Agreement. All these results only reinforce the potential policies have in mitigating future environmental impact.

Secondly, regarding the importance of a broader life cycle analysis, since the 1990s the adoption of LCA methodology as an ecological tool has become increasingly widespread in the industrial and governmental sphere (GUINÉE, 2001; 2015). Assessing environmental impacts helps to identify areas that needs improvements and to potentially guide directions towards more sustainable future. While strategies analysis that focuses on the fleet are especially important in reducing local TTW air pollutants emission, reducing traffic, and mitigating GHG (BENVENUTTI; URIONA-MALDONADO; CAMPOS, 2019; BENVENUTTI; CAMPOS, 2019; GONZÁLEZ PALENCIA *et al.*, 2017; IANKOV; TAYLOR; SCRAFTON, 2017), by considering a broader life cycle scale, such as the WTW cycle assessment, more robust directions can be provided to reach longer term sustainability goals.

In this sense, recognizing the country's transport trajectory is important as it can guide to more meaningful directions for future fuel-technology pathways thus better guiding the WTW evaluation in the long-term. The 'fortuitous' sustainability pathway that Brazil followed, has put biofuel industry on a relevant and mostly salient role. As seen, this industry, however, has not gone by without challenges. Besides the exogenous pressure experienced such as economic crisis and political regime shifts, and the endogenous pressure such as the credibility loss towards ethanol-based cars in the 1990s, the biofuel production has been topic of important debate regarding LUC for biofuel production and its relationship between food, energy and sustainability overall (SOUZA *et al.*, 2015). While CO_2 emission from biofuel combustion is considered a carbon neutral due to its biogenic source, its production involves land use expansion, in which together with forestry have been the source of the largest net GHG emissions in Brazil over the past decade (BORDONAL *et al.*, 2018). Additionally, the discrepancies of results, and the use of different assumptions have hindered its LCA use for policy support especially for biofuel case (PEREIRA *et al.*, 2019).

In this regard, one of the main contributions of this thesis was the development of FWEMPS. Designed in system dynamics, the fleet-based model expands the ability of current LCA models to support policy by broadening the level of analysis from a single product to a system-oriented perspective, engaging with temporality in policy testing, and integrating different methods/techniques to assess sustainability impact (e.g. system dynamic modelling, LCIA, Bass diffusion model), which have been encouraged for future sustainability studies (BORNEMANN; STRASSHEIM, 2019; GUINÉE, 2015; GUINÉE *et al.*, 2011; HALOG; MANIK, 2011; ONAT *et al.*, 2017). FWEMPS is able to estimative the fuel/power production potential impacts (well-to-tank) as well as of the vehicles on the roads (tank-to-wheel), considering a temporal perspective (2020-2050). Also, by using characterization factors specifically for Brazil (some which has been recently added in international databases such as in Ecoinvent version 3.6, DONKE *et al.*, 2020), it contributes to bringing more representative results when compared with other LCA studies for the Brazilian vehicles case as it avoids using emission factors from other regions (CHOMA; UGAYA, 2017; DE SOUZA *et al.*, 2018; GLENSOR; MUÑOZ B., 2019). Results indicates that by adopting and keeping the best practices in place, such as keeping the boundaries of agro-ecological zoning (AEZ) land expansion within the RenovaBio policy regulations (which prohibits the land use expansion in native biomass from 2018 onward, article 24, BRAZIL, 2017a), Brazil's perspective to go in the direction of either biofuel or electric vehicles are overall promising in respect to environment and human health impact (with EVs potentially achieving higher emission mitigation results in the long-term). But results also revealed the importance of the way the modelling is conducted and, more specifically, the assumptions considered, as it can lead to different results and if not carefully clear, can lead to further discrepancies among the literature.

Thirdly, the results highlight the importance of the main players embracing innovative practices to keep up with the current energy transition towards renewables. In this regard, one other main contribution of this thesis was providing a historical analysis of the past 50 year of the socio-technical transition experienced by Brazil's passenger vehicles fleet. By including this qualitative approach, an improved understanding and insights could be provided for future fuel-technology pathways. Economic shakings seemed to have provided a strong driving force towards widening the window of opportunity for change. Aligned with this, regime incumbents clearly played different roles, sometimes dominating efforts for change (e.g. towards biofuel national policy), other times in the backstage of unfolding trajectories. Within this context, translating the system through the lens of the MLP framework was helpful to better understand how window of opportunity emerged, as a response to the interactions between three socio-technical levels (niche, regime, and landscape). However, due to the limited MLP explanatory power regarding explaining the political and agency factors influencing policy formation processes in response to such windows of opportunity (DERWORT; NEWIG; JAGER, 2018; EDMONDSON; KERN; ROGGE, 2018; SMITH; STIRLING; BERKHOUT, 2005), a combination of an *actor-centred* MLP with the multiple streams approach (MSA) from policy process was conducted in this thesis. The inclusion of policy process theories has been encouraged for transition scholars (KERN; ROGGE, 2018; KÖHLER *et al.*, 2019). MSA, for instance, is an example of a policy process framework that aims to understand how and why one policy is formed and addresses the role of actors' agency for policy enactment through the interconnection of policy entrepreneurs (KINGDON, 1984). Although the MLP, in respect to actors' agency, has incorporated a reformulated typology highlighting the endogenous enactment of transition pathway and further theoretical coupling to explain the underlying dynamics of agency (GEELS, 2020; GEELS *et al.*, 2016), further research assessing the main actors' different motivations and capabilities to effect change has still been encouraged to make more explicit the issues of agency, power and politics (DE HAAN; ROTMANS, 2018; KANGER; SOVACOOL; NOORKÕIV, 2020). In this context, by drawing insights from stakeholder theory, institutional work and policy position theories (MITCHELL; AGLE; WOOD, 1997; NEVILLE; MENGUC, 2006; RIAZ; BUCHANAN; BAPUJI, 2011; INGOLD *et al.*, 2020), this thesis has contributed to the literature by proposing a combination of the aforementioned *actor-centred* MLP and MSA frameworks but with added features of the monitoring the actors' *stance* and *salience* within a transition.

Basically, by evidencing the dominant response of an agent within a certain period, the historical analysis provided means to analyse how actors' motivations varied when engaging in fuel-technology change. Whether supportive or more resistant towards a policy or technology insertion that would shift their business-as-usual operations, actors assumed different stances and saliences at different stages. Different salience, mostly based on their level of responsibility or contribution towards a shift being experienced (e.g. consumers acceptance of ethanol-based cars in stage 2) by either a particular policy of technology insertion being proposed. Different stance, mostly based on their level of supportiveness or willingness towards a more sustainable change (technology or policy-wise), which was mostly directly proportional to their financial benefits inside the regime. In the case of the empirical system of this study, for instance, although not an ethanol-niche producer, Petrobras gained a relevant (salient) role as distributors in *Proálcool* phase II (80's), which contributed to ethanol-based vehicles diffusion. In this new business role, Petrobras' stance towards the *Proálcool* was basically supportive until financial losses turned too weighty that they changed their stance towards the policy. Automakers had to adapt themselves in many ways, not only in terms of vehicles' portfolio but also to attend PROCONVE emission targets set for them in the 90s onward. Ethanol-based vehicles ended up losing its credibility among consumers in the 90's, and while gasoline vehicles regained its strength in sales, FFV were introduced at a promising time (2003). These dynamics only reinforces the complexity inherent in a sociotechnical transition and the level of both the challenges and the required innovative stances the main actors must adopt. In fact, technological innovation is one of the three main organizational dimensions of companies (others are operations management and organization performance), in which environmental innovations are a part of businesses aiming to leverage innovative environmental-focused actions (ASSUMPÇÃO *et al.*, 2019).

Nowadays, societies dynamics are changing at perhaps an even faster pace than before. Environmental concerns and awareness are increasingly rising. If recent history has shown the importance of actors attaining innovative roles, today this reality is even more pronounced. For example, with the current tendency towards fleet electrification, the energy sector is expected to play a more salient role in the coming years. Currently, five oil majors (Royal Dutch Shell, Total, BP, Eni, and Equinor) out of eight (those mentioned and ExxonMobil, Chevron, and Petrobras) are pursing strategies to transition from purely oil companies to energy companies (PICKL, 2019). If oil companies are to remain relevant in the long term of fuel-technology vehicles system, it must be on alert and agile to adapt its strategic planning. A sustainable transition does not mean necessarily their extinction, but a transition towards embracing more sustainable practices and product portfolios.

The same goes to other players such as the automakers. For instance, in the period of 2006-2015, most of automotive exports destinations were directed to Argentina, followed by United States, European Union, Mexico and then to other Latin America countries, such as Colombia, Peru and Uruguay (ANFAVEA, 2018). As socio-technical systems are often affected by international networks (FUENFSCHILLING; BINZ, 2018), it is reasonable to infer that a general international shift from one type of driving technology (or mobility pattern) to another will likely impact the country's international trade.

This international dynamic is so impactful that a recent event is worth mentioning. For instance, in the beginning of 2021, the automaker Ford announced its three manufacturing operation closure in Brazil after more than a century in the country (FORD, 2021). According to their statement, the significant financial losses over the past years aligned with the Covid-19 pandemic amplification of the industry idle capacity have led them into this global strategic decision. After 2021, Ford vehicles will still remain in the Brazilian market, but with imported vehicles from Argentina, Uruguay (and other markets), such as the electrified SUVs and new Ranger pickups. This shift drew the attention of many. In other point, Ford affirmed that their business strategy plans are to focus more on connected and electrified vehicles. Although a strategic decision as such involves a set of other factors (e.g. costs, tax, incentives, workforce), the fact that Argentina Ford site were ahead in its high value added-models know-how says something about the current fuel-technology transition. Considering that the country's automakers have made significant investments in the near past (BERMÚDEZ RODRÍGUEZ, 2018), bold decision and agile actions are (still) needed in this time, to remain competitive in a world leaning towards low-carbon transitions.

Finally, challenging and important decisions towards this socio-technical system future directions lies ahead. When considering the WTW results, both biofuel and electrics vehicles scenarios can overall achieve satisfactory environmental mitigation results in the long-term. Considering a biofuel increase perspective, the country's know-how with its sugarcane industry (and recently increasing its corn production) plays a great role in advancing the ethanol as fuel, but the same rate of cautions is needed for its land use expansion. Considering an electric vehicles perspective, this thesis confirmed that the country's mostly clean electric grid indeed provides a great territory to boost these vehicles, but their average high price has put them in a farther perspective of reach compared to the widely spread FFV (BENVENUTTI; RIBEIRO; URIONA, 2017). On top of that, it seems that by investing on only one or another type of technology may be risky in terms of international competitiveness. The combined advantages of both technologies, such as electric hybrid vehicles involving ethanol as one of the main fuels – and considering current sociotechnical regime capabilities - may be a proper next step for the sustainability transition.

8.1 FRAMEWORK FOR POLICY-MAKING AND RECOMMENDATIONS FOR BRAZIL

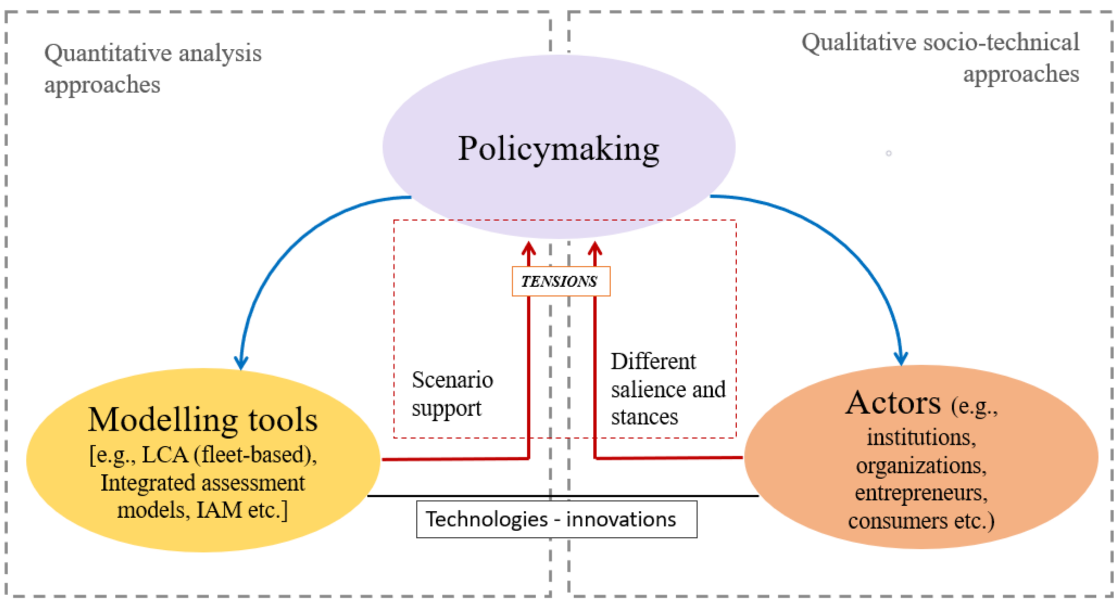
This thesis has shown the impact policies can have in the long term, and thus how important they are if long-term mitigation emission goals (e.g. NDC) are to be reached. Three main points of discussion was highlighted involving the importance of policy enactment, broader life cycle evaluation analysis and the actors' stance towards innovation. From these points, this thesis ends with a proposal of a conceptual framework for policymaking towards accelerating sustainability transition (Figure 50).

As in Kingdon's multiple stream approach, this conceptual framework also considers that policymaking does not always follow a rational, comprehensive model with an orderly (linear) problem-solution process (KINGDON, 1984). MSA main purpose involves the understanding of policy formation and how and why one issue occupies administrations' attention. The proposed framework also involves aspects of policy formation process, but it attains on focusing on how to generate a process that is more flexible and pragmatic to ultimately accelerate desired transitions. By considering a hybrid approach, i.e. by considering both policy formation types of process - problem-solution and solution-problem – the dynamic of this framework aims to enable a more critical view of the policy-making process. In this view, policies are seen as in "constant probation", involving a process of examination of its impacts but also keeping a look at the external environment to identify alternative solutions.

Therefore, on the one hand, there are those plans for coordinated transitions that follow the foundational rational approach from policy process theory (red arrows, Figure 50), where there exist a problem and solutions are sought after (unknown solution for known problem). On the other hand, decision-makers can also be scanning the environment for technological, social changes and indicators (blue arrows, Figure 50), to look for problems that can be solved by some of them (unknown problem for known solution) (see BÉLAND; HOWLETT, 2016 for other references relating to this problem-solution issue process). Regarding the latter (solution-problem), importantly in the context of sustainability transitions, it may be that a solution may exist before a problem detection – as the case of Brazil's original purpose for *Proálcool* enactment, unrelated to sustainability issues. Solution existed before the problem (sustainability) was formally detected (officialised).

In addition, the conceptual framework also acknowledges the potential occurrences of tensions. In this regard, at least three spheres of tensions can be pointed out among: (i) incumbents, (ii) data discrepancies, and (iii) between qualitative and quantitative model scenarios (Rogge, 2018). In the first sphere of tension, depending on the policy being sought after or proposed, different group of actors will have different roles to play, some will end up more salient than other and therefore different stances towards the policy proposal/enactment will be seen (BENVENUTTI *et al.*, 2021b). In the second sphere, discrepancies in quantitative data available to support policymaking may bring ambiguous interpretations and results, which can delay or unable an approval of a beneficial technology (BENVENUTTI *et al.*, 2021a). Finally, in the third sphere, named as 'transition challenges', to reach a certain goal tensions may occur between quantitative model scenarios and the socio-technical system developments ones (ROGGE; PFLUGER; GEELS, 2018).

Figure 50 – Conceptual framework for policymaking.



Source: Elaborated by the author (2021).

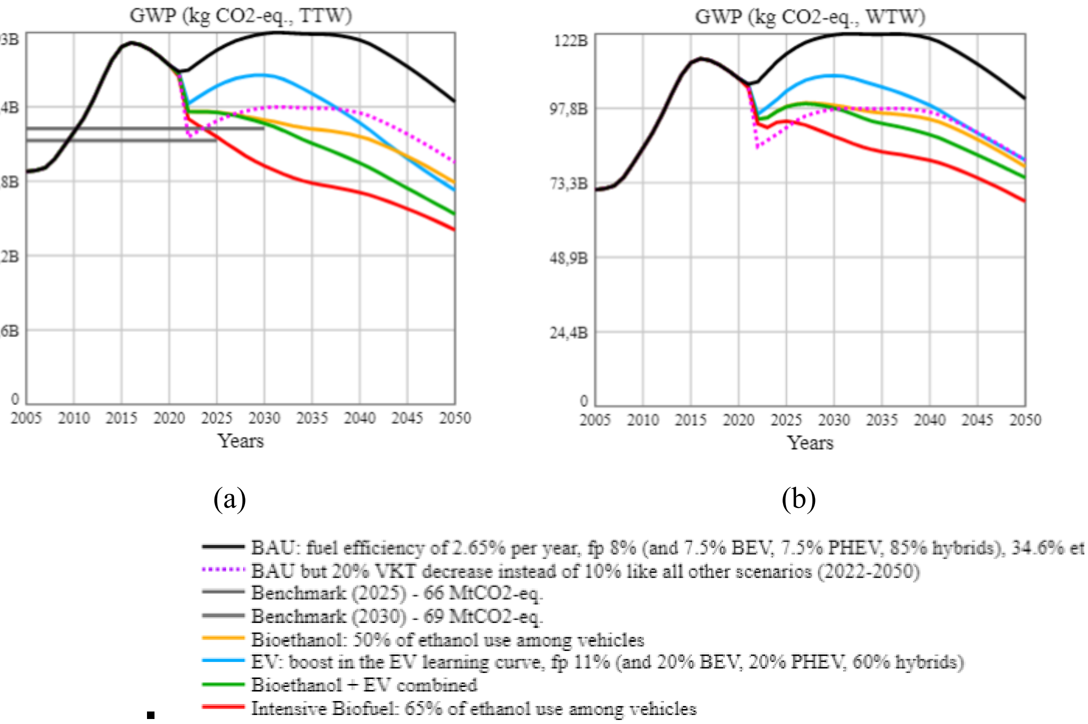
Regarding Brazil, Figure 51 reveals that in order to reach the GHG benchmark targets for TTW emissions proposed in Benvenutti & Campos (2019) (first paper result of this thesis, chapter 3), accelerated actions must take place and already in the short-term. While the country has the advantage of using biofuel in a greater measure (FFV), if no further actions are proposed, the perspective growth of the fleet might lead to an increase of 9.5 $MtCO_2$-eq. emissions by 2030 (compared to 2021 level, BAU scenario). In turn, with a biofuel boost incentive, the fleet can potentially mitigate about 12 $MtCO_2$-eq. by 2030 and, in doing so, reach the 2030 benchmark target. If a more intensive use of biofuel occurs, then this could lead to the achievement of the 2025 benchmark target and mitigation up to 23 $MtCO_2$-eq. by 2030. As it can be seen, the EV boost scenario has more an impactful effect in the long term due to its little present in the country today.

These figures indicate that a combination of incentives that affects both different niches would be useful, the biofuel, aiming towards the near to mid-term emission targets and the EVs towards a long-time goal. Regarding the biofuel, the recent RenovaBio policy can be mentioned. Considered an economic policy inspired by the California Renewable Fuel Standard (RFS) program, RenovaBio aims to increase the stability of the biofuels market by boosting renewable fuel production, through the means of three axis: (i) decarbonization goals; (ii) certification of biofuel production; and (iii) biofuel decarbonization credit (CBIO). It is a policy that reaches two points of policy intervention (KANGER; SOVACOOL; NOORKÕIV, 2020), i.e. accelerating the niche (biofuel) and destabilising the regime (although voluntary for producers, the creation of CBIO stock market stimulates competitiveness among producers in a greater measure).

However, although RenovaBio enactment is expected to induce a higher incentive for ethanol production, there is no incentive to date for its higher use among consumers. In 2018, some speculations of a possible rise of the anhydrous ethanol content in the gasoline blend from the current 27% to 40% by 2030 were heard (WIZIACK; URIBE, 2018), but this did not take place and some criticisms such as the potential of this leading to fuel price rise arose. By considering both Figure 50 and Figure 51, it seems that there is a need to include other measures to successfully direct this sociotechnical system and avoid transition or policy failures. Following the 'policy mixes' premisses, it is favourable to include a set of policy goals, strategies, instruments and processes when aiming to shift a sociotechnical system (KERN; HOWLETT, 2009; ROGGE; PFLUGER; GEELS, 2018). In fact, the country's initial NDC plan did mention the need for public policies in addition to the RenovaBio to better manage the transition (CCAC, 2018). It may be strategic to elevate the content of ethanol in the gasoline for at least a few years until the electric vehicles niche are more consolidated and accessible to consumers. Since most vehicles consumers (FFV) have a choice to use either gasoline or ethanol, by imposing a higher content of ethanol in the gasoline can be a quicker way to increase ethanol use and accommodate the increasing perspective of ethanol production by RenovaBio policy. Also, the rise on ethanol use does not dispense further actions towards EV investments.

Another promising strategy to reduce emissions in the short term is by creating measures that reduces intensity use of cars – vehicles kilometre travelled (VKT). Figure 51 shows the potential a reduce intensity of cars use can have in the short to mid-term. The enactment of a regulation in this sense can be seen as a measure that would tackle both directions proposed in the framework of policymaking. The problem-solution way, corresponding to a possible solution aid for sustainability problem. And the solution-problem way, corresponding to the detection of current social change occurrences due to the Covid-19 pandemic, which can facilitate the enactment of regulations and measurers towards e.g. establishing a minimum teleworking rate among professionals within companies. Ultimately, the goal should be proposing measures while enhancing people's awareness of the benefits of adopting renewable energy sources in a way to generate positive feedback from the society and consequently its engagement towards a potential regulation (ROBERTS *et al.*, 2018). Finally, further research that considers other sustainability impacts (e.g. economic indicators) for this light-vehicles fleet transition are recommended for future research.

Figure 51 – GWP of (a) TTW and (b) WTW cycle phases.



Source: Elaborated by the author, based on FWEMPS (2021).

CHAPTER IX

9 CONCLUSION

This thesis has proposed a fleet-based well-to-wheel model that estimates potential environment and human health impacts of the light vehicles fleet in the long-term to guide and support decision making towards accelerating sustainability transitions. In doing so, it has responded to these three research questions:

1. How can different measures and/or policies mitigate GHG emissions of light-vehicles fleet, giving attention for potential setbacks in the long run?

2. How have the main actors evolved in terms of their stances and salience in the historical vehicles transition?

3. How to account the effectiveness of potential sustainability actions in the vehicles fleet to serve as policy support in the long term?

Regarding the first research question, this thesis has provided quantitative estimation results on the potential impact of mitigating actions and possible policies towards reducing GHG emission of the light-vehicles fleet in Brazil in the long-term. Examples of GHG mitigation action and/or strategies tested were: fuel efficiency improvement, biofuel use increase, EVs diffusion boost, renovation of the fleet, and teleworking increase. Because of the country's fleet characteristics, biofuel use increase showed as a promising strategy to mitigate GHG emission in the short to mid-term period, as well as long-term. On the other hand, the renovation of the fleet showed to be a less promising strategy due to the pattern of car intensity use aligned with the increased rate of newer cars (driven more) that this strategy would generate, which could end up increasing emission depending on the policy stringency. Increasing the vehicles' fuel efficiency and changing modal pattern have shown to be impactful in a long-term perspective. The prominence of the integration of different actions has also been revealed. By conducting these analyses, the specific objective number 1 was fulfilled, which resulted in two papers. The first paper, presented in chapter 3 with the title "A fleet-based tank-to-wheel greenhouse gas emission analysis of light vehicles in Brazil and cooperation towards integrated policies", was published in the International Journal of Sustainable Transportation. The second paper, presented in chapter 4 with the title "The impact of CO_2 mitigation policies on light vehicle fleet in Brazil", was published in the Energy Policy journal.

Regarding the second research question, this thesis has made use of qualitative approach involving archive and historical content analyses to answer it. By combining two theoretical frameworks, the multi-level perspective framework from transitions research, and the multiple stream approach from policy process theories, a historical analysis of the 50-year sociotechnical transition experienced by Brazil's passenger vehicles fleet was conducted. By doing so, the main actors of the empirical focus were identified along with the monitoring of their stances (supportive, resistant, or indifferent) and saliences (relevant or secondary) towards a specific transition at different times. The results revealed the different roles played by the regime incumbents, sometimes dominating efforts of change (e.g. automakers relevance to the launching of ethanol-based vehicles and flexible fuel vehicles, Petrobras salience as the main responsible for ethanol tanking in the 80s), other times in the backstage of unfolding trajectories (e.g. consumers' preference towards ethanol increase rate in gasoline content in the 70s). Additionally, actors' motivations varied when engaging in fuel-technology change according to their own interests, mostly financial reasons. Ultimately, by showing how actors assumed different stances and salience at different stages, this thesis has reinforced the complexity inherent in a socio-technical transition. Additionally, a 'fortuitous' sustainability transitions was identified to the case of Brazil's course (biofuel and FFV). The original purpose of *Proálcool* enactment was not driven by sustainability reasons, although it eventually led to a more sustainable path for this system (and later became one of the reason themes supporting it). The result of this study fulfilled specific objective number 2, resulting in the paper presented in chapter 5 with the title "'Fortuitous' sustainability transitions: an analysis of Brazil's passenger vehicles fuel technology from 1970 to 2020", currently under journal submission.

Regarding the third research question, this thesis has provided the development of a fleet-based well-to-wheel model for policy support (FWEMPS) designed in system dynamics modelling approach that can estimates potential environment and human health impacts of the light vehicles fleet. With this model, the emission analysis scope grew from GHG emission only, to a set of other tailpipe air pollutants that are regulated by PROCONVE emission standard, i.e. particulate matter (PM), aldehyde (RCHO), nitrogen oxides (NOx), nonmethane organic gas (NMOG), and monoxide carbon (CO). With this, environmental impact from the vehicles fleet (2020-2050) was estimated using the midpoint impact categories: global warming potential (GWP), photochemical ozone formation (POF) and fine particulate matter formation

(PM) for both WTT and TTW analysis, and stratospheric ozone depletion, ionizing radiation, and toxicity (cancer and non-cancer) for WTT analysis only. Additionally, human health impact was also estimated by using the endpoint impact category - human health (disability adjusted life years, DALY). By doing so, it has made possible to simulate the effectiveness of potential sustainability actions all in a long-term perspective (by 2050). Because of its mostly clean electricity grid, if directions towards EVs are taken, there is a prominent perspective in mitigating environmental impact, which in fact was revealed in the results. If directions head towards an increase of biofuel use, considering the new agro-ecological zoning regulation imposed by Renovabio, there is also a good potential perspective (in a slight less degree than an extreme EVs scenario) in mitigating environmental footprint in the long term. This reveals the flexibility that this socio-technical system has, but it does not decrease the challenge in facing future uncertainties in regard to not losing international competitiveness and to making sure that actions are indeed taken towards sustainability goals. Furthermore, by using FWEMPS model, an application of the model was made regarding the perspective the vehicles have in meeting PROCONVE L7 and L8 targets. Indeed, there is a good perspective that the vehicles will meet the proposed limits by 2031, except for the new implemented limit "NMOG+NOx", responsible for POF. Results corroborated with what has been heard from some automakers executives, that the FFV will have an increasing challenge ahead, and results of this thesis have shown that CONAMA may have to review this particular limit. With this, results from the last two specific objectives (3 and 4) resulted in two papers. The first one, presented in chapter 6 with the title "Electric versus ethanol-based vehicles: A new system dynamic model of Brazil's case". The second one, presented in chapter 7 with the title "National perspectives and challenges for achieving the PROCONVE L7 and L8 vehicles emission limits". Hence, these five papers fulfil the main general objective of proposing a fleet-based well-to-wheel model that estimates potential environment and human health impacts of the light vehicles fleet in the long-term to guide and support decision making towards accelerating sustainability transitions.

In terms of future emission perspective, the results from this thesis have highlighted the importance of policy enactment for reaching less emission goals. Although the country has this advantage of using renewable fuel in a greater measure (biofuel), if no further measures are taken in the short to mid-term perspective, emissions could increase and remain in higher levels over the next decades. Since the fleet-based model enables the evaluation of the potential outcome in the long-term, the increase in the technology efficiency can eventually lead to a decrease in emissions in the long-term. But the pace is slow, and accelerated actions are needed in every sector in quicker time. For this, a hybrid approach of the way policymaking is conducted can be of interest, one where when problems are detected, a solution is sought after while recursively considering possible technologies, innovations and social changes that can be fit to solve a potential not yet officialised problem.

Finally, the completion of this thesis and analysis here obtained has reinforced the importance of combining both qualitative and quantitative analysis of a system. While socio-technical system analysis is strong in examining the historical and current transition periods, future-oriented projection and investigation are better explored through quantitative systems modelling. The methodology adopted in this thesis did not involve their full integration, but by combining these different analytical approaches, the discussion on the country sustainability transition was enriched. Socio-technical analysis contributed to the modelling development as it brought closer to more meaningful and relevant results to the local context. By recognizing the country fuel-technology production trajectory and strengths, improved insights were provided for both the future transition and actors involved.

9.1 LIMITATIONS AND OPPORTUNITIES FOR FUTURE WORK

As with any research, this thesis has some limitations. Three main limitations can be pointed out, which some of them can provide opportunities for future work. They can be summarized as: (i) uncertainties related to the future and in terms of policy support, (ii) the general assumption behind EVs diffusion, (iii) some assumptions to the well-to-wheel cycle analysis.

In terms of the uncertainties, as this thesis provides simulation results using a time span of 30 years (2020-2050), one main limitation regards to the uncertainties of such results. This limitation is inherent with any type of modelling results. There are things that hard or even impossible to predict such as the recent event of the global Covid-19 pandemic. Furthermore, there are uncertainties to the extent of policy support therefore limiting mitigation accomplishment perspective presented in this work. In this respect, results should be interpreted accordingly.

In terms of the general assumptions, despite diffusion forces related to the Generalized Bass model with its innovation and imitation factors strength, the other assumption to the EVs diffusion in contrast with conventional cars relates to their average vehicles' price. This assumption is stated in the papers, but it is a limitation of this work since it does not include other customer acceptance variables that can also influence their diffusion, such as charging time, driving range, maintenance and driving costs and so on. In this regard, to bring other assumptions and factors to this dynamic can be a possible opportunity to future work to those researchers who aim to put their focus on diffusion models theories.

In terms of the third and last main limitation of this work, some data availability challenges for the WTW analysis were faced. First, due to lack of available comparable results to the potential impact of transporting the fuels (ethanol from the fabric/mills, and gasoline from the oil refinery process) and electricity power to the gas stations of the country (assuming EVs cars could be powered in current stations), this was not included in the overall WTW analysis. While electricity transmission and overall transportation impact characterization factors are available, the estimate of their volume (or power) transport to the stations are not and, and at this stage, the boundary of this work focused in including comparable results. In this regard, an opportunity of future research can address this by proposing an estimation methodology of this life cycle stage. Also, the limitation regarding the LUC consideration must be pointed out. At this stage, only direct LUC impact was considered. There are still many uncertainties to how to model the indirect LUC impact, being outside of the scope of this thesis. However, an opportunity for future work is the inclusion of this aspect to the production of biofuel, by proposing a methodology and proper scenario testing and then adding to the results here obtained.

Finally, one potential final opportunity for future research can relate to further enhancing FWEMPS' strength and purpose of providing policy support. One example of such includes for instance the application of a multi criteria decision analysis, by incorporating potential analyses of decision makers and stakeholders, on top of the technical information here presented. This could further enhance the guidance and support of the energy transition of the transportation subsector. These opportunities for future research are in line with what the research core is about, when specific research questions are answered, new ones should arise, allowing the state of art of science to progressively increase.

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