UNIVERSIDADE ESTADUAL DE CAMPINAS
Faculdade de Engenharia Mecânica

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Trends in technology, efficiency and performance in the Brazilian light-duty vehicle fleet

Tendências em tecnologia, eficiência e performance na frota de veículos leves do Brasil

CAMPINAS
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Tese apresentada à Faculdade de Engenharia Mecânica da Universidade Estadual de Campinas como parte dos requisitos exigidos para a obtenção do título de Doutor em Planejamento de Sistemas Energéticos.

Thesis presented to the School of Mechanical Engineering of the University of Campinas in partial fulfillment of the requirements for the degree of Doctor in Energy Systems Planning.

Orientador: Prof. Dr. Carlos Eduardo Keutenedjian Mady

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TESE DE DOUTORADO

Trends in technology, efficiency and performance in the Brazilian light-duty vehicle fleet

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Essa tese é dedicada a meus pais, João Carlos e Maria Alice.

Eu sou é eu mesmo. Divêrjo de todo o mundo... Eu quase que nada não sei. Mas desconfio de muita coisa. O senhor concedendo, eu digo: para pensar longe, sou cão mestre - o senhor solte em minha frente uma idéia ligeira, e eu rastreio essa por fundo de todos os matos, amém!
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Resumo

O setor de transportes é um dos maiores consumidores de energia no Brasil e sua demanda aumentou em mais de cinco vezes desde 1970. O modo rodoviário é predominante e os veículos leves, para uso pessoal, respondem por aproximadamente metade dessa demanda. Diversos estudos buscam estimar essa demanda futura quando suprida por diferentes tecnologias, como híbridos, puramente elétricos, ou mesmo a combustão interna, sem contar a possibilidade de outros meios, como o transporte público. Pouco explorado é como esse setor se desenvolveu ao longo dos anos. Realizar um estudo desse tipo permite avaliar a viabilidade de cenários futuros e responder a questões importantes sobre preferência dos consumidores e progresso tecnológico. Para tanto, primeiramente são feitos diagnósticos abordando o problema por ângulos distintos, porém interrelacionados. Quando o transporte individual é visto como um serviço para movimentar pessoas, uma definição de eficiência exergética permite relacionar atributos do veículo, como peso, coeficiente de arrasto e de rolamento, e da viagem realizada com o combustível necessário para tanto. Foram encontrados valores entre 3,4% e 8,3%, com tendência apenas recente de melhora. A taxa de progresso tecnológica foi estimada em 30% para o período 1990–2020. Desse total, aproximadamente 35% foi usada para ganhos em performance, o resto em eficiência. Esse trade-off é vital para projeções. Faixas de eficiência global da frota de veículos para 2030 e 2035 foram estimadas. Os valores podem diferir em até 50% e 120%, respectivamente. Essa variação é explicada pelas potenciais taxas de ganhos tecnológicos, trade-offs, vendas de veículos elétricos e demanda por veículos maiores e mais potentes. Aproximadamente 20% mais performance pode ser obtida pela mesma potência, comparando 2020 com 1990. A difusão de novas tecnologias foi traçada, e um atraso de aproximadamente 10 anos foi estimada, comparando com o os Estados Unidos. O futuro do motor à combustão interna no Brasil foi discutido. Por fim, a evolução tecnológica fez com que a taxação baseada em cilindrada do motor ficasse desatualizada. Fatores de emissão para motores 1.0 podem variar em até 40%. Assim, uma taxação baseada em fatores de emissão de CO_2 é proposta, com o objetivo de reduzir as emissões.

Abstract

The Transportation sector is one of the major energy consumers in Brazil and its demand increased more than five times since 1970. Road transport is predominant and light-duty vehicles for personal use are responsible for about half of this demand. Many studies try to estimate this future demand being supplied by different vehicle technologies, such as pure electric, hybrids, advanced internal combustion engines, or shifts towards public or other modes of transportation. What is less explored is how the sector developed through the years. By doing so some questions can be answered and the feasibility of future scenarios evaluated. As such, a series of interconnected diagnostics are made. By defining the transportation as a service, an exergy efficiency index can relate vehicle attributes such as weight, drag coefficient, tire rolling resistance and travel characteristics, with fuel economy. Efficiencies in the order of 3.4% to 8.3% were found, and improvements observed only recently. Technological progress was estimated at about 30% for the period 1990-2020. Of this, about 35% was used for performance, the other 65% for fuel efficiency. This trade-off is vital for projections. Ranges of fleet-wide fuel efficiency for 2030 and 2035 were estimated and can vary by factors of 50% and 120%, respectively. This variability is due to future rates of technological progress, the level of trade-offs, EV uptake and shifts in consumer preferences towards size and power. Engineers can extract about 20% more performance from the same level of power in 2020 compared to 1990. The deployment of improved technology was traced, and a 10 year gap in adoption compared to the USA was estimated. The future of the ICE engine was discussed. Lastly, developments in engine technology made the displacement-based tax out of date, as 1.0 liter engines today have substantial emission rate variability, about 40%. As such, a CO_2 tax is proposed, with the objective of reducing emissions.

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Nomenclature

Acronyms

ABNT*	Brazilian Association of Technical Standards
AFV	Alternative Fuel Vehicles
ANFAVEA*	The Brazilian National Association of Vehicle Manufacturers
AT	Automatic Transmission
BAU	Business As Usual
BCG	Boston Consulting Group
BEV	Battery-Electric Vehicles
CI	Carbon Intensity
DVVL	Discrete Variable Valve Lift
EGR	Exhaust Gas Re-circulation
EPA	Environmental Protection Agency
ERFC	Emphasis on Reducing Fuel Consumption
EV	Electric Vehicle
FE	Fuel Economy
FFV	Flexible-Fuel Vehicles
GDI	Gasoline Direct Injection
GDP	Gross Domestic Product
GHG	Greenhouse Gases
GPM	Gallons Per Mile
HEV	Hybrid-electric Vehicles
ICE	Internal Combustion Engine
INMETRO*	The National Institute of Metrology, Quality and Technology
LDV	Light-duty Vehicle

MFES	Mandatory Fuel Economy Standards
MHEV	Mild Hybrid Electric Vehicle
MPG	Miles Per Gallon
MT	Manual Transmission
MY	Model Year
PHEV	Plug-in Hybrid Electric Vehicles
PSFI	Performance, Size, Fuel Economy Index
RMA	Rubber Manufacturers Association
STEP	Stochastic Transport Emissions Policy
SUV	Sport Utility Vehicles
TEG	Thermoelectric Generator
ULEV	Ultra-low Emission Vehicles
VKT	Vehicle Kilometers Travelled
WTW	Well-To-Wheel

Symbols

η	efficiency
ϕ	chemical exergy to lower heating value ratio
ρ_{air}	air density (1.180 kg/m^3)
ρ_{fuel}	fuel density (kg/L)
A	vehicle frontal area (m^2)
a	acceleration (m/s^2)
B	exergy (kJ)
b	specific exergy (kJ/kg)
C_d	drag coefficient (dimensionless)
C_c	combined fuel economy (km/L)
C_r	rolling coefficient (dimensionless)
F	force (N)
g	gravitational constant (9.81 m/s^2)
LHV	lower heating value (kJ/kg)

m_f	fuel mass (kg)
m_v	vehicle mass (kg)
V	speed (m/s)
W	work (kJ), power (kW)

Contents

Chapter 1

Introduction

Energy consumption in the Transportation sector is significant in most countries and Brazil is not different. The share of total energy consumption rose from 21.2% in 1970 to 31.2% in 2020 (EPE, 2021). Total energy demand increased by more than six times, while *per capita* demand almost tripled. The inhabitants per vehicle ratio sharply decreased from about 38.7 in 1965 to 4.4 nowadays (ANFAVEA, 2020), but is still lower than for developed countries, typically below two. Road transport is responsible for about 90% of the sector's consumption, roughly divided in Light-Duty Vehicles (LDVs) using gasoline and ethanol, and Heavy-Duty Vehicles, fuelled by diesel[1]. Due to very different characteristics, this thesis will focus on LDVs.

In a general form, environmental impact in the transportation sector can be estimated by the ASIF equation, defined by Schipper (2002).

$$G = A \times S_i \times I_i \times F_i \tag{1.1}$$

Where,

- G is the total emission of any pollutant,
- A is the kilometers traveled per year per vehicle (activity level),
- S is related to the modal mix; hence, the percentage of travel by personal vehicle, public transport, bicycle, foot, and others,

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[1] Motorcycles are responsible for about 2–9% of emissions and will not be considered (SEEG, 2022)

- I is the fuel intensity of each mode for a light-duty vehicle (LDV), which is the inverse of fuel economy,
- F is the fuel type, e.g., gasoline, ethanol, electricity.

While greenhouse gases (GHG) emissions from the use and production of fuels in the Transportation sector are still one order of magnitude lower than those from the agricultural industry, or those associated with land use change, they have very different emission trends. Emissions from the agricultural sector peaked in 2003 and dropped by half by 2007. Such profound reduction in the Transportation sector is much more challenging to achieve (CHEAH et al., 2008). This thesis will outline some of the mechanisms behind this. Of all parameters, Intensity is the one this thesis focus on, specifically, the technological evolution of LDVs, exergy efficiency, and possible trade-offs between efficiency and performance.

Craglia and Cullen (2020) further expanded the Equation 1.1, or ASIF rationale, dividing the emissions model into five modules: travel demand, vehicle stock, power-train shares, embodied CO_2 and fuel efficiency. Stochastic variables are: Car mode share, Hybrid-electric Vehicles (HEVs) market share, Internal Combustion Engine (ICE) ban-year, share of Battery-Electric Vehicles (BEVs) in Ultra-low Emission Vehicles (ULEV), rate of change in technical improvements and vehicle attributes, possible rebound effect due to improved fuel efficiency, electricity grid carbon intensity and utilization factor for Plug-in Hybrid Electric Vehicles (PHEVs). There are another 29 endogenous variables in the model. Outputs are vehicle kilometer travelled (VKT), final energy consumption, well-to-wheel (WTW) $\mathrm{CO_2}$ and Life-cycle $\mathrm{CO_2}$ emissions. With access to reliable data for Great Britain, authors were able to estimate where most of future uncertainty lies. They were electric vehicle uptake and vehicle size and power. No trends in key vehicle parameters, in line with published by the Environmental Protection Agency (EPA) (ADMINISTRATION et al., 2010) for the USA market, exists for Brazil. This thesis will systematize such information in the next few chapters, along with many others related to LDVs and their market. It is the first of its kind in breadth and scope.

Forecasting total emissions introduces another layer of complexity, as many of those variables mentioned above are dynamic, interplay with each other, and their future pathways can be very uncertain. When all these factors are considered, scenario analysis should produce multiple results. Trying to determine a single, precise outcome, is simply impossible. Long-term energy forecasts can be very useful but also prone to failure. This may happen for a number of reasons. One is simply its complexity, with many factors interacting in often unpredictable ways, specially those which depend on social interactions. On the one hand, forecasts can fail because, in order to reach results, necessary simplifications had to be made. When compounded, these simplifications may render the forecast of little use. On the other, results may follow directly from the input assumptions (CRAIG; GADGIL; KOOMEY, 2002). These assumptions may be biased with a pre-determined goal in mind. If a modeller considers all other variables to be fixed, the introduction of more efficient vehicles must result in lower energy consumption compared with a "business as usual scenario" (BAU). In fact, the creation of a BAU scenario may already be subjected to biases when choosing inputs. The effects of a proposed policy may be amplified beyond realistic levels if compared with an overly pessimist, unreal BAU scenario.

Forecasting can be mistakenly or unknowingly confused with backcasting. See Robinson (1982) for a thorough discussion about this issue. Very briefly, backcasting does not try to show what the future will be, but works backwards from an intended goal, to illustrate the effect of a policy, for example. Thus, accuracy is not an issue, as it happens with forecasting. The problem is when a study is in fact a backcasting disguised as forecasting. The approach used should be explicitly stated by energy modellers.

Deterministic scenarios by definition cannot produce a range of possible outcomes. They also fail to give the reader the *likelihood* of that precise estimated outcome. For this reason Bastani et al. (2012a, 2012b) introduced the STEP (Stochastic Transport Emissions Policy) model. The model is built upon 27 equations and 38 variables, with minimum, maximum, mean, standard deviation and uncertainty levels. The model is able to produce a range of outcomes for gasoline equivalent fuel use and total GHG emissions, with levels of uncertainty. Figure 38 in (BASTANI; HEYWOOD; HOPE, 2012a) neatly illustrates the shortcomings of single-result forecasting, as no likelihood can be assessed. It can also test sensitivities to variables and rank them accordingly. This is a key aspect for policy-makers. The modellers are helped by the fact that research for the US LDV fleet is more advanced and variables' behaviour better understood. Simply put, our knowledge for Brazil is still significantly lagging behind, making this type of model impractical. The model is very sensitive to vehicle scrappage rate and kilometers travelled (VKT), for example, which could be more thoroughly researched in Brazil.

LDV GHG mitigation strategies usually follow the well-established avoid-shift-improve approach (CREUTZIG et al., 2018; MILOVANOFF; POSEN; MACLEAN, 2020). Avoid is self-explanatory, but probably harder to implement, as they are influenced by land-use planning and city size, urban density, and infrastructure. Shift means moving away from the car towards public transit, cycling or walking. The Improve factor receives by far the most attention as it is related to EVs and improving fuel efficiency. These ultimately are supply-side, technological, solutions. It is argued that more focus should be given towards demand-side, multidisciplinary solutions (CREUTZIG et al., 2018). Milovanoff et al. (2020) concludes that, for the USA, EVs are not a silver bullet. Authors neatly illustrate the size of the problem by calculating "extra-EVs" needed to offset stagnated ICE fuel efficiency, more vehicle size and power, and consumer preferences towards light-trucks.

Fuel type (F) receives a great deal of attention due to the possible competition between technologies to best mitigate emissions. As mentioned above, this can reach as far as modelling the year ICEs will be banned from sale. This topic is evidently controversial and a thorough discussion is outside the scope of this thesis. Brazil's case is specially complex due to ethanol being a viable third option compared to gasoline and electricity (not to mention the possible combination in flex-fuel or hybrid-electric vehicles). What is of concern here is that ICEs will still be prevalent for some decades, due to slow fleet turnover and very low starting EV fleet. Also, significant improvements in ICE technology can still be achieved (MALAQUIAS et al., 2019; REITZ et al., 2020; KALGHATGI, 2018).

Ethanol is slightly more efficient than gasoline (GALLO; MILANEZ, 1992; RUFINO et al., 2019), which is illustrated in Chapter 3. After this chapter, no more consideration is given for this fuel, which may seem strange given that Brazil is known for its sugar-cane ethanol. First, figures and data analysis for both ethanol and gasoline would simply double the amount of data presented, with little extra understanding to be gained. Relationships illustrated for gasoline also hold for ethanol. The second is that introducing ethanol into the picture would produce another layer of complexity, analogous to that of EVs. The reason is that variability in emission factors lies elsewhere than in the vehicle itself. For ethanol, in the harvest and production processes and those related to land use (SANT'ANNA, 2015). Also, gasoline is still the predominant fuel in Brazil, its share of LDV energy consumption in 2021 was 60%, against 40% for ethanol (EPE, 2021).

Lastly, due to its uncertainty, the investigation of electrification and its various extents will be minimal. This thesis will focus on ICEs. The main reason is this thesis intends to provide the historicity that is neglected in Brazil. Trends in critical variables, such as weight, power, size, and fuel economy, are among the main contributions. By the end of this thesis the reader will be able to critically judge a number of modellers assumptions regarding these and derivative variables, such as the yearly rate of technological gains.

The thesis's central premise is that energy use and GHG emissions prognosis for the Brazilian LDV fleet can be improved, giving a more meticulous examination of all those variables. Appropriate consideration of all variables, though, is beyond any thesis' scope. There is no attempt to estimate total energy use or GHG emissions. Estimations will go as far as fleet-wide fuel efficiency in 2030 and 2035, in Chapter 4. The second premise is that ICEs will still be the primary propulsion system in LDVs for a considerable time, regardless of the still uncertain future EV uptake (KALGHATGI, 2018).

Main contributions of this thesis are:

- an update on the exergy efficiency in the transportation sector, based on proper vehicle data from 1970 to 2020. This gives a better understating of resource use in society.
- the trade-off between LDV efficiency and performance from 1990 to 2020. This is a key factor in estimating possible future efficiency improvements.
- deployment of technology to improve vehicle performance. A proposed new taxation scheme to induce lower CO_2 emissions.

To achieve these main objectives a thorough investigation of many related LDV variables were traced. They are: average vehicle size, measured in weight and frontal area, fuel efficiency, acceleration performance, horsepower, power-to-weight ratio, specific power, market share by LDV category and displacement. There is also a presentation of the effects and rate of deployment of newer power-train technologies and the time gap compared with the USA market. This allows a better estimation of when improved technologies will be cost-efficient for the Brazilian market.

The policy-oriented reader will benefit from knowing feasible rates of technical improvements, trends in key LDV parameters such as size and power, which influence energy consumption. The researcher can use many of the tables and figures to improve his model and also judge the feasibility of his assumptions. The interested reader can realise that many of the developments in the LDV sector run against reducing its climate impact, there are many conflicting tendencies. Better aerodynamics were accompanied by larger vehicles, improved technology used to make heavier and faster cars, consumer preferences tending towards power.

1.1 Overview

This thesis is based on three articles, two already published and another submitted to peer-review in a reputable journal. As such, articles are self-contained, meaning they can be read separately. They all share the same basic background, though, which ultimately leads to a thesis: they all improve our understanding about the LDV fleet in Brazil. They all focus on past developments, in order to produce insights for future energy planning. They all rely on a main target variable, which in turn allows the tracing of the evolution of other, related key variables. Readers will gain through this thesis knowledge about the LDV fleet which were never published before. Future energy modellers will be able to use various figures, tables, relationships, tendencies and insights to improve their forecasts.

Chapter 2 presents some preliminary data regarding the LDV market evolution. Total energy consumption, sales by fuel and category, as well as sales-weighted average fuel economy for the period 1990–2020 is presented. The latter was never done for Brazil an its results are integral to any forecast, because they reflect potential shifts in consumer preferences which might not be captured if market availability alone is considered.

Chapter 3, with minor stylistic alterations, was published in (MOSQUIM; MADY, 2021). It is dedicated to diagnose the evolution of vehicle performance via exergy analysis, by considering the transportation as a *service* to move people and goods. There is more than one way to define exergy efficiency, which is discussed there. The method employed relies on definitions made by Dewulf and Langenhove (2003) and Florez-Orrego et al. (2015). When considering the forces against which a vehicle moves and the power generated by the fuel consumed, a relationship can be established between vehicle parameters such as drag coefficient, frontal area, weight, travel characteristics and fuel economy. When applied for a period of time, the evolution of such parameters can be traced. The main results obtained in this chapter are the exergy efficiency for the Brazilian LDV fleet from 1970–2020. Separate illustration of transportation service and fuel exergy, respectively nominator and denominator of the efficiency index, are done as well. The definition of exergy efficiency bears some resemblance with another approach to the problem (LUTSEY; SPERLING, 2005), discussed and explored in Chapters 4 and 5.

Chapters 4 and 5 mainly follow an MIT work-group which, between 2000–2015, published a series of works about LDVs (WEISS et al., 2000; BANDIVADEKAR et al., 2008; HEYWOOD et al., 2015). Trying to replicate that in a single thesis would be impractical, thus the main methods employed were An and Deccico's (2007) Performance, Size, Fuel Economy Index (PSFI), Bandivadekar's (2008) Emphasis in Reducing Fuel Consumption and MacKenzie's (2013) regression analysis method, which was inspired by Knittel's (2011) research, but followed An and Deccico's approach.

Chapter 4 was published in (MOSQUIM; MADY, 2022). It estimates the trade-off between efficiency and performance. This trade-off is vital because technical improvements are finite and may be used to improve either, but not both. The rate of technological improvement for the period 1990–2020 was estimated at about 1% per year, on average. Of all this progress, about 31–39% were spent on performance. The evolution of key vehicle parameters were traced as well. Future fleet-wide fuel efficiency were estimated for a number of assumptions related to consumer preferences and EVs uptake.

Chapter 5 focuses on acceleration, the main performance indicator. Technology diffusion means a vehicle in 2020 is very different from one made in 1990. One implication is that direct taxes on LDVs are outdated, as they are based on displacement. The chapter makes this explicit by illustrating the improvements in power-to-weight ratio and specific power and torque. Thus, the main contribution is the proposal of a new tax, based on CO_2 emission rates, to induce downsizing and lower relative energy consumption. Technological adoption has a remarkably constant 10-year delay when comparing with the USA market.

Chapter 6 discusses main implications of this thesis, limitations and future research. Chapter 7 concludes this thesis.

Chapter 2

The Brazilian context

This chapter will give a contextualization about key Brazilian LDV factors pertinent to the ASIF equation, but which will not be further discussed for the remaining of this thesis. The reasons for that will be given as well. First, an overview of LDV sales, fuel consumption and total emissions are illustrated. Then, a discussion about VKT, scrappage rates, emission factors from fuel use, gasoline, ethanol and electricity. A very brief outline of public policies is presented.

Also, as this thesis' structure is based on research papers, each chapter contains a literature review pertinent to the problem considered. Conciseness was preferred against prolixity, thus no formal literature review chapter is to be found here. Section 4.2 can be used as such, as it contains the main ideas which guide this thesis. Also, this thesis avoided lengthy discussions and systematization of common knowledge. For example, the reader will not find detailed discussions about ICE technologies and the finer workings of a vehicle. The simple reason is that better sources can be found elsewhere (HEYWOOD, 2018). Footnotes and the bibliography can be used by the interested reader to explore topics which were mentioned here in passing.

2.1 Total sales

The Brazilian LDV market has some unique features which differentiates it from other countries. First, ethanol from sugar-cane was developed as a substitute for gasoline in response to the oil-shocks in the 1970s. The first vehicles of its kind appeared in 1979, quickly gained market share against gasoline and dominated sales throughout the 1980s, as illustrated in Fig. 2.1 below. Total sales remained constant as Brazil experienced great economic problems throughout the 1980s.

Dedicated ethanol engines failed for a number of reasons; technological shortcomings, such as difficulties to start in cold weather and to adapt 1000cc engines to the tax incentive scheme for popular, affordable cars; the steady increase in relative ethanol prices, from 64.5% in 1979 to 80% of that of gasoline; supply reliability concerns. These factors led to the disappearance of dedicated ethanol vehicles by the end of the 1980 decade (MOREIRA; GOLDEMBERG, 1999).

In the 1990s, specially after tackling hyperinflation, sales of gasoline vehicles went from about 500 thousands to as high as 1.5 million in 1997, before stabilizing at about 1.0 million units until 2003.

Ethanol, though, would make a revival in the form of other unique feature of the Brazilian LDV market[1]. 2003 was the year Flexible-Fuel Vehicles (FFVs) were introduced, a novel technology which enabled engines to run on gasoline, ethanol, or any mixture of both. Its success was immediate and by the end of the decade almost all vehicles licensed were of this kind. The economic boom in the 2000s also created the conditions for total sales to rapidly climb from about 1.2 to 3.1 million in 2012, before a economic and political crisis reduced sales to about 2.0 millions.

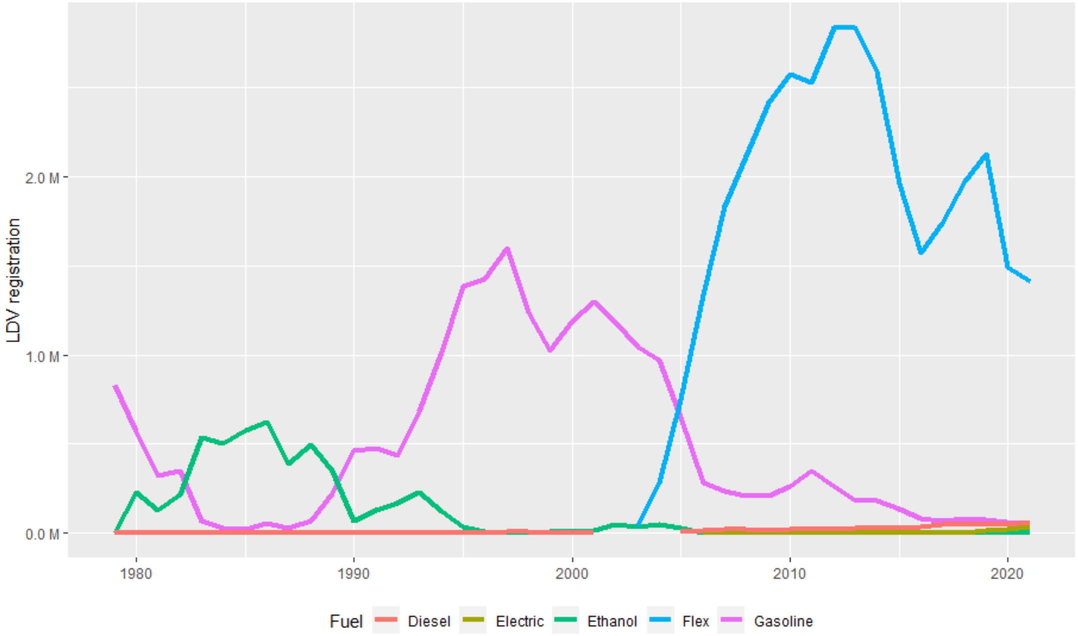

Figure 2.1: Total vehicle sales per fuel technology, 1980–2020, in millions. Data obtained in (ANFAVEA, 2020)

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[1] Another country feature is that LDV vehicles are not allowed to run on diesel, even though SUVs and trucks which run on it are gaining market recently.

2.2 Fuel Consumption

Total fuel consumption is illustrated in Fig. 2.2 below. Consumption increased more than five times in the period 1970–2020, doubling in 2005–2015 alone. It is likely that activity level (A in the ASIF Equation 1.1 above, kilometers travelled per vehicle per year), increased in the period, following the economic expansion, but no reliable estimation exists for Brazil.

The main takeaway from this picture is that ethanol consumption only surpassed that of gasoline for a few years in the heyday of dedicated ethanol engines, in the latter years of the 1980s. Not even the total market domination of flex-fuel vehicles, illustrated in Figure 2.1, tipped the scale in favor of ethanol. As gasoline is still the most consumed fuel, and will likely be so, it received most attention in this thesis.

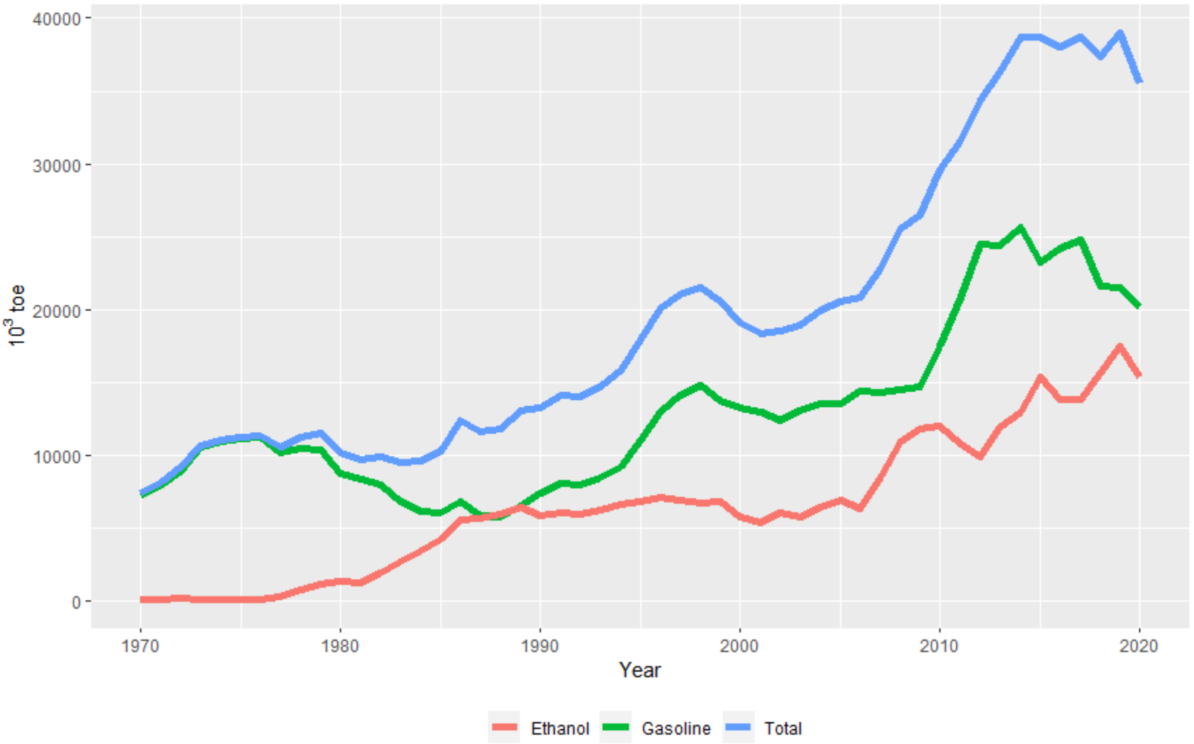

Figure 2.2: LDV Energy consumption 1970–2020, from (EPE, 2020)

2.3 Greenhouse Gas Emissions

GHG emissions were multiplied by 5.7 from 1970 to 2014, when it peaked. LDV share of emissions from the Transportation sector were in the range of 25.3–34.3%, with a slight upward trajectory. Total emissions, similarly to LDV sales and fuel use, peaked around 2012–2015. The main factor behind this is the severe economic crisis since 2014, with negative average GDP growth from 2014–2019. 2020 is obviously an outlier due to the Covid-19 pandemic. It is unlikely that LDV sales, fuel use and emissions will not resume their growth trajectory in the near future, pending economic recovery.

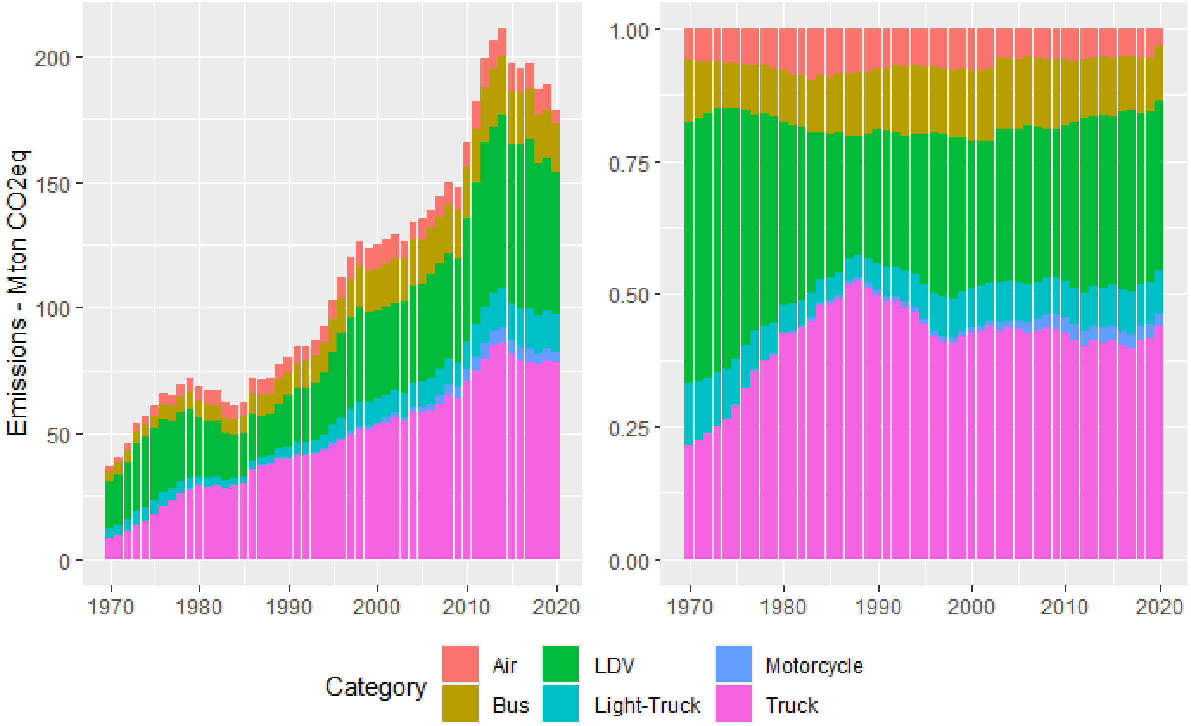

Figure 2.3: Transportation sector CO2eq emissions, 1970–2020. Data obtained in (SEEG, 2022).

2.4 Policy

Policies to reduce GHG emissions can be roughly divided into three main strategies: i) incentives towards low(er)-carbon fuels, ii) increase fuel efficiency and iii) reduce travel. Mechanisms can be mainly regulatory, economic or information-based in nature. Probably only a combination of policies will achieve the the deep levels of GHG reductions required, and synergies between policies are essential (AXSEN; PLÖTZ; WOLINETZ, 2020).

The Brazilian program to control vehicle pollutants (PROCONVE, in Portuguese) was implemented in May 1986 (PROCONVE, 2022). Its main objective was to reduce emission rates for LDVs, with Table 2.1 above giving a general overview of emission rate evolution for each program's phase. The program also aimed at establishing guidelines for measuring and controlling emissions, and also promote technological improvements in this regard.

While inserted in a more general context of an industrial policy (IBUSUKI; BERNARDES; CONSONI, 2015)[2], INOVAR-AUTO ((FINANCE, 2020)) established a target of 12% in fuel efficiency improvement, comparing 2017 to 2012. Further tax exemptions were in place for overachievers, 15.4% and 18.8%. Rota 2030 is the heir of INOVAR-AUTO (BRAZIL, 2022). Its aims are also broader in scope than just efficiency standards, and a brief discussion about its targets are analyzed in Section 4.6.3.

Starting in 2018 the Brazilian Government instituted the RenovaBio program, with the purpose of reducing fuel carbon intensity (CI). This is expected to be achieved by increasing the relative importance of ethanol, due to its lower emission factor (official data is 87.4g of CO2eq per MJ for gasoline and 20.8 CO2eq for ethanol). CI targets are thought to induce the market towards biofuels, and also to promote efficiency in producing ethanol (GRASSI; PEREIRA, 2019).

Key variables which influence total fuel use and emissions will be discussed below. Research opportunities will be discussed as well. A central premise of this thesis is that our level of understanding about these variables is still insufficient, and this discussion will try to shed some light on this issue. Forecasting is inherently difficult and accuracy very hard to achieve. But extrapolating with so many unknowns may turn forecasting into little more than shooting in the dark.

2.5 Activity

Activity level is dependent on two main variables, i) total vehicle fleet and ii) distance travelled by each vehicle per year. Vehicle fleet is subject to new vehicle sales and old vehicles being taken out of circulation. New vehicle sales depend on population growth, active population, economic factors, vehicle price. Distance travelled per vehicle is complicated, as will be discussed in more detail below. Simply put, there is no reliable estimation for this number for Brazil.

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[2] Authors cite a 2012 ANFAVEA projection of 6 million LDV units sold in 2017, more than 4 million above actual values. One glance at Figure 2.1 illustrates the perils of the linear extrapolation of recent tendencies.

2.5.1 Activity level - VKT

Estimating total vehicle kilometers travelled (VKT) is certainly not an easy task. It also applies to average VKT per vehicle and per capita. There are three main methods for estimating VKT (KUMAPLEY; FRICKER, 1996). Traffic count, in which traffic in a section of a roadway is directly measured and then VKT is estimated by extrapolating this count. Socioeconomic-based, either by surveys, fuel sales. Lastly, odometer readings. With fleets in the millions, direct odometer readings are impractical for the whole country.

Generally, VKT is influenced by demographic and economic factors, as well as driving habits (LEARD; LINN; MUNNINGS, 2019). Estimations for annual fleet numbers are readily found in (SINDIPEÇAS, 2021) or the National Transit Department (Denatran), though the latter does not consider scrappage, only licensing, thus likely overestimates the number of vehicles actually in use.

The majority of studies (2000, 2010, 2004, 1998, 1997, 2018, 2005) estimating LDV impact rely on the same survey, done in 1982 by CETESB for the metropolitan region of São Paulo. It was estimated that a vehicle travelled 22000km in the first year and steadily decays until the 11th year and 9500km, remaining at this level until being scrapped. For comparisons, estimated average VKT for 1982 in the USA was about 14500km and 20000km in 2004 (BANDIVADEKAR, 2008), with values from the U.S. Energy Information Administration.

This rate of decay also seems overestimated, as kilometers are more then halved for a 10-year old vehicle. Estimated halving of kilometers travelled are only reached in year 20 in the USA (BANDIVADEKAR, 2008). All in all, this would mean a vehicle would travel 250000km for a 20 year lifetime[3], or 12500 on average per year.

The same company updated its estimates in 2013, but now based on actual odometer readings for thousands of vehicles in the metropolitan region of São Paulo, for the years 2010–2011. First-year distances were estimated to be 16000 for flex-fuel vehicles and 13000km for dedicated gasoline. Flex-fuel vehicle average use decays very slightly towards 15000 per year, in year eight, while for gasoline it peaks at around 15000km in year 10, dropping to about 12000km in year 20 (BRUNI; BALES, 2013). The fact that, after more than three decades, first year VKT values were adjusted *down* by almost 30%, when it is known (ECOLA et al., 2014) that VKT tends to increase with increasing income and the passing of time [4], makes that first

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[3] Cetesb (BRUNI; BALES, 2013) estimated about 96.25% of vehicles had 20 years or less in 2010–2011

[4] GDP per capita increased by almost 50% in the period (BANK, 2021)

estimation of questionable value for forecasting.

Borba (2008) critiques CETESB's 1982 values for not reflecting the realities of each state, and his Thesis's objective was to regionalize the Brazilian's fuel market. Indeed, Brazil is a continental country with enormous socioeconomic disparity, and may have different VKT among regions and states. Nevertheless, the author estimated 16596km average VKT for the Northern region, and only 8405km for São Paulo in 2004.

Vieira (1999) estimated 10437km for the year 1996 and stated that total kilometers travelled, some 285 billions, would be similar to 1970s levels for West Germany and Japan.

Ecola et al. (2014) use a VKT per capita of 1136km for 2008. With an estimated population of 192 millions that would result in 218 billion VKT. With 22.9 million vehicles (SINDIPEÇAS, 2021) in the fleet this would mean about average 9525 VKT per vehicle. They also estimated saturation levels at about 11300km per capita, a number they revised to 9900km (SEUM; SCHULZ; KUHNIMHOF, 2020).

Another CETESB (2019) publication estimates averages of 12360km per vehicle per year for São Paulo state for 2006. This number steadily increases and reach 14910km in 2019. VKT are also estimated, going from 88 to 155 billion in the period. VKT per capita would go from 2229 to 3498km.

These numbers generally clash with each other and vary widely. This makes identifying trends very difficult. All considered, this last estimation is likely to be the most accurate, but still does not account for regional differences, nor are there any information regarding possible rates of increase in the future. One would need to extrapolate tendencies from past data, which is always a dangerous proposition. As VKT has great impact on total emissions, and seems to be not properly understood (or "The forgotten Channel" to reduce emissions (KNITTEL, 2012)), a more thorough research is desirable.

2.5.2 Vehicle scrappage

Vehicle scrappage is perhaps the least understood factor of all. This therm refers to the retirement of older vehicles and is directly related to fleet turnover. As about 96% of the 2021 fleet is more than one year old (SINDIPEÇAS, 2021), this scrap rate has profound impacts on average fleet fuel economy. In fact, future scenarios seems to be very sensitive about this rate (BASTANI; HEYWOOD; HOPE, 2012a). While Sindipeças provides annual values for fleet age and their distribution, the scrap rate function parameters are not disclosed.

A more discreet, but nonetheless important effect of scrap rate is its relationship with fuel price and used vehicle resale value. This is called the Gruenspecht effect (GRUENSPECHT, 1982). In a very simplified form, the tightening of fuel economy standards increases new vehicle prices due to improved technology. This in turn increases the used car values. This makes used vehicle owners postpone scrappage. As older vehicles tend to have lower fuel economy, this makes the whole fleet less efficient. This effect was estimated to induce 13–16% lower fuel savings from fuel-economy standards, due to "leakages" in the USA used car fleet (JACOBSEN; BENTHEM, 2015).

Scrap rates are dynamic and change over time. Also, average vehicle lifetime has increased by more than 50% in the US in half a century (BENTO; ROTH; ZUO, 2018). Comparing a 10-year old with an up-to-date scrap function resulted in an 8% efficiency gap, which translates to about 90 million more tons of carbon emitted than otherwise estimated in the US. These findings also have profound implications for fuel-economy standards, as a slower fleet turnover requires higher mandates than if a static, out of date scrap function was employed. As with VKT, the scrap rate function used in Brazil usually converges towards a single study ((AZUAGA et al., 2000; URIA; SCHAEFFER, 1997; MENDES, 2004), published in 1996 (MATTOS; CORREIA, 1996) apud (SCHMITT, 2010)).

For Brazil, fuel-economy, safety and emission regulations might also affect prices in a way that makes the popular car obsolete. These entry-level, low-margin vehicles are equipped with the most basic technology, a fact that will be explored in Chapter 5 from a performance perspective. Efficiency, safety and emission mandates require a level of technology that may make this vehicles unprofitable.

2.6 Share

Share refers to the mode of transportation used to move passengers. One can choose a personal vehicle, a bus, a bicycle, by foot, an airplane. Trains and boats could be used, but are negligible in Brazil. According to IPEA 2021, there is a tendency for Brazilians to substitute public for personal transportation. Holistic estimations should consider this fact when proposing public (electric) buses to solve our problems. Inadequate public transport may repel users, who purchase individual transport as soon as income allows for it. All these factors contribute to overall energy demand and must be properly contemplated.

2.7 Fuel

Fuel emission factor, F, gets complicated as well. For one, Brazilians now mostly buy flexible-fuel vehicles. These can run on either ethanol, gasoline, or any mixture of both. GHG emission factors for these two fuels are very different, thus heavily impacting total emissions. Even though price sensitive, there is a non-negligible share of drivers who show strong preference towards either fuels. This should be kept in mind when creating scenarios of "total ethanol use" or something.

Lastly, there is the obvious prospect of electricity. Vehicles using this "fuel" are perceived as cleaner and car-makers like to advertise them as zero emissions. While labelling them is zero emissions is obviously scientific inaccurate (and misleading), the concerning problem here is possible variability in emission factors. Electricity can be generated by solar panels, wind turbines, hydro-power, coal or gas power plants. An often-neglected consideration is the marginal emission factor, that which occurs to emit extra electricity to supply this new demand. Emission factors can also vary depending on the time of day (BURTON et al., 2023). There is also the uncertainty in future EV uptake, and by which type. Electrification can cover a very wide spectrum, from very mild, start-stop systems in ICEs, to vehicles moved solely by a battery (BEV).

2.7.1 Fuel emission factors

Since 2009 the Brazilian Labelling Program (PBE, in Portuguese) publishes official data for LDVs. Main categories are fuel efficiency for ethanol and gasoline, for both road and urban driving. Also published are engine displacement and number of valves, transmission, number of gears, presence of air-conditioner, steering and fuel type. Emission factors for selected pollutants, namely CO, NOx, Non-methane Hydrocarbon (NHMC) and CO_2 are presented as well. The latter is considered zero for ethanol. For gasoline it is directly correlated with fuel use as Figure 2.4 illustrates, in blue for flex-fuel vehicles and red for dedicated gasoline engines.

Criteria pollutant is constantly and drastically being reduced over the years, as Table 2.1 below illustrates. CO was reduced in 95% since 1989, NOx in more than 99%. Particulate Matter (PM) emissions were so deeply reduced that tire wear is now a larger source than engine combustion itself (REITZ et al., 2020).

For reasons discussed above, this thesis will not attempt to estimate future CO_2 emissions.

Table 2.1: Evolution of emission factors for criteria pollutant according to Proconve phase. Data from (PROCONVE, 2022).

Phase	Period	CO	HC	$NMHC$	NO_x	$RCHO$	PM
L1	1989–1991	24.0	2.10	–	2.0	–	–
L2	1992–1996	12.0	1.20	–	1.4	0.15	–
L3	1997–2004	2.0	0.30	–	0.6	0.03	0.05
L4	2005–2007	2.0	0.30	0.16	0.25	0.03	0.05
L5	2009–2013	2.0	0.30	0.05	0.12	0.02	0.05
L6	2013–2015	1.3	–	0.05	0.08	0.02	–
L7	2022	1.0	–	0.0080	0.08	0.015	0.006

This linear relationship between gasoline consumption and CO_2 emissions, though, should be kept in mind for the remaining of this thesis. Thus, factors which impact fuel use similarly impact CO_2 emissions, and results can be read in this light.

Lastly, the reader at this point may be inclined to question why sugar-cane ethanol is not the focus here, since its relative reductions in GHG emissions are well established (WANG et al., 2012; WANG et al., 2008; MACEDO; SEABRA; SILVA, 2008; SEABRA et al., 2011). The reason is that gasoline is still the most consumed fuel, and its total displacement by ethanol highly unlikely, with reasons going as far as some consumers' reluctance to switching fuels (SALVO, 2018), regardless of the economics.

There is much to be discussed before becoming any public policy applies to Brazil, as discussed by Rovai, Seixas e Mady (2022); for instance, ethanol-fueled vehicles may be better for decarbonization at this moment than electric vehicles, at least until it achieves 200,000km travelled.

2.8 Intensity

Intensity of use is discussed last as it is the main focus of this thesis. What drives vehicle fuel consumption, by how much did it improve in the period? What makes it improve, what reduces it? How feasible is to consider a 3% rate of improvement in efficiency per year? What would drivers have to give up in terms of size and power for the fleet to achieve that? What if Brazilians substitute the popular car for a SUV? What if EVs don't penetrate the market in significant rates? What if performance is emphasized against efficiency? As it will be shown, fleet-wide average fuel efficiency can vary by a factor of more than two in the near future. This wide range alone justifies not trying to estimate total GHG emissions. Likely, all other

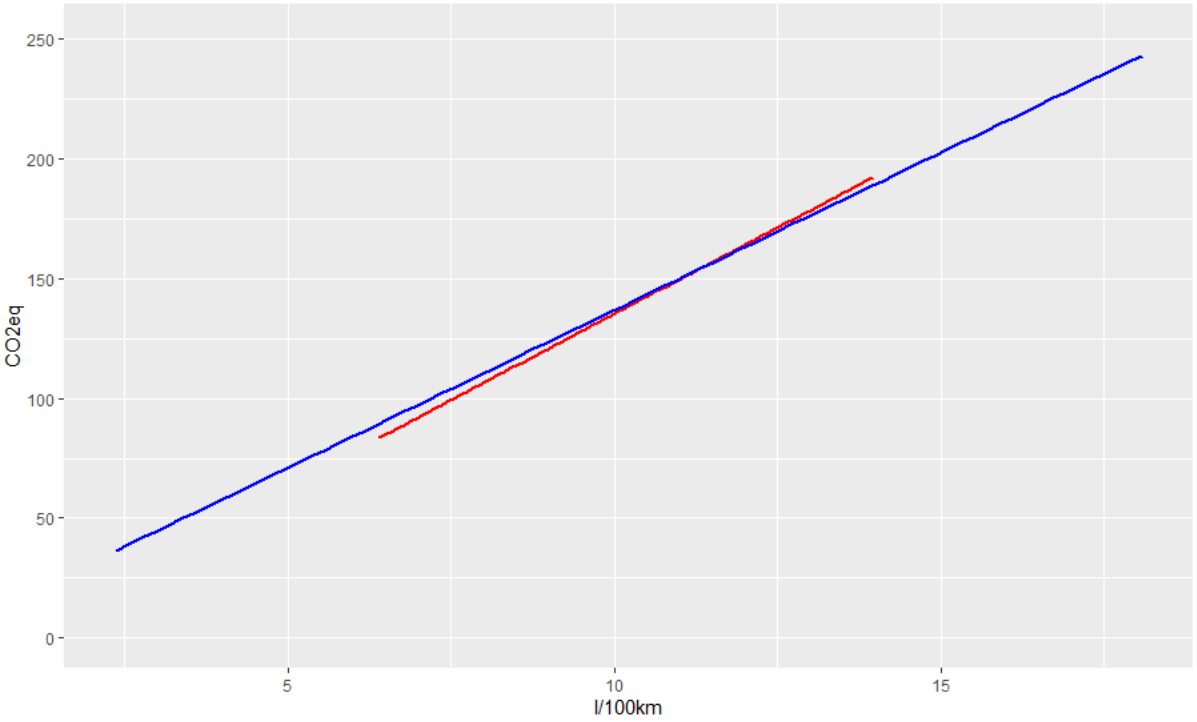

Figure 2.4: Direct relationship between fuel consumption and CO_2 emissions. Blue for flex-fuel vehicles running on gasoline, red for dedicated gasoline engines. Data from INMETRO (2022).

important variables discussed in this Chapter can vary by the same range as well.

Chapter 3

Design, performance trends, and exergy efficiency of the Brazilian passenger vehicle fleet: 1970–2020

This Chapter, with minor alterations, was published as Mosquim, R.F. and Mady, C.E.K., 2021. Design, performance trends, and exergy efficiency of the Brazilian passenger vehicle fleet: 1970–2020. Journal of Cleaner Production, 290, p.125788.

The transportation sector in Brazil is a significant consumer of energy. This consumption progressed at a regular speed, even though vehicles individually become more efficient. The exergy analysis of societies conventionally consists of a single efficiency value applied to extended periods, and this value is essentially a reproduction of an instant. In this study, the exergy efficiencies are calculated for the Brazilian passenger vehicle fleet from 1970 to 2020 based on a definition of efficiency (ratio of the transport service needed to the fuel exergy consumed), which differs from traditional input/output analysis. To calculate efficiencies, some key vehicle parameters were analyzed, and their evolution was measured over time. Exergy efficiencies were low in the period, between 3.4% and 8.3%, with a recent improvement tendency. Transportation service required fell steadily until around 2010 when the trend was reversed. This formulation of efficiency should improve conventional exergy analysis applied to societies and help understand the administration of vehicle improvement and consumer choice, improving policy motivations for better resource use in the future.

3.1 Introduction

Due to its generalized nature, traditional exergy analysis applied to societies relies on estimations for the transportation sector's efficiency. Most estimations, with minor variations, can be traced back to a few sources in the literature. A proper definition of exergy efficiency was obtained to improve the preciseness of applying this analysis, based on the concept of transportation service (DEWULF; LANGENHOVE, 2003) and measures its inevitable destroyed exergy (FLÓREZ-ORREGO; SILVA; OLIVEIRA, 2015). This definition is a function of vehicle parameters and travel conditions, so the process of calculating efficiencies for a period of 50 years provides useful information about the evolution of such parameters. This can help to understand better technological and market tendencies in the Brazilian passenger vehicle fleet. It can also be useful to grasp the past better to build scenarios and design policies to mitigate greenhouse gas emissions from the transportation sector in the future, such as performed by (BENVENUTTI; RIBEIRO; URIONA, 2017; BENVENUTTI; URIONA-MALDONADO; CAMPOS, 2019; MELO; JANNUZZI; SANTANA, 2018).

The transportation sector in Brazil was responsible for 35% of total energy consumption in 2017, with most of the required energy derived from fossil fuels. Road transport is the main consumer of energy, responsible for about 90% of the sector's total demand (EPE, 2020). From 1970 to 2017 consumption rose by more than six times. Some factors may help explain this. The population more than doubled in the period, from approximately 95 million in 1970 to more than 206 million in 2015 (IBGE, 2015). Vehicle ownership increased as well, going from about 24 persons per vehicle to about 4.8, estimated from vehicle licensing (ANFAVEA, 2020). Road transport in Brazil can be roughly divided in heavy-duty vehicles, running on diesel and biodiesel, and light-duty vehicles, running on ethanol, gasoline, or any mixture of both[1]. The latter is called a flex-fuel vehicle, which quickly gained market share since its introduction in 2003. Heavy-duty and light-duty vehicles split this 90% of total energy demand in road transport in equal shares, with minor fluctuations.

Exergy analysis combines the first and second laws of thermodynamics, which allows for the comparison of different systems on the same thermodynamic basis. This can be helpful when considering that different technologies, such as electrical, hybrid, hydrogen-powered and advanced internal combustion engines will likely compete as solutions against the challenges

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[1] This distinction can be easily made in Brazil because light-duty vehicles are not allowed to run on diesel, contrarily to what happens in Europe, for example.

of climate change (FLÓREZ-ORREGO; SILVA; OLIVEIRA, 2015). Even though primarily used for thermal system optimization, its analytical power can be applied in various fields, with applications in bio-thermodynamics to assess the health of people subjected to pollution (CENZI; ALBUQUERQUE; MADY, 2018; CENZI; ALBUQUERQUE; MADY, 2019), for example, and is summarized in (FLÓREZ-ORREGO et al., 2018). As will be discussed in more detail below, exergy efficiency does not benefit from a established definition in the literature, so some review of the existing approaches must be done before choosing the most suitable method.

The objectives of this chapter are as follows:

- To improve the transportation sector's exergy analysis by basing it in vehicle and travel parameters, moving continuously away from estimates.
- To calculate exergy efficiency for a considerable period, to trace the development of vehicle performance parameters and design.

This chapter is divided into six sections. After this introduction, a discussion of the conceptual framework used for analysis, exergy, is arranged in Section 3.2. A literature review was also carried to discuss the different approaches to the problem and why the concept of "transportation service" was used to define exergy efficiency. In Section 3.3, a brief examination is performed on the evolution of crucial vehicle parameters through time to provide a better comprehension of the data-set. Section 3.4 compiles the main results of this study from the Brazilian passenger car fleet's overall exergy performance for the years from 1970 to 2020. A brief sensitivity analysis was carried as well. The discussion of the main results is done in section 3.5. Section 3.6 ends this chapter with the main findings, potential implications of the results, weaknesses in the method, and future research.

3.2 Methods

This section is structured into three main parts. First, exergy is defined, and the reasons for selecting this framework are provided. A novel approach to exergy output, the concept of "transportation service", is used to obtain an exergy efficiency equation in line with the objectives. Then, the parameters used to calculate the efficiency are discussed, and the vehicle data-set used in this work is briefly explained.

The data was analyzed in R-Studio (R Core Team, 2017), and graphics were generated using the package ggplot2 (WICKHAM, 2009). Smoothing lines were added to each graph by the function $geom\_smooth$ in *ggplot2*. This function makes seeing patterns easier when there is over-plotting, which can happen if the data-set is large or not many unique data points. Normalization is performed by the function $data.Normalization$, function $n5$, with normalization in the range (-1,1). The equation is evaluated according to Equation 3.1, where, $x_{i,normalized}$ is the value to be normalized, x_i is the variable value, $x_{average}$ is the average value, and the denominator is the maximum difference between the variable and mean values. Normalizations were made in order to grasp tendencies in parameters, such as acceleration, torque or horse power, measured in different units.

$$x_{i,normalized} = \frac{(x_i - x_{average})}{(MAX\,|x_i - x_{average}|)}. \tag{3.1}$$

3.2.1 Exergy

Exergy measures the capacity of a resource to deliver useful work. It can be defined as a measure of disequilibrium between a given state and the reference state, usually at p_0 = 1.01325 bar and T_0 = $298.15K$ (SZARGUT, 2005). This disequilibrium is the maximum capacity to perform useful work. It makes a distinction between quantity *and* quality of an energy resource (KOTAS, 2013), whereas energy only quantifies it. Exergy can be destroyed. Energy is only transferred from one form to another. Furthermore, it measures inputs in the same physical unit, comparing the exergy consumption of different devices more objective. Indeed, exergy is of particular interest from a society's perspective (MADY; PINTO; PEREIRA, 2020), especially in a sector where technological diversification is approaching, with advanced internal combustion engines, hybrids, and pure electric vehicles that may compete for the most appropriate solution deal with reducing greenhouse gas emissions.

3.2.2 Exergy analysis applied to societies - top-down approach

Exergy analysis applied to societies is an established field with numerous publications dealing with different regions, countries, and sectors. Analyses can be made for a single year, for decades, or to project the future. The first was published by Reistad (REISTAD, 1980) for the United States, followed by Wall (WALL et al., 1986) for Sweden. Since then, it was expanded to a variety of countries and regions, such as Jordan (AL-GHANDOOR, 2013), the United States

(AYRES; AYRES; WARR, 2003), China (CHEN; CHEN, 2009), Norway (ERTESVÅG; MIELNIK, 2000), Greece (KORONEOS; NANAKI; XYDIS, 2011), Sao Paulo State (MOSQUIM; OLIVEIRA; MADY, 2018), Canada (ROSEN, 1992), Brazil (SCHAEFFER; WIRTSHAFTER, 1992), Japan (WALL, 1990), and Italy (WALL et al., 1994). A meta-analysis and compilation of these studies can be found in (ERTESVÅG, 2001) and (UTLU; HEPBASLI, 2007). This subject has recently obtained academic attention due to the necessity of accurately understanding the quality of the energy conversion processes in society to propose suitable solutions (CHOWDHURY et al., 2019c; CHOWDHURY et al., 2019b; CHOWDHURY et al., 2019a; TCHANCHE, 2017; RODRÍGUEZ-MERCHAN; ULLOA-TESSER; CASAS-LEDÓN, 2020).

This type of analysis follows a top-down approach, starting with total or a sector's exergy consumption and applying appropriate estimations or calculations for process efficiencies. For instance, the residential sector (MADY; PINTO; PEREIRA, 2020) may be represented by an average house, and exergy consumption divided between space heating, water heating, electrical appliances and others. Then each process has its exergy efficiency calculated, and weighted averages result in each sector's and the whole economy's efficiency. Each study makes simplifications more suitable for the region of interest, and results provide a valuable overview end use exergy efficiency. For the transportation sector, an efficiency estimated by Reistad (REISTAD, 1980) for the United States in 1975 is usually applied. As the author states in the article, the main concern there was to proper estimate part-load efficiencies for usual operation. As will be discussed with more detail below in 3.5, this estimation lacks a proper physical definition and is fixed, thus making it difficult to trace the evolution of exergy efficiency over time. As well, analysis of this kind inevitably trade detail for generalization.

3.2.3 Vehicle exergy analysis - bottom-up approach

A bottom-up approach would take an engine and possibly other vehicle components item by item, apply appropriate physical equations for each heat or work interaction and calculate efficiencies, destroyed exergy and/or potential exergy recovery. This can be seem as an optimization approach. When the system boundary is the engine, exergy analysis provides an account for the work obtained by fuel consumed (its chemical exergy), and allows for comparisons such as gasoline vs. ethanol engines, or diesel vs. gasoline. Exergy efficiencies for ethanol and gasoline engines operating at compression rates of 12 and 8 were 38.27% and 33.32%, respectively. Heat loss (8.76% and 7.95%), exhaust gases (24.47% and 30.03%) and irreversibilities (28.52% and

28.70%) account for the remaining exergy. These numbers were obtained in (RAKOPOULOS; GIAKOUMIS, 2006), where an extensive review of the subject can be found.

The boundary can be chosen to quantify exergy lost by the exhaust gases (FERNÁNDEZ-YÁÑEZ et al., 2018b). The research found that up to 20–30% of exhaust gas energy could be retrieved by a thermoelectric generator (TEG) at the exhaust system of a light-duty diesel vehicle under real-world driving conditions (GARCÍA-CONTRERAS et al., 2019). Feasible recovery, due to technical limitations, was found to be about 6% (AGUDELO et al., 2016). By moving the system boundary under analysis, it is possible to detect where the highest exergy losses may occur, thus finding a more suitable place to install an exergy-recovery device. Agudelo et al. (AGUDELO et al., 2016) found that such a place is the muffler; therefore, a TEG should be installed at the outlet of the diesel particle filter. In terms of fuel savings, Fernández-Yáñes et. al (FERNÁNDEZ-YÁÑEZ et al., 2018a) found that up to 0.6% and 1.1% reduction in fuel consumption could be obtained in conventional driving conditions for diesel and gasoline engines, respectively. Brazilian passenger vehicles are not allowed to run on diesel. Thus this approach was not further considered. The amount of detail and computation required for this type of analysis would make it challenging to apply for hundreds of vehicles, the objective of this research.

Another, more general approach, is to calculate the theoretical maximum efficiency for the engine operating in an Otto thermodynamic cycle, according to Eq. 3.2 below, from (SERRENHO et al., 2014), with r as the compression ratio and γ the specific heat ratio ($\gamma = C_p/C_v \approx 1.4$). For an engine whit a compression ratio of 12, this theoretical maximum efficiency would be about 63%, whereas for a ratio of 8, about 56%.

$$\eta = 1 - \left(\frac{1}{r}\right)^{\gamma-1} \tag{3.2}$$

The deviation from this theoretical maximum can be estimated by multiplying coefficients, ranging from zero to one, from combustion to power delivered at the wheels. Such coefficients can be: stoichiometry deviations (0.75), combustion (0.75), friction (0.85–0.90), transmission (0.75 for automatic, 0.90 for manual) and accessories (0.90) losses, as well that of the engine not operating at full load at all times (0.40–0.45), from (SERRENHO et al., 2014).

Another estimate of this kind was made by the Pollution Prevention Division of the United States Environmental Protection Agency (EPA). It was calculated using Q as the unit for exergy. For a 19 Q of input, only 1.6 Q of useful work (exergy) was obtained, thus an 8.3% exergy efficiency. Losses were estimated at 3 Q for idling in traffic, 9.5 Q in waste heat, 2.4 Q for the engine and parasitic accessories, 0.5 Q for drive-line friction, and 1.6 Q for overcoming aerodynamic drag (AYRES; AYRES; WARR, 2003). This method requires the possibility of calculating efficiencies for many different vehicles, as variability would be only in compression ratio and transmission technology. Thus, it is not the most appropriate for the objectives of this chapter. Lastly exergy conversion efficiency was approximated as a proportion of miles per gallon (AYRES; AYRES; WARR, 2003). The constant was chosen for an efficiency of 8.33% for the year 1989. With 15.9 mpg this constant was 0.52. Authors stated that the differentiation between conversion and payload efficiency would not be discussed, but estimate a real payload efficiency of about 3% (AYRES; AYRES; WARR, 2003).

3.2.4 Exergy efficiency

The approach most suitable for the objectives stated above is to find a definition of exergy efficiency with adequate level of detail, but simple enough to allow for generalization and differentiate on the vehicle level. Breaking each individual vehicle into its parts to calculate overall efficiency would require immense computation time and so was discarded as an alternative. Lastly, it is important to mention that there is no standardization for the definition of exergy efficiency though a detailed discussion is beyond the scope of this chapter. Reviews and discussions of the different possible exergy efficiency assessments can be found in (LIOR; ZHANG, 2007) and (MARMOLEJO-CORREA; GUNDERSEN, 2012). A generic exergy efficiency definition such as Eq. 3.3 is written in input/output terms. Exergy [2] can be further split in four main parts, Potential (*P*), Kinetic (*K*), Physical (*PH*) and Chemical (*CH*). This definition allows for some flexibility regarding the choice of the system's boundary. Different placement of this boundary will produce different analysis and results.

$$\eta_{ex} = \frac{\sum B_{output}}{\sum B_{input}} = \frac{\sum(B^P + B^K + B^{PH} + B^{CH})_{output}}{\sum(B^P + B^K + B^{PH} + B^{CH})_{input}} \tag{3.3}$$

A control volume boundary considering the entire vehicle would define the input as the exergy provided by the fuel, and the output as the exergy dissipated through thermal losses and exhaust gases to the air, as well as other losses (FLÓREZ-ORREGO; SILVA; OLIVEIRA, 2015). As this output is not useful in the sense that electricity is the output in an thermal power

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[2] Throughout this chapter the letter B is used for exergy, in kJ

plant, for instance, efficiency would be zero, which leads to nowhere (DEWULF; LANGENHOVE, 2003). In this case it is more appropriate to consider that a vehicle is used to provide a *transportation service*, to move people and/or goods from point A to point B. Thus, exergy output in 3.3 is transformed into exergy service in 3.4. The exergy input remains the exergy of fuel consumed in order to provide this service.

$$\eta_{ex} = \frac{\sum B_{service}}{\sum B_{input}} \tag{3.4}$$

Developing further this rationale, Dewulf and Van Langenhove (DEWULF; LANGENHOVE, 2003) defined the transportation resource productivity [3] in terms of Total Mass (*TM*) transported, Mass Per Single Transport (*MPST*), Delivery Time (*DT*), and Total Distance (*TD*). The equation is maintained in a generalized (differential) form. The focus was to compare and optimize different transportation modes such as air, road (passenger and cargo), and railway.

Following this definition and considering the forces acting on a vehicle for a defined travel profile, Flórez-Orrego et al. 2015 calculated exergy efficiencies for vehicles with different propulsion technologies, such as internal combustion engines, hybrids, electrical and fuel-cell for the current technological state. This chapter follows this approach but expands for an extended period while focusing exclusively on internal combustion engines running on gasoline, ethanol, or a mixture of both.

3.2.5 Exergy efficiency for a transportation service

Exergy efficiency is defined as the ratio between the minimum amount of exergy needed to overcome forces to which a vehicle is subjected for a given travel profile (transportation service) and the consumed fuel exergy. It measures the unavoidable destroyed exergy necessary to provide the service (FLÓREZ-ORREGO; SILVA; OLIVEIRA, 2015). The system boundary is the vehicle itself. Suppose a free body diagram is drawn for a moving vehicle. In that case, it is subjected to such forces: air resistance, gravitational forces, rolling forces due to tire friction as well as inertia forces. Traction force counteracts those forces to move the vehicle, as illustrated in figure 3.1.

The exergy efficiency equation is reached by applying Newton's Second law and resolving for the traction force, then applying the concept of work, force developed by a distance. The

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[3] Resource productivity in (DEWULF; LANGENHOVE, 2003) is just the inverted form of Eq. 3.4

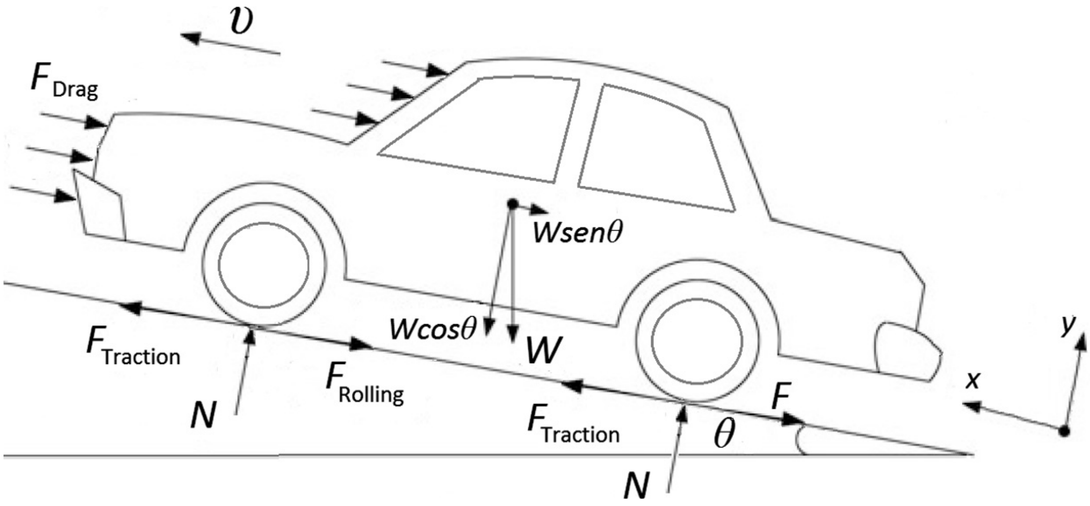

Figure 3.1: Free-body diagram of a moving vehicle, obtained in (FLÓREZ-ORREGO; SILVA; OLIVEIRA, 2015), adapted from (YOUNG et al., 2013)

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development below is obtained from (FLÓREZ-ORREGO; SILVA; OLIVEIRA, 2015).

- Gravitational force as a function of vehicle weight:

$$\overrightarrow{W} = -m_v \cdot \overrightarrow{g} \tag{3.5}$$

- Traction Force by the ground on the tires to prevent sliding:

$$\overrightarrow{F}_{Traction} = (\mu_s \times W \times \cos\theta)\hat{e}_x = (\mu_s \times m_v \times g \times cos\theta)\hat{e}_x \tag{3.6}$$

- Drag force, with no relative wind velocity, and constant drag coefficient:

$$\overrightarrow{F}_{Drag} = \frac{1}{2}\left(\rho_{air} \times A \times C_d \times V_x^2\right)\hat{e}_x \tag{3.7}$$

- Rolling resistance, exerted by the ground on the tires, against the movement of the vehicle:

$$\overrightarrow{F}_{Rolling} = -(C_r \times \overrightarrow{W} \times cos\theta)\hat{e}_x = -(C_r \times \overrightarrow{m}_v \times g \times cos\theta)\hat{e}_x \tag{3.8}$$

- Inertial force relates to the variation of momentum by the vehicle:

$$\overrightarrow{F}_{Inertia} = m_v \times \overrightarrow{a}_v \tag{3.9}$$

Newton's Second Law states that the acceleration of an object is directly related to the net force and inversely to its mass. For a flat-plane (θ = 0) the x-coordinate component is:

$$\sum \overrightarrow{F}_i = \overrightarrow{F}_{Traction} + \overrightarrow{F}_{Drag} + \overrightarrow{F}_{Rolling} + \overrightarrow{W} = m_v \times \overrightarrow{a}_v \tag{3.10}$$

$$\overrightarrow{F}_{Traction} = m_v \times \overrightarrow{a}_v + \frac{1}{2}\left(\rho_{air} \times A \times C_d \times V_x^2\right) + \left(C_r \times \overrightarrow{m}_v \times g\right) \tag{3.11}$$

Minimum work or Exergy is defined by:

$$dB_{service} = \overrightarrow{F} \times d\overrightarrow{s} \tag{3.12}$$

with

$$\overrightarrow{m}_v = \frac{\Delta x}{\Delta t} \tag{3.13}$$

thus,

$$B_{service} = \frac{1}{2} \times m_v \times V_x^2 + \frac{1}{2} \times \rho_{air} \times A \times C_d \times V_x^2 \times \Delta x + m_v \times C_r \times g \times \Delta x \tag{3.14}$$

Exergy efficiency, from the definition in Eq. 3.4:

$$\eta_{ex} = \frac{B_{service}}{B_{fuel}} = \frac{\frac{1}{2} \times m_v \times V_x^2 + \frac{1}{2} \times \rho_{air} \times A \times C_d \times V_x^2 \times \Delta x + m_v \times C_r \times g \times \Delta x}{m_{fuel} \times b_{fuel}} \tag{3.15}$$

with the fuel consumption m_{fuel} defined as a function of the distance (Δx), consumption (C_c) and specific masss (ρ_{fuel}), by Equation 3.16.

$$m_{fuel} = \frac{\rho_{fuel} \times \Delta x}{C_c} \tag{3.16}$$

3.2.6 Parameters

It can be seen by inspection of Equations 3.14, 3.15 and 3.16 that exergy efficiency can be defined as the minimum exergy required for the vehicle overcome resistive forces and achieve average travelling speed, divided by the fuel exergy consumed. It is a function of both vehicle characteristics and travel conditions. Table 3.1 summarizes the parameters.

Table 3.1: Physical parameters in Equations 3.14 3.15 and 3.16

Exergy	Equation	Parameter	Definition
Kinetic (B_K)	$\frac{1}{2} \times m_v \times V_x^2$	m_v	Mass of the vehicle (kg)
-	-	V_x	Average velocity (m/s)
Drag (B_d)	$\frac{1}{2} \times \rho_{ar} \times A \times C_d \times V_x^2\ \Delta$ x	A	Frontal area (m^2)
-	-	C_d	Drag coefficient
Rolling (B_{RR})	$m_v \times C_r \times g\ \Delta\ x$	C_r	Rolling coefficient
-	-	g	Gravitational acc. (m/s^2)
-	-	Δx	Distance travelled (km)

Table 3.2: Fuel properties

Fuel	ρ_{fuel} (kg/L)	LHV (MJ/kg)	ϕ	b_{fuel} (MJ/kg)
Gasoline	0.745	38.92	1.066	41.49
Ethanol	0.810	24.80	1.097	27.21

Physical properties

The air specific mass (ρ_{air}) is 1.180 kg/m^3, and the gravitational acceleration (g) is 9.81 m/s^2. Physical properties for both gasoline C (with 22$\%$ v/v anhydrous ethanol) and Ethanol are summarized in Table 3.2. Chemical exergy of fuel (b_{fuel}, in MJ/kg) is obtained by multiplying the Lower Heating Value (LHV) by the ratio ϕ, obtained in (RAKOPOULOS; GIAKOUMIS, 2006; FLÓREZ-ORREGO; SILVA; OLIVEIRA, 2015).

Standardized tests

Average velocity (V_x = 34.12 km/h) and distance traveled (Δx = 17.77 km) are those defined by the Brazilian Association of Technical Standards (ABNT, in Portuguese) normative NBR 6601 and 7024 for urban and highway driving, respectively, which are based on the FTP-75 e HWFET driving tests, respectively, and were obtained in (FLÓREZ-ORREGO; SILVA; OLIVEIRA, 2015; ADMINISTRATION et al., 2010).

Fuel economy values in Brazil are regulated by two technical standards, ABNT NBR 6601 and 7024, for urban and highway cycles, respectively. They are based on cycles FTP-75 and HWFET, by the EPA, depicted below in Figs. 3.2 and 3.3.

Values are then adjusted to account for real world conditions and its variability, according to Equations 3.17 and 3.18 below.

$$kml_{urban,real} = \frac{1}{[(0.0076712 + (1.18053/kml_{urban,test})]} \tag{3.17}$$

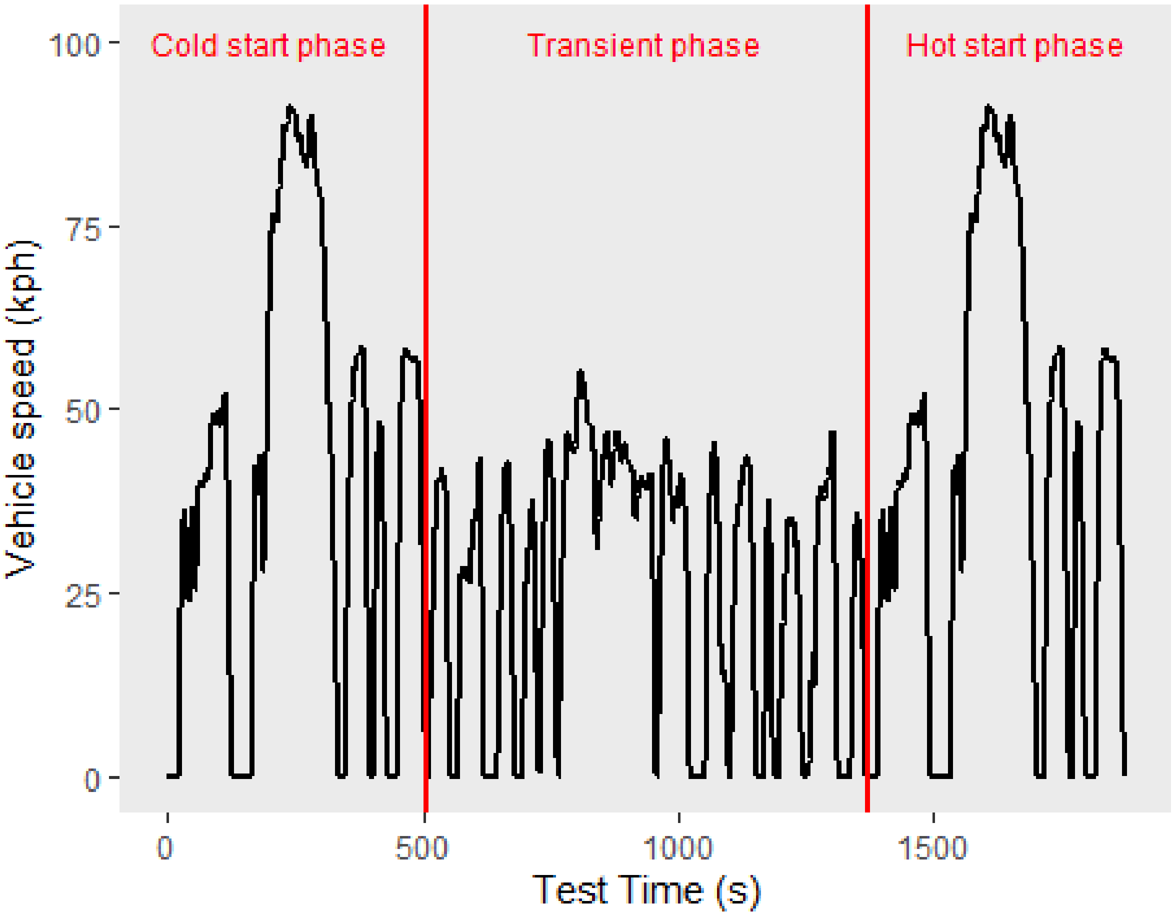

Figure 3.2: FTP-75 Test Cycle, adapted from EPA (2021).

$$kml_{highway,real} = \frac{1}{[(0.0032389 + (1.3466/kml_{highway,test})]} \tag{3.18}$$

Finally, urban and highway fuel consumption can be combined to a single value according to Equation 3.19, from (ADMINISTRATION et al., 2010).

$$kml_{combined} = \frac{1}{[(0.55/kml_{u,r}) + (0.45/kml_{h,r})]} \tag{3.19}$$

Vehicle properties

Vehicle mass (m_v), frontal area (A), drag coefficient (C_d), and vehicle fuel economy for urban and highway travel, in km/L, were obtained from the Catálogo Carros na WEB, a comprehensive internet database which compiles data for vehicles (CARROSNAWEB, 2020). This reference was used in other publications as well (SILVA et al., 2018; OLIVEIRA; BENEVENUTTI, 2019). To check for data reliability fuel economy values were compared with those from the governmental energy efficiency program (CONPET) (INMETRO, 2022).

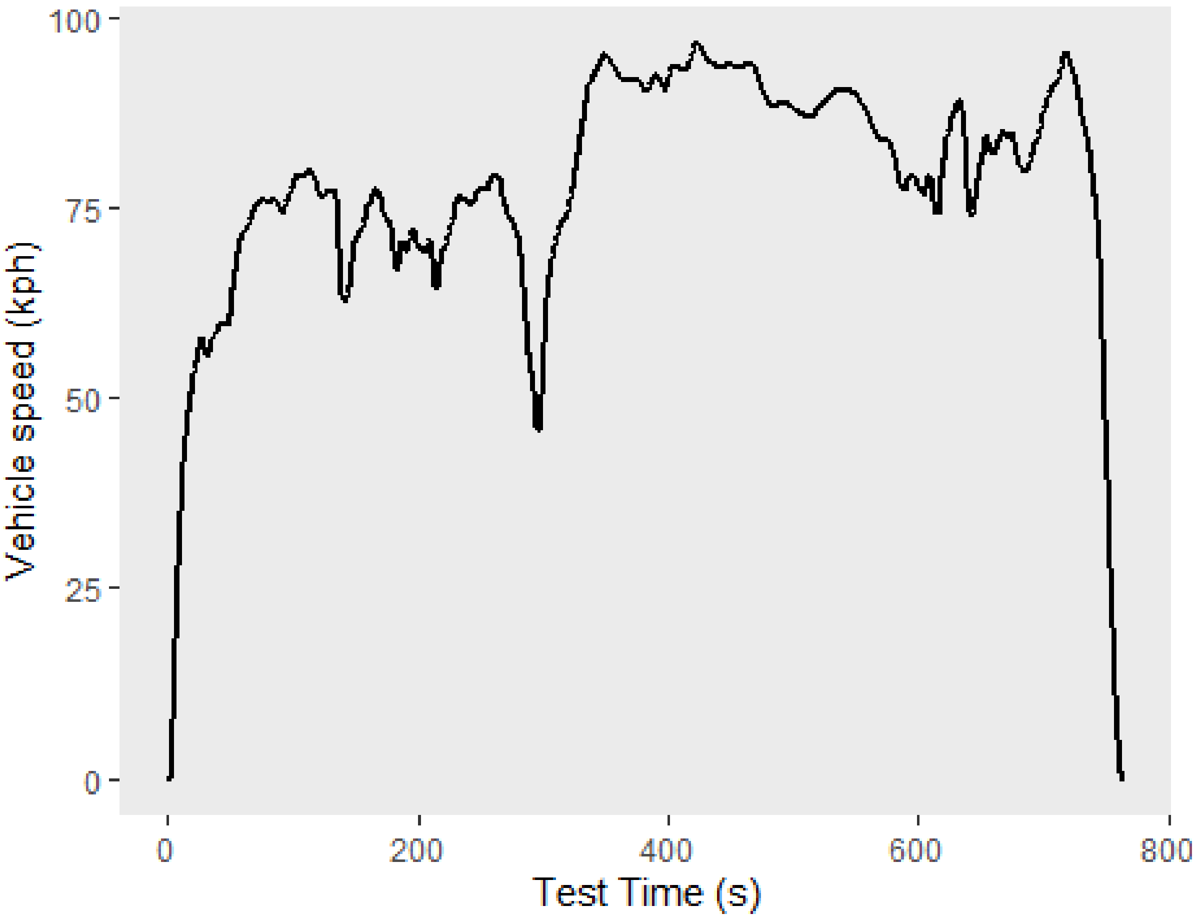

Figure 3.3: HWFET Test Cycle, adapted from EPA (2021).

3.2.7 The data-set

Selecting all passenger vehicle data for a given year would be time-consuming and impractical. As such, vehicle sales for the period were considered as a guide to select models that could best represent the actual fleet. Therefore, the best selling vehicles which represented at least 50% of total sales for each year were selected. As will be discussed in more detail; subsequently, the Brazilian fleet's characteristic is that only a few models (sometimes two or three) were responsible for about half of the total sales a year. This model was usually a (sub)compact, hatchback, 1.0-liter vehicle, by far the best-selling in Brazil. In recent years the market diversified, and more vehicles were selected, accordingly. There are 1857 entries in the data-set. Some vehicles differ only in trim level, hence 1244 different models are considered. As the vehicles may not change from one model-year to another, there are 710 unique vehicles in the data-set. When no data for a specific vehicle were found, a similar vehicle was used as a representative. For example, a sedan's drag coefficient was assigned to a similar compact car for which no drag coefficient is available, as sometimes these vehicles are part of the same family and therefore share design characteristics.

3.3 Evolution of key vehicle parameters

From Equations 3.15, 3.16, and 3.14 and subsequent discussion, exergy efficiency is a function of some key vehicle parameters, namely the weight (m_v), frontal area (A), drag coefficient (C_d), and fuel economy (C_c). These are the key variables in this study and the evolution for each will be discussed below. Even though not used for the calculations, the evolution of some other vehicle parameters, such as acceleration, top speed and horse power, were traced as well, in 3.3.5. These parameters may help explaining the results and discussions.

3.3.1 Aerodynamic Drag

Aerodynamic drag, represented by the green line in Fig. 3.4 below, is the product of the frontal area A (red line) and the drag coefficient C_d (blue line). At first this value decreased as drag coefficient reductions outpaced increases in frontal area. Around the year 2000 drag coefficient stagnated while frontal area continued to increase, thus drag force increased as well. Minimum, mean, and maximum values for the frontal area were 1.77 m^2, 2.06 m^2, and 2.61 m^2; for the drag coefficient 0.28, 0.35, and 0.5; for the aerodynamic drag 0.57, 0.72, and 0.96, respectively.

Two factors could explain this behavior. First, historically best-selling vehicles, such as the Volkswagen Gol [4], Fiat Palio, and Fiat Uno, increased their frontal areas from 1.84 m^2 to 2.08 m^2, 1.98 m^2 to 2.18 m^2, and 1.9 m^2 to 2.18 m^2, respectively. Since 2015, the best-selling vehicles in Brazil have been the Chevrolet Onix and Hyundai HB20, which have frontal areas of 2.15 m^2 and 2.10 m^2, respectively. Another factor is that, while still dominated by subcompact vehicles, the market in Brazil is undergoing a diversification, featuring sedans such as the Toyota Corolla (2.23 m^2), SUVs such as the Jeep Renegade and Compass (both with 2.55 m^2), and compact pickup trucks such as the Fiat Strada (2.18 m^2) and Toro (2.53 m^2). Other parameters such as comfort, security, and stability may explain why this trend was observed; however, the understanding of why it is happening is out of the scope of this discussion.

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[4] Unless noted, vehicles are produced in Brazil. VW Gol is a entry-level subcompact car for the Latin America market, not to be confused with the VW Golf

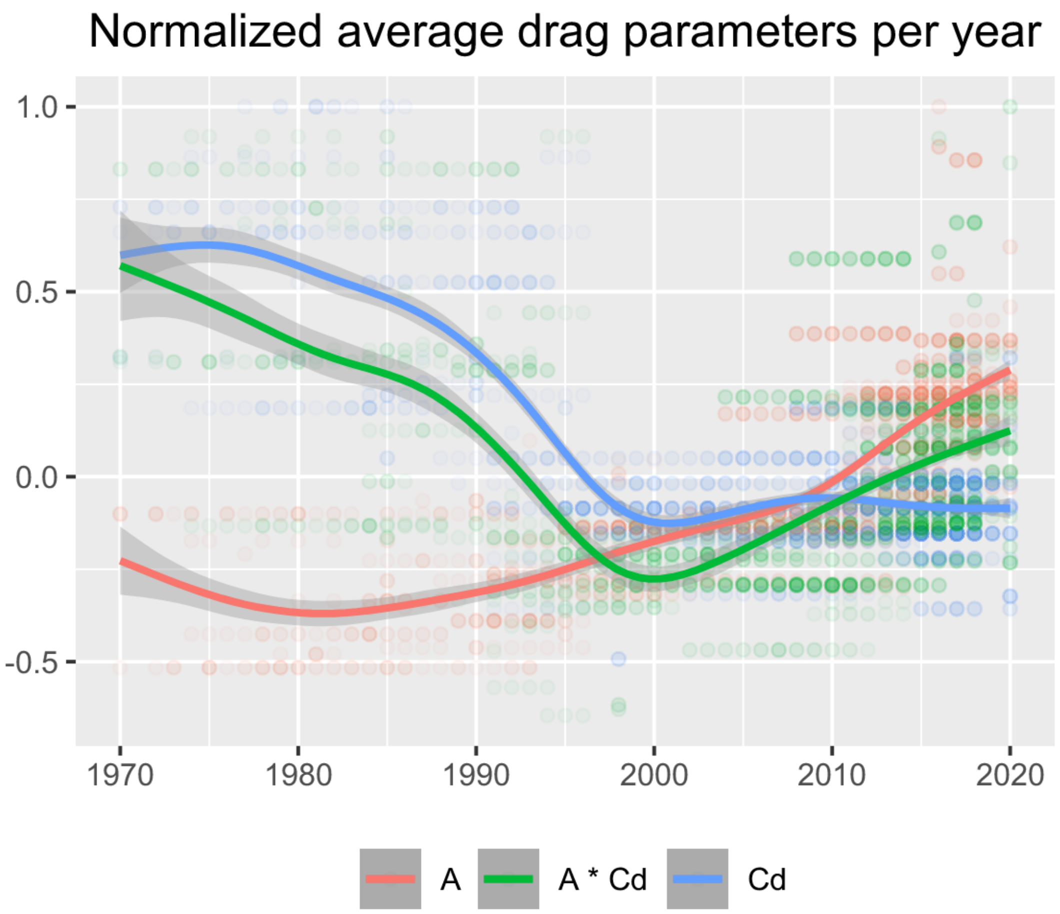

Figure 3.4: Normalized average drag parameters and weight for the Brazilian fleet, 1970–2020. Adapted from (CARROSNAWEB, 2020).

3.3.2 Weight

Average vehicle weight trends are shown in Fig. 3.5. The minimum, mean, and maximum values were 758 kg, 1033 kg, and 1871 kg, respectively. Values were almost constant from 1970 to 2010, when an upward trend started. This may be explained because the increase in weight model-by-model was not as prominent as observed in the frontal area. The Volkswagen Gol increased its average weight from 900 kg in the 1980s to 966 kg in the 2010s. The Fiat Uno and Palio also increased from 859 kg to 943 kg and 943 kg to 1021 kg, respectively. Here market diversification and the entrance of larger and heavier vehicles into the best-selling lists might be a reason. The 2018 Toyota Corolla weighs 1315 kg, the 2016 Jeep Renegade weighs as much as 1440 kg, and the 2018 Jeep Compass and Fiat Toro weigh 1704 kg, for example.

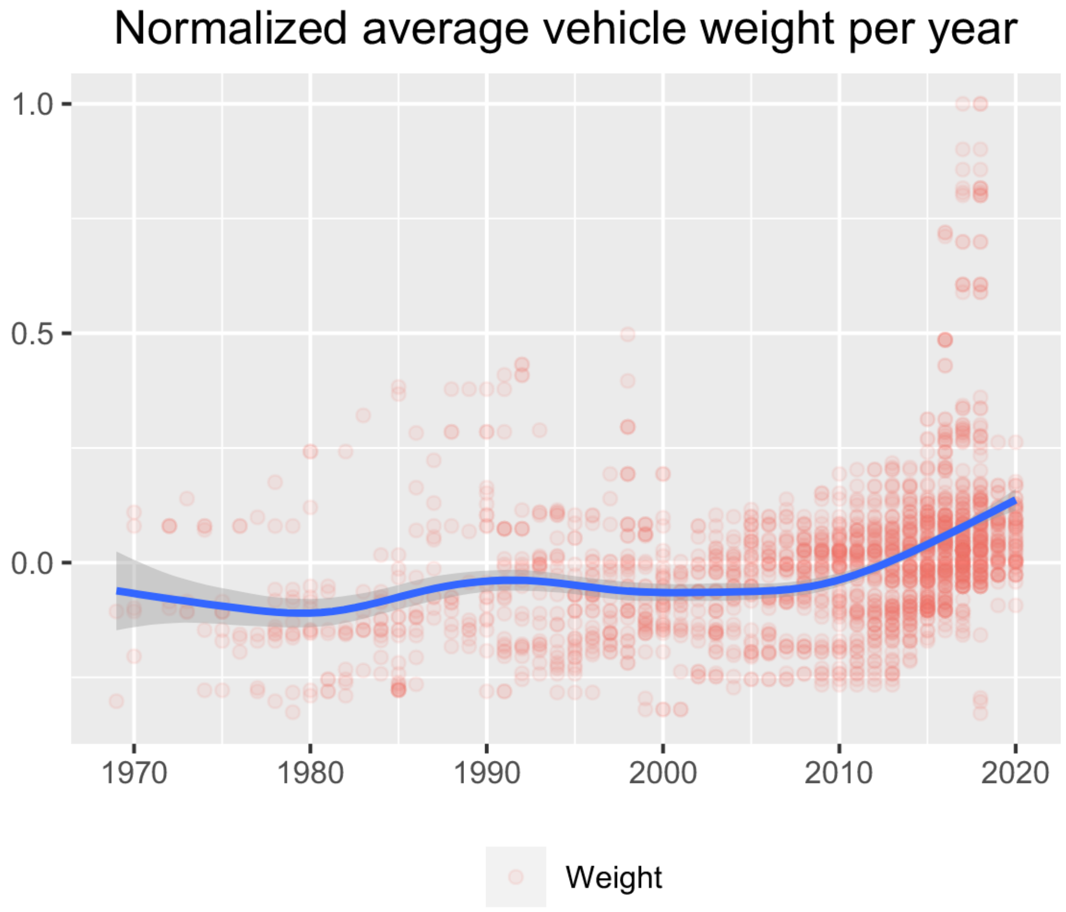

Figure 3.5: Normalized average drag parameters and frontal area for the Brazilian fleet, 1970–2020. Adapted from (CARROSNAWEB, 2020).

3.3.3 Fuel Economy

Brazilian vehicles ran only on gasoline in the 1970s. By the end of the decade, as a response to the oil shocks, the Brazilian military government created a program to develop ethanol as an alternative fuel. Therefore, in the 1980s, vehicles capable of using this renewable fuel appeared in the market. As oil prices fell by the 1990s, ethanol was effectively discarded as an alternative, until the advent of flex-fuel vehicles in 2003. As for the differences between fuels, it was found that ethanol exergy efficiencies were 38.27% and 34.48% for compression rates of 12:1 and 8:1, respectively, while a gasoline engine with a compression rate of 8:1 was 33.32% (GALLO; MILANEZ, 1992; RAKOPOULOS; GIAKOUMIS, 2006). Ayres (AYRES; AYRES; WARR, 2003) states, contrary to popular belief, that engine thermal efficiency has not significantly improved since the 1970s.

A flex-fuel engine can run either on ethanol, gasoline, or a mixture of both, and the consumer is free to choose at the fuel station. From a strict efficiency perspective, such an engine is optimized for neither gasoline nor ethanol. Thus, fuel economy is slightly lower than that of an engine specifically designed for one of these fuels alone. Almost all vehicles sold in Brazil are now flex-fuel, with a market share rapidly reaching above 90% (ANFAVEA, 2020).

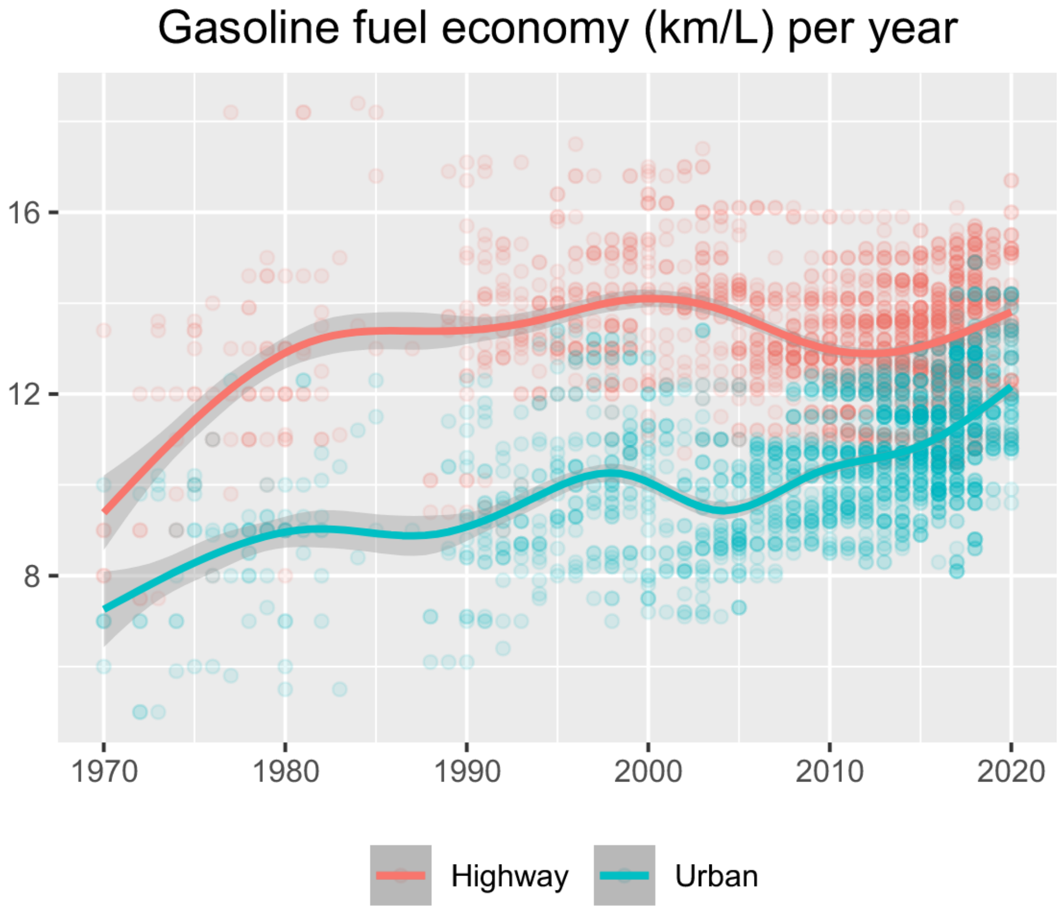

Figure 3.6: Gasoline fuel economy, 1970–2020. Adapted from (CARROSNAWEB, 2020).

Gasoline

Gasoline in Brazil is blended with anhydrous ethanol to reduce emissions. This added volume of anhydrous ethanol is 27% v/v by the time this chapter was prepared, and it steadily rose throughout the years. For simplification purposes, it was considered to be constant at %22 v/v.

Fig.3.6 illustrate a significant improvement in gasoline fuel economy for the considered period, rising by almost 80% for urban and 50% for highway travel. The effect of the introduction of flex-fuel vehicles can be observed by the temporary drop in fuel economy around mid-2000s, which was expected for reasons discussed in Section 3.3.3 above. Since then, values started to rise again. Fuel economy of flex-fuel vehicles was split into gasoline and ethanol and displayed along with the values of dedicated gasoline and ethanol vehicles.

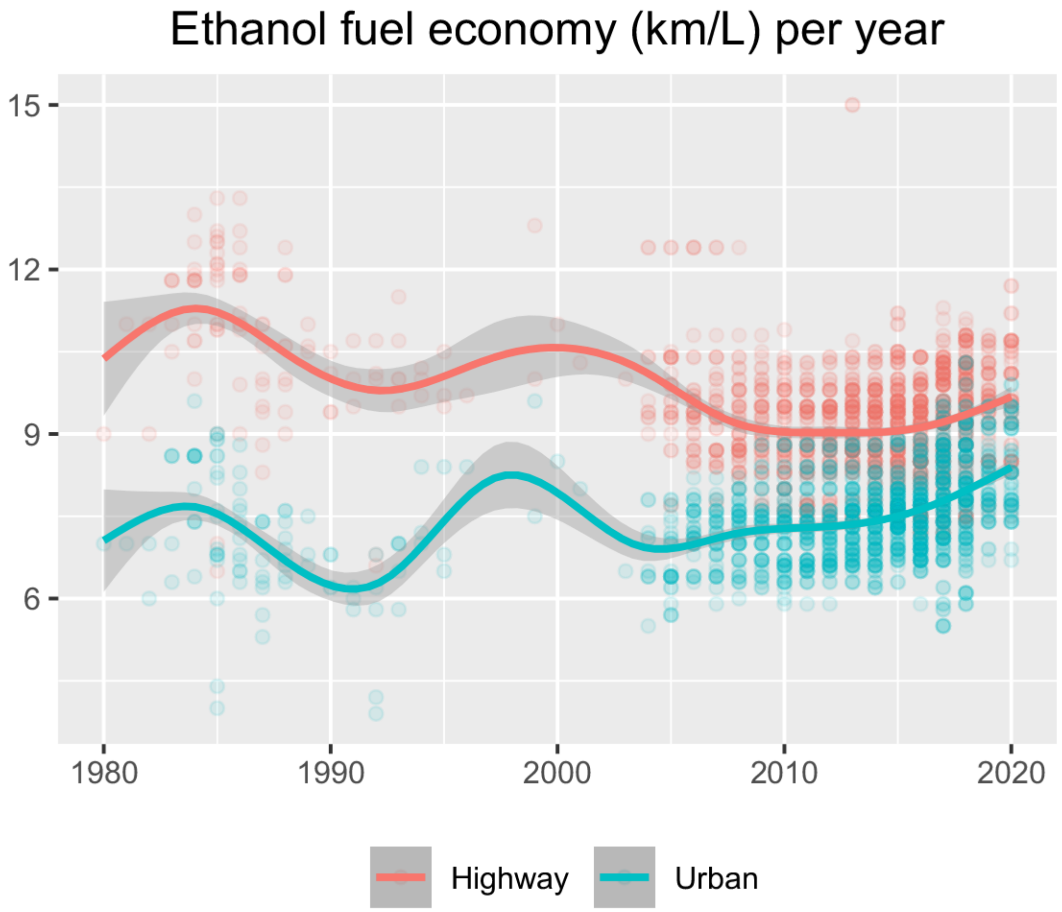

Figure 3.7: Ethanol fuel economy, 1970–2020. Adapted from (CARROSNAWEB, 2020).

Ethanol

For ethanol Fig. 3.7 illustrates a more complicated behavior. Fuel economy improved very little for urban travel and actually decreased for highway. While it is not the purpose, at this stage of research, to determine the reasons, some explanations may be attempted. By being a novel technology, and by being discarded rapidly over a decade, maybe there was not enough time to properly develop and optimize ethanol engines. By the advent of flex-fuel vehicles, this fuel economy was penalized because the engine could not be optimized for ethanol to the detriment of gasoline performance, with a middle ground being necessary. Whatever the reasons may be, the recent trend is that fuel economy is increasing steadily.

3.3.4 Rolling Coefficient

To properly estimate the rolling coefficient for any given vehicle on the road is a very difficult task. To trace its evolution even harder. Technology, road surface, inflation pressure, size, wheel maintenance and alignment, wear, temperature, all influence the coefficient. What can be said with certainty is that, on average, tire rolling coefficient was reduced in the period (BOARD, 2006). The range of values found in this comprehensive study, which compiles results from the Environmental Protection Agency (EPA), a private consulting firm, tire manufactures and the Rubber Manufacturers Association (RMA) is from 0.007 to 0.014, even though values below 0.008 and above 0.013 were unusual.

The simplifying assumption was to consider the rolling coefficient to be 0.0130 for the 1970s and to decrease by 0.001 for each passing decade, reaching 0.008 in the 2010s. This value does not consider drive-train resistance, which could add about 0.002 to the coefficient (KÜHLWEIN, 2016).

3.3.5 Other Performance indicators

While key performance parameters such as horsepower, top speed, and acceleration (measured as the time the vehicle require to go from 0 to 100 km/h) are not used to calculate exergy efficiencies, it is of interest to study their evolution because there might be some explanatory power in these values. Values are summarized in Table 3.3. Up to the mid-1990s, the evolution may seem complicated and erratic, with fluctuations in all parameters except for the top speed. Since then, there is a clear tendency for vehicles to be faster and more powerful.

Table 3.3: Other performance indicators

Parameter	Minimum	Mean	Maximum
Acceleration (s)	6.1	12.8	45.0
Displacement (cc)	994	1433	4093
Top Speed (km/h)	105	170	225
Torque (N.m)	7.1	13.5	35.7
Horse Power	35.8	93.4	220.0

Figure 3.8 illustrates the evolution of the acceleration, top speed, horsepower, displacement, and torque, normalized to produce a more generalized view fleet during 1970–2020. It is interesting to see that top speed increased over time, and acceleration had some decrease in this period. These facts will be better explained over the text since, bearing in mind, the efficiency is inverse proportional to these performance gains.

3.4 Results

3.4.1 Exergy efficiencies

Exergy efficiencies from 1970 to 2020 were low, never reaching 9%. There is a downward trend until 2010, then a reversion. Gasoline exergy efficiencies were in the range from 3.4% to 6.9% and ethanol exergy efficiencies from 4.0% to 8.3%. Figure 3.9 illustrates the results.

Exergy efficiency as defined in Eq. 3.4 is the ratio between the transportation service provided and the fuel exergy consumed in the process[5]. Fuel exergy is inversely proportional to fuel economy, as in Eq 3.16. Gasoline fuel economy increased in the period, as in Fig 3.6. For Ethanol, as Fig. 3.7 illustrates, values are roughly constant.

Transportation service[6] is a function of vehicle parameters and travel characteristics. Rolling and drag coefficients were reduced in the period, while weight and frontal area increased, as shown in Figs 3.4 and 3.5. Thus, until 2010 it can be said that ethanol fuel exergy was somewhat constant, while the service required fell. As such, efficiency falls. For gasoline, service required and fuel exergy both fell. The proportions of these reductions dictate if efficiency increased or decreased, as the line fluctuates. From about 2010 transportation service increased, while fuel

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[5] It is important to emphasize that exergy efficiency is not only a function of fuel economy but vehicle and travel characteristics as well, as defined by Eqs. 3.15 and 3.16. This ratio can remain constant if both increase or decrease by the same proportion. If the same quantity of fuel exergy now provides more service, efficiency increases.

[6] Dedicated ethanol and gasoline vehicles differ only in engine, thus the transportation service can be considered the same for both

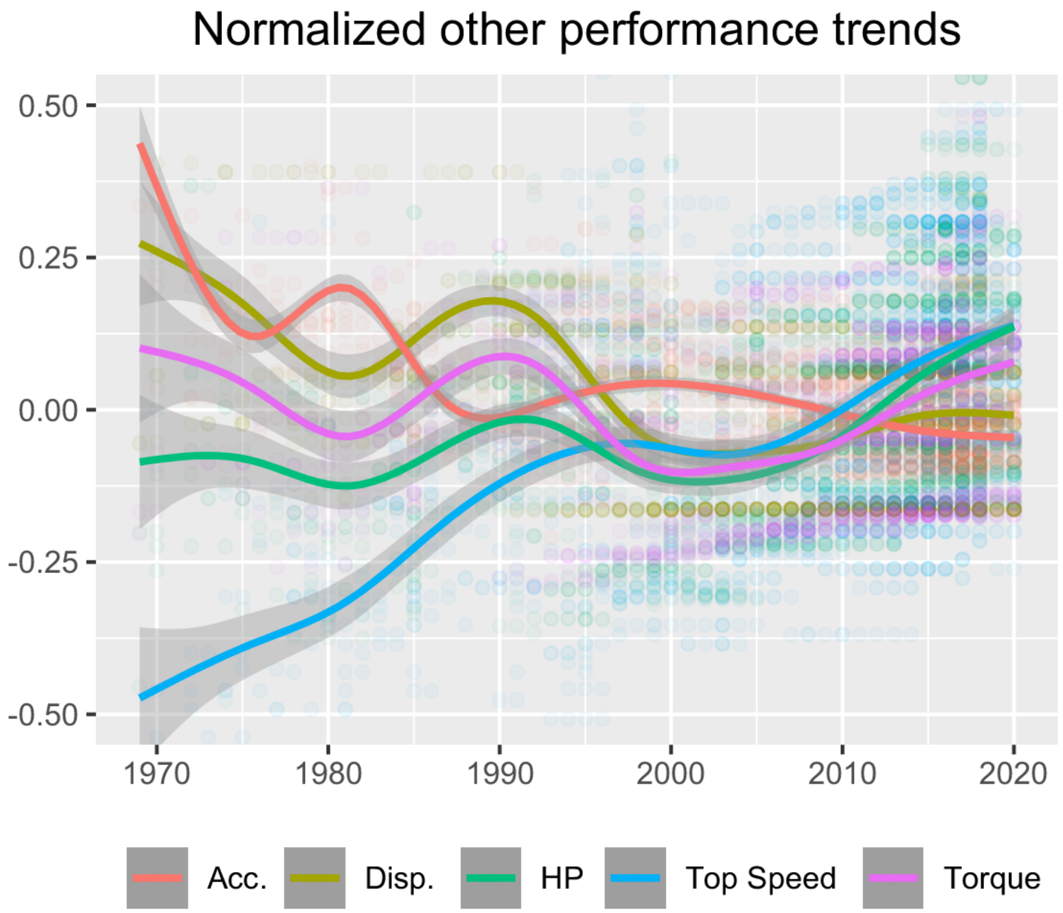

Figure 3.8: Normalized other performance trends of the Brazilian fleet during 1970–2020. Adapted from (CARROSNAWEB, 2020).

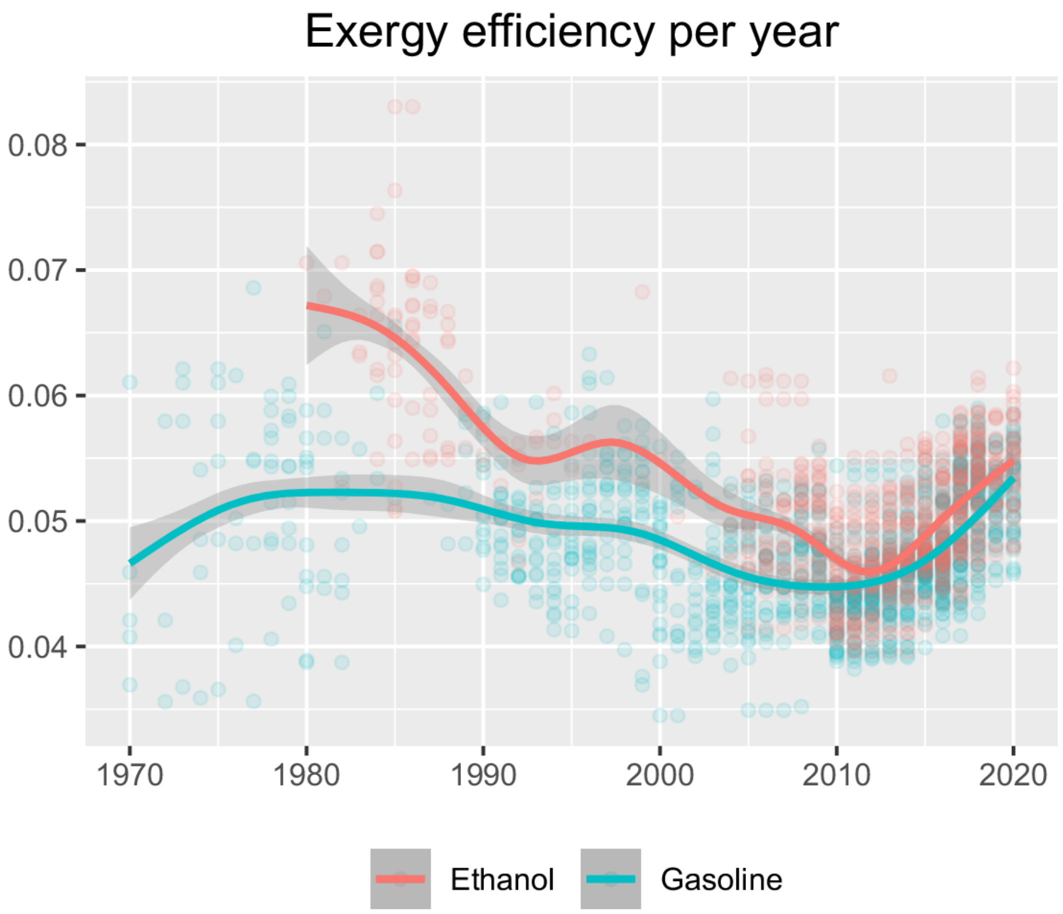

Figure 3.9: Ethanol and Gasoline exergy efficiency of the Brazilian fleet during 1970–2020.

exergy decreased, thus efficiencies show an upward trend.

3.4.2 Sensitivity Analysis

There is an inevitable uncertainty when calculating efficiencies, as some parameters may vary. Fuel economy in real-world driving may not be the same as that in a test, vehicle weight may change due to occupation or cargo, average velocity and distance travelled are from a standardized test as well. As such, a sensitivity analysis was made in order to analyse potential variation in the results obtained. Calculations were made for the 2020 flex-fuel Fiat Uno Drive 1.0, which shares many of the most common features in the Brazilian fleet, and has average efficiencies.

The National Institute of Metrology, Quality and Technology (INMETRO) defines correction formulas for urban and highway fuel economies, as in Eqs. 3.17 and 3.18. These corrections reduces fuel economy by 17–20%. Other parameters were varied more freely, as no such

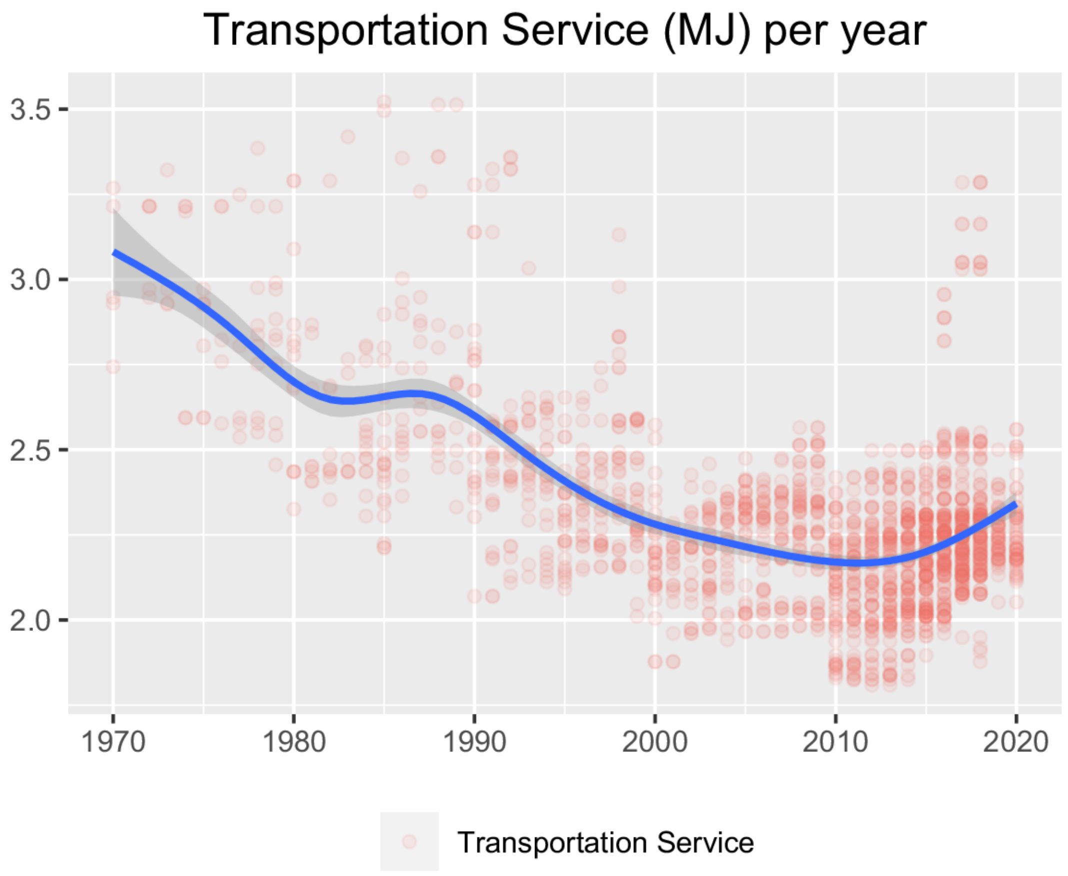

Figure 3.10: Transportation Service per year

corrector exists. Average velocity and total distance were multiplied by 1.2 and 0.8, drag coefficient by 1.1 and 0.9. Rolling resistance was increased from 0.008 to 0.009 and 0.010. Finally, a 80kg person was added to total weight. Table 3.4 below summarize the values.

Naturally, all else equal, if a vehicle is considered to be travelling with higher average velocity or larger distances than baseline values, efficiency would be greater. If baseline fuel economy was achieved against increased resistance (increased rolling and drag coefficients or total weight), efficiency would be greater as well. Individual parameter variation resulted in no more than 1% variation in either direction. Varying more than one parameter simultaneously would require a more complex analysis. It is expected that a reduction in the drag coefficient would reduce the drag force, and, all else equal, improve fuel economy. The interplay between changes in such parameters would fall outside the scope of this chapter but a brief discussion is made below.

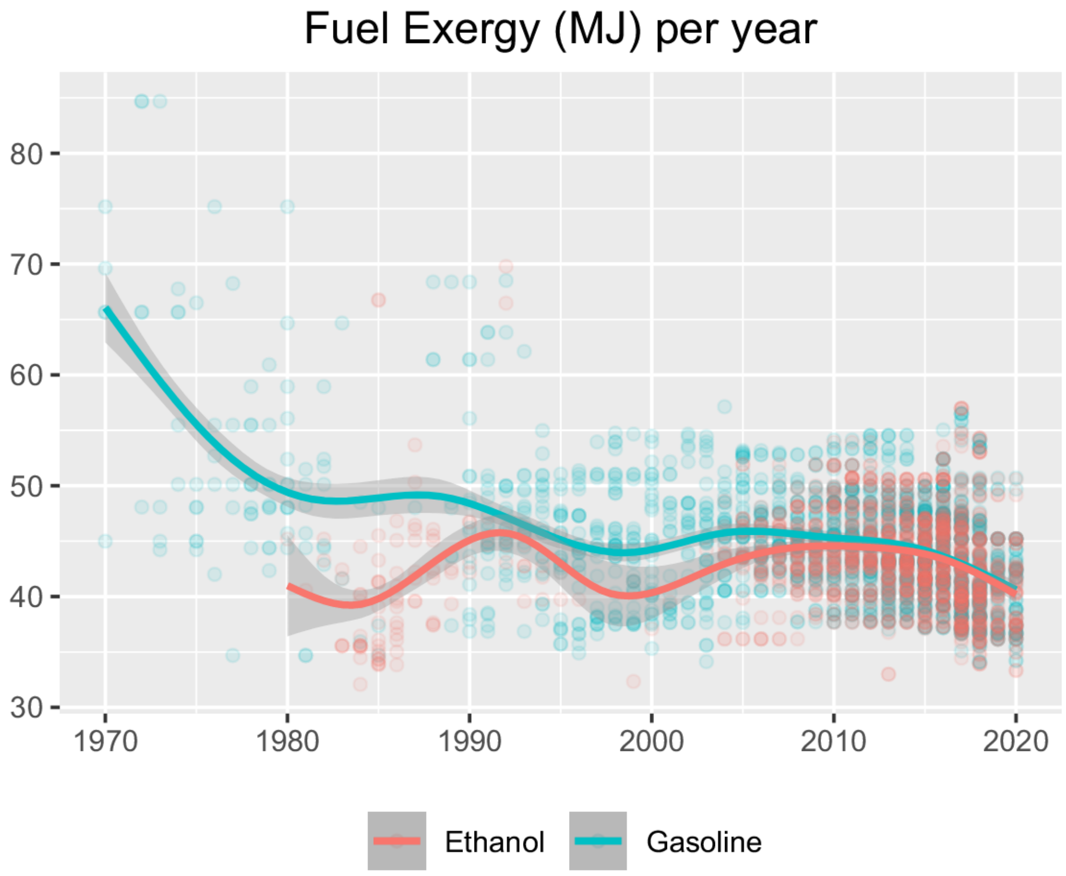

Figure 3.11: Fuel exergy per year

Table 3.4: Exergy efficiency sensitivity to parameter variation

Parameter	$\eta_{ex,g}$	$\eta_{ex,e}$
Baseline	5.4	5.7
C_{actual}	4.2	4.3
$1.2V_x$	6.2	6.5
$0.8.V_x$	4.8	5.0
$1.2\Delta X$	5.4	5.6
$0.8\Delta X$	5.5	5.7
m_v + 80 kg	5.7	6.0
C_r = 0.009	5.9	6.1
C_r = 0.010	6.3	6.6
$1.1C_d$	5.6	5.8
$0.9C_d$	5.3	5.5

3.5 Discussion

As discussed above in section 3.2, the main issue when comparing results is that there is no standardization of exergy efficiency definition. Table 3.5 shows a compilation of studies, their approaches and results for road transport. Reistad's and Wall's approaches are estimations from each author and were cited in subsequent studies. The term "Author" indicates that no work was cited as an origin for the efficiencies equation (probably the author defined a different efficiency). Thus it is considered each author's estimation. Ayre's approach was discussed above in section 3.2.3. Dewulf means following the definition of transportation service, as was carried in this chapter.

Naturally, results were consistent with (DEWULF; LANGENHOVE, 2003) and (FLÓREZ-ORREGO; SILVA; OLIVEIRA, 2015), from where the method was obtained. As well, it is close to the results from Wall's approach. Considering that engine exergy efficiency is in the range of 30–35%, a real-world efficiency of 22% is probably overestimated. If one considers that exergy is destroyed in many stages for power to be delivered at the wheels and that a vehicle is almost never in full load for the whole trip. The lowest estimation observed in the literature was the payload efficiency of 3% in (AYRES; AYRES; WARR, 2003). As no discussion was made for the differences in payload and conversion efficiencies, it is difficult to ascertain what exactly this means.

Even considering that a vehicle is a very complex machine, no standardization of exergy efficiency exists, and it is very difficult to account for variations in the trip (city center with traffic or no traffic, suburb, highway, individual driver behavior, among other many other factors). It is probably safe to assume, though, that a vehicle destroys about 90% of total exergy of fuel.

Table 3.5: Road transport exergy efficiency compilation.

Region	Period	η_{ex} (%)	Approach	Reference
USA	1970	25–15	Reistad	(1980)
Sweden	1975	10	Wall	(1986)
Jordan	2010	22	Author	(2013)
China	1978–2002	22	Reistad	(2006)
Norway	1995	13	Author[1]	(2000)
Greece	1980–2003	22	Reistad	(2008)
Canada	1986	22	Reistad	(1992)
Brazil	1987	10	Reistad	(1992)
Japan	1985	10	Wall	(1990)
Italy	1990	7	Wall	(1994)
Canada	1990–2023	22	Reistad	(2014)
Global and OECD	1990	11.0–10.9	Author	(1996)
UK	1970–2010	17	Various	(2009)
US	1950–1998	5.2–6.4	Ayres	(2003)
UK	2010–2050	11.2–22	Ayres	(2015)
–	–	7.2	Dewulf	(2003)
Brazil	2014	5.7, 8.7, 8.7	Dewulf	(2015)

1. Author's estimation, no work cited.

Precision is almost impossible to obtain and would miss the point of trying to provide a more generalized view of exergy use in the transportation sector.

Results show that efficiencies did not improve significantly over the period. Why is that so? Intuitively we know that in 50 years, technology has evolved. Vehicles today are less energy demanding, with a higher fuel economy than those of the past. Nevertheless, vehicles are also faster, wider, heavier, and more powerful. All of those features acting as "sinks" to some efficiency gains. Average acceleration was cut by almost 50% in this period, according to Figure 3.8. MacKenzie (MACKENZIE, 2013) stated that, apart from fuel economy improvements, the most massive "sink" for new efficiency technologies since 1975 was acceleration performance. Knittel (KNITTEL, 2011) estimates, for the United States market that, if horsepower, torque, and weight were held at 1980 values, a 2006 model would be 60% more fuel-efficient. Nevertheless, the actual value was only 15% higher. Cheah (CHEAH, 2010) found that, for the American market, every 10% reduction in vehicle mass reduced fuel consumption by about 7%.

Transportation service showed an upward tendency since 2010, after decades of decline. This may have potential implications in future energy demand. Fleet diversification may mean the relative share of subcompact 1.0-liter vehicles to fall in favor of larger, more powerful machines, such as SUV and sedans, which is something that is already seen in recent sales figures.

Ideally, society's requirement for transportation service, as defined here, would continue to decline, and fuel exergy expended to decline at an even steeper rate, thus improving exergy efficiency.

The recent trend of increasing transportation service and declining fuel exergy needed, which resulted in increased efficiency, is not ideal as well, as some technological gains were offset in favor of larger and more powerful vehicles. Policies must take into account these conflicting tendencies. On the one hand, it may be correct to assume the fuel economy to improve, as observed in figs. 3.6 and 3.6. On the other hand, the total *potential* of fuel economy gains may not be realized if Brazilians continue to expect cars to become faster and heavier, as seen in figs. 3.4, 3.5 and 3.8. This forecast is the subject of future research, once an appropriate account of past behavior is done.

3.6 Conclusions

Exergy efficiencies were low throughout the period, between 3.8% and 8.3%. For ethanol, a downward tendency occurred until approximately 2010. Since then, a clear tendency of improvement has been present; however, the overall improvement is less than 1%. Gasoline efficiencies fluctuate, before the same tendency was observed from about 2010.

To calculate exergy efficiencies, actual vehicle parameters were required. By considering a period of 50 years, the evolution of these parameters was traced. Cars became heavier, larger, faster, powerful, and aerodynamically improved, while fuel economy improved as well, even though these performance gains tend to require more energy. As well, the application of the concept of transportation service to derive an efficiency formula is valuable when dealing with resource use in society. It is useful to compare different technologies and provides more detail than found in the literature. Also, it can be replicated anywhere, thus allowing for more accurate comparisons.

Policies which aim to reduce the environmental impact of the transportation sector can benefit from a more detailed picture of the evolution the sector had so far. This chapter may help in that regard, specially towards evaluating the feasibility of technological advancements and where they are may be employed in a vehicle. As well, it was shown that there are conflicting tendencies regarding energy use, specially in recent years, when transportation service started to increase after decades of decline. The reason may be that Brazilians are starting to favor larger and more powerful vehicles and this has potential implications in future energy use.

Limitations of this research are the omission of diesel vehicles, responsible for about half of total energy consumption in the sector. Actual fleet characterization would improve when sales-weighted averages, scrap rates and average vehicle life are considered. Finally, the interplay between vehicle performance parameters, such as the effect of weight increases have on fuel economy, would help to quantify technological trade-offs, and this is the next step of this research.

Chapter 4

Performance and efficiency trade-offs in Brazilian passenger vehicle fleet

This Chapter, with minor alterations, was published as Mosquim, R.F. and Mady, C.E.K., 2022. Performance and Efficiency Trade-Offs in Brazilian Passenger Vehicle Fleet. Energies, 15(15), p.5416.

The rate of technological progress is an important metric used for predicting the energy consumption and greenhouse gas emissions of future light-duty fleets. A trade-off between efficiency and performance is essential due to its implications on fuel consumption and efficiency improvement. These values are not directly available in the Brazilian fleet. Hence this is the main knowledge gap to be overcome. Tendencies in all relevant parameters were also unknown, and we have traced them as well established on several publications data and models. We estimate the three indicators mentioned above for the Brazilian fleet from 1990 to 2020. Although the rate of technological progress was lower in Brazil than that in the developed countries, it has increased from 0.39% to 0.61% to 1.7% to 1.9% in the subsequent decades. Performance improvements offset approximately 31% to 39% of these efficiency gains. Moreover, the vehicle market is shifting toward larger vehicles, thus offsetting some efficiency improvements. We predict the fleet fuel efficiency for the years 2030 and 2035 using the above-mentioned factors. The predicted values for efficiency can vary by a factor of two. Thus, trade-off policies play a vital role in steering toward the desired goals of reducing the transportation sector's impact on the environment.

4.1 Introduction

The transportation sector is one of the primary energy consumers globally. The sector's share of total energy consumption represented 25% in 1990 and 33% in 2020 in Brazil. Fuel use increased by 83.3% between 2004 and 2018. Light-duty vehicles (LDVs), used for personal transportation, account for about half of the total energy consumed by the transportation sector; the remaining energy is consumed by heavy trucks, used for cargo transportation (EPE, 2020).

Due to technological advancements, a LDV has become faster, more powerful, larger, and heavier today. Furthermore, it is safer, causes less impact on the environment, and uses fuel more efficiently.

The first fundamental aspect considered in this study is to estimate the rate of technological improvement for the LDV fleet in Brazil for the period 1990–2020. The two main approaches to assess this are: (1) to estimate the extra amount of fuel that would have been consumed if not for these advancements (GREENE; SIMS; MURATORI, 2020), or (2) to assess technological evolution in a broader sense, meaning either better efficiency or more performance (KNITTEL, 2011; MACKENZIE, 2013). The key insight is that efficiency has to be traded-off for performance, thus theoretical technological gains are not always translated into more efficiency. If these trade-offs are not adequately considered, projections can be overly optimistic.

It should be noted that in this study, FE represents the number of kilometers that can be traveled by consuming one liter of fuel (km/L). This unity system is analogous to the miles per gallon (MPG) unit system used in the United States (10 km/L is equal to 23.52 MPG). In Europe, fuel efficiency is considered as the relationship between fuel consumed and distance traveled; i.e., liters per 100 km. The relationship between both metrics is not linear but curvilinear, and this may cause misconceptions regarding fuel savings (LARRICK; SOLL, 2008). In this study, improved FE and efficiency are used interchangeably, and both terms indicate an increase in km/L.

The second aspect considered in this study is the dynamic nature of the LDV market. Consumer preferences may shift toward heavier and more powerful vehicle categories, thereby offsetting some or all of the efficiency improvements that might have occurred in individual models. Recently, compact SUVs have gained market share at the expense of the traditional Brazilian vehicle categories, the subcompact and compact models. Such transformation is equivalent, in a lesser extent, to the light-truck reaching half of total sales in the USA, from a few percent in the 1970s.

These factors have not been thoroughly studied for the transportation sector of Brazil, and future scenarios are usually predicted using the data from a limited set of years (there is not sufficient government data in Brazil for these predictions as in the USA). From a study conducted by Mosquim and Mady (2021), the following key insights into the technological developments between 1990 and 2020 were obtained. First, the rate of technological progress during this period and the changes in these rates between decades were observed. Second, the consequences of significant consumer preference shift were identified. These findings could help policymakers to improve projections.

The final aspect considered in this study is the hybridization of LDVs. Electricity is a prospective fuel for LDVs. Hybrid-electric and electric vehicles are developed with various degrees of hybridization and by full electrification, respectively. As the market share of hybrid LDVs in Brazil is still low, accounting for 2% of total sales in 2021, internal combustion engines (ICEs) are expected to power a vast majority of vehicles in the near future (KALGHATGI, 2018). In Brazil, the discussion about the transition of the vehicle fleet toward electrification is not straightforward (FALCO; SACILOTTO; CAVALIERO, 2021) as there are numerous factors involved in the development of this technology. First, researchers agree that owing to the Brazilian reality of biofuels, the transition across regions may differ; thus, it must respect the regionalities and accommodate accordingly to avoid a higher carbon transportation system (MALAQUIAS et al., 2019). Second, the fuel production from second-generation biomass, i.e., from a different source of biomass (NOGUEIRA et al., 2021). Third, CO_2 emissions during vehicle transportation for battery recycling (VARGAS et al., 2020) and (TOMANIK; POLICARPO; ROVAI, 2022). There exist certain questions including whether any guarantee can be provided such that the biorefinery production occurs with minimum or negative carbon production (FERRARI et al., 2021). Each country has its own characteristics, a case by case study may be conducted in order to achieve a more sustainable transportation sector and with correct transition (HE et al., 2019; TOMANIK; POLICARPO; ROVAI, 2022).

Thus, the objectives are to study the FE of Brazil's LDV fleet and the factors that affect it. First, we applied regression analysis to estimate the rate of technological improvements during the 1990 to 2020 period. Next, we assessed the impact of certain vehicle features, such as weight and power, and certain engine and power-train technologies have on FE. Furthermore, we evaluated the trade-offs between performance and efficiency and market evolution. Finally, we simulated a few scenarios for predicting the average fleet FE in 2030 and 2035 using the study findings.

The remainder of this study is structured as follows. A literature review is provided in Section 4.2 to discuss previous works and to identify the research gap and course of action. The methods are detailed in Section 4.3. A brief discussion on the Brazilian LDV market and the evolution of key LDV parameters are provided in Section 4.4. The regression analysis results and discussion are provided in Section 4.5.The possible future pathways for key variables that affect fleet FE are discussed in Section 4.6, and the possible future fleet-wide FE is presented in Section 4.7. Finally, the main conclusions, policy implications, and opportunities for future research are presented in Section 4.8.

4.2 Literature review

A question researchers frequently ask in the field of transportation is *"by how much can technology reduce fuel consumption compared to a baseline scenario?"*. Green et al. (2020) estimated two trillion gallons of gasoline for the USA from 1975 to 2018, which is approximately the total US LDV energy consumption from 2004 to 2018, or the total GHG emissions for the USA from 2016 to 2018. However, one caveat that the authors acknowledge as not realistic, taken only for illustrative purposes, is that the FE would remain at the 1975 levels. This kind of study can be categorised as ”things could have been worse”, and credit technological progress for not allowing that to happen.

An opposite approach acknowledges this technological progress, but tries to estimate by how much could efficiency be improved if performance were held to some baseline level. Knittel (2011) found that MPG could have been improved by 60% in the period 1980-2006 in the US, if performance were held at 1980 levels. Actual improvements were in the order of 15%, thus the majority of technological gains were spent in better performance and not efficiency. The quantification of this trade-off is useful in illustrating the choices made regarding where this technological budget was spent. This line of reasoning could be described as ”things could have been better”.

Chea et al. (2008) identified three main technological options to achieve factor-of-two reductions in fuel consumption in the USA by 2035 (from 2007). They are: i) to focus future technological developments in reducing fuel consumption, maintaining performance fixed; ii) market penetration of alternative power trains, such as diesel, turbocharged gasoline, and hybrids; iii) weight and size reductions. Their findings suggest that only a combination of these three pathways can achieve the stated goal and that it would take "striking changes from the status quo". For example, estimated values for 2020 would be approximately 32 MPG, whereas the actual values were 25.4 MPG, which is still record-high (EPA, 2022).

We revised a few works on the LDV fleet in Brazil, identified certain critical assumptions made and compared them with actual developments. Certain simplifications are inevitable, particularly when trying to quantify the total GHG emissions, which are dependent on several variables (including the number of cars with better efficiency) and presented in Section 4.7.1. By decomposing the more significant problem and delving deeper into a few key variables, this study can improve future models. Here, the assumptions about the rates of efficiency improvements and market-share by vehicle classes are given particular interest, both of which impact the fleet FE, and thus, affects the fuel consumption.

Schmitt et al. (2011) used numerical simulation to estimate fuel efficiency of future vehicles. Their approach was to represent the fleet by some vehicle categories, 26 in total, and evaluate the total fuel consumption in two scenarios by comparing it to the baseline. By using some modifications in the technological factor to improve the FE, the following values can be achieved: approximately 9% to 17% of FE reductions represent a decline in GHG emissions by 9% to 20%, and 0.9 to 1.8 million hectares of land spared for other uses. Assumptions for achieving these numbers were: subcompact and compact vehicles would represent approximately 60% of the fleet in 2030, compared to 45% in 2007. Incremental efficiency gains would be 15%. Drag and rolling coefficients would be reduced by 15% and 20%. Moreover, there would be a weight reduction by 10% or 20% in each category. Estimated travel per vehicle would remain constant. As was reported in (MOSQUIM; MADY, 2021), although the drag coefficient reduces slightly over time, the frontal area continues increasing as vehicles get bigger. Also, the sales of subcompact and compact declined steadily from 75% in 2000 to 35% in 2020. In addition, a 1.0 liter model year (MY) in 2020 is significantly different from one in 2000 because of improvements in technology and engine downsizing, as engineers can extract more performance today for the same level of engine power than in the past (MACKENZIE, 2013).

Other researchers, including Benvenutti et al. (2019, 2017), estimated the future GHG emissions by considering four main strategies for mitigating carbon footprint: improving energy efficiency, a modal shift towards public transport, a renovation of the fleet (older vehicles have higher emission factors), and increased use of biofuels. Each main strategy had more than one assumption related to its degree of application. Thus, the efficiency scenario was divided into three pathways with variable improvement rates. The more conservative among them was a 2.2% and 2.0% improvement in efficiency per year until 2030 and 2050, respectively. The second had a 3.14% and 2.2%, whereas the third had a 3.8% and 2.0% improvement in efficiency, respectively. According to that study, even the most conservative rate of improvement was higher than the historical rate of 1.6%.

From the point of view of policymakers, De Melo et al. (2018) argued about the necessity of mandatory fuel economy standards (MFES), in line with the practices established in the United States, European Union, Japan, China, South Korea, Canada, and Mexico. An extensive discussion about those standards are available in (SMITH, 2010); for an abridged version in English, refer to (BASTIN; SZKLO; ROSA, 2010), which focuses on the Brazilian history.

Their method (MELO; JANNUZZI; SANTANA, 2018) was to estimate the improvements in efficiency exceeding baseline by the implementation of MFES. The average fuel efficiency for compact and subcompact vehicles were approximately 1.85 MJ/km and 1.66 MJ/km, respectively, in 2017[1]. The combined market share for these two classes was 65% and remained constant until 2035, the final year of the projections. Their results showed an improvement of 1% to 2%. The MFES was modeled as step-wise improvements by increasing the efficiency by 10% every four years. The results showed potential and avoided emissions of 62 Gg of CO_2 compared to baseline. In reality, the average values for subcompact (19 models) and compact (78 models) in 2020, according to (INMETRO, 2022), were 1.49 MJ/km and 1.67 MJ/km, which are close to the projected values. Nevertheless, the importance of the article is its reduction perspective. Unfortunately, the market shares of both classes were reducing and reached 35% in 2020.

Wills and La Rovere (2010) simulated three scenarios from 2000 to 2030, with yearly efficiency improvements of 0.25% (baseline), 1.12% (adjusted), and 2.38% (optimistic). Each scenario denoted 14.2% to 30.7% of energy consumption decrease in 2030. Emissions in 2019 were estimated to be in the range of (35–40) Mton CO_2, which was approximately 50% below what was actually observed in Brazil in 2019 (SEEG, 2022). Moreover, the avoided CO_2 emissions in 2030 for each scenario were predicted to be 1.3 to 2.6 what was emitted in 2019.

Modelling future energy consumption and GHG emissions can be very tricky. De Andrade

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[1] MJ/km is obtained by dividing the heating value of fuel in MJ/L by the fuel economy in km/l.

Junior et al. (2019) employed a highly detailed partial equilibrium model to estimate ethanol demand for the year 2030, along with sugarcane planted area required to meet such a demand for fuel. Variables used were gross domestic product (GDP), population growth, fuel blend directives, fuel prices, fleet composition, and efficiency gains. Ethanol demand could be 13% to 114% higher in 2030 than in 2018. Moreover, there are numerous known and unknown variables, which affect FE. One of the highest uncertainties is related to future fuel efficiency assumptions, by using 2013 data as a baseline. A BAU scenario implied yearly improvements of 1.0%, a renewable fuel-oriented 1.53%, and a fossil fuel-oriented 0%.

De Salvo Jr. et al. (2019, 2021) made extensive analyses of engine technology impacts on energy efficiency first for a single year, 2017, and subsequently, compared the evolution over the years 2013, 2015, and 2017. Based on the official labeling program (INMETRO, 2022), which has published FE for selected LDVs since 2009, they found that the overall efficiency improved by 3.5% from 2013 to 2017. The same observation can be obtained by dividing vehicle categories. Both papers further offer a review of engine technologies, quantify their impacts on efficiency, and trace their diffusion. The analysis focused on the models available in the market in that year; thus, those studies were not concerned with possible sales-weighted effects, such as consumers shifting preference toward a larger class of vehicles over time. However, even if efficiency improves on a class-by-class basis, this sales shift can impact overall efficiency, and Brazilians are showing a tendency to buy larger vehicles, which is discussed in Section 4.4.4.

4.2.1 Estimating technological progress and trade-offs

The United States' Environmental Protection Agency (EPA) publishes vehicle data, as well as sales-weighted averages, going back to 1975. An efficiency metric, ton.mpg, is published as well. Because this metric fails to account for performance improvements and mass efficiency due to lightweight materials, studies based on this data-set tried to establish these efficiency and performance trade-offs (LUTSEY; SPERLING, 2005; AN; DECICCO, 2007). The main vehicle features which offset efficiency gains from the use of energy saving technologies are more performance, which can be modelled as either more torque, horsepower or faster acceleration, which tend to be highly correlated, and more weight, due to increases in size, on-board features and/or more safety[2]. Lutsey and Sperling (2005) considered that ton.mpg was insuffi-

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[2] Mackenzie estimates that features added 223 kg to a vehicle in 2010. Among these, 28% are related to safety, 11% for emission control, and 61% for comfort and convenience (MACKENZIE, 2013).

cient as it does not account for improvements in drag and rolling coefficient or the deployment of drive-train efficiency technologies. They defined engine and drive-train efficiency to vehicle characteristics, such as mass, acceleration, drag coefficient, frontal area, and tire rolling resistance. Combined with FE data, they estimated the elasticities for the variables mentioned via regression analysis. Thus, it was subsequently possible to estimate trade-offs between efficiency, performance, and size. The FE for cars and light trucks could be 12% higher in 2004 compared with that in 1987 if all technological improvements were directed toward more efficiency. Actual values were 2% higher for LDVs and 3% lower for light trucks.

An and DeCicco (2007) identified the same problem with ton.mpg as Lutsey and Sperling did, while using different vehicle attributes for analysis. Consequently, they developed a performance index that could capture trade-offs between size, performance and FE. Equation 4.1 presents the performance-size-FE index (PSFI) for light-duty vehicles. The term HP is the horse-power, LB is the weight in (lb), MPG is the engine consumption in miles per gallons and FT^3 is the interior volume in cubic feet.

$$PSFI = P.S.F = \frac{HP}{LB}.FT^3.MPG \tag{4.1}$$

Their results (AN; DECICCO, 2007) indicate that PSFI increased linearly from 1977 to 2005. Another inference was that no FE gains were realized in the period by keeping size and performance fixed, and a warn was made for prospective studies to consider this important fact. Figures 4.1 and 4.2 illustrates these tendencies for the Brazilian market. As with ton.mpg, these metrics will help dissect what happened to the LDV market in Brazil, although the method was not employed here. The PSFI for Brazil behaved better than ton.mpg. Apart from a slight dip in the beginning of the 1990s, the values increased constantly. Performance (P, in blue) reached a peak between 1993 and 1994, declined to a bottom in 1999, and then improved constantly. Herein, size (S, in purple) was measured, length x height x width, instead of interior volume, which decreased in the 1990s before increasing steadily. The FE (F, in red) decreased in this period, discussed in detail in Section 4.4, as the Brazilian market changed significantly.

Bandivadekar (2008) further expanded on the rationale behind PSFI proposing the *Emphasis on Reducing Fuel Consumption* (ERFC) according to Eq. 4.2. This simple concept allows the illustration of the magnitude of these trade-offs. A generic gasoline ICE 2035 model with 0% ERFC would see an increase in its power-to-weight ratio (HP/WT, in horsepower and lbs) from 0.059 to 0.087 (47.5%), with time to accelerate from 0 to 100 km/h reduced from 8.7 to 6.4

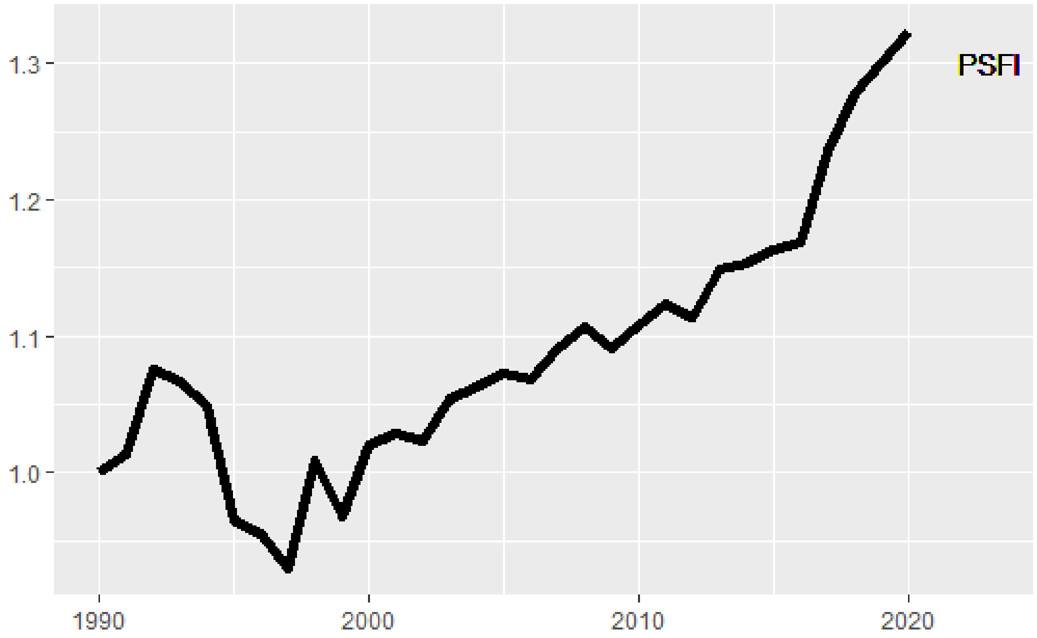

Figure 4.1: An and DeCicco's PSFI for Brazil, 1990 to 2020, adapted from (AN; DECICCO, 2007)

seconds while maintaining fuel consumption at 8.1 L/100 km. In contrast, if the power-to-weigh ratio and acceleration remained at 2008 levels (i.e., a 100% ERFC) FE would reach 5.5 L/100 km, a 47.3% reduction. From a GHG emissions perspective, a 35% reduction from a No Change scenario would be possible by 2035. However, "all current trends run counter to the required changes". Note that ERFC does not need to stop at 100% as performance could reduce below baseline grades, thus reaching even more significant improvements in the FE.

$$ERFC = \frac{FC_{current} - FC_{realized}}{FC_{current} - FC_{potential}} \tag{4.2}$$

According to Mackenzie (2013) there are two drawbacks to An and DeCicco's approach. First, acceleration, and not power-to-weight ratio, should be the preferred performance measure. Second, and most importantly, their approach assumes a 1:1:1 trade-off between size, power-to-weight ratio, and FE with no theoretical reason.

Knittel (2011), which is extensively cited in this study, estimated that when all other parameters are equal, a 10% reduction in weight produced a 4.19% increase in FE. and a 10% increase in horsepower decreased FE by 2.62%. Thus, the 1:1:1 trade-off does not occur. Torque effects were not statistically significant. The econometric model used to reach these numbers is discussed in detail in Section 4.3. Another important conclusion was found: average FE could

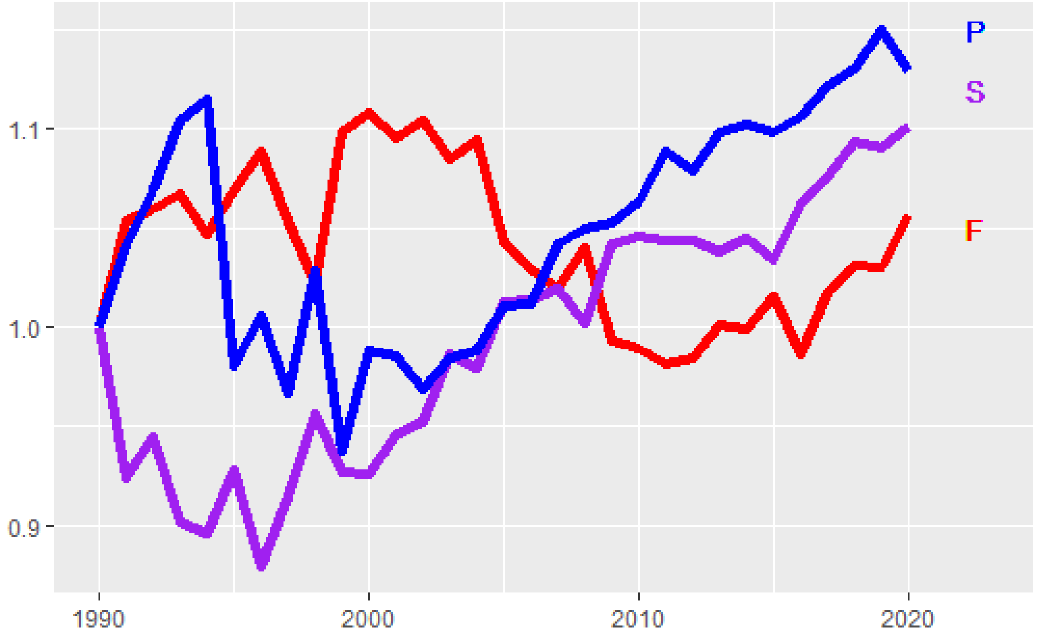

Figure 4.2: P, S and F for Brazil, 1990 to 2020, adapted from (AN; DECICCO, 2007)

have increased by approximately 60% in the period 1980–2006 if vehicle attributes, such as weight, horsepower, and torque, were maintained at the 1980 levels. Actual realized improvements were 15%. This fact may raise questions about incentives to consumption trends, such as for house-hold appliances (MADY; PINTO; PEREIRA, 2020). Some of these are: what kind of vehicles are suitable for urban, highway, and other different applications? In which policies may the exergy analysis contribute to the better end-use of exergy, considering technological gains and security parameters?

Mackenzie (2013) followed this approach and modeled fuel consumption in gallons per mile (GPM) as a function of inertia weight (IWT) in kg, acceleration from 0 to 97 km/h (Z97), and other vehicle parameters. The authors used eight econometric models in their analyses and accounted for weight reductions that would have happened if not for changes in size, features, and functionality. This potential mass reduction was 650 kg, or 40% for the average vehicle from 1975 to 2009 (CHEAH, 2010). Additionally, they found that a 10% reduction in inertia weight resulted in a 6.9% decrease in fuel consumption for the same period. Furthermore, a 10% improvement in acceleration resulted in a 4.4% increase in fuel consumption without modifications in other variables. Moreover, it was estimated that per-mile fuel consumption could have been reduced by about 70% (3.4% per year) if not for improvements in acceleration, new features, and functionalities. The rate of technological progress was not uniform, averaging

5% and 2.1% per year during the periods 1975–1990 and 1990—2009, respectively.

Subsequently, an adapted version of Bandivadekar's ERFC was used to calculate values for the period 1975–2009. The evolution follows a "V-shaped" curve, with ERFC exceeding 100% from 1975 to 1980 (when performance was reduced to increase efficiency), *minus* 25% in 1995–2000 (when performance improvements outpaced technological capability, thus efficiency was reduced), before rebounding to 75% in 2005–2009 (a value between 0 and 1 implies both performance and efficiency improved simultaneously, but at compromised levels).

Hu and Chen (2016) applied Knittel and Mackenzie's method for the European market from 1975 to 2015. They found that the rates of technological progress were slightly lower than those in the USA. However, the most interesting finding was that engine size, weight and power were actually reduced by 20%, 5%, and 2% respectively, from 2006 to 2015. Although torque and acceleration performance increased by 11% and 7%, respectively, these developments, combined with increased penetration of diesel vehicles, increased FE by 32% in the period. This shift was also observed in the Swedish market, where 33% of technological development was used for improved FE in 1975–2007 and 77% in 2007–2010 (SPREI; KARLSSON, 2013). Kwon (2006) controlled the engine size for the Great Britain market from 1979 to 2000. FE improved by 0.9% per year but could have been 1.1% if not for the increased average engine capacity. Furthermore, performance offsetting better technological gains was observed in the Dutch market from 1990 to 1997 because of higher engine capacity and more weight (BRINK; WEE, 2001). J. Wu et al. (2021) applied Knittel's approach to the Chinese market from 2010 to 2019 and differentiated between indigenous, joint-venture, and foreign vehicle manufacturers. They found rates of yearly technological progress between 3.1% and 3.9%.

Drawbacks of this econometric approach are that it assumes constant elasticities and trade-offs for the entire period studied, which usually spans a few decades.This may not necessarily be the case, according to Moskalik (2020). By modeling individual engines, Moskalik found a general trend toward lower elasticity values for the trade-off between acceleration and fuel economy over time. This is because modern engines have broader efficiency islands. Another drawback is that this approach relies on FE from standardized tests, which could differ significantly from real-world conditions. Craglia and Cullen (2019) used real-world FE data and further divided regression analysis on the basis of powertrain, petrol, diesel, and hybrid engines in Britain from 2001 to 2018. They found different elasticities for different powertrains by justifying the division. Additionally, they found that 60% of potential efficiency gains were offset by increasing size and power.

4.3 Methods

Knittel (2011) empirically estimated the efficiency trade-offs and technological progress of the United States vehicle market by considering FE (mpg) as a function of attributes, such as weight (wt), horsepower (hp), torque (tq), and a vector of other vehicle characteristics **X** related to FE, for vehicle *i* in year *t*. A multiplicative term referred to as technological progress *T*, also called "year fixed effects", and an average zero error term, ϵ, is expressed in equation 4.3.

$$mpg_{it} = T_t f(wt_{it}, hp_{it}, tq_{it}, \mathbf{X}_{it}, \epsilon_{it}) \tag{4.3}$$

To apply the linear regression analysis, natural logarithm is applied to both sides of (4.3), which results in

$$\ln mpg_{it} = T_t + \beta_1 \times \ln wt_{it} + \beta_2 \times \ln hp_{it} + \beta_3 \times \ln tq_{it} + \mathbf{X'}_{it} \times \mathbf{B} + \epsilon_{it} \tag{4.4}$$

Mackenzie (2013) followed this approach. However, the fuel consumption was modeled in gallons per mile (gpm) as a function of inertia weight (IWT) in kg, acceleration (from 0 km/h to 97 km/h) (Z97) in seconds, interior volume (VOL) in m^3, a vector of other vehicle characteristics **X**, and the mean zero error term ϵ, according to (4.5).

$$\ln gpm_{it} = T_t + \beta_1 \times \ln IWT_{it} + \beta_2 \times \ln Z97_{it} + \beta_3 \times \ln VOL_{it} + \mathbf{X'}_{it} \times \mathbf{B} + \epsilon_{it} \tag{4.5}$$

4.3.1 Model Specifications

FE here was modeled as a function of vehicle weight and a term related to performance (either torque, horsepower or acceleration, in Models 1–3, respectively) and vector **X**, which includes dummy variables for powertrain, and gearbox. Applying the natural logarithm to Eq. 4.3 yields Eq. 4.6. If the objective is to estimate technological advancements, including these covariates related to technology, such as fuel injection or turbo-compressors, would result in underestimating the year-fixed effects as these features would absorb technological improvements. If the objective is to estimate the effects of each of these technologies on FE, they should be included in the models. The first approach was preferred in this study.

$$\ln kml_{it} = T_t + \beta_1 \times \ln wt_{it} + \beta_2 \times \ln performance_{it} + \mathbf{X'}_{it} \times \mathbf{B} + \epsilon_{it} \tag{4.6}$$

The discussion presented in Section 4.4.3 describes the trends relating horsepower, torque, and acceleration. They are highly correlated with engine displacement, the combined volume swept by all cylinders. Thus, three models, corresponding to each performance variable, were estimated.

4.4 Brazilian LDV market evolution

This section provides an overview of specific LDV parameters pertinent to the models used and to the sales-mix during the 1990—2020 period. Data visualization is performed before performing regression analysis, which helps understating trends and trade-offs.

4.4.1 Establishing data-set

For creating a data-set, some assumptions were made. There is no available data-set, such as the one provided by EPA for the USA, for Brazil. Since 2009, the Brazilian National Institute of Metrology Standardization and Industrial Quality (INMETRO) have been publishing FE[3] and certain vehicle parametric data, such as engine displacement and transmission, for the labelling program of Brazil. Manufactures can choose the model data that they want to publish, and there is generally an overlap between categories, which are based on size (SMITH, 2010). However, crucial data, such as vehicle weight, is not available. Thus, a data-set was established using values from the website (CARROSNAWEB, 2020). These values were checked for consistency and compared with the data obtained from specialized research magazines to the greatest extent.

Because the data-set was established without a reference, it was not possible to compile data from more than 10,000 vehicle models, which is generally the norm observed in existing studies. To best represent an actual fleet, the best-selling models, targeting approximately 75% to 80% of sales in that year, were selected. Thus, the established data-set reflects neither all models available in that particular year, nor are sales-weighted, but it is a compromise between both. Including low-selling, high-price models, inherently more technologically advanced, could bias the results upwards, inflating the rate of technological improvement, which

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[3] FE values in Brazil are regulated by two technical standards: ABNT NBR 6601 and 7024 for urban and highway cycles, respectively. They are based on cycles FTP-75 and HWFET provided by the EPA.

would not be reflected in the streets. Using sales as a guide may allow for the results to reflect shifts in market-share. Therefore, using actual sales values as a reference may enable the results to reflect the shifts in market share.

Generally, LDVs are not allowed to operate on diesel fuel. Therefore, the vehicles using diesel fuel, such as light trucks, were not considered in this study. The established data-set consists of 2615 vehicles from 1990 to 2020. Since 2003, flex-fuel vehicles, which can operate on either ethanol or gasoline[4] or a mixture of both, rapidly gained market share (approximately 90% of vehicle licensing). The FE values of ethanol in flex-fuel vehicles are not reported here because it would only double the amount of data presented. The average FE value for ethanol is 0.7 times that of gasoline owing to its lower heating value.

The R-environment and R-Studio (R Core Team, 2017) were used for data processing and analysis. Graphics were generated using ggplot2 package (WICKHAM, 2009). The technical details and steps to perform the regression in R were obtained using (HANCK et al., 2019).

4.4.2 Evolution of key parameters

Evolution of certain key parameters used in the regression analyses are illustrated here to understand their developments. As observed in Fig.4.3, FE undergoes three distinct phases. First, it improved from 1990 to 1998, then regressed slightly until 2004, and finally improved again.

Acceleration, horsepower, torque, and displacement were highly correlated, and therefore, their trajectories exhibit resemblance. Average torque and horsepower initially decreased until 2003, and subsequently increased. Consequently, acceleration time initially increased from 1990 to 2002. However, it is currently below its value in 1990. Average weight (Fig 4.4 exhibited a stable trend until 2003; however, it is currently exhibiting an upward trend. This loss of power throughout the 1990s may be related to the mandatory inclusion of catalytic converters in 1997, which was already introduced in 1992, or the entry-level, compact and low-powered popular gaining market share.

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[4] By government decree, gasoline in Brazil has anhydrous ethanol mixed in it, with values fluctuating between 18% and 27.5% in volume.

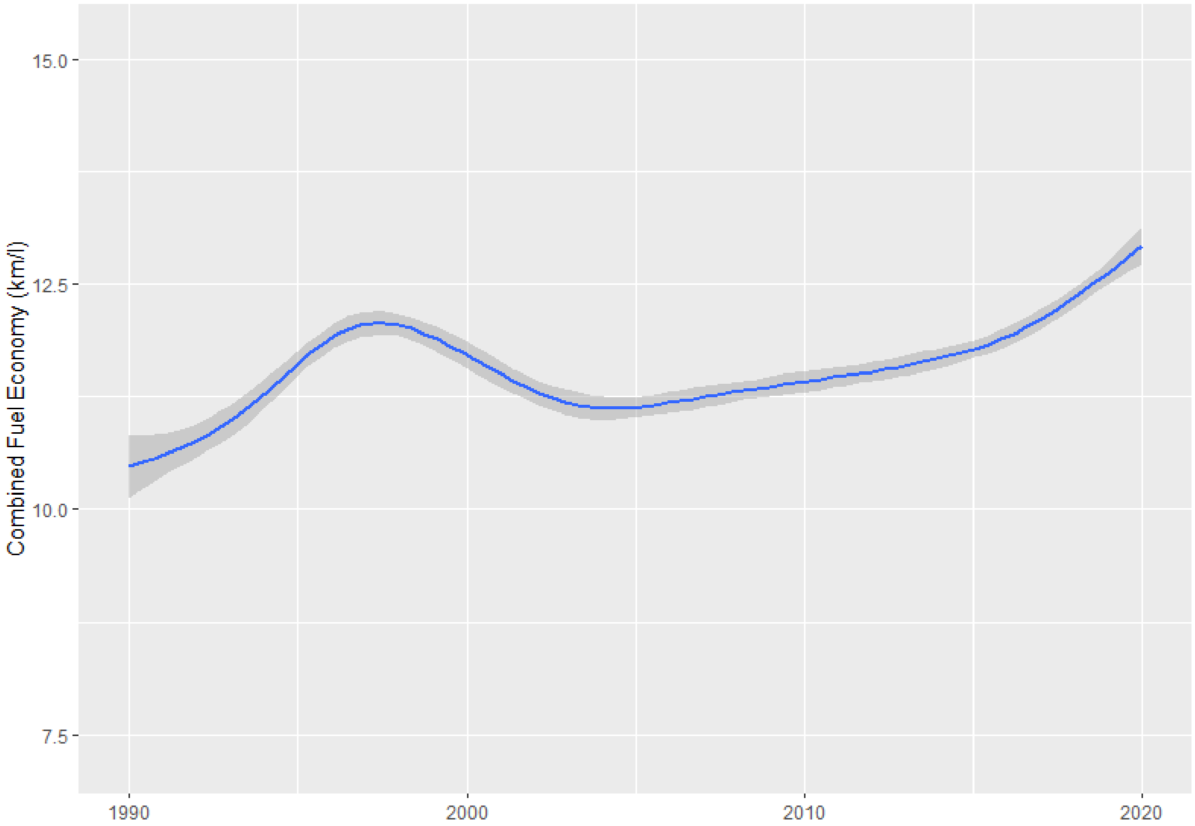

Figure 4.3: Combined FE in Brazilian transportation sector from 1990 to 2020 (horizontal axis)

4.4.3 Performance parameters and fuel economy

Both Knittel (2011) and Mackenzie (2013) used weight in regression analyses as one of the main explanatory variables influencing FE, and Fig. 4.5 illustrates the reason for using weight. By keeping other parameters constant, a heavier car consumes more fuel than a lighter car. Values represented in blue are for the year 1990 and those in black are for 2018[5]. A straight trend line was added for illustrative purposes. The trend line shifting up from 1990 to 2018 indicates that when all other parameters are equal, a vehicle with the same weight today has better FE owing to technological improvements.

Knittel (2011) employed both horsepower and torque as performance variables, whereas Mackenzie (2013) employed acceleration time, in seconds, required for a vehicle to reach a speed of 97 km/h from 0 km/h.

In addition, torque, horsepower, and acceleration were highly correlated with displacement, as shown in Figs. 4.6 and 4.7. A higher value of displacement indicates higher values of torque and horsepower, and a lower value of acceleration time. Knittel (2011) justified the

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[5] Although analyses were performed until 2020, the results from 2018 were used in the figures as there are slightly greater number of vehicles in the data-set of 2018.

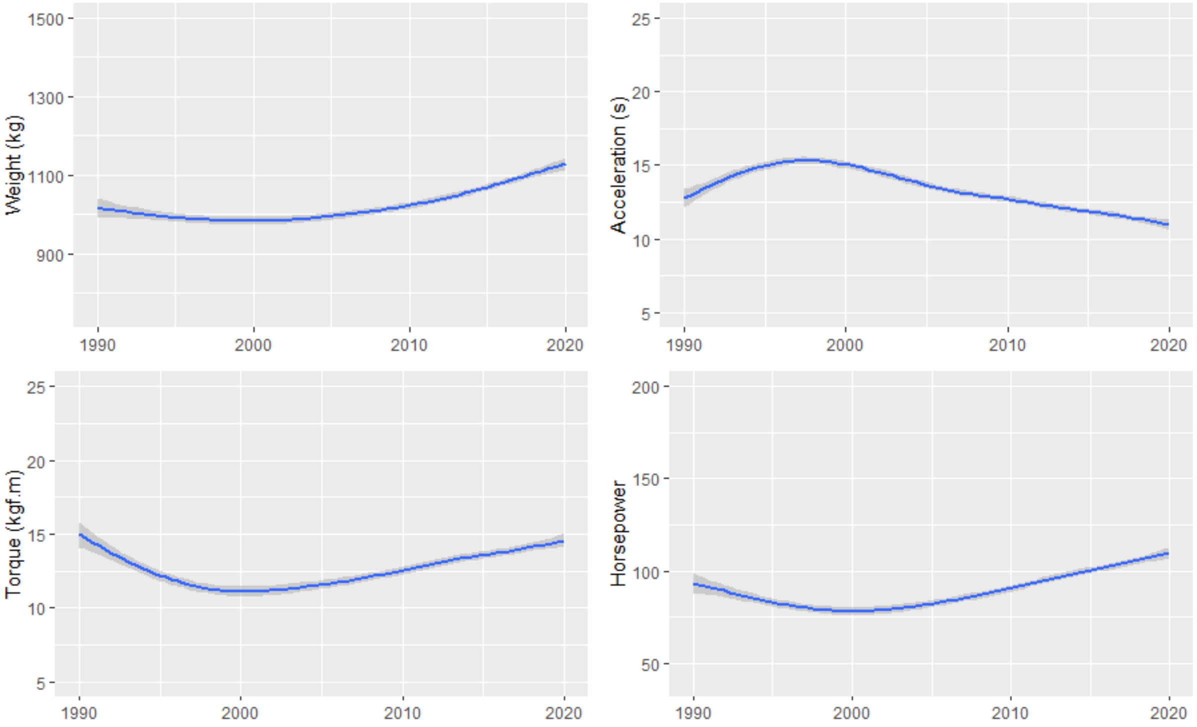

Figure 4.4: Evolution of key LDV parameters used in the regression models from 1990 to 2020 (horizontal axis)

inclusion of both horsepower and torque in the same model as the maximum values occur under different RPMs. For the data-set established and used in this study, models employing both of these variables resulted in estimators with opposing signals, which should not ideally happen. Therefore, they were considered separately.

Here, Fig. 4.8 illustrates that the above-mentioned parameters are highly correlated with fuel consumption. When all other parameters are equal, higher torque, higher horsepower, and lower acceleration time imply that the vehicle requires more energy. The blue and black lines represent the results in year 1990 and 2018, respectively. The curves exhibit an increasing trend from 1990 to 2018. This indicates the improvements in FE for the same performance. In the case of displacement, the lines are more ambiguous as specific power and torque per liter of cylinder displacement steadily increased in this period by 44% and 15.3%, respectively. This indicates that a 1.6 L engine in 2020 exhibits better performance than that of its 1990 counterpart. Although a typical 1.6 L engine in 1990–1992 generated approximately 77 HP and 13 kgfm of power and torque, respectively, these values increased to approximately 113 HP (+46.7%) and 15.8 kgfm (+21.5%), respectively, in 2018–2020[6].

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[6] There is no turbocharged 1.6 L engine in the data-set; otherwise, the average HP and torque would have been even higher.

Figure 4.5: FE vs. weight (1990 in blue and 2018 in black)

4.4.4 Relative sales categories

Vehicle registration increased from approximately 500,000 units to more than 3,000,000 units in 2013[7]. Furthermore, the market is diversifying; it is moving away from the subcompact, affordable vehicles and toward larger, heavier, and more powerful units (MOSQUIM; MADY, 2021). The appearance of the SUV, compact or large, is observed. One can compare this scenario with the scenario in the USA, wherein the advent of the light truck increased the market share from less than 2% in 1975 to 49% in 2009 (CHEAH, 2010). This had significant impacts on sales-weighted FE averages. Figure 4.9 illustrates this diversification and tendency toward larger vehicle categories. Subcompact and compact cars accounted for approximately 75% of total sales in 2004, and this ratio dropped to approximately 35% in 2020. Compact and large SUVs occupied a majority of this market share during this period. Although FE improved during this period in every category, it was slightly lower for the compact SUV model than for a compact vehicle, as listed in Table 4.3.

Since 2003, the LDVs sold in Brazil were capable of operating on gasoline, ethanol, or on a mixture of both. These flex-fuel vehicles (FFVs) enable higher flexibility in terms of fuel usage to the consumer. However, this flexibility comes at a cost as engines cannot be optimized

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[7] There is no sales model available for the years 1999 and 2000. The values for 1998 are for January–May only

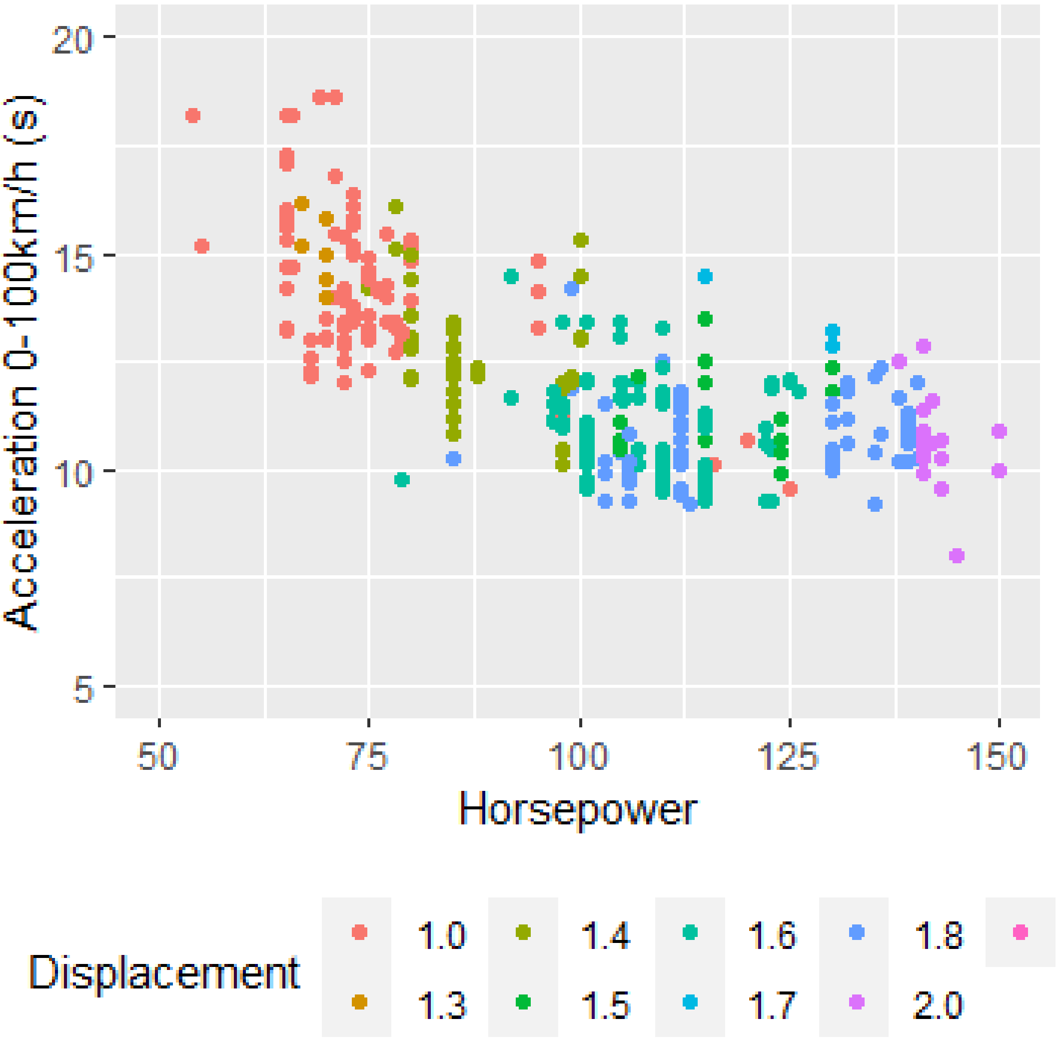

Figure 4.6: Acceleration vs. Horsepower

for either fuel, which typically requires different compression ratios; for example, 12:1 for ethanol and 8:1 for gasoline. As compression ratio is directly correlated to maximum theoretical efficiency (SERRENHO et al., 2014; MOSQUIM; MADY, 2021), the result exhibits a slight decrease in FE when compared to the dedicated-fuel engines. Regression models included this variable to capture its effect on FE.

As no official published data regarding the sales-weighted average FE for Brazil was available, these values were estimated by making some simplifications. First, the best sales models were selected, which represented approximately 75% of the total sales. Some models featured more than one engine; for example, featuring both 1.0 L and 1.6 L engines. However, the sales figures do not show such details. Thus, the FE values of all models that were available in the chosen year were averaged. In addition, only the values of highway FE were shown. On an

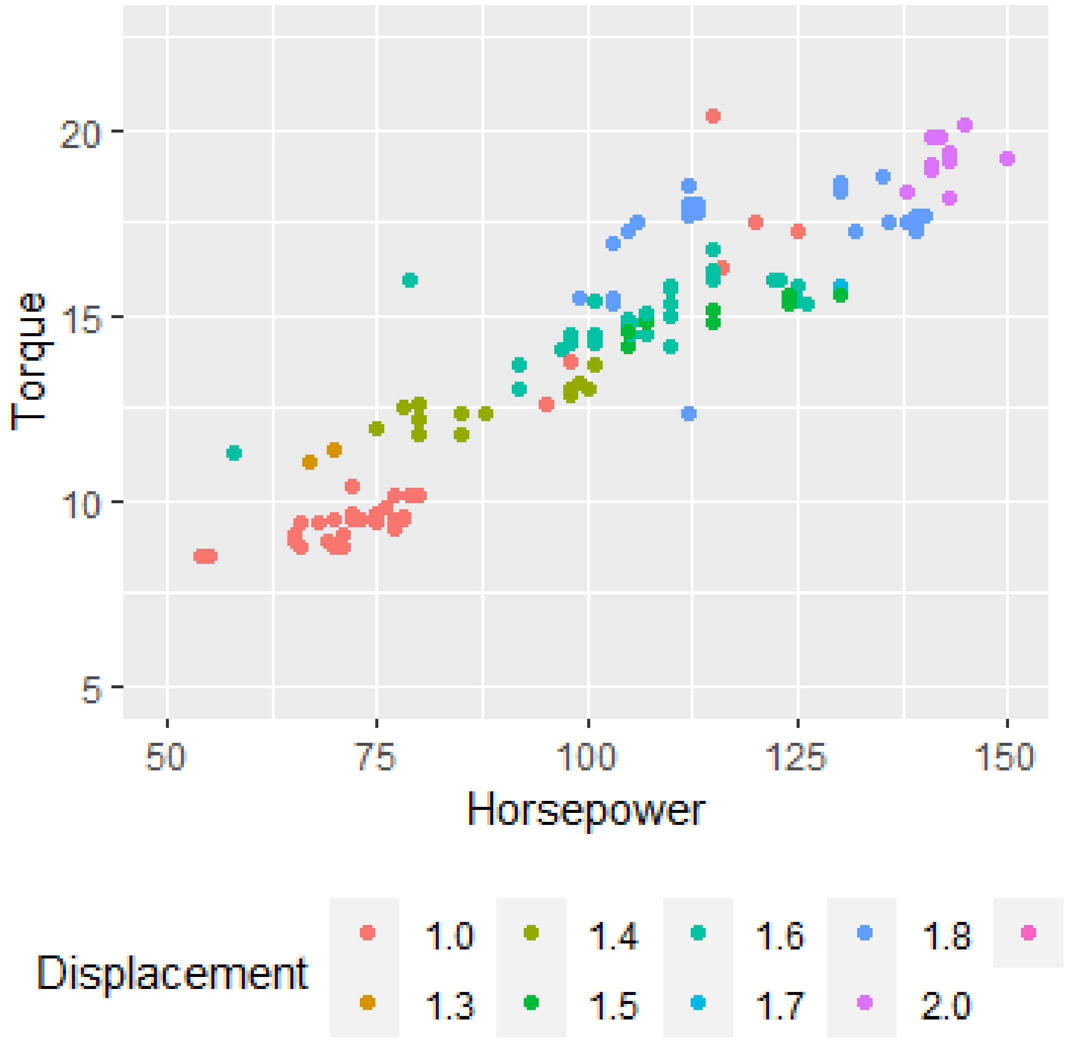

Figure 4.7: Torque vs. Horsepower

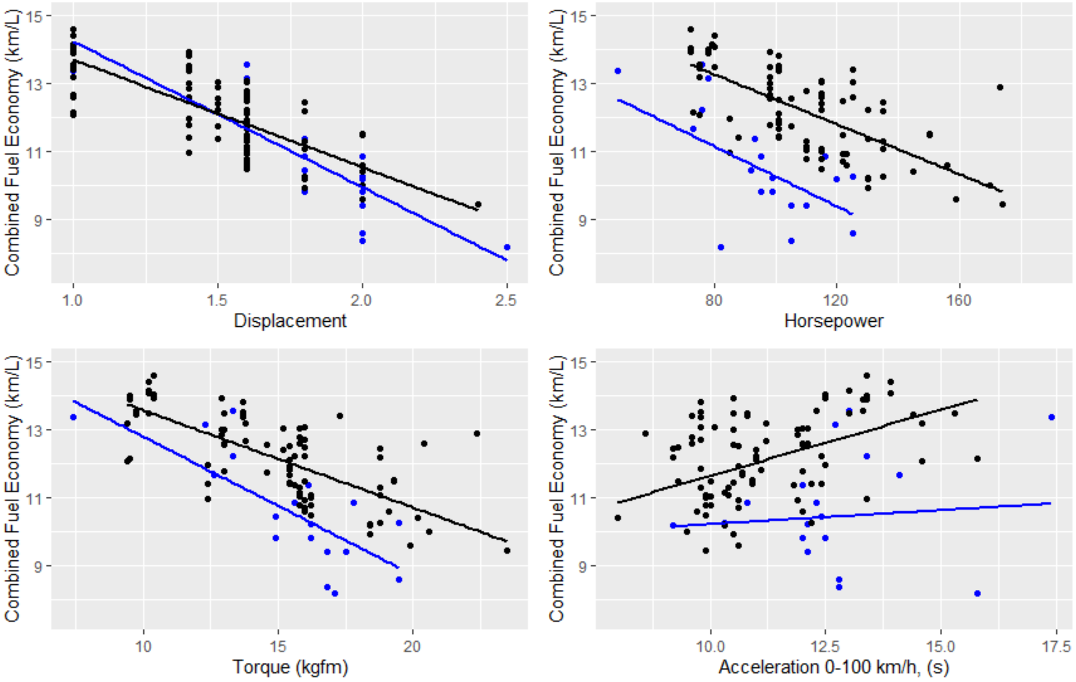

Figure 4.8: Performance parameters and FE (1990 in blue and 2018 in black)

average, the urban FE value was approximately 82% of the highway FE value. This implies that the average FE for an urban drive is 0.82 * 13.6 = 11.5 km/L and that for a combined 55/45 cycle is 12.0 km/L. Using the average FE values of every vehicle category from (INMETRO, 2022) along with the sales-mix data, the sales-weighted average FE for the combined cycle was obtained, which was 12.2 km/L.

4.5 Results and Discussion

4.5.1 Trade-offs

Results of the regression models are listed in Table 4.1, with standard errors provided within parenthesis. A 10% decrease in weight resulted in a 3.59–4.70% increase in FE, which is in good agreement with the previously reported results. The effects of performance generated a 0.97% decrease in FE for every 10% increase in torque, 0.59% decrease in horsepower, and 0.79% decrease in acceleration[8]. Effects for transmission causes a slight decrease in FE for automatic transmission (AT) vehicles than that for manual transmission (MT) vehicles. CVT and DCT provide FE benefits, but they are equipped in more expensive models, with more

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[8] Value is positive as the metric is the number of seconds required to reach 100 km/h from 0 km/h. Reducing this time requires more energy.

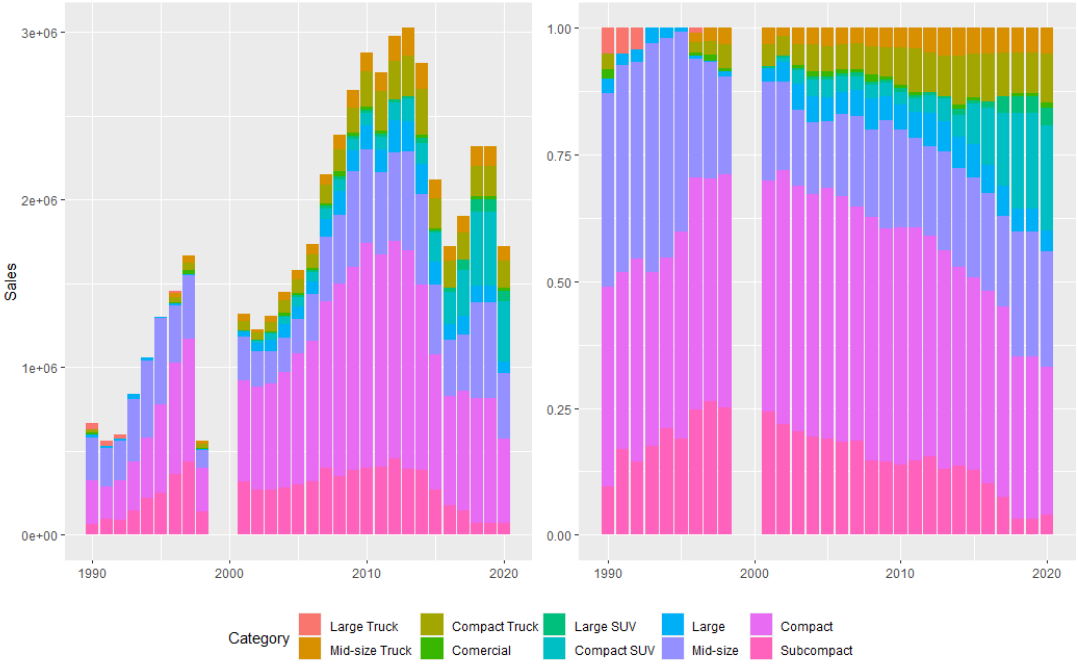

Figure 4.9: Vehicle registration categories from 1990 to 2020 (horizontal axis)

advanced technology, such as in fuel injection and variable valve timing.

As expected, the hybrid and pure-electric vehicles have significant impacts on FE (60% and 100%, respectively). The slight positive effect of dedicated gasoline engines was expected, as discussed above.

Two bestselling, long running models, were used to illustrate trade-offs. A typical subcompact MY1990 exhibited an acceleration, horsepower, torque, weight, and combined FE of 17.4s, 48.5 HP, 7.2 kgfm, 798 kg, and 13.4 km/L, respectively. In contrast, MY2020 exhibited 12.5s (+ 39.2%), 72 HP (+ 48.5%), 10.4 kgfm (+ 44.4%), 1025 kg (+ 28.4%), and 14.0 km/L (+ 4.5%), respectively.

For a typical 1.6 L compact vehicle, the acceleration time decreased from 13.0s to 9.8s, (+ 32.6%), power increased from 76 HP to 101 HP (+ 32.9%), torque increased from 13.3kgfm to 15.4kgfm (+ 15.8%), weight increased from 872 kg to 1036 kg (+ 18.8%), and FE decreased from 13.5 km/L to 12.1 km/L (- 10%). If the performance analyses were conducted at the 1990 levels, FE would have been 17.7 km/L and 17.8 km/L for the 1990 and 2000 models, respectively.

A family-sized sedan (MY1992) gained 20% in HP, 33.5% in torque, and 10% in acceleration owing to the increase in engine displacement from 1.6 L to 2.0 L. It further gained 24.6% in weight when CVT replaced MT, whereas FE remained almost constant (11.4 km/L (1.6 L) vs. 11.5 km/L (2.0 L)).

As reducing weight is associated with improvements in FE, vehicle downsizing[9] is considered for reducing fuel consumption in the fleet. However, this implies that the trend of vehicles getting larger and heavier, as shown in Figure 4.4 and discussed above, has to be reversed. There are a few more models in the dataset with 15 or more years on the market, and in none of them weight or power reductions occurred, quite the opposite. And this is not taking into account that weight-saving technologies were probably employed in the period (MACKENZIE, 2013). The same can be said for vehicle categories, all of which are more powerful and heavier.

Table 4.1: Regression results for FE, where model 1, 2 and 3 indicate the elasticity of each explanatory variable. Bearing in mind that torque, horsepower and acceleration are linear dependents

	Model 1	Model 2	Model 3
Weight	-0.359^{***}	-0.423^{***}	-0.470^{***}
	(0.023)	(0.025)	(0.018)
Torque	-0.097^{***}	-	-
	(0.010)		
Horsepower	-	-0.059^{***}	-
		(0.012)	
Acceleration	-	-	0.079^{***}
			(0.011)
Electric-vehicle	1.076^{***}	1.045^{***}	1.062^{***}
	(0.033)	(0.034)	(0.033)
Gasoline	0.042^{***}	0.046^{***}	0.041^{***}
	(0.010)	(0.010)	(0.010)
Hybrid	0.571^{***}	0.569^{***}	0.581^{***}
	(0.016)	(0.016)	(0.016)
AT	-0.003	-0.004	-0.010^{**}
	(0.005)	(0.005)	(0.005)
CVT	0.007	0.011	0.002
	(0.010)	(0.011)	(0.011)
DCT	0.348^{***}	0.328^{***}	0.319^{***}
	(0.087)	(0.088)	(0.088)
Constant	5.047^{***}	5.487^{***}	5.353^{***}
	(0.141)	(0.138)	(0.137)
Observations	2,621	2,622	2,622
R^2	0.601	0.590	0.593
Adjusted R^2	0.595	0.584	0.587
Note:	$^{*}p<0.1$; $^{**}p<0.05$; $^{***}p<0.01$		

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[9] Engine downsizing usually refers to reducing displacement and adding turbocharging to keep performance constant. Vehicle downsizing simply means making it smaller and lighter.

4.5.2 Technological progress

The logarithmic values of FE obtained from the year 2020 are 0.2607, 0.2825, and 0.2835 times greater than those from the year 1990 for Models 1–3, respectively. This translates to 29.8%, 32.6%, and 32.8% progress, respectively, or roughly 1.0% per year. These rates of progress are analogous to those observed in the PSFI index in Figure 4.1. Table 4.2 summarizes the rates of technological progress for each year during 1991–2020 (1990 being equal to zero) and for each model. These rates are uneven in the period considered, approximately 0.39–0.61%, 0.85–0.89%, and 1.7–1.9% during 1990–2000, 2001–2010, and 2011—2020, respectively. The lower rates in the 1990s may be related to electronic injection systems replacing carburetors. The former operates with stoichiometric mixtures, whereas carburetors operates on lean mixtures. This causes slight reduction in efficiency. In 2012, the Brazilian government set guidelines for mandatory FE improvements of at least 12.08% by the year 2017 compared to that in 2011 (INOVAR-AUTO program). This was observed to have a positive effect on the rates, which improved to approximately 3% recently.

The overall rate of improvement was lower than that observed in the studies discussed above, which is usually at least 3%. The reasons may be that the Brazilian market was traditionally dominated by cheaper models, with inherently lower technological levels. Higher rates were observed during the period when the market started to diversify. Weiss et al. (2020) applied the same method for model variants of the EU Volkswagen Golf, Opel Astra, and Ford Focus, considered compact vehicles in the EU. FE could be 23% higher in 2018 compared to 1980 if mass, power, and frontal area remained at the 1980 levels; thus, an 0.6% increase per year.

Furthermore, a hypothetical average FE value for year *t* can be obtained by multiplying the average FE of year *0* with the exponential of the difference between parameters T_t and T_0, according to (4.7).

$$\frac{\ln kml_t}{\ln kml_0} = T_t - T_0 \rightarrow kml_t = kml_0 e^{(T_t - T_0)} \tag{4.7}$$

The average combined FE values (across all models; not sales-weighted) in 1990 and 2020 were 10.43 km/L and 12.43 km/L, respectively, which indicates a 19.2% increase by 2020. The potential FE values in 2020, by applying the rates of technological progress according to Table 4.2, would be 13.36 km/L, 13.74 km/L, and 13.76 km/L. Thus, the ERFC values are, according to Eq. 4.2, 69%, 61%, and 61%. This implies that approximately 31–39% of technological

Table 4.2: Accumulated rates of technological progress estimated for Regression Models 1–3 (Percentage)

Year	Model 1	Model 2	Model 3
1991	1.7	1.3	1.2
1992	0.9	0.9	0.8
1993	3.3	3.9	3.7
1994	3.2	3.7	3.6
1995	6.3	7.1	6.8
1996	6.1	6.8	6.9
1997	6.4	7.5	7.5
1998	6.9	7.9	7.9
1999	8.0	9.5	9.5
2000	5.6	7.3	7.3
2001	3.6	5.3	5.1
2002	0.4	2.0	2.0
2003	3.3	4.8	4.8
2004	5.5	7.0	7.0
2005	5.1	6.5	6.4
2006	8.2	10.2	10.0
2007	8.5	10.5	10.4
2008	11.7	13.9	13.6
2009	11.2	13.4	13.0
2010	12.1	14.2	13.8
2011	12.4	14.5	14.2
2012	12.9	15.0	14.8
2013	15.3	17.4	17.3
2014	15.8	18.3	18.0
2015	17.8	20.2	20.3
2016	18.0	20.4	20.6
2017	22.3	24.9	25.0
2018	26.1	28.7	28.9
2019	25.9	28.7	28.7
2020	29.8	32.6	32.8

progress was spent in performance during the entire period.

4.6 The Future

The energy consumption variables of future transport are complex, such as energy production technology, economic and population growth, customer demands, industrial policy, air quality, alternative fuels, and technology trends (KALGHATGI, 2018). Transport in 2020 is 99.8% powered by ICEs, with approximately 1.1 billion LDVs, a number that is expected to reach 1.7–2.0 billion in 2040. Even with rapid expansion of alternative fuel vehicles (AFVs), it is expected that approximately 85–90% of transport energy will be obtained from liquid fuels powering ICEs (LEACH et al., 2020). This section presents a few possible pathways in technological progress rates and sales-mix evolution, including EVs. This enables building scenarios for fleet-wide FE in 2030 and 2035, which is presented in section 4.7.

4.6.1 Internal combustion engines

As discussed above, ICEs will still be the major prime movers for decades to come, regardless of AFVs penetration, because alternatives have to start from very low bases (KALGHATGI, 2018). ICEs can still benefit from newer technologies to increase their efficiency and performance. Although no attempt is made here to discuss all possible future technologies, a brief discussion to illustrate these possible gains in efficiency is provided.

Improvements can be in the form of over-expanded cycles, such as the Atkinson and Miller cycles (NABER; JOHNSON, 2014; TODA; SAKAI et al., 2017) replacing the traditional Otto cycle. Other areas of technological improvement include gasoline direct injection (GDI) with lean combustion, variable compression ratio, water injection, cylinder deactivation, external exhaust gas re-circulation (EGR), and multi-stage air charging (CESARE; CAVINA; PAIANO, 2017). Furthermore, GDI compression-ignition (SELLNAU et al., 2019) can allow ICES to reach the efficiency levels of HEVs. Moreover, engines can be downsized and turbocharged to improve efficiency (JONO et al., 2016).

Middleton et al. (2016a, 2016b) simulated the economic implications of technologies, from the perspectives of FE, in a baseline MY2012 Ford Fusion midsize sedan. The technologies included in their study were dual cam phasing, discrete variable valve lift (DVVL), engine friction reduction, GDI, downsizing with boosters, cooled EGR, and reductions in weight, drag and rolling resistances. By combining these technologies, the fuel consumption could reduce by 35%, from 31.8 MPG to 48.8 MPG in the 55/45 cycle.

4.6.2 Electrification

Electrification of transport is one of the most common solutions suggested when the topic of mitigation of GHG emissions arise. Battery electric vehicles (BEVs) rely only on electricity. Their main concerns are the battery capacity, weight, cost, range, charging infrastructure, and emissions associated with electricity generation. In contrast, HEVs employ a combination of an ICE and electric motor. The latter may be used for powering short trips. When the battery range is exhausted, the battery is recharged using the ICE. A plug-in hybrid electric vehicle (PHEV) combines the advantages of both HEV and BEV, wherein the battery can be recharged with an appropriated power outlet. A mild hybrid electric vehicle (MHEV) allows its engine to be turned off while idling and may employ regenerative breaking, which recovers some energy that would otherwise be lost while braking. Electric mobility uptake may be improved by educating citizens about their advantages, such as environmental, economic and quality of life (TUROŃ; KUBIK; CHEN, 2021). It is important to understand the specifics needs of each country as conducted by (HE et al., 2019; TOMANIK; POLICARPO; ROVAI, 2022).

As discussed above, higher performance and sales-mix shifts could offset these technical gains partially or totally. The same could happen in the case of EVs. According to Galvin 2022, EVs are still less powerful than ICEs in the US (254 HP vs. 284 HP on average); however, this gap may be closed by the emergence of super-powerful EVs, with power greater than 600 HP. It was estimated that a 5% increase in the weight of the smaller EVs results in a 4.7% increase in electricity demand, whereas for larger EVs, the increase is 10.5%. The latter gaining market-share would exert greater pressure on the rate of de-carbonization of electricity generation. While these findings should be kept in mind, this exercise in shifting EV market share would not be attempted here, as this would create yet another layer of complexity. Thus, EVs here are employed in a somewhat optimistic light. Also, EVs energy consumption are depended on travel time, distance and external temperature, but these refinements are not pursued here. Also not considered are the car-sharing services, which can play an important role in total energy consumption (TUROŃ; KUBIK; CHEN, 2019).

Some authors indicate the necessity of proper car-hailing and human mobility (ZENG et al., 2022; LI et al., 2022), moreover they show the need for policymakers to understand the specific characteristics of each kind of transportation toward a cleaner mobility sector. Another article (TUROŃ; KUBIK; CHEN, 2021) used the concept of “electric mobility education” to improve the effect and depth of the information and learning technologies, which is the basis for all policymakers.

4.6.3 Efficiency pathways

The results listed in Table 4.2 suggests about 30% efficiency improvement in 30 years, or 1% per year. With an ERFC of approximately 60%, FE improved by 0.6% per year. Development was considerably uneven; accumulated improvements reached 10% only in 2007 or 2008. Thus, six scenarios were selected, from 0.0% to 3.0% yearly improvement with 0.5% increments. Recently, an improvement of 3% was observed. However, this would require maintaining constant performance, which is unlikely to happen for prolonged periods. An improvement of 0% does not necessarily imply zero technological progress. It indicates that all technological improvements were used for improving the performance. This scenario is slightly less unlikely. Every rate between 0% and 3% may indicate a combination of a specific rate of technological progress and ERFC between 0 and 1. Exploring every combination of these two factors is unnecessary as these scenarios are of the "what if?" nature.

The Brazilian government instituted a target of 11% reduction in sales-weighted fleet FC by 2022 compared to that in 2017. FC in 2017 was 1.75 MJ/km, and the target was 1.55 MJ/km. This translates to a 2.4% reduction in FC per year. These values were adjusted for real-world conditions, thereby resulting in lower values. The adjusted values were 2.46 MJ/km and 2.18 MJ/km, respectively. With the official E22 heating value at 28.99 MJ/l, FE should be 11.8 km/L in 2017. Applying a rate of improvement of 2.4% per year, FE values in 2030 and 2035 would be 16.2 km/L and 18.3 km/L, respectively. These values are used as references for the scenarios presented in the subsequent sections.

4.6.4 Establishing baselines

To estimate possible efficiency pathways, first, it is necessary to establish a baseline. This is achieved by simplifying the actual fleet to correspond with a few representative models and dividing according to the vehicle category, as listed in Table 4.3, which further summarizes the market share during the years 2020 and 2001. These values were based on two different data-sets. The term sales-mix refers to the 50 best selling vehicles, which account for 88% of total registrations. FE values were obtained from (INMETRO, 2022), which contained 1034 models. FE values were not sales-weighted and corresponded to the combined 55/45 cycle. Extra-large[10], off-road, and sports cars were discarded due to their negligible number of sales.

Table 4.3: Baseline

Category	2020 avg. FE	2020 market share	2001 market share
Subcompact	13.8	4.0	23.8
Compact	13.0	29.1	44.5
Mid-size	13.1	22.8	19.0
Large	11.4	4.1	2.5
Compact SUV	11.5	20.6	–
SUV	9.6	3.6	0.4
Compact Truck	11.2	9.6	4.3
Truck (Diesel)	9.7	5.1	3.2

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[10] The Ford Fusion is categorized as an extra-large vehicle in Brazil, as opposed to it being in the mid-size category in the USA.

4.6.5 Sales-mix

Shift in sales-mix is an important and often neglected aspect. Therefore, four scenarios were created to explore this aspect. The first scenario is called SUV, wherein compact and full-size SUVs attain 40% and 50% combined market share in 2030 and 2035 (continuing their recent trends). The second scenario combines subcompact and compact vehicles, corresponding to 70% and 80% market share in 2030 and 2035, respectively; herein, they reach and subsequently exceed the values observed in 2001. xEVs in both cases are 5% and 10% in 2030 and 2035, respectively.

The Brazilian National Association of Vehicle Manufacturers (ANFAVEA) partnered with the Boston Consulting Group (BCG) (ANFAVEA; BCG, 2021) to create two scenarios for the market penetration of hybrid and electric vehicles (xEVs[11]) in Brazil for the years 2030 and 2035. The "Inertial" scenario projects aim for 12% and 32% xEVs market share in 2030 and 2035, respectively, whereas the "Global Convergence" scenario projects aim for 22% and 62%. With estimated rate of fleet turnover, xEVs are expected to make 2–4% of the fleet in 2030 and 10–18% in 2035. For simplification purposes xEVs were considered HEV and BE.

Table 4.4: Sales-mix scenarios

Scenario	xEV I		xEV II		SUV		CPT	
Year	2030	2035	2030	2035	2030	2035	2030	2035
Subcompact	0	0	0	0	0	0	25	30
Compact	20	10	15	5	15	10	45	50
Mid-size	15	10	13	5	20	20	15	3
Large	5	5	5	5	5	4	3	1
Cpt. SUV	28	20	25	10	35	40	0	0
Full-size SUV	5	8	5	5	5	10	0	0
Cpt. Truck	10	10	10	5	10	3	4	3
Truck	5	5	5	3	5	3	3	3
xEV	12	32	22	62	5	10	5	10

4.7 FE Scenarios in 2030 and 2035 - policy implications

Results in Tables 4.5 and 4.6 are for the sales-weighted FE in the 55/45 cycle. Baseline sales-weighted average FE was 12.2 km/L in 2020, as discussed in 4.4.4. Values for yearly technological improvements (0.0–3.0 in 0.5 increments) in both tables are in percentage. Values

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[11] This term is used to refer to PHEVs, BEVs, HEVs, and MHEVs.

in bold indicate that they exceed 16.2 km/L and 18.3 km/L in 2030 and 2035, respectively, as discussed in 4.6.3. To obtain these values, the rate of technological improvement should exceed the values observed in the last decade, i.e., 1.7–1.9%. However, the estimated average values from 2017 to 2020 were 3–3.1%. If performance continues to improve at such historical rates, consuming approximately 31–39% of technological improvements, a 4% yearly rate would be needed. Shifting toward smaller, more fuel efficient, and compact xEVs would require a smaller rate of improvement as these categories are inherently more efficient.

Moreover, extreme scenarios produce extreme results. If 62% of the new vehicles sold in 2035 are xEVs, combined with 3% yearly improvements in FE, the average FE would more than double to 28.2 km/L. The likelihood of the fleet FE doubling in 15 years is low. According to the EPA, FE increased from approximately 12.5 MPG to 25 MPG in 45 years (1975 to 2020) in the USA.

However, if the compact and full-size SUVs continue to gain market share and all efficiency gains are used for performance, the average FE would reach 12.3 km/L and 12.6 km/L, and the xEVs market share in this scenario would be 5% and 10% in 2030 and 2035, respectively. This indicates that the higher efficiency of xEVs would be almost completely offset by the shift in sales toward larger and less efficient ICE vehicle categories. However, this is not likely to happen as ERFC would remain at 0% for an extended period.

Conversely, if sales were to be shifted toward subcompact and compact, i.e., to the 2001 levels (70% combined) and beyond (80% in 2035), then FE would actually be higher than its value in the moderate xEV scenario in 2030 and approximately 4% lower in 2035. Making this shift toward smaller, less powerful vehicles would possibly require a combination of factors. Vehicles today are subject to different taxes according to their displacement capacity. With engines producing more power per displacement over time, this taxation could move toward weight and horsepower.

Table 4.5: 2030 FE scenarios. 0.0–3.0 refers to rates of yearly technological improvements

Scenario	3.0	2.5	2.0	1.5	1.0	0.5	0.0
SUV	**16.4**	15.6	14.9	14.1	13.5	12.8	12.3
xEV I	**17.1**	**16.3**	15.5	14.8	14.1	13.4	12.8
CPT	**17.9**	**17.0**	**16.2**	15.5	14.7	14.0	13.4
xEV II	**18.3**	**17.5**	**16.6**	15.8	15.1	14.3	13.7

These FE values should not be taken as forecasting, but merely to translate into numbers some possible developments. Fleet FE could remain stagnant for years, if Brazilians show

Table 4.6: 2035 FE scenarios

Scenario	3.0	2.5	2.0	1.5	1.0	0.5	0.0
SUV	**19.6**	18.2	16.9	15.7	14.6	13.6	12.6
xEV I	**22.4**	**20.8**	**19.4**	18.0	16.7	15.5	14.4
CPT	**21.5**	**19.9**	**18.6**	17.3	16.0	14.9	13.8
xEV II	**28.1**	**26.1**	**24.3**	**22.6**	**21.0**	**19.5**	**18.3**

preference towards performance and size, and xEVs fail to penetrate the fleet in any significant way. Dramatic FE improvements could be realized if efficiency is totally prioritized over performance

The policy implications are that regulations can help steer toward higher fleet FE. Recently, the rate of technological improvements has increased owing to the government instituting mandatory FE improvements. These mandates were revised and will be in place for another decade, but targets could be updated every five years. Recent targets are 2.4% improvements in fleet FE per year. Although this rate is higher than those observed thus far, it is still lower than those observed recently in China, or in the USA and Europe.

4.7.1 The road not taken

If this study was focused on estimating the total GHG emissions, the following values would be required. i) Total fleet per year; ii) vehicle age distribution per year; iii) kilometers travelled per vehicle, per age; iv) possible rate of increase in kilometers travelled per year, per vehicle; v) fuel sales-mix of ethanol and gasoline; vi) average GHG emissions for producing electricity used in xEVs; vii) possible difference in marginal rate of GHG emissions for accommodating the increasing demands for electricity for the xEVs; viii) sales-mix per vehicle category; and ix) average FE per vehicle category.

Average FE, as discussed above, can be varied by two or more factors. For other key variables listed above, the same possibilities exist. Holistic projections of such nature would require major assumptions/simplifications, which compound uncertainty as more variables are being considered. What this chapter tried to do was shed light on the evolution of some important variables: historical rates of technological improvement, trade-off between performance and efficiency and shifts in vehicle sales-mix.

4.8 Conclusions and Policy Implications

Rates of technological progress were estimated for the LDV fleet in Brazil from 1990 to 2020. These rates were lower than the rates observed in the developed countries; however, improvements were observed, from approximately 0.39% to 0.61%, 0.85% to 0.89%, and 1.7% to 1.9% in successive decades. Not all of this progress was used for improving FE, approximately 31–39% was offset by better performance, defined by weight and power in this study. This trade-off between efficiency and performance has major implications as it directly affects fleet-wide fuel efficiency.

Furthermore, shifts in market share play an important role as heavier vehicles require more energy, which were estimated using regression models. In Brazil, the traditional compact and subcompact vehicles are gradually being replaced by compact and full-size SUVs. Another observation is that LDVs in Brazil are getting bigger, heavier, and more powerful over time in every vehicle category. Thus, scenarios that consider vehicle downsizing, constant performance (or even regressing), and sales shifting toward smaller models must acknowledge that a reversal of trends would be necessary.

These rates of technological progress along with sales-mix shifts in favor of SUVs, compacts or xEVs were explored under various scenarios for the years 2030 and 2035. Sales-weighted fleet-wide FE can range between 12.3 km/L and 18.3 km/L in 2030 and between 12.6 km/L and 28.2 km/L in 2035. This variability reflects the effects of the main factors studied here, including technological improvements, trade-offs, and sales-mix, on FE. If the market shifts toward heavier and more powerful vehicles and manufactures expend all technological progress to improve performance, FE would remain stagnant for years. However, if the rate of technological progress continues to improve and is geared completely toward achieving higher efficiency, combined with the market shifting toward xEVs, then FE can more than double compared to baseline in 15 years. These results were used to assess the feasibility of the recent government program for improving FE, with the mandated rates being reached in the last few years. However, these rates are already observed in other countries, such as the USA and China.

Limitations of this study include the data set used for analyses, which was not as extensive as those used in similar studies. Although the values reported were statistically significant, and a more comprehensive data set may not alter the study results significantly, more data could aid in conducting a more detailed analysis, such as estimating if elasticities varied yearly or can be considered constant. Furthermore, an extensive data set could be used to obtain regressions for different power-trains, such as hybrids or electric vehicles. As discussed above, there are still significant gaps in our knowledge about the Brazilian fleet, and this research provided helpful figures, such as feasible rates of technological progress. These can be used to estimate better possible GHG emissions in the future, which is the ultimate research goal.

Chapter 5

Rise and fall of the Brazilian popular car: environmental consequences

5.1 Introduction

Avoided emissions in the transportation sector can be estimated by comparing newer, improved, and more efficient vehicles against a similar, older model. A typical entry-level, high-sales volume, Brazilian light-duty vehicle (LDV) in the mid-1990s had a combined fuel efficiency of 12 km/L, and the average fuel efficiency for this type of vehicle in 2020 was approximately 14 km/L. With a 200,000 km vehicle lifetime this means about 2340 L of fuel saved. Further calculations can be made by applying emission factors for the desired fuel and then for the entire fleet. A significant value for avoided emissions can be reached.

But what if we were to flip the problem? Consider we were to follow the IPCC's estimate, which states that global emissions need to be reduced from approximately 40 $GtCO_{2,eq}$ in 2020 to 10 $GtCO_{2,eq}$ in 2050 (MASSON-DELMOTTE et al., 2018). Thus, a more appropriate framework would involve estimating **extra** emissions compared with a hypothetical scenario. For the LDV, this can be achieved estimating by how much could efficiency be improved if performance was held constant at some chosen level (KNITTEL, 2011; MOSQUIM; MADY, 2022). This is not a realistic scenario. However, this may be exactly the problem: by generally expecting more power and performance from vehicles, we are making it more difficult to reduce emissions.

Internal combustion engines (ICEs) will be the main power source for LDVs in the foreseeable future (KALGHATGI, 2018) and can thus play a role in reducing GHG emissions (SELLNAU et al., 2019). The ICE technology has room for improvement, and directing it towards efficiency is crucial. Modelling future transport emissions is challenging because of the large number of variables involved, such as travel demand, transport mode, energy efficiency, and fuel type (SCHIPPER, 2002). To further complicate matters, these variables are dynamic and usually change over time, increasing the uncertainty (CRAGLIA; CULLEN, 2020). Knowledge of the Brazilian fleet is still lacking; therefore, this study focused on filling some of these gaps. While past studies have focused on exergy efficiency (MOSQUIM; MADY, 2021) and the performance vs. efficiency trade-offs (MOSQUIM; MADY, 2022), this Chapter is mostly concerned with acceleration performance during the period 1990-2020.

Price and tax regimes are powerful tools to induce changes in market shares in Brazil (QUADROS; CONSONI, 2009). The average tax burden of the total vehicle price is 30.4% in the country, compared to approximately 17% in some big European markets, 11.5% in Japan, and 6.8% in California, USA (ANFAVEA, 2020). A new category of low-powered, small-sized, and cheap vehicles, known as popular cars, is a direct result of a new tax bracket for 1000 cc engines in 1990 and further tax exemptions beginning in 1993. Flex-fuel vehicles, which can run on either ethanol, gasoline, or a mixture of both, were developed, to an extent, because of the lower tax rates for ethanol-fueled vehicles compared with dedicated gasoline engines.

The objective is to present key trends in the Brazilian LDV fleet, with a focus on acceleration performance and technological deployment. Ultimately, these parameters are related to fuel use and GHG emissions. This technological evolution, such as the use of turbochargers, made the direct tax based on displacement in need of an update, or use another metric altogether. A direct CO_2 tax is proposed, to help shift consumer demand away from power and size. This tax regime should complement other policies already in place in Brazil, namely Rota2030 (BRAZIL, 2022), directed towards fuel efficiency and targeted mainly at vehicle manufacturers, and RenovaBio (RENOVABIO, 2022), related to fuel carbon intensity and ethanol and biodiesel produced.

The remaining of this Chapter is divided as follows. General trends in the Brazilian fleet, with special attention to the 1.0 liter engine, are presented in Sections 5.2 and 5.3 . Section 5.4 traces the deployment of selected engine and power-train technologies, and a time gap compared to the USA is estimated in Section 5.5. Sections 5.6 and 5.7 discuss the methods and results used to estimate a rate of technological improvement and the impact engine technologies had on it. Section 5.8 discusses the future of the ICE engine in Brazil. Sections 5.9 and 5.10 are about the environmental cost of performance and the proposal of a carbon tax. Section 5.11

concludes.

5.2 Trends in performance in the Brazilian LDV fleet

A brief contextualization of some general developments in the LDV fleet is presented in the next paragraphs. Figure 5.1 shows the evolution of acceleration for the period 1990-2020 covered in this study, with the red line representing Brazil and the blue line representing the USA. An increase in acceleration times from 1990 to 2002 and then a steady decline thereafter was observed. This is different from the observations in the USA since 1975 (SANTINI; ANDERSON, 1993; MALLIARIS; HSIA; GOULD, 1976; MACKENZIE, 2013; KNITTEL, 2011). This is related to the rise of the "popular car" in the early 1990s. These entry-level LDVs were equipped with 1000 cc engines, which were exempted from the Industrialized Product Tax (IPI in Portuguese). They were smaller, cheaper, low-powered, and quickly gained the market share, ranging from 4.3% in 1990 to 50% in 1996 and peaking in 2000 with approximately 75% of the total sales. The exemption was abandoned in 2000, but the tax rate of 10% was still lower than the 25% for models above 1000 cc (QUADROS; CONSONI, 2009).

The fuel economy increased from 1990 to 1998, remained constant until around 2010, and then increased sharply. The following are some broad explanations for these trends: first, catalytic converters used in the late 1990s caused engine-power reduction. Second, air conditioning systems, which began to appear in the mid-1990s, caused a loss in power (approximately 10%), and finally, safety and necessary improvements (e.g., increase in airbag quantities) directly added some weight, affecting the vehicle performance.

In 2012, a government program called *INOVAR-AUTO* (FINANCE, 2020) established fiscal incentives via tax reductions for automakers to reduce vehicle fuel intensity (MJ/km) by 12% in 2017, compared to the baseline levels in 2011; the more aggressive targets were 15.4% and 18.8% reductions. Eight of the ten major automakers achieved the 15.4% goal, while two achieved 18.8%.

Existing literature on past developments in the Brazilian LDV fleet is insufficient (MOSQUIM; MADY, 2021) when performance parameters are concerned, and previous studies have focused mainly on projections (MELO; JANNUZZI; SANTANA, 2018; BENVENUTTI; URIONA-MALDONADO; CAMPOS, 2019; BENVENUTTI; RIBEIRO; URIONA, 2017; SCHMITT; SZKLO; SCHAEFFER, 2011; JUNIOR; ALMEIDA, 2019). LDV research has traditionally focused on alternative fuels, mainly sugar-cane-derived ethanol, and currently, the possible pathways for HEVs and pure EVs (LDVs in Brazil are not allowed to run on diesel; therefore, energy consumption refers to gasoline, ethanol, or both in flex-fuel vehicles). Even gasoline sold at the fuel stations has ethanol content (E27, 27%, is the historical ethanol content in gasoline). All approaches have merits, but the lack of historicity is critical. The benefits are: (i) a better understanding of the developments can help in projections, or at least help judge the feasibility of specific scenario construction; and (ii) comparisons with other countries become easier. Brazil is still in a motorization period, characterized by the LDV shifting from a luxury to a common good (ECOLA et al., 2014). Therefore, following the trajectory of the USA or Japan would result in distinct outcomes.

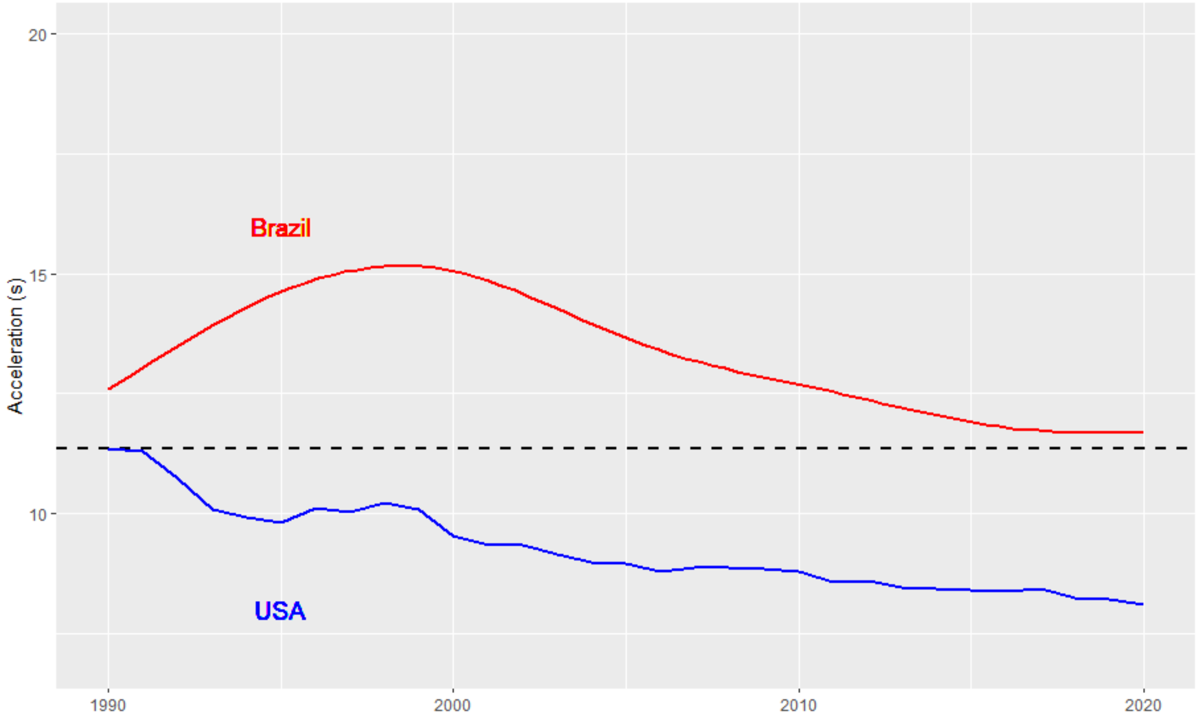

Figure 5.1: Acceleration times, 1990–2020. USA in blue (0–97km/h), Brazil in red (0-100km/h).

Figures 5.2 and 5.3 shows the trade-offs between fuel consumption and acceleration and power for 1990 (in red) and 2020 (in blue). While the trade-off is clear, it points to a diminishing relationship over time for acceleration times, corroborating the findings of Moskalik (MOSKALIK; NEWMAN, 2020). The line is not horizontal, though, and this indicates that improving the performance still requires more energy.

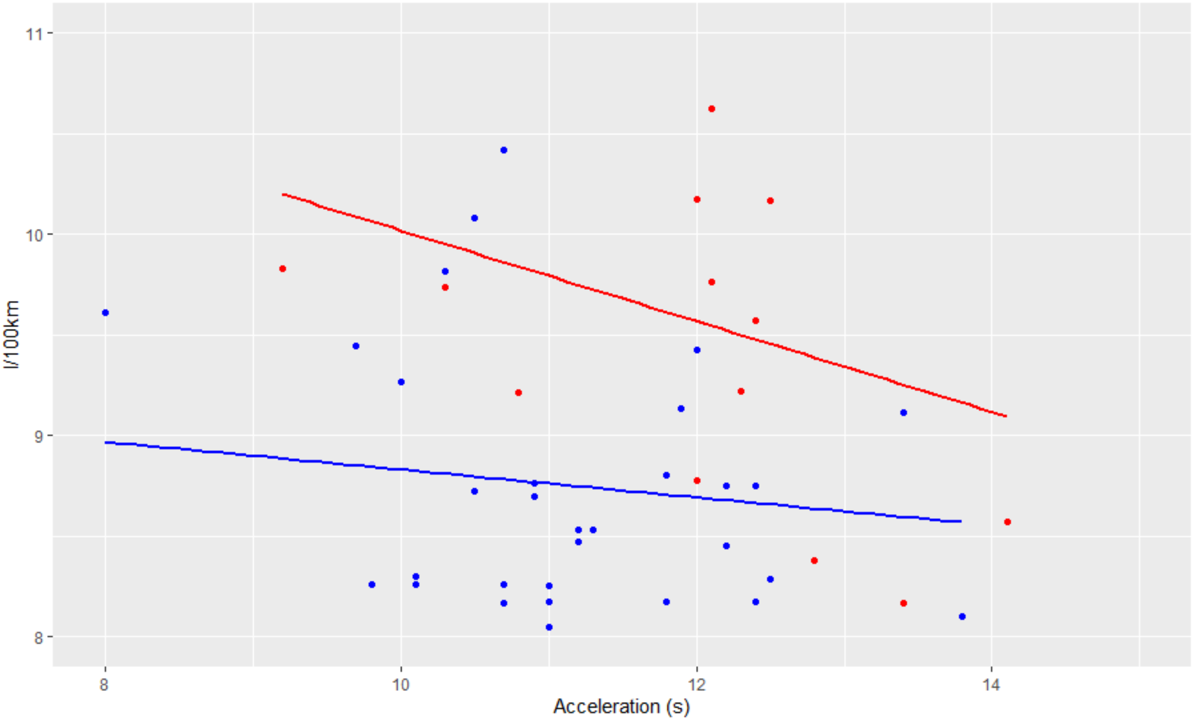

Figure 5.2: Trade-off between acceleration and fuel consumption, 1990 (red) and 2020 (blue)

5.3 Is the 1.0-liter LDV becoming too big?

Repressed demand[1] for vehicles makes the market highly sensitive to price and taxation, which is still one of the highest in the world. Direct taxes on Brazilian vehicles were bracketed by power (below or above 100 HP) and fuel type (ethanol or gasoline). In 1990 a new category was created for engines below or at 1000 cc. Figure 5.4 illustrates the progression of tax rates in Brazil. The black and dark blue lines are for engines above 2.0 liters, for gasoline and ethanol, respectively. Shades of light blue are for gasoline (13%) and ethanol (11%) engines above 1.0 liters, but below 2.0. Dashed vertical lines represent the transitional period. Before the first line, engines above 1000cc were taxed based on horsepower. After the second line, by displacement, with the creation of a bracket for engines above 2.0 liters.

The purple line in Figure 5.4, for 1000 cc engines, dives toward zero in 1993-1994. This development induced the the low-powered, small, cheap, and entry-level popular car. Market dominance occurred within a decade, as illustrated in Figure 5.5. But today's 1.0-liter engines are not necessarily found in entry-level vehicles alone, and this can have great impacts on overall fleet fuel efficiency and emissions. While the market-share of 1.0-liter vehicles in 2008 was

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[1] 11.3 inhabitants per vehicle in 1992 (4.8 in 2016), approximately double that of the neighbor Argentina, five times that of a European country, or approximately nine times that of the personal vehicle country par excellence, the USA.

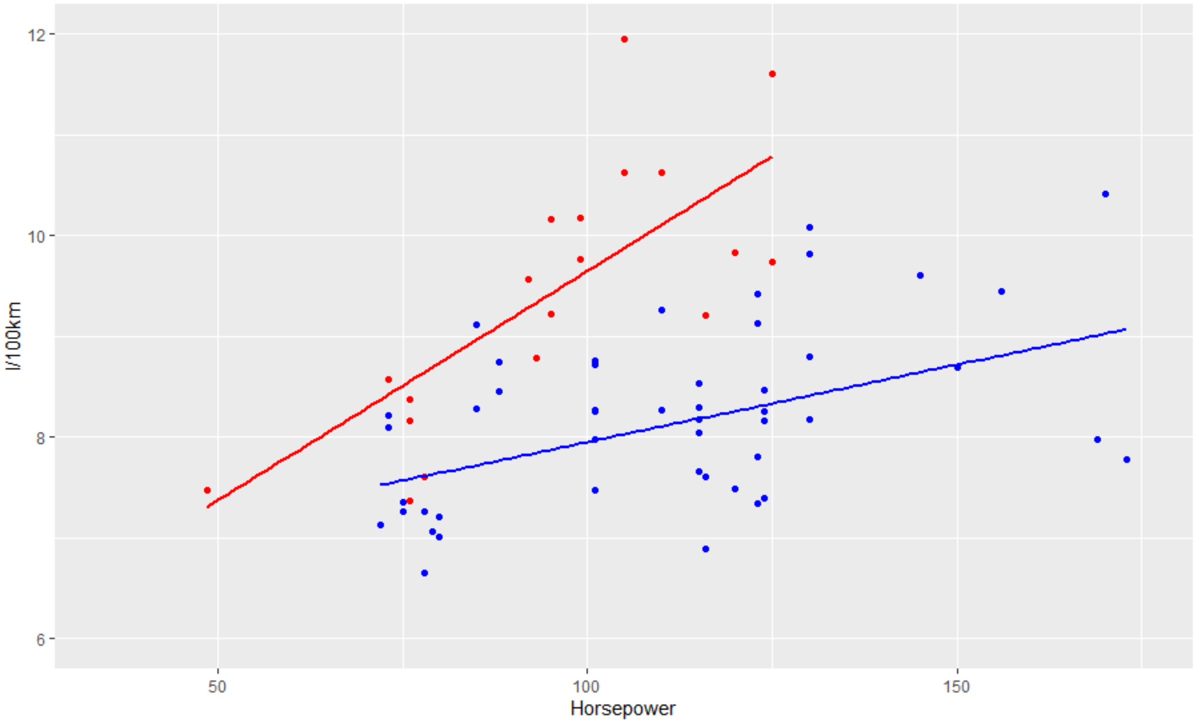

Figure 5.3: Trade-off between HP and fuel consumption, 1990 (red) and 2020 (blue)

slightly above 50%, that of the entry-level vehicles was approximately 40%. In 2020, these numbers were about 50% and 12.7%, respectively. Developments that induced this discrepancy are discussed in detail in the remainder of this text.

The 1.0-liter engines were synonymous with popular vehicles, but this gradually lost its meaning. The 1.0-liter-engine vehicles became heavier (Figure 5.6) and more powerful (Figure 5.7), with higher accelerations capability (Figure 5.8). Fuel economy, however, improved in a slower pace (Figure 5.9). This trade-off is well known (KNITTEL, 2011; MACKENZIE, 2013) and was estimated in Chapter 4. The deployment of turbochargers in downsized engines highlighted this discrepancy further, as illustrated in Figure 5.10

Although not all the weight gained is related to size, as safety and emission control improved over the years, the correlations between weight and size are evident, illustrated in Figures 5.11 and 5.12. It is likely that weight-saving technologies were employed during this period, but there was is thorough material tear-down, as reported in (CHEAH, 2010) for the USA, for Brazil. Zoepf and Mackenzie 2011, 2013 estimated that for a 223 kg increase in weight in a MY2010, 62 kg (27.8%) was related to safety; 25 (11.2%) kg, to emission control equipment; and the remaining 136 kg (60.9%), to convenience.

The deployment of more advanced technology made a 1000 cc 1990 vehicle significantly different from its 2020 correspondent. Metrics such as the specific power (HP/l), torque (kgm-

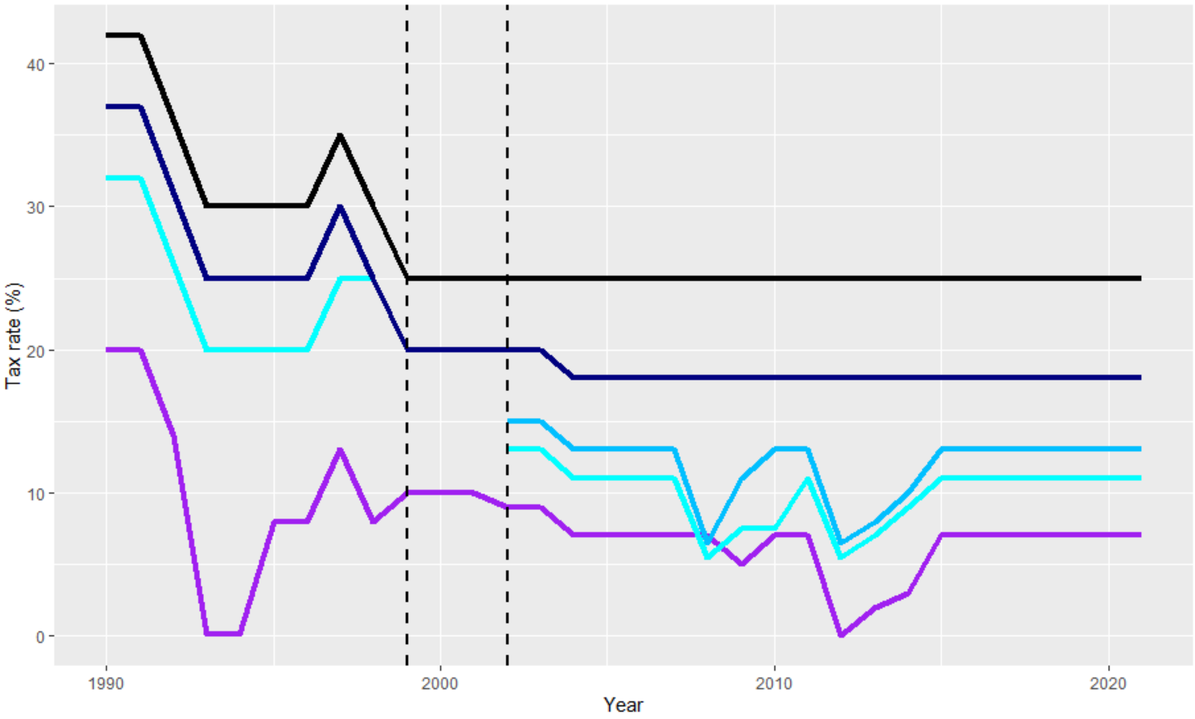

Figure 5.4: Tax rates for LDVs in Brazil - Each color represents a category

f/l), and power-to-weight ratio have improved markedly in the period. These metrics, and some of the technologies which made these improvements possible, will be discussed in more detail below.

5.4 Technology diffusion - we were always in transition

Acceleration performance improvements can be achieved by newer power-train and engine technologies, such as fuel injection replacing carburetors, variable valve timings and lifts, transmission innovations, and turbochargers or compressors replacing natural aspiration. In addition, parasitic losses, such as friction along cylinder walls or power trains may be reduced. Finally, vehicle and tire designs can reduce drag and rolling resistance, thereby improving the overall efficiency by reducing the forces that the vehicle must overcome (MOSQUIM; MADY, 2021).

This section presents the diffusion of different technologies employed over time, with a brief discussion for their functioning. More detailed explanations are provided in (JUNIOR; ALMEIDA, 2019). Note that some mathematical functions, such as the rate of technological diffusion done in (ZOEPF, 2011), are beyond the scope of this study. Moreover, not all technologies are covered here; only those pertinent to the regression model are detailed in Section 5.6.

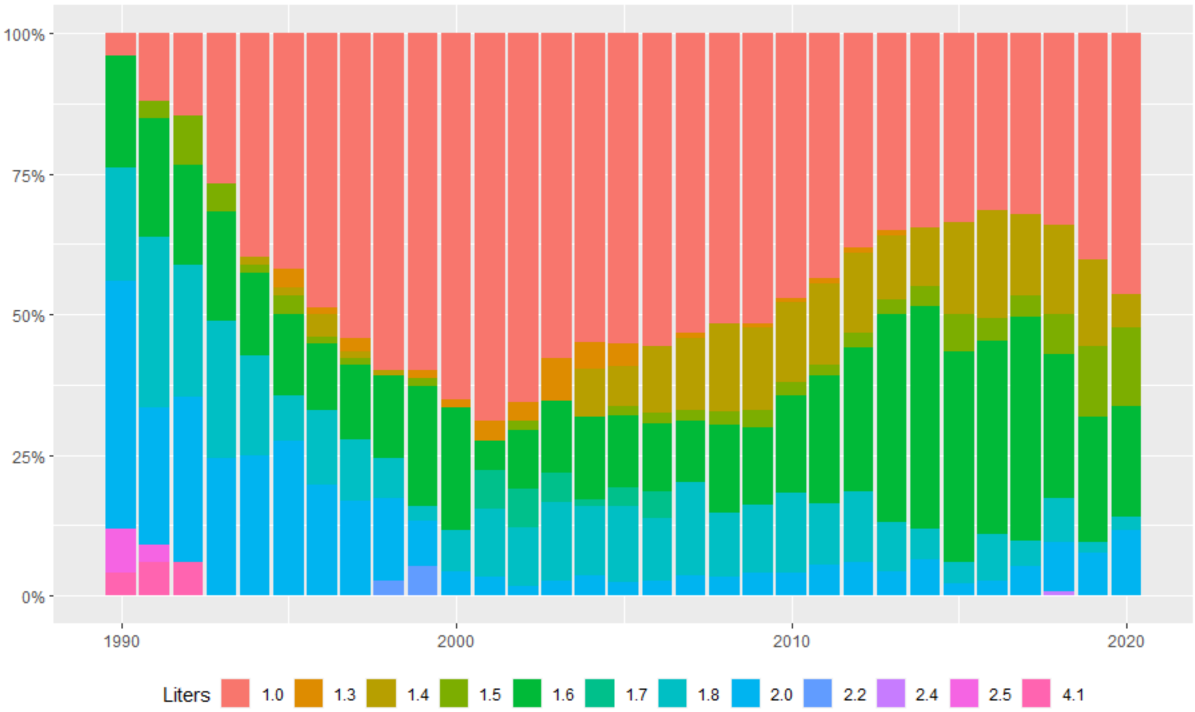

Figure 5.5: Engine Displacement (Liters), 1990–2020

5.4.1 Air Intake

Air-intake systems are mainly categorized into three types. First, naturally aspirated (NA), in which air intake relies on atmospheric pressure. Second and third types are when induction is forced via a supercharger and turbocharger, respectively. The difference between a turbocharger and supercharger is that the former is powered by exhaust gases, whereas the latter is powered by the engine. The forced induction of compressed air into the combustion chamber increases power. This allows for displacement reductions while maintaining a constant power. This is known as engine downsizing and is discussed in more detail below.

NA engines dominate the market, as shown in Figure 5.13. Superchargers (compressors) were found in a few models around 2000, but later they disappeared from the market. Turbo-compressors, which were found in performance-oriented vehicles in the 1990s, are now being deployed in smaller vehicles.

5.4.2 Fuel Delivery

Carburetors, which mix air and fuel before the fuel enters the combustion chamber, were the primary technology used in the 1990s. While mechanically simple devices, carburetors do not allow for great control over the air and fuel ratios, thereby limiting the efficiency. They have

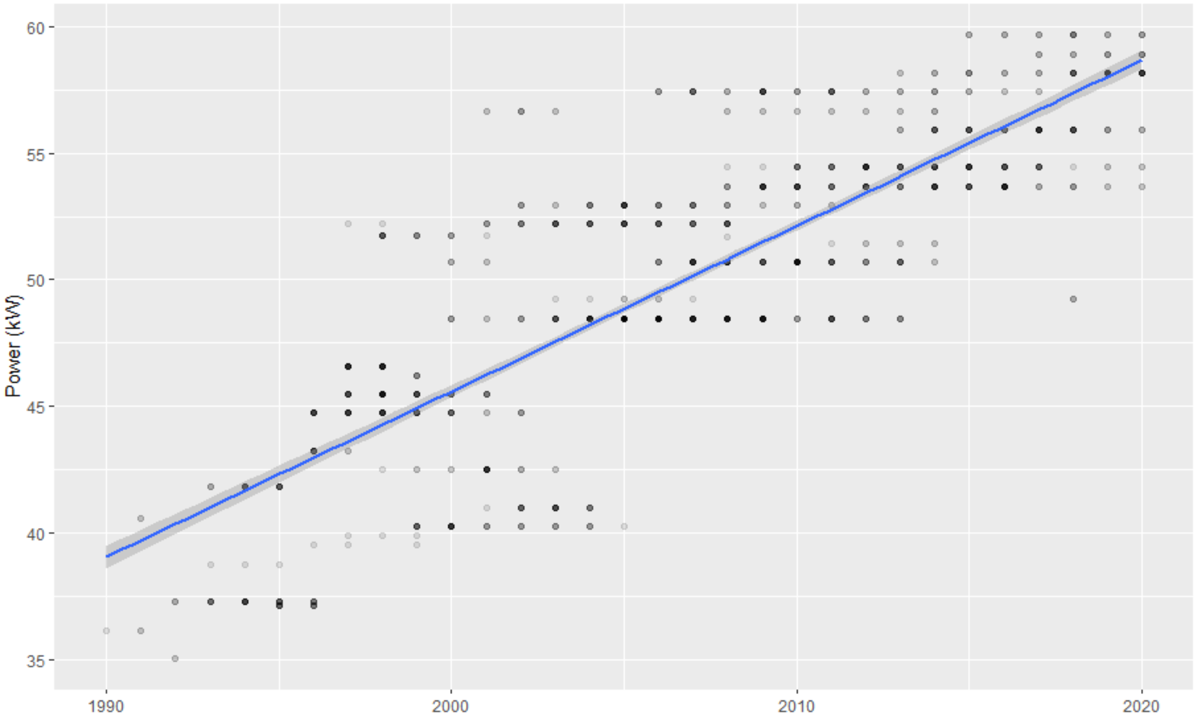

Figure 5.6: 1.0 liter, aspirated (nominal) Power, 1990–2020

been gradually replaced by electronically controlled injection systems. This transition implied a fuel economy penalty, as the electronic systems were running in stoichiometric mixtures, and the carburetors with lean mixtures had little regard for emissions. The injection can occur just before the valve and cylinder, in single-point (or mono-point) at the air-intake manifold of the engine or at port (multi-point) with a separate injection nozzle for each cylinder. Direct injection involves the direct injection of pressurized fuel into the combustion chamber. Both systems have benefits and weaknesses and recently have been employed together in dual systems. Multi-point injection is by far the most common system in the Brazilian LDV fleet, as illustrated in Figure 5.14.

5.4.3 Transmission

A gearbox is mainly related to comfort and convenience; however, it influences performance, and thus, vehicle efficiency. Automatic transmissions were only found in the upper strata of vehicles in 1990 but are now present in approximately half of the total number of models, if combined with continuously variable transmissions (CVTs). In the USA, automatic transmissions (ATs) were present in less than 70% of all models in 1980, and currently, in more than 90% (ZOEPF, 2011) of all models; hence, there is room for growth in market share if this

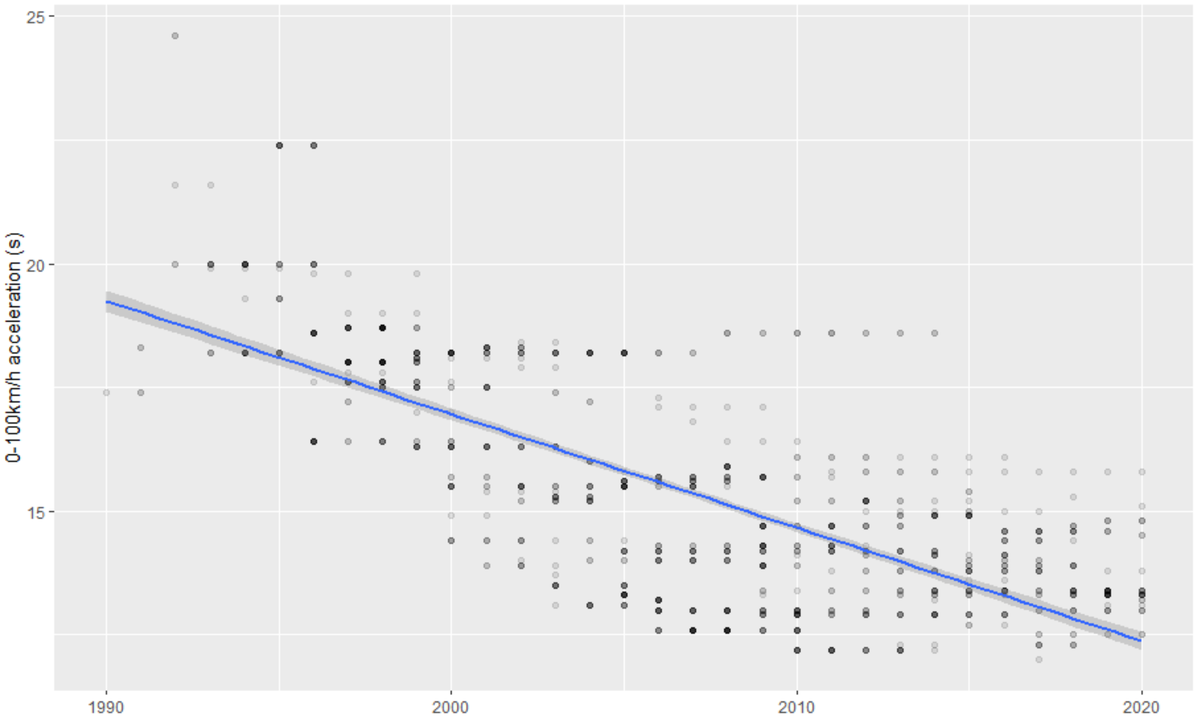

Figure 5.7: 1.0 liter NA acceleration, 1990–2020

trend continues, as illustrated in Figure 5.15 and 5.16. Five-speed manual transmissions were typical, whereas the AT had only three or four gears. Since 2010, six-speed or more ATs have begun to appear, as far as ten. More gears allow the engine to operate more efficiently at a more optimized RPM. CVTs are considered 0-speed.

5.4.4 Downsizing

Engine downsizing refers to the extraction of more power from smaller engines. In addition to the fuel injection and aspiration technologies discussed above, the number of cylinders has commonly decreased from four to three when deployed in line, as shown in Figure 5.17. This decrease is reflected in the total number of valves, from the typical eight or sixteen when the engine had two or four valves per cylinder, to six or twelve, respectively, as shown in Figure 5.18. Valve control systems typically consist of a push-rod (OHV) and a single overhead camshaft (SOHC) 5.20. Dual-over-head shafts (DOHC) allow for a wider angle between the intake and exhaust valves, improving their performance. This change also allowed the four valves per cylinder configuration, which were non-existent in the 1990s and are now found in the majority of vehicles 5.19, gradually replacing the more common two valves per cylinder systems.

Downsizing is reflected in the engine displacement, as shown in Figure 5.5. In the 1990s,

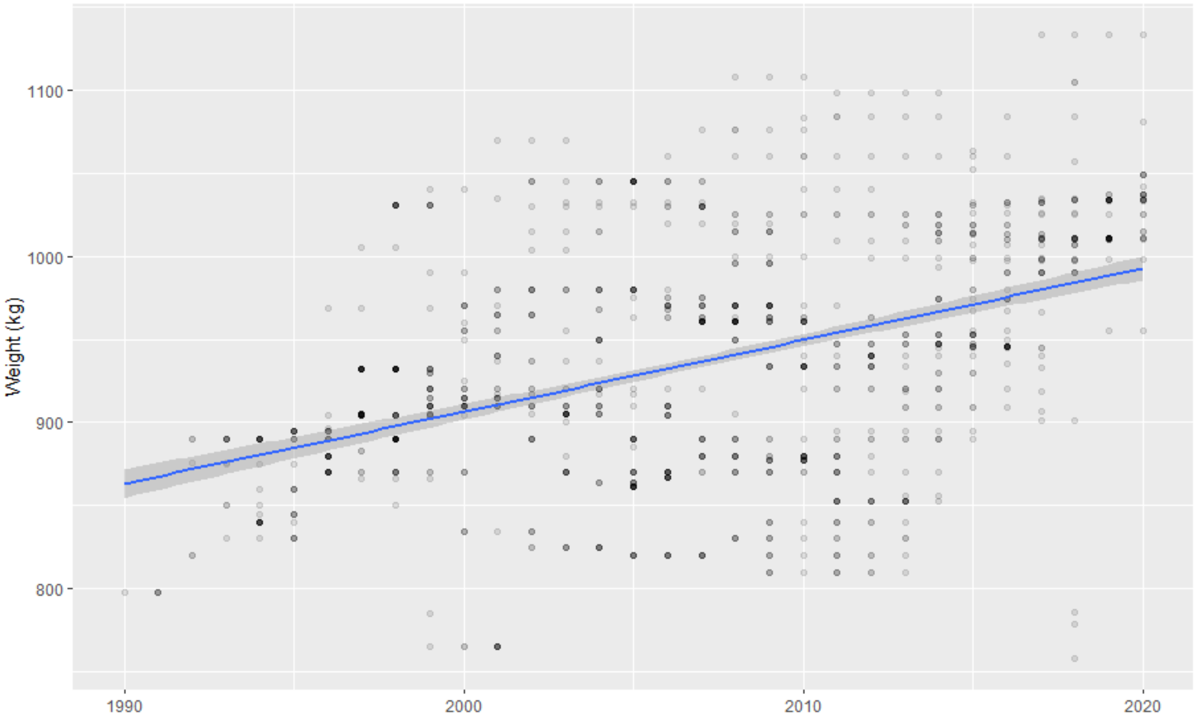

Figure 5.8: 1.0 liter NA weight, 1990–2020

4100 cc vehicles were not unusual, and 2000 cc vehicles were used in approximately one-third of the fleet. However, the 1000 cc vehicles present in the entry-level budget models were almost non-existent in the 1990s but were more than half of total models by the turn of the century. Currently, the market is dominated by 1000 cc, 1300 cc, and 1600 cc engines. In 1993, a 1.0-liter engine, found in an 850 kg compact vehicle, produced 53 HP and 7.8 torque and attained 100 km/h in approximately 20 s. In 2018, the same displacement was found in a 995 kg vehicle, producing 75 HP and 9.8 torque, requiring 13.7 s to attain 100 km/h. When equipped in a 2020 model with turbo aspiration, this engine produced 117 HP, 16.7 torque, and acceleration in 10.3 s while moving 1097 kg of vehicle mass.

5.5 Mind the technological gap

A fundamental aspect of technological progress is the rate of its adoption. In lower-income countries, such as Brazil, the adoption of newer, more efficient technologies may be delayed compared with developed countries. A simple explanation can be that cheaper, less powerful models are inherently less technologically advanced due to price constraints.

With several comparisons being made with the studies related to the USA, it is only natural to use the country as a benchmark. The readily available data produced by the EPA makes

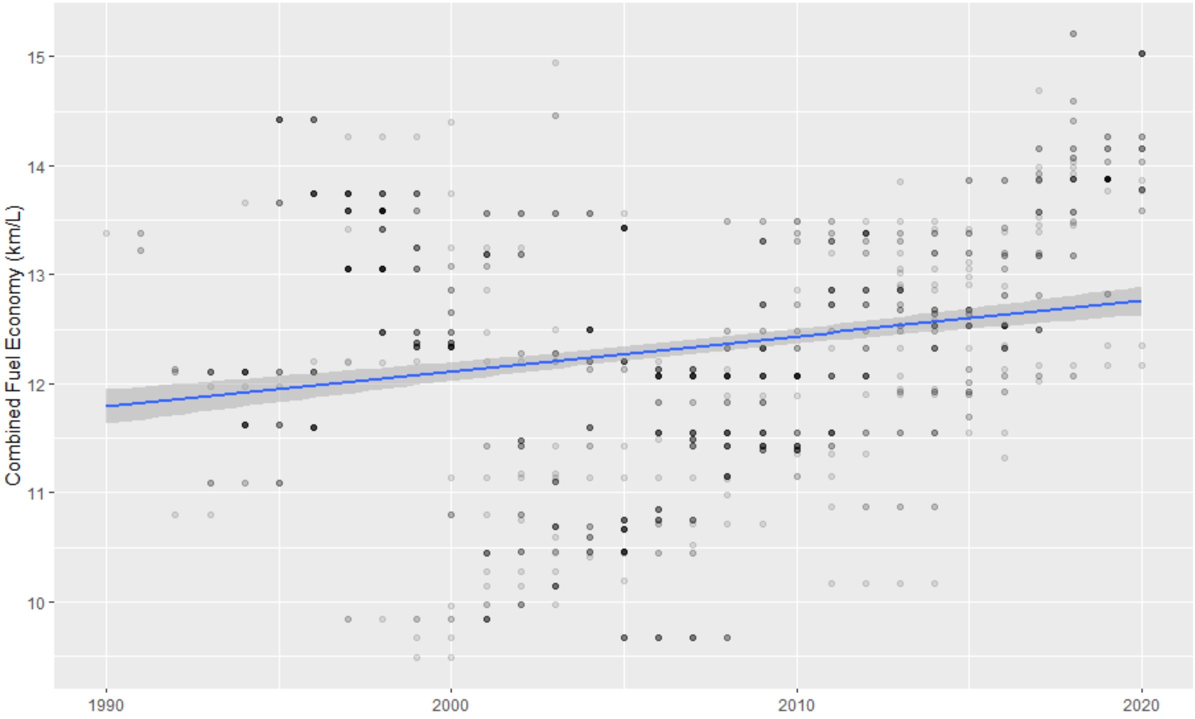

Figure 5.9: 1.0 liter NA fuel economy, 1990–2020

these comparisons easier. Figures 5.22 and 5.23 show the rate of adoption of selected engine technologies related to fuel delivery and other combustion improvements, as well as novel technologies, such as CVT, turbochargers, start-stop, and cylinder deactivation. The years in which these technologies were significantly employed, defined roughly as 1% market penetration and when it reached half of the total market were of special interest here. Precision matters less than overall trends, and for some technologies, including throttle body injection (TBI; also known as mono-point), market entry, saturation, and disappearance occurred briefly, with a peak at approximately 27%. This technology can be seen as a transition between carburetors and port injection (or multi-point). The latter quickly gained market share after appearing in 1985, dominating until 2016, when gasoline direct injection (GDI) overtook. Very recently, dual injections, combining GDI with port injection, have appeared in a few models, but the market share is still considerably low.

Multi-valve engines, in which each cylinder has more than two valves (typically, but not restricted to four), required 10 years to reach 50% in 1995, with adoption increasing until it reached more than 95%. Variable valve timing experienced a similar fate, but with even faster rates, reaching saturation in 2010. EPA began tracking VVT in 2000, when VVT was present in approximately 25% of all engines.

CVT, turbo, and start-stop technologies showed similar levels of uptake, with inflection

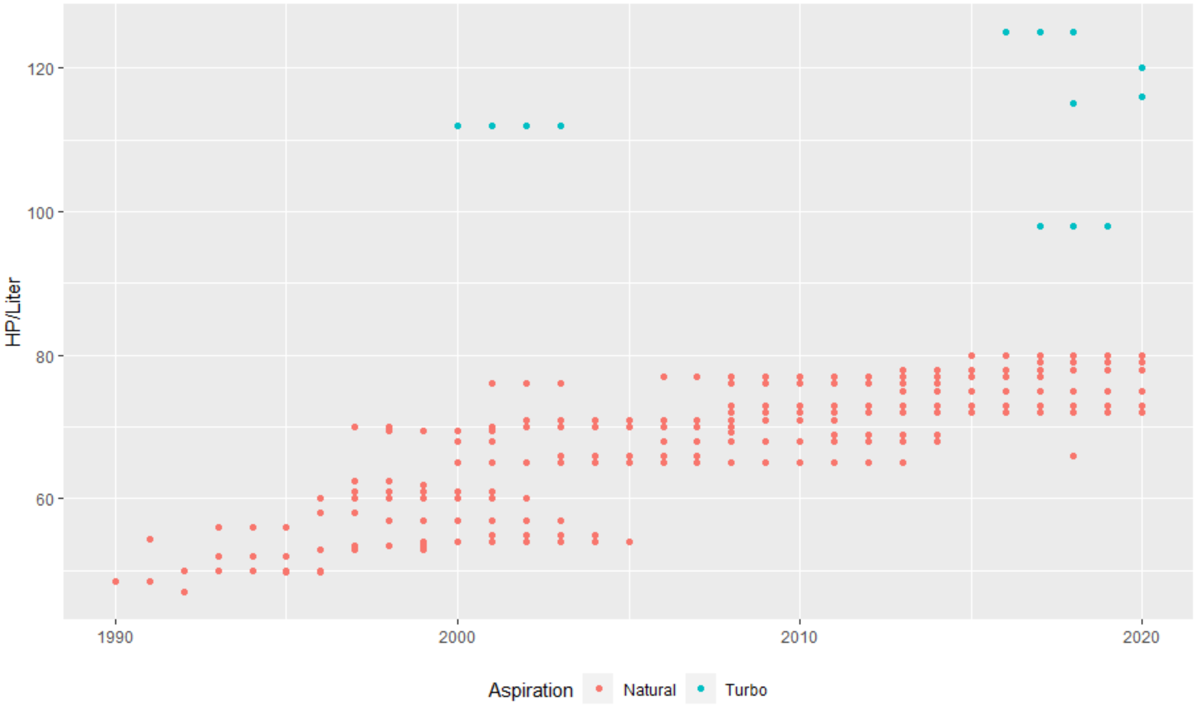

Figure 5.10: 1.0 specific power, NA vs. turbocharged, 1990–2020

points near 2010. It is interesting to note that the turbocharger technology is not novel, but its application has changed over time. Turbochargers allow more power to be extracted at the same displacement level. In the past, this usually meant more power; currently, it provides the same power with less displacement (engine downsizing). Cylinder deactivation remains incipient.

Six-gear transmission technology quickly gained market share since its inflection point around 2005 but are being replaced by transmission systems with comparatively greater number of gears (not discussed here), peaking in 2012. More gears provide more opportunities for the engine to operate in optimum regions in the torque vs. speed curve, and thus, more efficiency. Table 5.1 summarizes the years in which some engine and power-train technologies first gained significant use, and when it reached 50% market share, in both the USA and Brazil markets. It is interesting to note the remarkably consistent delay in technological adoption in Brazil, approximately 10 years for both the first adoption and the significant market penetration. Some technologies, such as GDI, turbo, CVT, and six gears, are yet to reach this mark in Brazil. The multi-valve engine gap would be similar, but popular perception about it then held back its penetration for more than a decade from an early peak at around 2000.

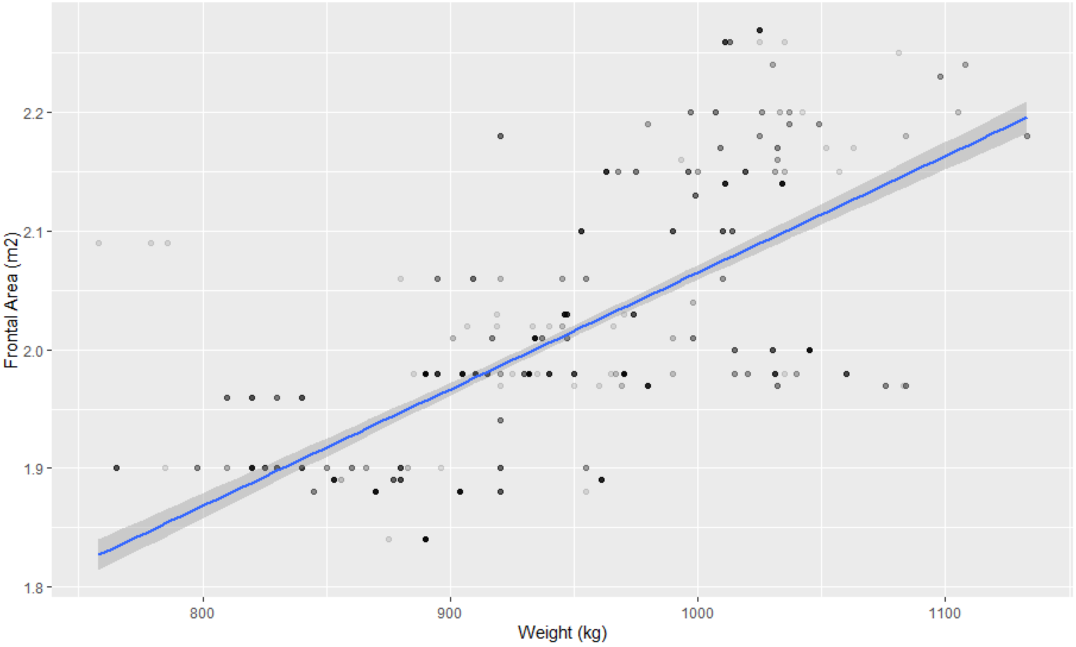

Figure 5.11: 1.0 Frontal Area vs. Weight

Table 5.1: Rates of technological adoption, EUA vs. Brazil

Technology	EUA		Brazil		Gap	
	1%	50%	1%	50%	1%	50%
Monopoint	1981	1985 (24.8%)	1992	1996 (40%)	11	11
Multipoint	1980	1988	1990	1997	10	9
GDI	2008	2018	2017	–	9	–
Turbo	2010	2020 (34.7%)	2017	–	9	–
CVT	2008	2020	2014	–	6	–
6 Gears	2004	2011	2012	–	8	–
Multi-valve	1986	1995	1992	2001 (2014)	6	6 (19)
Cylinder deactivation	2006	2020 (14.7%)	–	–	–	–

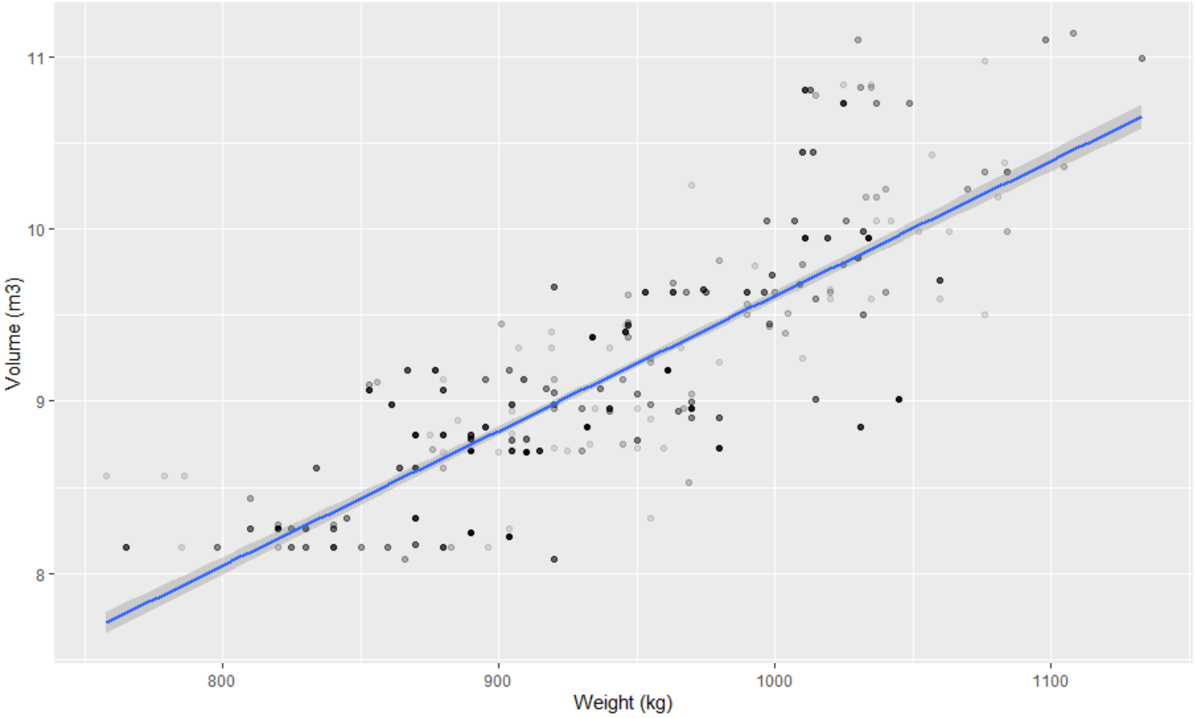

Figure 5.12: 1.0 Volume vs. Weight

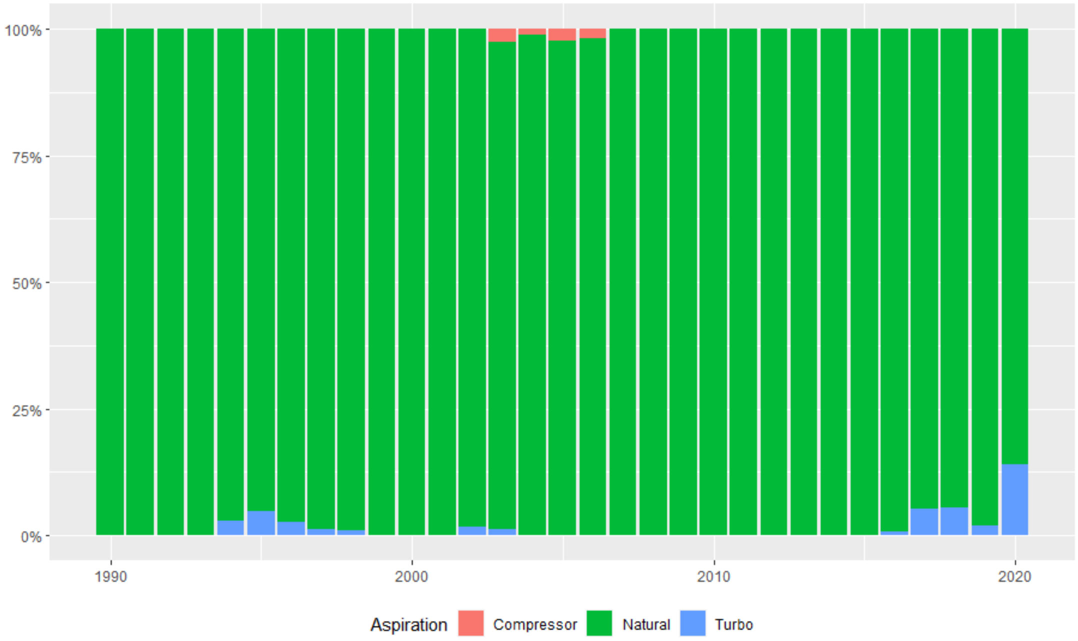

Figure 5.13: Aspiration technology diffusion, 1990–2020

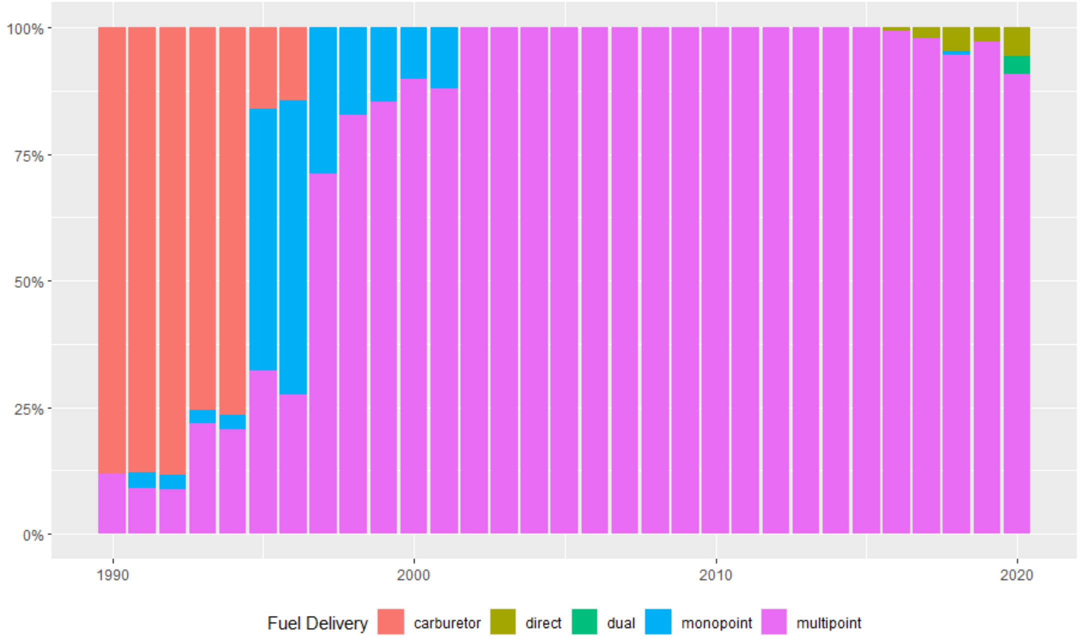

Figure 5.14: Fuel Delivery technology diffusion, 1990–2020

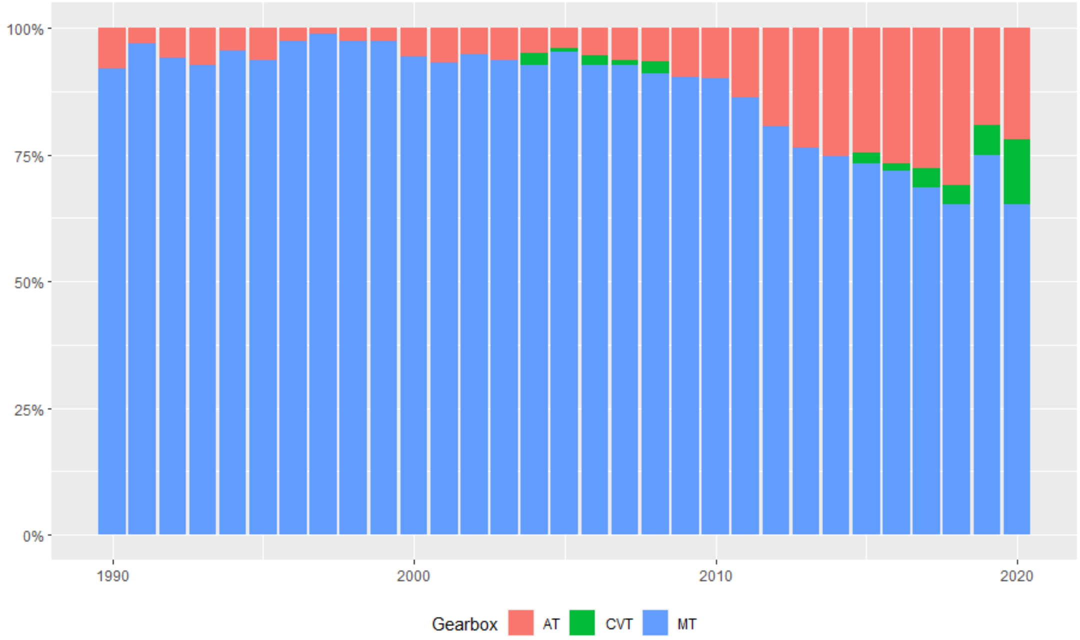

Figure 5.15: Gearbox technology diffusion, 1990–2020

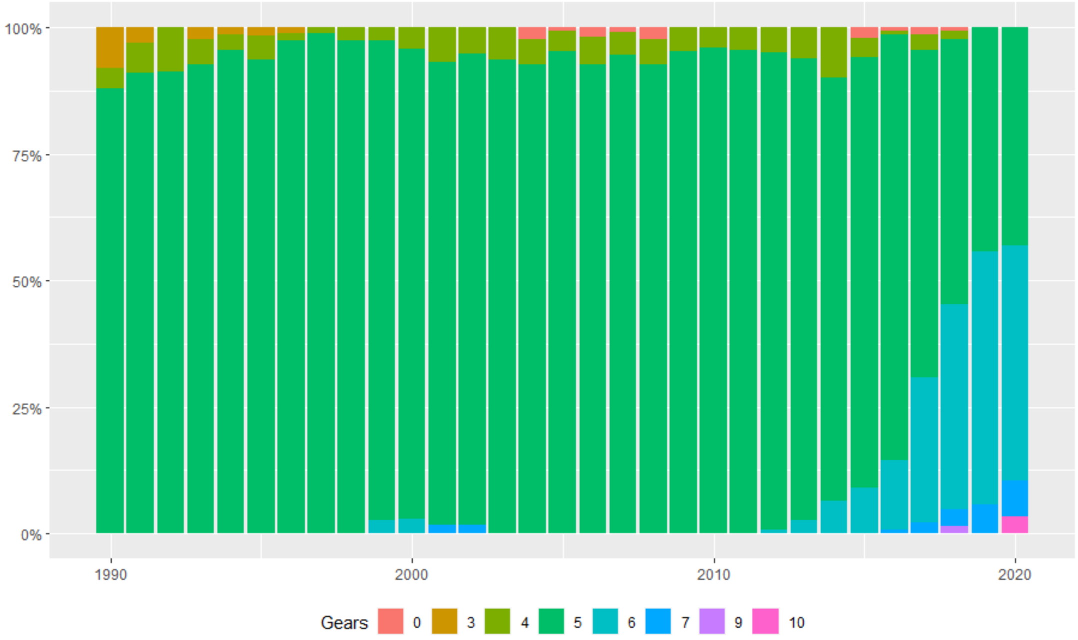

Figure 5.16: Number of gears, 1990–2020

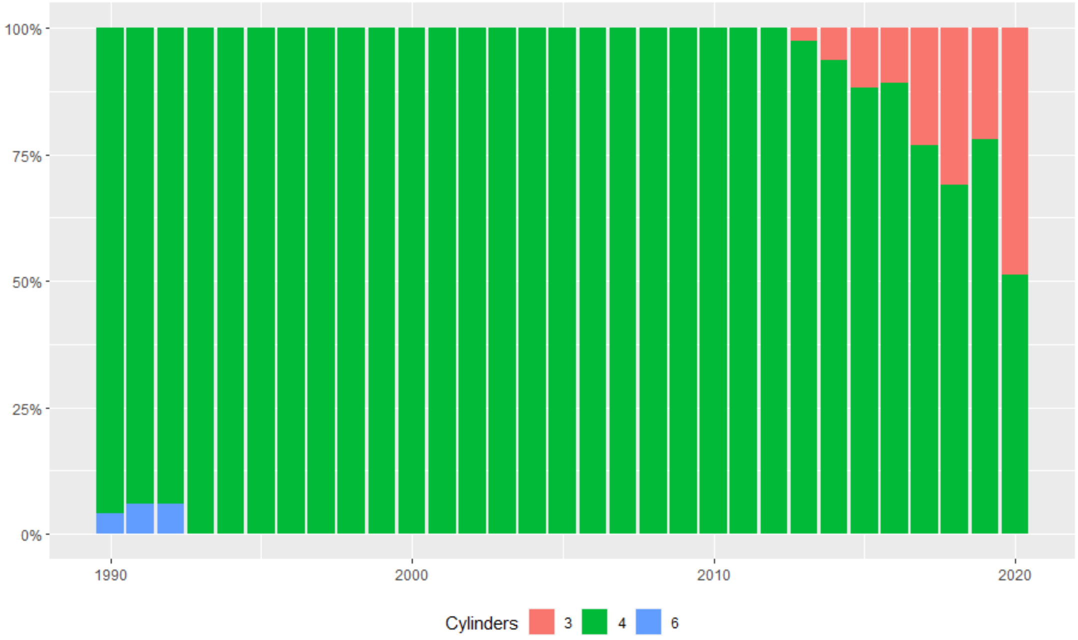

Figure 5.17: Number of cylinders, 1990–2020

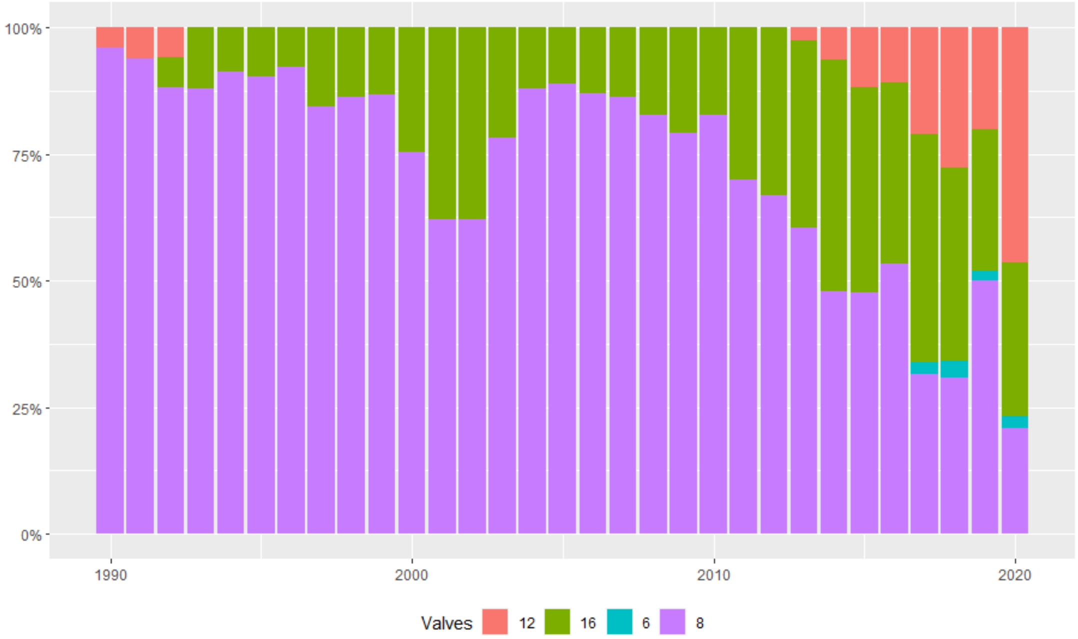

Figure 5.18: Number of valves, 1990–2020

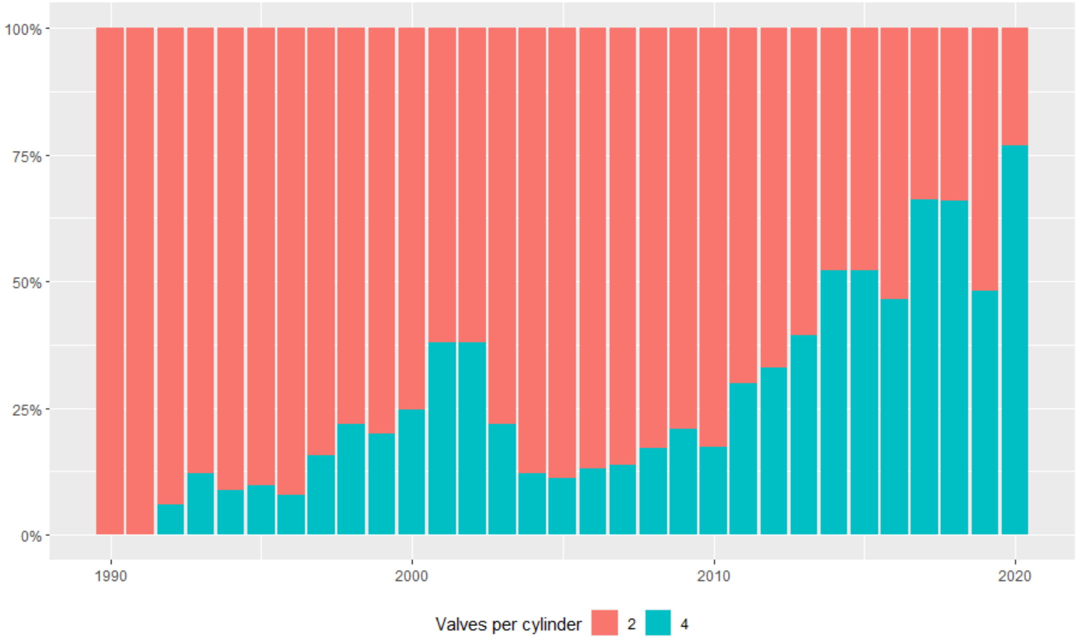

Figure 5.19: Valves per cylinder, 1990–2020

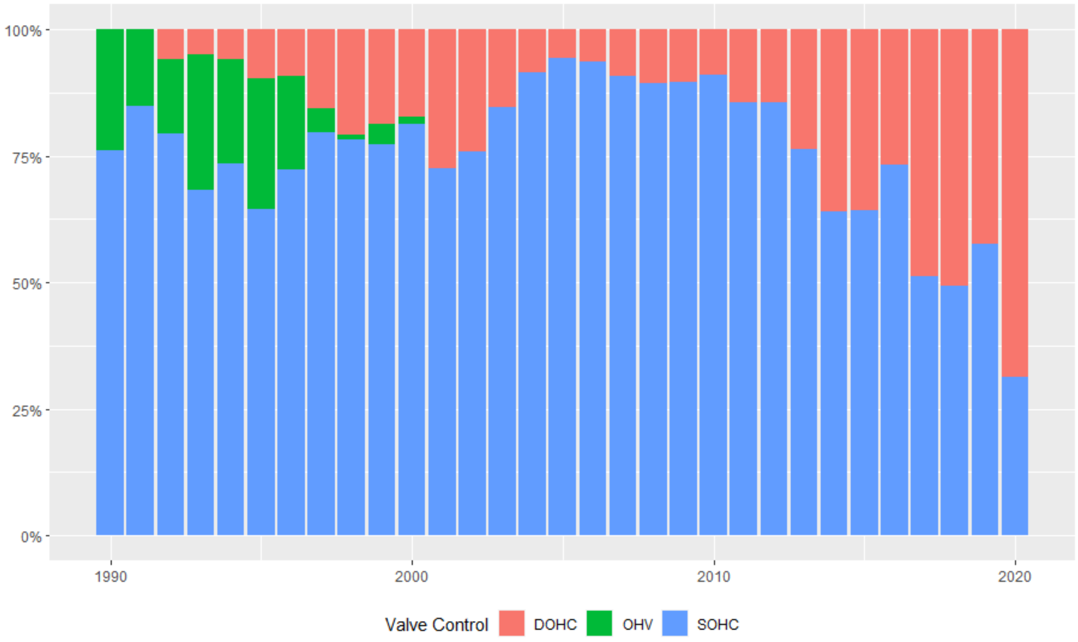

Figure 5.20: Valve control, 1990–2020

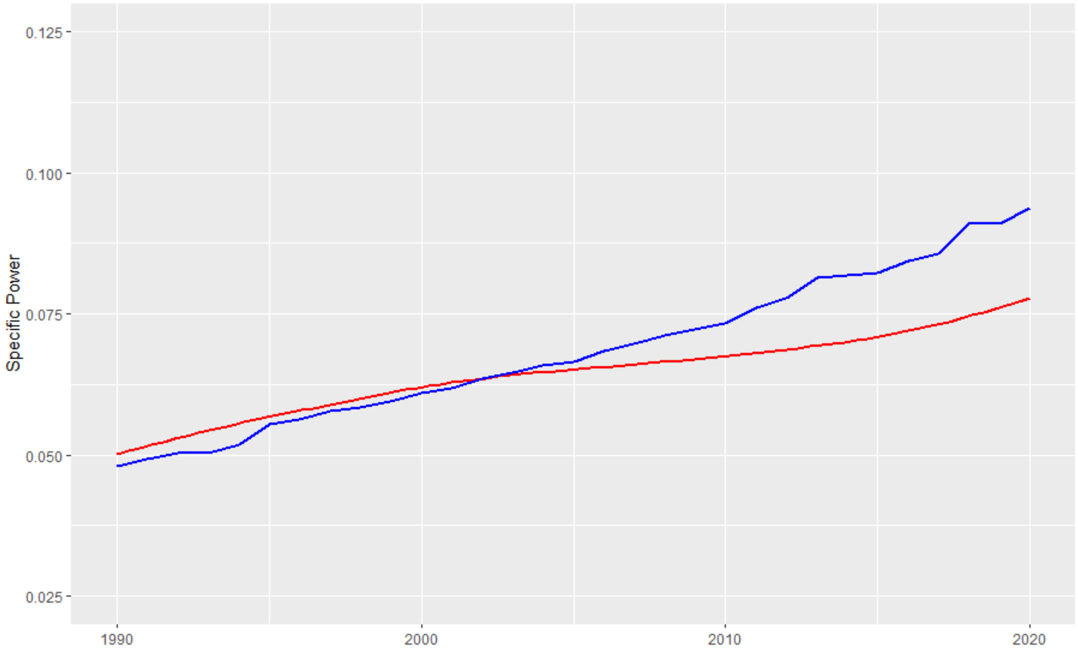

Figure 5.21: Specific power, 1990–2020. EUA in blue, Brazil in red.

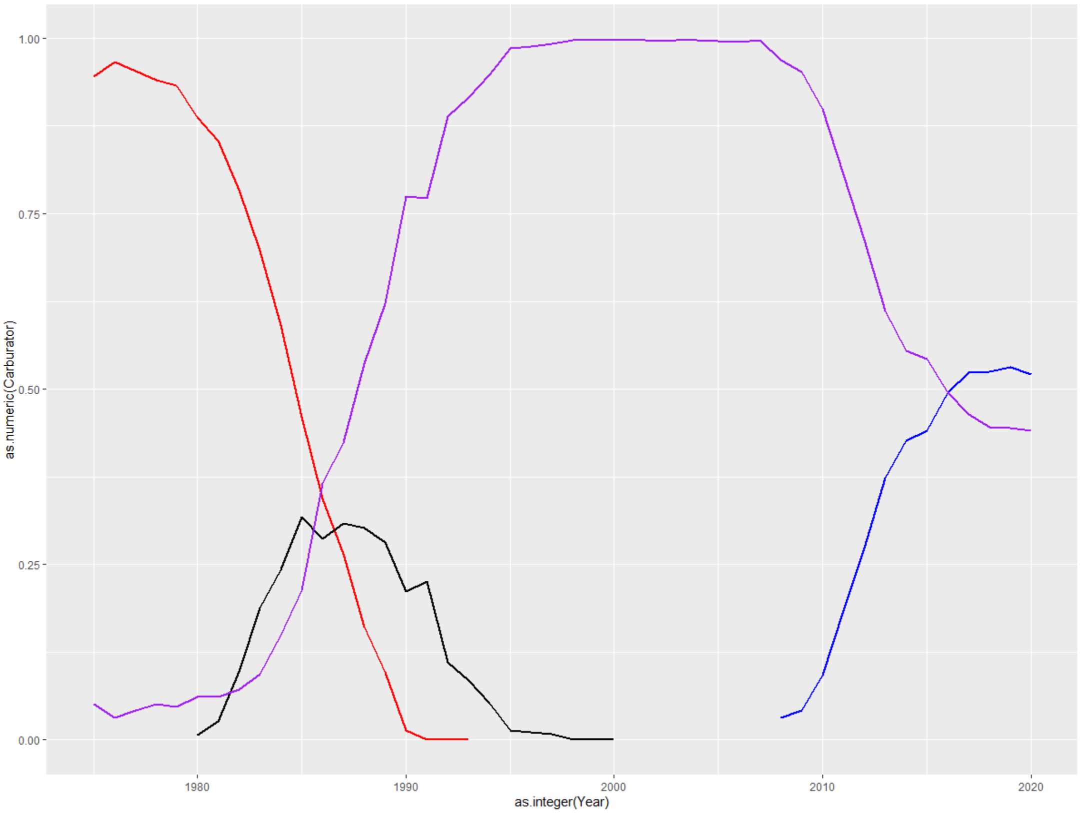

Figure 5.22: Fuel delivery technology USA, 1975–2020. Red for carburetor, black for monopoint, purple for multipoint and blue for direct injection. Data obtained in (EPA, 2022).

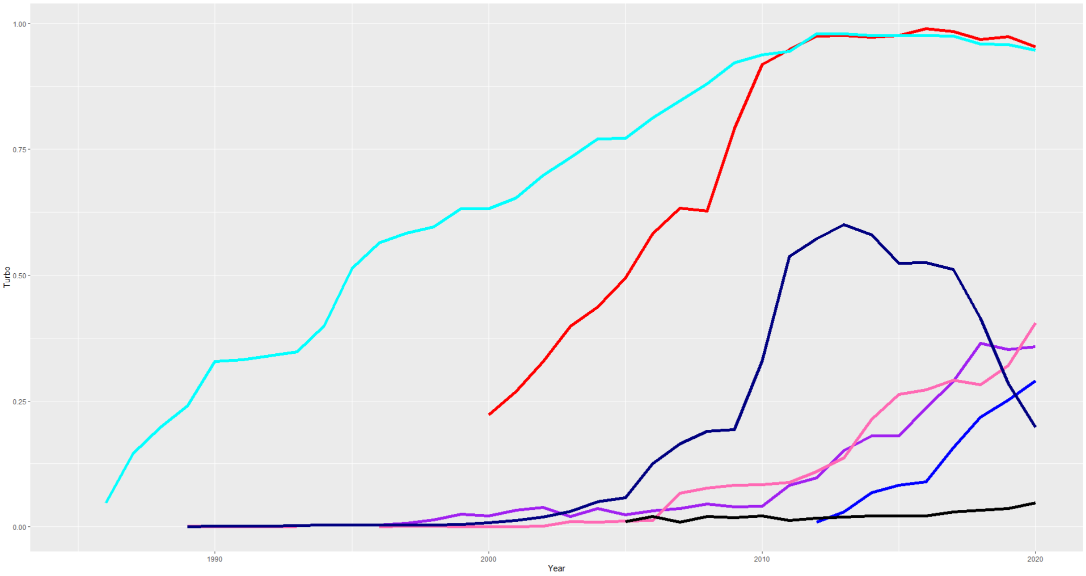

Figure 5.23: Other technologies USA, 1985–2020. Light-blue for multivalves, red for VVT, navy for 6 gears, pink for CVT, purple for Turbo, blue for start-stop and black for cylinder deactivation. Data obtained in (EPA, 2022).

5.6 Methods

In its most simplified form, we can calculate the acceleration using only two parameters: (i) peak power and (ii) weight (power-to-weight ratio, PWR hereafter). According to Malliaris et al. 1976, this relationship is "overwhelmingly influential" on acceleration performance. Figure 5.24 illustrates this ratio for the Brazilian (red line) and USA (blue line) LDV fleets during 1990-2020. Interestingly, this rate decreased for more than a decade, reversing this trend only in 2002 and continuing its upward trajectory to this day. Power-to-weight ratio reached the 1990 target levels around 2012.

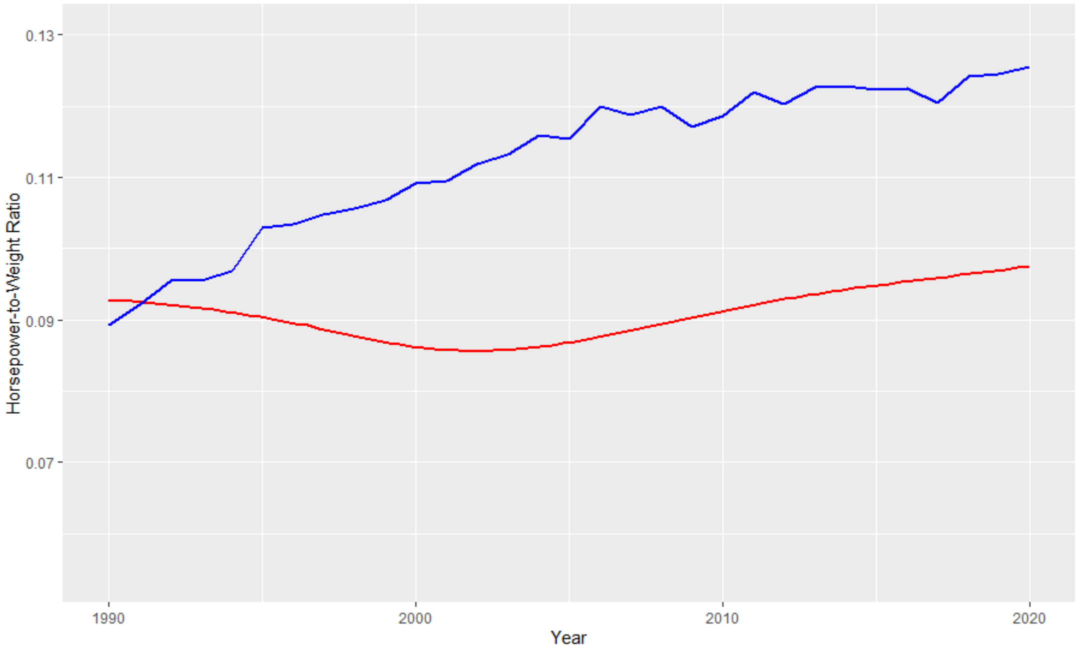

Figure 5.24: Power to weight ratio, 1990–2020. EUA in blue, Brazil in red.

Malliaris et al. (1976) estimated the acceleration performance using Eq. 5.1, with PWR (P/IWT) and estimated constants F and f from the available data. This can be useful to derive a rough estimate of acceleration performance with only two variables.

$$Acc = F \times \left(\frac{P}{IWT}\right)^{-f} \tag{5.1}$$

A less restricted form was employed by Santini and Anderson (1993) for 107 vehicles for the period 1986-1988, with acceleration estimated as a function of parameters such as displacement, frontal area, engine characteristics, peak power, and weight. They also estimated the effects of advanced engine technologies on the peak power per liter of displacement.

Finally, Mackenzie (2013) analyzed more than 1000 models for the period 1975-2010, including vehicle attributes such as power, displacement, weight, and transmission speed. His analysis followed the approach of Knittel 2011, which included a set of dummy variables for acceleration performance in each year. These year-fixed effects allowed the model to capture technological progress during the period. Effectively, it estimated how engineers can extract more performance from the same level of power over time (MACKENZIE, 2013).

A series of regression models were used to estimate the effects of vehicle attributes, such as horsepower, torque, displacement, and weight, on acceleration performance, following the approach in (KNITTEL, 2011; MACKENZIE, 2013), with Eq. 5.2 representing a generalized form. Year-fixed effects, T_t, captured the technical evolution compared to a base year, according to Eq. 5.2. Parameter **X** relates to air intake technology. The study period was 1990-2020.

$$\ln Acc_{it} = T_t + \beta_1 \times \ln wt_{it} + \beta_2 \times \ln performance_{it} + \mathbf{B} \times \mathbf{X}_{it} + \epsilon_{it} \tag{5.2}$$

Finally, the engine downsizing effects were explored according to Eq. 5.3, following the approach by Santini (SANTINI; ANDERSON, 1993), where L is the displacement, P denotes power, which could be in horsepower or torque. C is the intercept, and $EngineTech$ represents technologies, such as aspiration, fuel injection, valve control, valves per cylinder, transmission, and number of gears.

$$\ln\left(\frac{L}{P}\right) = C + \beta \times EngineTech \tag{5.3}$$

5.6.1 Data-set

The dataset consists of 2605 vehicles from 1990 to 2020. Sales were used as a rough guide to select models that best represented the actual fleet in Brazil. Data were analyzed in R-Studio (R Core Team, 2017) and all figures were generated using the ggplot2 (WICKHAM, 2009).

Table 5.2 summarizes the values used in this study. The average acceleration performance improved by 1.13 s during the mentioned period, that is, by approximately 10%. The average values for the USA market were 8.8 s, and approximately 1 s to reach an estimated asymptote (MACKENZIE, 2013). The average in 2020 was comparable to the 1990-1995 values for the USA market, indicating that there is still ample room for improvement in the Brazilian fleet. Working toward this improvement will probably imply a fuel economy penalty. A 2020 vehicle is likely to be heavier and more powerful, while requiring less energy and featuring a smaller engine.

Table 5.2: Summary statistics of the parameters studied.

Variable	Min	Max	Average in 1990	Average in 2020
Fuel Economy (km/L)	7.24	15.21	10.44	12.64
Weight (kg)	758	1704	1050	1159
Horsepower (HP)	47.0	177.0	96.23	112.48
Torque (kgfm)	7.10	29.00	15.82	15.90
Acceleration (s)	8.00	26.10	12.62	11.49
Displacement (Liter)	1.00	4.00	2.0	1.5

5.7 Results and discussions

The results for specific power are summarized in Table 5.3. The four models were estimated using Eq. 5.1, one for each decade and one for the entire period. The sensitivity (f) decreased from approximately from -0.982 to -0.743, and the average values of -0.819 were in the range of those estimated by Malliaris (MALLIARIS; HSIA; GOULD, 1976). As the engineering relationships are well established, these regressions serve the purpose of aiding in estimating acceleration performance from limited data, namely just horsepower and weight.

Table 5.3: Specific power sensitivity regression parameters

Period	F	f	R^2
1990–2020	0.530	-0.819	0.702
1990–1990	0.169	-0.982	0.837
2000–2009	0.650	-0.777	0.706
2010–2020	0.710	-0.736	0.636

The results of the regressions, according to Eq. 5.2, are summarized in Table 5.4. Models 1-3 considered displacement, horsepower, or torque separately because they were highly correlated. Model 4 included displacement and horsepower, whereas Model 5 included horsepower and torque. Sensitivities to power parameters in Models 1-3 were in the range of 0.717-0.784, similar to those in Models 4-5 when horsepower was combined with either displacement or torque. These values are similar to those found in the USA (MALLIARIS; HSIA; GOULD, 1976) and (SANTINI; ANDERSON, 1993).

The sensitivity of acceleration to weight was in the range of 0.542-0.809. It indicated the extent of the increased acceleration times (if positive) with a 1% increase in weight. The results for compressors and turbo-compressors were more ambiguous because very few models in the dataset used these technologies. Other engine technologies were tested in some models but did not improve their fit, which was unexpected. This issue is discussed in Section 5.7.1, wherein the effects of these technologies on allowing for more power and torque to be extracted from the same level of displacement are presented.

Table 5.4: Regression results for acceleration

	Model 1	Model 2	Model 3	Model 4	Model 5
ln(Weight)	0.542^{***}	0.704^{***}	0.780^{***}	0.809^{***}	0.770^{***}
	(0.024)	(0.021)	(0.026)	(0.024)	(0.022)
ln(Displacement)	-0.717^{***}	-	-	-0.372^{***}	-
	(0.011)			(0.015)	
ln(Torque)	-	-0.755^{***}	-	-	-0.611^{***}
		(0.009)			(0.020)
ln(HP)	-	-	-0.784^{***}	$--0.467^{***}$	-0.180^{***}
			(0.012)	(0.017)	(0.022)
Compressor	-0.202^{***}	0.022	0.074^{**}	-0.076^{*}	0.029
	(0.033)	(0.028)	(0.032)	(0.030)	(0.028)
Turbo	-0.377^{***}	-0.032^{**}	-0.065^{***}	-0.213^{***}	-0.034^{**}
	(0.016)	(0.013)	(0.015)	(0.015)	(0.013)
Observations	2,576	2,573	2,574	2,574	2,573
R^2	0.710	0.795	0.727	0.754	0.800
Adjusted R^2	0.706	0.792	0.723	0.751	0.797
Note:			*p<0.1; **p<0.05; ***p<0.01		

The year-fixed effects for all regression models are summarized in Table 5.5. Values for 1990 are set as the baseline, and thus, zero. These values can be interpreted as the percent decrease in acceleration time a MY1990 vehicle would have if benefited from technological improvements in year t, holding all other attributes equal. Broadly, this value captures technological improvements that allow more performance to be extracted from the same level of power (MACKENZIE, 2013).

$$\frac{ACC_t}{ACC_{base}} = e^{\beta_t} \tag{5.4}$$

Models 1 and 3 resulted in upper and lower limits for these effects at -0.327 and -0.038, respectively. Significance values for Model 3 indicate poor fit, and no explanation could be found for this. Models 2, 4, and 5 were in the range of -0.180–0.213. Mackenzie (MACKENZIE, 2013) found values between 20% and 30% for the USA market for the period 1975-2010.

Table 5.5: Year-fixed effects for each model

Year	Model 1	Model 2	Model 3	Model 4	Model 5
1991	0.003	0.006	0.013	0.013	0.008
1992	-0.006	-0.009	0.024	0.011	-0.002
1993	-0.041^{*}	-0.039^{*}	0.032	-0.006	-0.026
1994	-0.074^{***}	-0.065^{***}	0.015	-0.029	-0.049^{**}
1995	-0.047^{**}	-0.045^{**}	0.037^{*}	-0.007	-0.029
1996	-0.079^{***}	-0.082^{***}	-0.006	-0.044^{**}	-0.068^{***}
1997	-0.116^{***}	-0.096^{***}	-0.001	-0.063^{***}	-0.079^{***}
1998	-0.131^{***}	-0.106^{***}	-0.004	-0.070^{***}	-0.087^{***}
1999	-0.119^{***}	-0.107^{***}	-0.004	-0.072^{***}	-0.090^{***}
2000	-0.171^{***}	-0.135^{***}	-0.002	-0.094^{***}	-0.111^{***}
2001	-0.159^{***}	-0.099^{***}	0.034	-0.071^{***}	-0.075^{***}
2002	-0.191^{***}	-0.124^{***}	0.008	-0.101^{***}	-0.101^{***}
2003	-0.169^{***}	-0.117^{***}	0.001	-0.093^{***}	-0.096^{***}
2004	-0.172^{***}	-0.123^{***}	-0.009	-0.098^{***}	-0.103^{***}
2005	-0.187^{***}	-0.128^{***}	-0.015	-0.106^{***}	-0.107^{***}
2006	-0.204^{***}	-0.145^{***}	-0.013	-0.115^{***}	-0.121^{***}
2007	-0.227^{***}	-0.160^{***}	-0.027	-0.134^{***}	-0.135^{***}
2008	-0.229^{***}	-0.163^{***}	-0.019	-0.130^{***}	-0.136^{***}
2009	-0.228^{***}	-0.151^{***}	-0.009	-0.125^{***}	-0.125^{***}
2010	-0.231^{***}	-0.152^{***}	-0.018	-0.130^{***}	-0.126^{***}
2011	-0.246^{***}	-0.159^{***}	-0.017	-0.135^{***}	-0.131^{***}
2012	-0.252^{***}	-0.167^{***}	-0.023	-0.141^{***}	-0.139^{***}
2013	-0.277^{***}	-0.181^{***}	-0.036^{*}	-0.159^{***}	-0.152^{***}
2014	-0.278^{***}	-0.183^{***}	-0.025	-0.155^{***}	-0.152^{***}
2015	-0.304^{***}	-0.204^{***}	-0.047^{**}	-0.178^{***}	-0.173^{***}
2016	-0.310^{***}	-0.211^{***}	-0.062^{***}	-0.190^{***}	-0.182^{***}
2017	-0.315^{***}	-0.215^{***}	-0.053^{***}	-0.188^{***}	-0.184^{***}
2018	-0.327^{***}	-0.219^{***}	-0.058^{***}	-0.197^{***}	-0.188^{***}
2019	-0.321^{***}	-0.218^{***}	-0.044^{**}	-0.186^{***}	-0.184^{***}
2020	-0.327^{***}	-0.213^{***}	-0.038^{*}	-0.189^{***}	-0.180^{***}
Note:			$^{*}p<0.1$; $^{**}p<0.05$; $^{***}p<0.01$		

5.7.1 Downsizing

Year-fixed effects broadly capture technical improvement. The results indicate how much more performance can be extracted for the same level of power relative to the baseline year. Models 1-5 in Table 5.5 indicate that this value lies somewhere around 20%. However, these models are limited in quantifying exactly how this came to be. Parameters such as fuel injection, valve control, and valves per cylinder, did not significantly improve the model accuracy, although engineering principles dictate they must have affected the engine performance in some way. Figures 5.25 and 5.26 illustrate that increasing amounts of horsepower and torque can be extracted for the same level of displacement, which can be achieved, along with factors such as better tire design and aerodynamics, by deploying newer engine technologies, as discussed in Section 5.4.

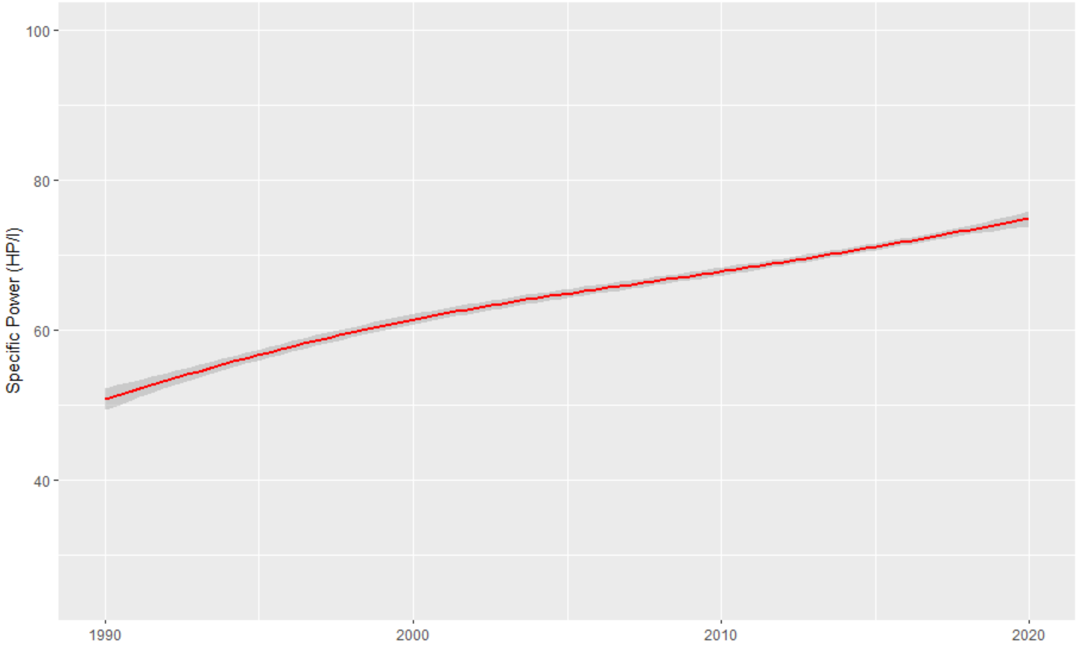

Figure 5.25: Specific HP, 1990–2020

The results for engine downsizing are summarized in Table 5.6 and are estimated according to Eq.5.3. The baseline engine technology represented an NA engine with a carburetor, an overhead valve, and manual transmission.

5.8 The Future of the Internal Combustion Engine in Brazil

ICEs will still be the major power source for decades to come, regardless of AFVs[2] penetration, because the latter must start from very low bases (KALGHATGI, 2018). Also, ICEs can still benefit from newer technologies to increase their efficiency and performance (KARGUL et al., 2016; JOHNSON; JOSHI, 2018; DAHHAM; WEI; PAN, 2022). The two main directions are improving conventional designs, such as the NA engine, and engine downsizing with turbocharging. This section will give a brief overview of newer technologies which may be deployed in the near-future.

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[2] Alternative Fuel Vehicles in this sense can be anything which does not rely solely on gasoline in an ICE.

Table 5.6: Effects of engine technology on engine downsizing

	HP/l	Torque/l
Compressor	0.405^{***}	0.328^{***}
	(0.032)	(0.017)
Turbo	0.341^{***}	0.415^{***}
	(0.018)	(0.010)
Direct	0.319^{***}	0.181^{***}
	(0.029)	(0.016)
Dual	0.219^{**}	0.152^{***}
	(0.093)	(0.052)
Multi-point	0.199^{***}	0.092^{***}
	(0.009)	(0.005)
Mono-point	0.051^{***}	-0.008
	(0.013)	(0.007)
DOHC	0.137^{***}	0.084^{***}
	(0.016)	(0.009)
SOHC	0.156^{***}	0.084^{***}
	(0.015)	(0.008)
4 Val/cyl	0.075^{***}	0.034^{***}
	(0.003)	(0.002)
NGears	0.023^{***}	0.007^{***}
	(0.003)	(0.002)
AT	0.016^{**}	0.012^{***}
	(0.006)	(0.003)
CVT	0.025	0.001
	(0.017)	(0.009)
Constant	3.531^{***}	1.926^{***}
	(0.023)	(0.013)
Observations	1,802	1,802
Adjusted R^2	0.686	0.767
Note:	$^{*}p<0.1$; $^{**}p<0.05$; $^{***}p<0.01$	

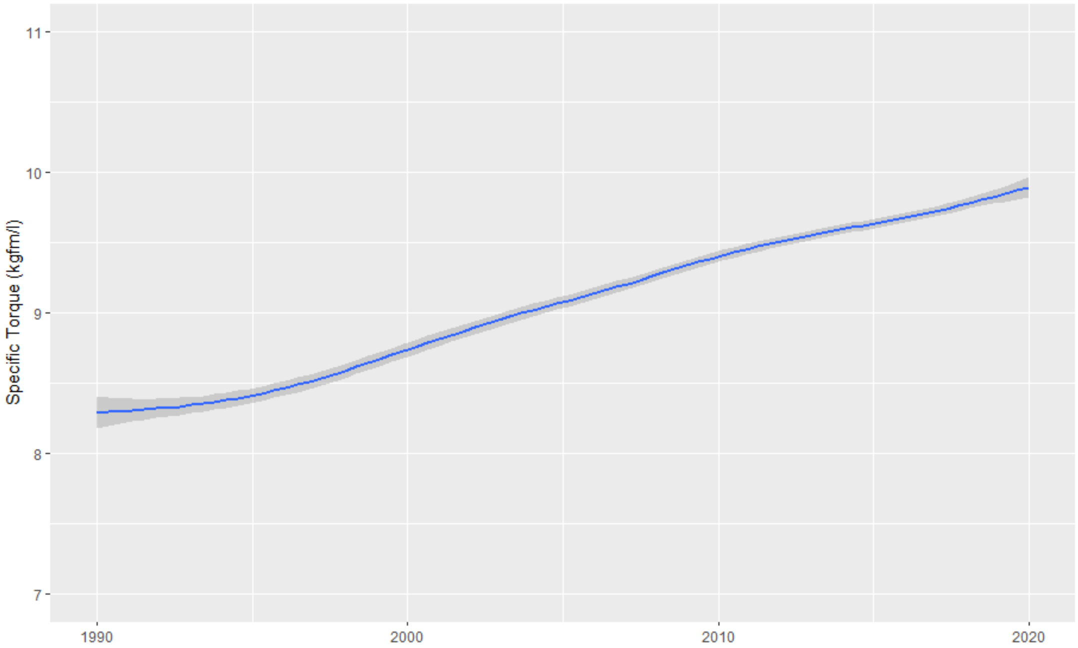

Figure 5.26: Specific Torque, 1990–2020

De Cesare et al. (2017) listed technologies for improving efficiency in the near future (2025). These include gasoline direct injection (GDI) with lean combustion, Miller/Atkinson cycles, variable compression ratio (VCR), water injection (WI), cylinder deactivation (CD), external exhaust gas re-circulation (EGR), and multi-stage air charging.

Sellnau et al. (2019) demonstrated a Gasoline Direct-Injection Compression-Ignition (GDCI) engine with 43% BTE at 12 bar IMEP and 40% BTE over a 5–20 bar IMEP range (Gen3X engine). Author's stated that practical limits for BTE in Spark Ignition (SI) engines are at about 40%, while for GDCI 50%, with possible improvements in heat loss and friction reductions, as well as improved turbocharger efficiency (Gen4X). Vehicle simulations for Gen3x with 6-speed automatic transmission (AU), 8-speed AU with 12V start/stop and 8-speed AU with 48V integrated starter generator resulted in 35.9%, 45.4% and 50.9% improvement in combined FE compared with a baseline SI turbo engine. Gen4X concept produced 68.4% and 78.1% improvements. These results compared favorably with hybrid-electric technologies. Simulations for a 2.2L Gen3X equipped vehicle resulted in combined FE in the 41–46 mpg range for a various sized SUVs and a midsize Sedan.

Toyota's 2017 2.5 L, 150 kW inline 4-cylinder engine achieved 40% thermal efficiency and 16% improvements in FE by employing an Atkinson cycle, a new electrical variable valve timing (VVT), a multi-hole type direct fuel injector (DI), a variable cooling system, and an oil pump. Specific power was targeted at 60 kW/L to provide a "fun-to-drive" experience (TODA;

SAKAI et al., 2017). Honda's 2016 1.5 L downsized turbocharged engine was intended to replace 1.8-2.4 L NA engines (JONO et al., 2016). Their aim was also to provide "fun-to-drive" experience while meeting the environmental regulations by improving the existing 1.8 L NA design. In addition to turbocharging, DI replaced port injection and dual valve timing control (VTC) allowed for better optimization of the intake/exhaust valve overlap and timing. The power output increased by 21% to attain 130 kW (86.7 kW/L), and the torque increased by 26%. This design achieved 38% thermal efficiency and 16% better FE than the 1.8 L NA engine, from 33 MPG to 35 MPG for the EPA ratings.

Middleton et al. (2016a, 2016b) simulated the FE implications of technologies in a baseline MY2012 Ford Fusion midsize sedan. Technology included dual-cam phasing, discrete variable valve lift (DVVL), engine friction reduction, GDI, downsizing with boost, cooled EGR, and reductions in weight, drag, and rolling resistances. The engine downsizing with a turbocharger provided the largest reduction in fuel consumption (9.6%). DVVL provided a 5.7% improvement in fuel consumption. By employing a 50% downsizing, that is, from 2.5 L NA to 1.25 L TC, the FE was improved by 4.6%. Employing all technological packages along with a 10% reduction in weight and 20% reduction in drag and rolling coefficients reduced the fuel consumption by 35%, that is, from 31.8 MPG to 48.8 MPG for the combined cycle.

Spark ignition (SI) ICEs operate in a standard four-stroke Otto cycle, in which the compression and expansion strokes are symmetrical. Two over-expanded cycles, Atkinson and Miller, can increase efficiency; the former by altering the exhaust valve opening and intake valve closing timings, and the latter by having a higher expansion than the compression ratio (NABER; JOHNSON, 2014).

As discussed above, these technical gains may be partially (or totally) offset by more performance and sales-mix shifts. The same could happen for EVs. Galvin 2022 explained that EVs are still less powerful than ICEs in the US, 254 HP vs. 284 HP on average, but this gap may be closed by the emergence of super-powerful EVs, with more than 600 HP. He estimated that a 5% weight increase in smaller EVs resulted in a 4.7% increase in electricity demand, whereas for larger EVs, this number was 10.5%. If the latter were to gain the market share, it would put greater pressure on the rate of decarbonization of electricity generation. While these findings should be kept in mind, this exercise in shifting the EV market share would not be attempted here, as this would create yet another layer of complexity for the predictions.

Table 5.7 summarizes the attempt to simplify the Brazilian LDV market into a few representative models and to establish their baseline technologies in 2020. Unsurprisingly, the subcompact 1.0-liter model was the least advanced in terms of technological deployment. The most advanced was the large sedan with turbocharger, direct injection, and CVT. Turbochargers were not deployed in any significant way until 2015 (Figure 5.13, but they are now found in 1.0-liter models. Entry-level models are cheaper and profit margins are low, and thus, trickle-down effects may take some time, delaying widespread technological adoption. Additionally, if efficiency, emission control and safety requirements get above a certain point, these models stop making economic sense and tend to disappear from the market. This can have substantial environmental consequences.

Table 5.7: Baseline Technology for representative vehicle classes

Category	Eng.	Asp.	Valv. Com.	Inj.	Val/cyl	Trn.	Ngear
Subcpt.	1.0-8V	NA	SOHC	Mult.	2	MT	5
Compact	1.0-12V	NA	DOHC	Mult.	4	MT	5
Compact	1.0-12V	T	DOHC	Mult.	4	MT	6
Compact	1.6-16V	NA	DOHC	Mult.	4	MT	6
Mid-size	1.0-12V	NA	DOHC	Mult.	4	MT	5
Mid-size	1.0-12V	T	DOHC	GDI	4	MT	5
Mid-size	1.6-16V	NA	DOHC	GDI	4	AT	6
Large	1.5-16V	T	DOHC	GDI	4	CVT	0
Large	2.0-16V	NA	DOHC	Both	4	CVT	0
Cpt. SUV	1.0-12V	NA	DOHC	Multi.	4	MT	5
Cpt. SUV	1.0-12V	T	DOHC	Multi	4	AT	6
Cpt. SUV	1.6-16V	NA	DOHC	Multi	4	AT	6
SUV	2.0-16V	NA	DOHC	Multi	4	AT	6
Cpt. Truck	1.3-8V	NA	SOHC	Multi	2	MT	5

5.9 Environmental Cost of performance

This exercise consists of answering the following questions: "What if the 1.0-liter LDV were to maintain performance at the 1994 level? By how much could fuel efficiency be improved above actual values?" "What is the environmental cost?". To estimate 2020 km/L in Table 5.8, if performance held constant, values were taken from previous research (MOSQUIM; MADY, 2022). If a hypothetical vehicle was purchased in 2020, and it travelled 200000 km in its lifetime, this would mean a difference in total fuel consumption of 1027-1197 L. If this vehicle runs on gasoline with an emission factor of 2.27 kg/L, difference in total emissions would be 2.33-2.72 tCO_2. If half of the total fleet of approximately 40 million vehicles in 2020 were to be like this, lifetime avoided emissions would be in the range of 46.6-54.4 $MtCO_2$, or approximately the total LDV emissions in 2020.

Table 5.8: An exercise in "extra" GHG emissions

	Weight (kg)	Horsepower	Acceleration (s)	FE (km/l)
1994	862	53.3	19.0	11.9
2020 actual	1033	81.1	13.6	14.1
2020 fixed	862	53.3	19.0	15.2–15.4

The 2018 entry-level model actually reached 15.2 km/L combined fuel economy while accelerating in 14.7 s, with 66 HP. This was achieved by reducing model weight to 758 kg. This rate of weight reduction, while significant, is nowhere near the levels advocated by Lovins (LOVINS, 2020). In fact, he advocated for shifting the design toward aggressively reducing the tractive load. As illustrated in Table 5.4, this is the most effective way to improve fuel efficiency. The counterpoint was presented by Galvin (GALVIN, 2022), illustrating that EVs are catching up with ICE vehicles, narrowing the gap in terms of size and power, with implications for emissions.

5.10 Policy implications

Improved technology deployed since 1990 made the displacement-based tax outdated. A 1.0 liter today can move a compact SUV and be equipped with a turbocharger, thus very far from being an "entry-level" vehicle. At the same time, safety, emission control and efficiency mandates require a technological level that may take the popular car out of the market. Lastly, the emission rate dispersion in 1.0 liter engines can be quite high, with maximum rates almost 40% higher than the lowest (115 g/km vs. 83 g/km)[3], as illustrated in Figure 5.27. Note that this figure is not sales-weighted, but merely reflect available models in that year, from Inmetro (2022). Sales in Brazil are heavily skewed towards 1.0 liter models, and engines above 2.0 are far less common.

These developments may have profound consequences in future emissions, specially if consumer demand for size and power persists. Again using 200,000 km as a vehicle lifetime, and 20 million vehicles, this emission rate discrepancy in the 1.0 liter category may translate into a

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[3] This difference increases to 63% (145 vs. 89 g/km) in category B and 133% in C (240 vs. 103 g/km)

whopping 128 $MtCO_2$. These back-of-the-envelope calculations are not intended as forecasts, but merely to illustrate the major variability in future emissions within the same tax bracket.

Thus, a taxation based on CO_2 emission rates is proposed for Brazil, in line with what is practiced in Europe (ACEA, 2020). Note that it should be based on gasoline emission rates, discussed here, as the official Brazilian vehicle labelling program considers tailpipe emissions for ethanol to be zero. Obviously, it could be argued that, since rates for ethanol are zero[4], government should focus its efforts to encourage flex-fuel vehicle owners, the vast majority of the LDV Brazilian fleet, to choose this fuel. For reasons beyond the scope of this research to investigate, Brazilians choose gasoline to ethanol at about a 60:40 rate.

Policy design must be properly discussed with all stakeholders, thus the intent here is to show that the existing tax regime is outdated, and point towards its improvement. This tax can be linearly (and positively) correlated with emission rates, such as in Germany and Sweden, or nonlinear, step-wise, as in France (KLIER; LINN, 2015). It can be negative/positive for rates below/above a certain threshold, effectively subsidizing vehicles with lower environmental impact. Subsidizing entry-level vehicles, and heavily taxing the larger, more pollutant models, may be more just than the import-tax exemption for HEV and EVs, whose entry-level prices make them unavailable for the vast majority of the Brazilian population.

This policy should be placed in a broader context of improving the rate of technological adoption in Brazil[5]. Brazil has recently implemented what effectively is a fuel standard (BRAZIL, 2022). The country also has a policy to reduce average fuel carbon intensity and promote sugar-cane ethanol (RENOVABIO, 2022). The Brazilian fleet in 2013 had similar average emission rates as the United States, but vehicles here had half average power, 50% less weight, and 70% lower engine size. Conversely, Brazil had very similar numbers in these parameters as that of Japan, but 13% higher emission rates (and Japanese numbers are for 2011) (YANG; BANDIVADEKAR, 2017). This can be explained by the delayed rate of technological adoption.

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[4] While life cycle sugar-cane ethanol may not be zero, its reduction compared to gasoline is well established (WANG et al., 2012; WANG et al., 2008; MACEDO; SEABRA; SILVA, 2008; SEABRA et al., 2011).

[5] It is likely that only a mix of policies can be hopeful to achieve the deep levels of emission reductions required, and no single policy can be this effective (AXSEN; PLÖTZ; WOLINETZ, 2020)

Figure 5.27: Fossil CO_2 emissions rates for displacement group. A refers to 1.0 liter engines, B for above 1.0l and below 2.0l, C for more than 2.0l. Values for 2021 from Inmetro (2022)

5.11 Conclusions

This Chapter estimated rates of technological progress for the LDV fleet in Brazil for the period 1990–2020. The main focus was on LDV acceleration performance, which can be estimated, with good accuracy, using just vehicle horsepower and weight. On average, about 20% more performance can be extracted from the same level of power, comparing a 2020 with a 1990 model. Deployment of newer engine technologies allowed more power and torque to be extracted from the same engine size and their effects were numerically estimated as well. A 10-year delay in technological adoption, comparing the Brazilian to the USA fleet, was found. This gap makes the Brazilian fleet, while smaller and less powerful, relatively "dirt".

The heyday of the Brazilian popular car is over and this can have profound environmental consequences. The pursuit of a fun-to-drive experience means acceleration performance tend to improve over time. This is true within a LDV category and for the whole fleet. Brazil is no different in this regard, though economic reasons may keep this magnitude lower than in developed countries. This has implications in fuel efficiency and thus GHG emissions. Also, technological advancements over time may affect LDVs is subtle ways. The first is that a taxation based on displacement may have become obsolete since it was instituted. The second is a pronounced variability in emission rates within the same engine size. Two main policies are in place in Brazil, one which effectively acts as a fuel standard, Rota 2030, the other as a fuel standard, RenovaBio. This can be complemented with a CO_2 tax for LDVs, with hopes to skew consumers towards less environmentally damaging models. This proposed tax could complement or replace the taxation based on displacement, which may have lost some of its effectiveness, due to reasons exposed in this text.

The need to act now to avoid dangerous climate change means focusing on the ICE, which is present in the overwhelming majority of LDVs in Brazil and will continue to be so for the next years. Also, shifting perspective towards absolute, or "avoidable", emissions may be necessary. Theoretical, relative, "avoided" emissions may not bring the deep levels of reductions needed. Pursuit of size and power make the challenge of reducing emissions greater, and this may have implications beyond the ICE.

Chapter 6

Final discussions

This chapter will provide a discussion summarizing and connect the three main chapters in this thesis.

This thesis main premise is that we have a considerable knowledge gap regarding critical variables related to LDV fuel use and GHG emissions. Forecasting and policy accuracy can be significantly improved when these are properly researched. However, providing an exhaustive examination of all those variables is beyond a single thesis scope. The focus here was on Internal Combustion Engines. ICEs will still power the majority of LDVs in the near future, at least. The need to act now to avoid dangerous climate change, and the room from improvement in this technology, was the main reasons for studying it.

While the technological forward march is inexorable, efficiency may be less so. This distinction is fundamental, as many aspects of a LDV run against better fuel economy, such as more weight, power, and size. This thesis sought to estimate technological improvement rates from various angles. In the process, trends in key variables related to technology, performance, and acceleration were systematized for Brazil for the first time. Lastly, this thesis avoided making bold, single-outcome predictions, as this would contradict the central premise. Fuel economy can be doubled or stagnate in the next 10 to 15 years. What path the society will follow depends on economic, political and social factors, which, by nature, are very uncertain. What is certain is that, to achieve deep reductions in emissions, several trends must be reversed.

6.1 Main findings

Chapter 3 main idea was to use an updated definition of exergy efficiency to provide a glimpse of resource use in society. Formal studies in the area depended on estimations with no connection with actual vehicle data. A novel way of using the Second Law of Thermodynamics defined the vehicle as a transportation service provider. Its efficiency is related to how much fuel is needed for this service. This definition, in turn, produced the necessity to compile actual vehicle data and allowed to trace its evolution for the period 1970–2020. Efficiencies were low, never above 10%, as in Figure 3.9. This value is below the traditionally used in the literature, which usually converges to a critical study published in 1980 (see Table 3.5).

The efficiency definition uses vehicle mass, but if one considers that the purpose of a vehicle is to move people, efficiencies drop even further. While technologically impressive, using 1000 kg of material and fuel to carry an 80 kg person is not very efficient.

An essential aspect of these developments is that variables which affect a vehicle's fuel consumption may evolve in opposite ways, partially or totally offsetting each other. A lower drag coefficient reduces road load, thus the energy required to move the vehicle (Eq. 3.15). But reductions in drag coefficient ocurred simultaneously with increases in frontal area Figure 3.4). This last variable directly correlates with additional weight (Figure 5.11). Vehicle weight, in turn, is one of the most critical factors which affect fuel efficiency (Table 4.2). This chapter was the first to be finished and published. With hindsight, Lutsey and Sperling's (2005) approach is similar, with the critical difference being that their work relied on statistical analysis, which was the primary method for the remaining of this thesis. The modular approach has its shortcomings and this is certainly one.

Chapter 4 objective was to estimate rates of technological progress. This expands the definition beyond fuel efficiency, accounting for improvements in performance as well. In fact, the key aspect is that improvements in performance offset some potential fuel economy gains. This trade-off is vital, because failure to consider it may result in projections being overly optimistic and unrealistic. Emphasis in Reducing Fuel Consumption (ERFC) is a metric used to illustrate this trade-off. A value of one means all technology was spent in fuel efficiency, zero that all was spent in performance.

The rate of technological progress was estimated at 30% for the period 1990–2020 (Table 4.2), of which about 35% was used for performance improvements. This rate of improvement was uneven, though, with current values reaching close to 3% per year. An estimate of sales-weighted average fuel economy was also made (Figure 4.3). Trends in key vehicle parameters and how they relate to fuel economy may be seen in Figure 4.4. Vehicle characteristics' impact on fuel economy are close to engineering principles (Table 4.1) and those found in the literature. Their usefulness here was to estimate rates of technological development.

Lastly, this range of technological progress and sales-mix scenarios for vehicle categories were employed to estimate fleet-wide fuel efficiency for the years 2030 and 2035. Future fuel efficiency can vary by more than 50% in 2030 (Table 4.5) and 120% in 2035 (Table 4.5), depending on the rate of technological improvements, EV uptake, fleet downsizing, and ERFC. To achieve the highest values in fleet-wide fuel efficiency consumers may need to renounce vehicle size and power.

Chapter 5 main objective was to trace the evolution of acceleration, the key performance indicator. Enhancing acceleration capability requires more power, thus energy (Table 4.1), all else equal. A similar approach was that employed in Chapter 4 was used to estimate technological improvements, from an acceleration performance perspective. Engineers can extract about 20% more performance from the same level of power, comparing 2020 with 1990. This happened because of the deployment of more advanced technology over time. The deployment of key technologies were traced. Comparisons with the USA market point that there is about a 10-year gap in a technology adoption for the Brazilian market (Table 5.1). This may be explained by the dominance of cheaper, thus technologically less advanced, models (Table 5.7).

Technological progress had other subtle, but important implications. The first is that the 1.0 liter engine, historically associated with entry-level models, can now be found in a turbocharged, compact SUV. This distinctively Brazilian vehicle is also getting bigger, heavier and more powerful, to the point than entry-level and 1.0 liter vehicles are not synonyms any more. As illustrated in Chapter 3, this directly impacts fuel efficiency. Also, as specific power (Horsepower per liter of engine displacement, 5.25) and torque (5.26) have increased in the period 1990–2020, displacement based taxation may be in need of an update.

Finally, emission rates for 1.0 liter engines have a substantial dispersion, about 40% (Figure 5.27). This is true for engines between 1.0 and 2.0 liters as well. Taxing LDVs by emission rate is already done in Europe, and it is proposed here that Brazil institute one as well. The finer details of the workings of this taxation scheme are beyond the scope of this thesis, which sought to illustrate the out-of-date nature of the one in place today.

6.2 Contributions

Main contributions are the rates of technological improvements and what impacts fuel efficiency. The **direction** many of the variables discussed are headed is also presented, most of them for the first time in Brazil, either in the depth presented or the time period, or both. This is fundamental when modellers choose to select an input value. What this thesis provides now is the likelihood for that to happen. In practical terms, if a modeller says that in her version of the future fleet-average vehicle weight is reduced, this is counter the tendencies observed until now. Not that this is impossible to happen, just that her assumption is optimistic.

6.3 Limitations and future work

The main limitation of this thesis is access to data. Many hours were spent compiling and crossing information from different sources. While main findings are statistically significant, regression analysis can always be improved with more data. Not all variables related to engine performance could be used, such as compression ratio. More data-points could refine key metrics such as ERFC, here presented as an average value for 1990–2020. Yearly values could give better insight and correlated with metrics such as economic growth, fuel prices and fuel economy standards. A key question not answered here is if Brazilians buy more efficient vehicles if fuel prices are high, or if cheaper models are sold in times of economic crisis.

Vehicle weight is one of the most important parameters, as it directly impacts all metrics studied here: exergy efficiency, fuel efficiency and acceleration performance. While general trends were shown, they hide the fact that the deployment of weight-saving materials are simultaneous with the inclusion of safety, emission control and comfort features, all of which add weight. A proper consideration of these developments is desired.

Electric vehicles of all sorts will probably play an important role in the future, so they could benefit from the same level of scrutiny given here to ICEs. Rates of technical improvements could be estimated, as well as engineering relationships such as trade-offs between efficiency and performance.

Economic aspects were not considered here. More expensive models tend to have improved technology compared with cheaper ones, thus they can be relatively more efficient. Or they can be as efficient, but with improved performance. But, as discussed above, shifting the fleet towards smaller vehicles can have great impact in reducing overall fuel consumption and emissions. Safety, efficiency and emission requirements may also make entry-level models disappear from the market, due to their lower price and profit margins. How to solve this issue was not attempted. Though an update to the taxation regime was proposed, the exact details were not discussed. This discussion needs to be done with all stakeholders involved.

There is a need to better understand vehicle kilometers travelled. Many studies relied on an estimation from 1982 for São Paulo. This estimation was revised down in 2012, by the same source. It is unlikely VKT was reduced in the period, as this runs counter tendencies observed everywhere. This gap was the main reason no attempt was made to forecast GHG emissions. Vehicle scrap rates also play a major role, due to extended lifetimes and slow fleet turnover. While a thorough review was not attempted, studies usually converge towards a single source, also static in nature.

Ethanol from sugar-cane has potential to reduce emissions. This is well established, even though land use implications from its expansion are a source of uncertainty. The sparse attention to ethanol here was not an attempt to discard the fuel as an alternative. The main fact is that gasoline, for reasons beyond the scope of this thesis, is still the main fuel used in Brazil. Second, most of the findings here, such as the impact size and power have on fuel efficiency, are the same for ethanol.

Chapter 7

Conclusions

This thesis sought to improve our understanding about the LDV in Brazil, analysing it from three distinct, but related, approaches. The main focus was on technology, past developments, and the ICE engine. From a broader perspective, the LDV is simply not very efficient at providing the service of moving people, and this fact did not change much over time. Delving deeper into the vehicle itself, technological advancements were estimated from different angles. A yearly rate of 1% in technological gains was observed, but about a third was offset by better performance. This means some extra emissions were caused by vehicles getting larger and faster, and this trend continues. Fleet-wide fuel efficiency may vary by a factor of more than two in the next decade or so, depending on the trajectory of key variables. Trends in some of these characteristics, such as weight, size, power, acceleration performance were traced, most of which were unpublished in Brazil. Understanding these trends is necessary for better energy planning. This thesis also provides inputs to modelling future energy use. This modelling should be of a stochastic nature, to account for uncertainties. Finally, technological improvements made the displacement-based tax in need of an update. As such, a direct carbon tax is proposed.

Studies about the future of the LDV tend to estimate avoided emissions on a relative basis, by a number of different pathways. The most common are those which rely on technology. Thus a prospective future, in which technology is employed in a efficiency-oriented manner, is compared with a BAU. This BAU sometimes takes the form of a "no change". As extensively shown here, things are changing all the time. While this reasoning can be important to illustrate the effects some policy or technology can have, dealing in relative terms may not be the best approach. If we take into account the fact that there is a carbon budget in which we have to operate in order to avoid dangerous climate change, we have to approach the problem in absolute therms. This means every extra gram of CO_2 that was sent into the atmosphere to be accounted for. Evidently, this "extra" can be a very controversial topic, as we are dealing with human desires and needs. As shown here, desire for size and power makes the challenge of reducing absolute emissions harder.

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