Regulation as inductor of environmental technologies for the reduction of toxic emissions from light vehicles in Brazil

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Abstract

In recent decades many countries have taken actions to reduce toxic emissions from cars and, especially, reduce risks to public health. Research indicates a statistically significant relationship between carbon monoxide (CO) and respiratory diseases. Regulations were vital to set targets and standards that fostered the technological improvement of automobiles. The goal of this research was to analyze the role of regulation as an inductor to automotive environmental technologies in the reduction of toxic emissions from light vehicles manufactured in Brazil. A qualitative descriptive research with a documentary base was carried out. The diffusion of these technologies in Brazil shows a chronological gap between the implementation phases of the European regulations and Program for the Control of Air Pollution from Automotive Vehicle (PROCONVE). Research results show that regulation has fostered the diffusion of environmental technological innovation, with the introduction of electronic fuel injection, catalytic converter and engine improvement. According to the changes identified, legislation leads to a technological balancing process among car manufacturers with a scale gain, in order to promote the diffusion of environmental technologies to reduce emissions of toxic gases..

Keywords: Environmental Technologies. Environmental Regulation. Eco-innovation. Light vehicles. Emission reductions of toxic gases.

A regulamentação como indutora de tecnologias ambientais para a redução de emissões tóxicas em veículos leves no Brasil

Resumo

Nas últimas décadas, diversos países adotaram ações para mitigar as emissões tóxicas dos automóveis e, principalmente, reduzir riscos à saúde pública. Pesquisas indicam uma relação estatisticamente significativa entre monóxido de carbono (CO) e doenças respiratórias. A regulamentação teve um papel vital na definição de metas e padrões que fomentaram o desenvolvimento tecnológico dos automóveis. O objetivo deste artigo é analisar o papel da regulamentação como indutora da inovação tecnológica ambiental na redução de emissões tóxicas de veículos leves fabricados no Brasil. Realizou-se uma pesquisa qualitativa descritiva de base documental. A difusão dessas tecnologias no Brasil mostra defasagem cronológica entre a implementação das fases da legislação Euro e do Programa de Controle da Poluição do Ar por Veículos Automotores (PROCONVE). Os resultados da pesquisa mostram que a regulamentação fomentou a difusão da inovação tecnológica ambiental, com a introdução de injeção eletrônica de combustível, catalisador e melhoria da motorização. Diante das mudanças identificadas, a regulamentação leva a um processo de balanceamento tecnológico entre as montadoras com ganho de escala, de modo a favorecer a difusão de tecnologias ambientais para mitigar as emissões de gases tóxicos.

Palavras-chave: Tecnologias ambientais. Regulamentação ambiental. Ecoinovação. Veículos leves. Redução de emissões de gases tóxicos.

La reglamentación como inductora de tecnologías ambientales para la reducción de emisiones tóxicas de vehículos livianos en Brasil

Resumen

En las últimas décadas muchos países han tomado medidas para mitigar las emisiones tóxicas de los automóviles y, sobre todo, reducir los riesgos para la salud pública. Las investigaciones indican una relación estadísticamente significativa entre el monóxido de carbono (CO) y las enfermedades respiratorias. La reglamentación tuvo un papel vital en el establecimiento de metas y estándares que fomentaran el desarrollo tecnológico de los automóviles. El objetivo de esta investigación es analizar el papel de la legislación como inductora de la innovación tecnológica ambiental en la reducción de emisiones tóxicas de los vehículos livianos fabricados en Brasil. Para lograr este objetivo, se realizó una investigación cualitativa descriptiva de base documental. La difusión de estas tecnologías en Brasil muestra el desfase cronológico entre las fases de implantación de la reglamentación en Europa y del Programa de Control de Contaminación del Aire por Vehículos Automotores (PROCONVE) en Brasil. Los resultados de la investigación muestran que la reglamentación fomentó la difusión de la innovación tecnológica ambiental, con la introducción de inyección electrónica de combustible, conversión catalítica y mejora en los motores. Ante los cambios identificados, la legislación lleva a un proceso de equilibrio tecnológico entre los fabricantes de automóviles con economías de escala, con el fin de promover la difusión de tecnologías ambientales para mitigar las emisiones de gases tóxicos.

Palabras clave: Tecnologías ambientales. Reglamentación ambiental. Vehículos livianos. Ecoinnovación. Reducción de emisiones de gases tóxicos.

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INTRODUCTION

The individual transportation model has led to an increase in energy consumption and, consequently, in emissions. Governments of developed countries have acted to manage mobility means and the control and planning of transportation modes, due to the environmental and energy impacts caused by this sector. Emissions from means of transportation, including light vehicles, have drawn attention because they affect public health. This was observed in many studies (FREITAS, BREMNER, GOUVEIA et al., 2004; CANÇADO, BRAGA, PEREIRA et al., 2006; CARVALHO, FREITAS, MARTINS et al., 2015; BERGEK and BERGGREN, 2014) that show the cause and effect relationship between emissions from modes of transportation and their impact on public health.

According to Carvalho, Freitas, Martins et al. (2015), air pollution has affected population health, and automobiles and other means of land transportation were identified as the major cause of this environmental imbalance in metropolitan areas. Among the main pollutants emitted by automobiles are carbon monoxide (CO), nitrogen oxides (NO_x), and hydrocarbons (HC) - the last two are ozone (O_3) precursors. As a result of pollutants that originate from fossil fuels burn, we observe the increase in mortality and the incidence of respiratory diseases (CANÇADO, BRAGA, PEREIRA et al., 2006).

Since the 1940s, air contamination episodes in different regions of the planet led to the control of air pollutants in several countries. In the 1970s, researchers believed that these limits were safe, but only in the 1980s, with the emergence of computing, a more accurate analysis of health effects became possible. A survey with statistical analyses of air quality, from 1993 to 1997, identified a statistically significant relationship between CO and the incidence of illnesses related to the respiratory system, as well as increased mortality - mainly among elderly people. O_3 was also associated with respiratory diseases (FREITAS, BREMNER, GOUVEIA et al., 2004).

Automobiles are responsible for the largest volume of toxic gas emissions in the atmosphere. To change this scenario, in 1986, the National Council for the Environment (CONAMA) established the Program for the Control of Air Pollution by Automotive Vehicles (PROCONVE). According to Carvalho, Freitas, Martins et al. (2015), there were reductions of CO and NO_x concentration in the Metropolitan Region of São Paulo between 1996 and 2009, despite the fact that the fleet more than doubled during these years.

For Lee, Veloso, Hounshell et al. (2010), the rigor of the environmental legislation is a challenge for automakers and suppliers; the authors also mention the regulatory policy of command and control as one of the main factors of compliance with the automobile environmental legislation in the United States. Since 1960, Organization for Economic Co-operation and Development (OECD) members have encouraged the development of technologies to reduce emissions from mobile sources, and in the following decades, legislation in several countries lowered emission limits. Technological or economic control instruments led to different types of innovation (BERGEK and BERGGREN, 2014). The regulation of automobile emissions in the US began in the mid-1970s, and progressed during the 1990s, with the introduction of the low-emission vehicle program. European automobile environmental regulation began in 1985, aiming to reduce toxic gas emissions (DIJK and YARIME, 2010). In 1979, Japan introduced the first standard for fuel economy (LIPSCY and SCHIPPER, 2013).

Due to the impact of automobile toxic emissions on the environment, the car industry has acted according to regulations. In the last decades there were several actions to meet the new regulations and seek more competitive products. In this scenario, automakers have implemented environmental technological innovations in their products and spread them to the different countries where they operate. Thus, the objective of this article is to analyze the role of regulation as an inductor of environmental technological innovation in the reduction of toxic emissions from light vehicles manufactured in Brazil. This descriptive qualitative study contributes to the systematization of information on automobile environmental technologies related to the spark ignition internal combustion engine (SI - Otto cycle) and its process of diffusion in the Brazilian market.

THEORETICAL FRAMEWORK

According to a report from the Institute for Environmental Studies (IVM, 2006, p. 3), “eco-innovation is also synonymous of innovation in environmental technology”. Environmental innovation can be translated as “innovation that serves to prevent or reduce anthropogenic pressure on the environment, to clean the damage already caused, or to diagnose and monitor environmental problems” (HEMMELSKAMP, 1997; VINNOVA, 2001, p. 14). External factors that drive companies to use solutions based on environmental innovation range from the reduction in the use of resources to optimize product price, passing through the competitive advantage of environmentally correct products, to reach cases that comply with government regulations that focus on the improvement of environmental performance (VINNOVA, 2001).

For OECD (2009), the objectives of eco-innovation are based on the four types of innovation described in the Oslo Manual: product, process, marketing, and organizational. The first two types, product and process, depend on a broad technological development, while the others consist more of non-technological changes. Based on the literature on eco-innovation, we observe how this concept has gained relevance, but its attributes and impacts are often unknown to companies and not considered in policy decisions. To improve the understanding of eco-innovation's concept and practices, qualitative measurements can provide inputs to decision makers in order to analyze trends, and identify drivers and barriers (BOCKEN, FARRACHO, BOSWORTH et al., 2014). Greater proximity between innovation and environmental policy could benefit both areas and foster efforts towards eco-innovation (OECD, 2009).

Carrillo-Hermosilla, Del Río and Könnölä (2010) observe that the definitions of eco-innovation are generic; for this reason, the need to classify eco-innovation has increased, aiming to broaden the specific understanding of this concept. Eco-innovation definitions focus on reducing environmental impact and may or not be motivated by environmental issues. The result of an environmental innovation may originate from a proposal for this purpose or be a side effect of an innovation, but both fall within the concept of eco-innovation. For the authors, eco-innovation is the improvement of environmental performance with the consequent reduction of environmental impact, and it can be incremental or radical. The former adds value to the current model and keeps existing systems and networks, while the latter creates added value by replacing and building new networks and systems. Design is a crucial feature in addressing both the improvement of an existing system and the creation of a totally new one.

The rigor of emissions regulation drove investments in environmental technologies to reach the limits established by legislation in several countries (BERGEK and BERGGREN, 2014). The incremental environmental innovation (CARRILLO-HERMOSILLA, DEL RÍO and KÖNNÖLÄ, 2010) was introduced in the SI engine propulsion system to reduce toxic gas emissions such as CO, HC, NO_x, which made the regulation one of the main drivers of environmental innovation in the automotive industry (DIJK and YARIME , 2010). As of the 1970s, there was an emergence of government programs in the United States, European countries, Japan and several others to control the emission of toxic gas from cars (BERGEK and BERGGREN, 2014; DIJK and YARIME, 2010; LIPSCY and SCHIPPER, 2013).

Regulation as inductor of environmental technological innovation in the car industry

Kneller and Manderson (2012) investigated the relationship between environmental legislation and innovation, and used manufacturing industry data between 2000 and 2006, a period of strong regulation in the United Kingdom. Environmental legislation encourages innovation, but the environmental impact of economic activity is closely related to the available technology. Literature reviewed for this study shows some articles that assessed the relationship between environmental legislation and innovation. In many cases, both go in the same direction; on the other hand, long-term analysis does not keep the same correlation. Our hypothesis that environmental legislation stimulates innovation identified that there is an incentive for research and development (R&D). However, we did not observe a positive impact of the costs for meeting the environmental requirements on total investment. We also observed the reduction of investments in conventional innovation, under the pressure of environmental legislation, and their redirection to environmental innovation.

Horbach's (2008) analysis of innovative firms in Germany found that regulatory measures and cooperative innovation among highly skilled firms are more favorable to environmental innovation than to other types of innovation. Another attribute identified in the study refers to companies in sectors with a significant sales volume of new products, which also tend to be more innovative, thus having an environmental gain. The author analyzed environmental innovation beyond a momentary vision of a stage, instead took into account the dynamics of the whole process. He found that environmental innovation has been little influenced by the market, as compared to other innovations, indicating that regulation is the main inductor of this type of innovation. Regulation can also contribute to increase the company's perception of the benefits achieved with environmental innovation, which would otherwise occur in an unstructured way, hindering this perception.

Zapata and Nieuwenhuis (2010) pointed to the European market as an innovator in the automotive sector, as well as in the regulatory process, sometimes relying on references from other markets, such as Japan. Automotive competition events served as a laboratory for some technologies inherited by industry. In addition to technologies that enhance performance and safety, the increase in the strictness of legislation on emissions has driven the improvement of this segment.

The control of toxic gas emissions from automobiles originated in the United States in the 1960s, culminating in 1970 with the US Clean Air Act Amendment (USCAAA). It set targets that limited CO, HC and NO_x emissions by 90%, in 1975 and 1976. There was no reduction of limits in the 1980s, but again in 1990 (Tier I standard). Tier 2 standard was established in 2004 and was expected to achieve 98% of HC reduction and 95% of CO reduction compared to 1970s' standards. Europe introduced a similar regulation, by imposing limits on cars emissions. Euro 1 level was introduced in 1992, Euro 2 in 1996, Euro 3 in 2000, Euro 4 in 2005, Euro 5 in 2009, and Euro 6 in 2014, reducing by 90% the vehicles' toxic gas, in relation to the pre-regulatory period (BERGEK and BERGGREN, 2014).

As an example of the effects of legislation, Box 1 summarizes the main technologies introduced in gasoline vehicles in Europe, to comply with the legislation on toxic gas emission control.

Box 1

Technologies introduced in each stage of legislation on emissions in Europe

Legislation Stage	Year	Technologies
Euro 1	1992	MPFI* and three-way catalyst
Euro 2	1996	MPFI and three-way catalyst
Euro 3	2000	MPFI, three-way catalyst and second oxygen sensor
Euro 4	2005	MPFI, three-way catalyst and second oxygen sensor
Euro 5	2010	MPFI, three-way catalyst, second oxygen sensor and catalyst improvement

* MPFI = multi-point fuel injection.
Source: KOUSOULIDOU, NTZIACHRISTOS, MELLIOS et al. (2008).

To comply with the limits set by legislation, some technologies were introduced into the propulsion system to reduce toxic gas emissions. Prior to Euro 1 (ECE 15/04), the technology of gasoline cars was the single-point fuel injection system with oxidation catalyst. Since the introduction of Euro 1, gasoline vehicles are equipped with multi-point fuel injection (MPFI) and three-way catalyst. In phases 3 and 4, vehicles received the second oxygen sensor and, in phase 5, in 2010, vehicles were equipped with catalysts with better materials for gas conversion (KOUSOULIDOU, NTZIACHRISTOS, MELLIOS et al., 2008).

Environmental technologies for the reduction of automobile toxic emissions

In order to improve air quality, harmed by pollutants expelled by automobiles, developed countries created several environmental technologies innovations and spread them to other countries. Since the 1980s, Brazil has received several technologies for toxic gas reduction, either from exhaust or fuel evaporation system. In this case, changes occurred to comply with environmental requirements.

The current technology of internal combustion engines follows the same operating principle developed by German engineer Nikolaus August Otto (1832-1891), used in automobiles since the 1880s. From the 1990 decade, this motorization has received several technological innovations to improve performance and decrease emissions, which significantly reduced fuel consumption and in some cases kept it, even with the increase in the number of cars. After 1990, engines were gradually equipped with the variable valve timing (VVT), in US and Europe, and since 2002 direct fuel injection has furnished car engines. These technologies increased power without raising emission levels. In the mid-1990s, electric technologies became part of the automotive scenario, starting with the electric (battery) propulsion, but with low sales volume due to their high price. After 1997, the electric hybrid vehicle got on the scene, with more expressive sales from the following decade (DIJK and YARIME, 2010). The diffusion process of environmental innovation does not always result from a spontaneous market demand, since customers do not necessarily accept price increases due to environmental improvements in the product (OLTRA and SAINT JEAN, 2009).

The international diffusion of emission-related innovation technologies requires a lot of R&D effort, which demands a large volume of units to amortize costs. Patents researched by Dechezleprêtre, Neumayer and Perkins (2015) were extracted from seven categories of automotive emissions' reduction: air/fuel ratio devices; technologies for fuel injection; catalysts and other post-combustion devices; ventilation device to purify air after exiting the crankcase; exhaust gas recirculation valve (EGR); on-board diagnostic (OBD) systems; and oxygen, NO_x and temperature sensors. And two others were identified: monitoring device for exhaust gas treatment; and closed-loop correction control (DECHEZLEPRÊTRE, NEUMAYER and PERKINS, 2015).

Lee, Veloso, Hounshell et al. (2010) observed that regulatory pressure leads to innovation, and also evaluated the main components introduced in US vehicles, from 1970 to 1998, based on patents and publications regarding automotive emission. The components introduced at the time were: catalyst, crankcase positive ventilation system, evaporation control system, electric control of the vacuum feed line, thermal valve for vacuum control (thermal control of the vacuum line for high temperature advance), air injection reactor (injects air into the exhaust for HC burning) and EGR valve. These components were adjusted to work in the engines of that time (1975). Currently, some of these devices are still used, but under electronic command. In the 1990s, electronically controlled devices were introduced, such as fuel injector, a system to accelerate the catalyst heating (a secondary air injection), oxygen and nitrogen oxides (NO_x) sensors, and on-board electronic management system. Based on statistical analysis, Lee, Veloso, Hounshell et al. (2010) identified that 93% of the patents on automotive emission technology are concentrated in automakers and suppliers, and more than 80% are American or Japanese.

These technologies for reducing toxic gas emissions from automobiles played an important role in improving air quality. Box 2 presents the environmental technologies for the decreasing automotive toxic emissions, classified as *incremental technological environmental innovation*.

Box 2

Incremental environmental innovation for the reduction and control of automobile toxic emissions

Environmental technologies	Definitions and indicators	Authors
Air/fuel ratio devices	Idle adjustment; adds small amount of secondary fuel; high-pressure gasoline device; adds secondary air to the mixture.	Dechezleprêtre, Neumayer and Perkins (2015).
Technologies for fuel injection	Electronic fuel injection; pump drives; fuel injection sequenced by distributor; anti-knock injection, pressure or volume adjustment device; heating devices; devices for cooling/heating or insulation; devices with fuel conduit or ventilation; injectors combined with other devices; low pressure fuel injection devices.	Dechezleprêtre, Neumayer and Perkins (2015); Lee, Veloso, Hounshell et al. (2010).
Catalysts and other post-combustion devices	Purification devices; exhaust inoculation or treatment; catalytic conversion of noxious exhaust components; regeneration or recycling of reagents; metal oxide or hydroxides catalyst; group of platinum metals.	Dechezleprêtre, Neumayer and Perkins (2015); Zapata and Nieuwenhuis (2010); Lee, Veloso, Hounshell et al. (2010); Oltra and Saint Jean (2009).
Crankcase positive ventilation system	Ventilation device for purifying the air before leaving the crankcase (for ex. oil removal).	Dechezleprêtre, Neumayer and Perkins (2015); Lee, Veloso, Hounshell et al. (2010).
Exhaust gas recirculation (EGR) valve	Exhaust device combined with profiting exhaust energy device	Dechezleprêtre, Neumayer and Perkins (2015); Lee, Veloso, Hounshell et al. (2010).
On-board diagnostic (OBD) systems	Electrical control of combustion engine; electrical control of fuel mixture supply; combined electric control of two or more functions; fuel injection device by electronic control; electronic control of exhaust gas treatment.	Dechezleprêtre, Neumayer and Perkins (2015); Lee, Veloso, Hounshell et al. (2010).
Oxygen, NO_x and temperature sensors	Monitoring devices of exhaust gas treatment; correction control of combustible mixture by closed loop.	Dechezleprêtre, Neumayer and Perkins (2015); Lee, Veloso, Hounshell et al. (2010).

Source: Adapted from Dechezleprêtre, Neumayer and Perkins (2015).

The flow between environmental policy and transnational diffusion of technology increases as the regulatory gap between countries becomes smaller. Thus, those that receive technologies for emission reduction have a greater regulatory proximity with developers, proving that high rigor in legislation has little effect on technology diffusion, but instead the similarity of regulation between donors and recipients. Countries that are pioneers in regulation tend to develop new technologies, achieve productive scales that make them feasible, as well as to patent and learn from these technologies (DECHEZLEPRÊTRE, NEUMAYER and PERKINS, 2015).

Automotive technological development can take place in automakers or originate from suppliers. When the innovation process occurs internally, it is a closed innovation, which gives a better financial return due to pioneerism. When innovation is open, technological development is carried out together with competitors and partners. This model allows the reduction of cost and term and dilutes risk of the new technology among the participants (LOPES, FERRARESE and CARVALHO, 2017).

METHODOLOGICAL PROCEDURE

We used the method of descriptive qualitative research. This type of study aims to get detailed field information, from people and documents, in order to understand the environment where the situation is inserted, seeking to understand a process and not just a simple result (GODOY, 1995). Our descriptive study sought data on regulation as inductor and diffuser of automotive environmental technologies for the reduction of toxic emissions from light vehicles manufactured in Brazil.

To do this we collected secondary data from documents at PROCONVE, CONAMA, Brazilian Institute for the Environment and Renewable Natural Resources (IBAMA), Environment State Council (CONEMA) and Ministry of Environment (MMA). Diesel vehicles were excluded because this type of engine has some technological differences compared to the Otto cycle; in addition, emissions have different components and proportions from spark ignition engines.

According to Bardin (2011), documentary analysis provides the representation of information with a suitable approach to the current context, adjusting the researched content to the study's scenario. The representation based on the original text allows the creation of categories with common themes, in order to handle the content towards the identified standards. For data processing it is necessary to codify them so as to achieve a representation of their attributes. The main categorization was the classification by sets and regroupings, according to the criteria defined in the theoretical framework. Thus, the qualitative analysis allowed deductions on the subject and specific inferences, which reduced the categories into topics of higher frequency, highlighting those with relevant values. In the category of "incremental environmental innovation", we identified seven subcategories: a) air/fuel ratio devices; b) technologies for fuel injection; c) catalysts and other post-combustion devices; d) crankcase positive ventilation system; e) EGR valve; (f) OBD systems; and g) oxygen, NO_x and temperature sensors (DECHEZLEPRÊTRE, NEUMAYER and PERKINS, 2015).

Result analysis was based on the evidence of secondary data, allowing the convergence between the sources. Documentary data collected at PROCONVE, IBAMA, MMA and CONEMA were triangulated with published articles, which enabled the creation of relationships and evidence that increased the reliability and internal validity of information (YIN, 2005). The articles addressed: reduction of emissions in the face of Brazilian automotive regulation; list of pollutants that cause health problems in Brazil; prediction of toxic emissions in Europe; study of energy efficiency in the Japanese transportation sector; technological evolution in the light of US regulation; environmental regulation and its influence on innovation in the UK; impact of policy instruments on environmental innovation in Germany; blockades and dimensions of innovation; and concepts of environmental innovation in the automotive industry.

RESEARCH RESULTS

In 1986, CONAMA Resolution 18 established PROCONVE, which inaugurated a new phase for the environmental control of Brazilian auto industry. This resolution establishes guidelines, deadlines and legal emission standards for each category of motor vehicles, whether domestic or imported. Several technological innovations were introduced in cars, aiming to improve air quality. PROCONVE has followed the technological evolution of Brazilian vehicles for three decades, contributing to reduce toxic gas emissions. For light vehicles, the program established stages for the control of different gases, both from exhaust and evaporative emissions.

The first phase, for light vehicles (L-1), introduced in 1988 the control of evaporative emissions in vents, caps and reservoir connections, with technologies to control fuel supply systems, tank and pipelines. The most noticeable change took place in Phase L-2, in 1992, when some cars were equipped with electronic fuel injection system, reducing vehicle consumption and emissions. The first two phases were carried out according to the limits set by CONAMA Resolution 18, in 1986. CONAMA Resolution 15, of 1995, established emission limits for phase L-3, with final implementation in 1997. In that phase, the mixture control was improved, as well as the engine electronic monitoring, with reduced CO emissions. In L-2 and L-3 phases, cars received significant enhancements in the mixture control, in the electronic fuel injection system and in the catalyst, technologies that were spread by suppliers.

CONAMA Resolution 315, of 2002, established new emission limits for phases L-4 and L-5, introduced in 2005 and 2009, respectively. In these stages, engines received improvements in internal components, developed by automakers, giving priority to the control of HC and NO_x emissions, as precursors of O_3, by introducing technological innovations in the combustion chamber. In addition to motorization, some components were improved by suppliers to reduce NO_x and HC emissions, such as injectors and catalyst. With these new technologies inserted in vehicles throughout the PROCONVE phases, the goal of reducing toxic gas emissions and improving population health conditions was met (IBAMA, 2011). The last phase of the program, L-6, started in 2014 for new models, and was completed in 2015 for all the other vehicles. In this phase the limits for CO and NO_x from gasoline (E22) or flex fuel engines were reduced (CONAMA, 2009). This stage was accomplished according to the limits established in CONAMA Resolution 415, of 2009. The diffusion of technologies for CO, HC and NO_x reduction went on, through continuous improvement and monitoring of cars emissions (CONAMA, 2009).

In order to ensure the integrity of these emission control technologies, CONAMA Resolution 354, of 2004, established that vehicles should be equipped with the on-board diagnostic system "OBDBr-2", for the electronic monitoring of emissions, introduced between 2010 (60% of vehicles) and 2011 (100%). Its technological base is the monitoring of emission control systems, acting with corrective measures to avoid the increase of pollutants' emissions. The system enables these functions through on-board programming of the engine control unit, and also uses a second oxygen sensor to monitor catalyst efficiency. In case of a fault that reaches the limit of toxic gas emission (IBAMA, 2009), the system turns on the Malfunction Indicator Lamp (MIL), which warns the driver of the existence of an emission problem in the car, that is, a failure in any component or an undesirable action that reaches the emission limit (CONAMA, 2004; IBAMA, 2009).

To keep the effectiveness and proper functioning of the devices and technologies inserted in automobiles, CONAMA Resolution 007/1993 established that all vehicles in use should be inspected periodically to evaluate components' integrity and, therefore, to ensure the authenticity of the of emission control systems. This should be done annually and the priority was to implement it in cities or regions where air quality was affected by pollutants' emission from the local fleet. In 2009, CONAMA Resolution 418 established criteria for the elaboration of Vehicle Pollution Control Plans (PCPV), for the implementation of environmental vehicle inspection, to be conducted by state and local agencies in cities with more than three million vehicles. Despite the existence of the resolution, this inspection is carried out just in a few locations in Brazil, such as the State of Rio de Janeiro (CONEMA, 2016).

Box 3 presents the summary of cars' technological innovations in order to comply with the level of emissions established in each phase of PROCONVE for light vehicles, as well as the two stages of the "OBDBr" system.

Box 3

Technologies introduced in cars in each phase of PROCONVE (light vehicles)

Legislation phases	Year	CONAMA Resolution	Objective	Technologies
L-1	1988	18 (of 1986)	Control of evaporative emission and from crankcase	Control of evaporative emission and improvement on ignition timing.
L-2	1992	18 (of 1986)	Control of exhaust emissions	Electronic carburetor, electronic fuel injection and catalyst.
L-3	1997	15 (of 1995)	CO reduction	MPFI*, three-way catalyst and oxygen sensor.
L-4	2005	315 (of 2002)	HC and NO_x reduction	MPFI, three-way catalyst, improvement of combustion chamber and injectors, and increase of fuel pressure.
OBDBr-1	2007	354 (of 2004)	On-board diagnostic systems	Monitoring of emission control systems and Malfunction Indicator Lamp (MIL)
L-5	2009	315 (of 2002)	HC and NO_x reduction	Similar to phase L-4.
OBDBr-2	2010	354 (of 2004)	On-board diagnostic systems	Second oxygen sensor (oxygen sensor post-catalyst).

* MPFI = multi-point fuel injection.

Source: Elaborated by the authors.

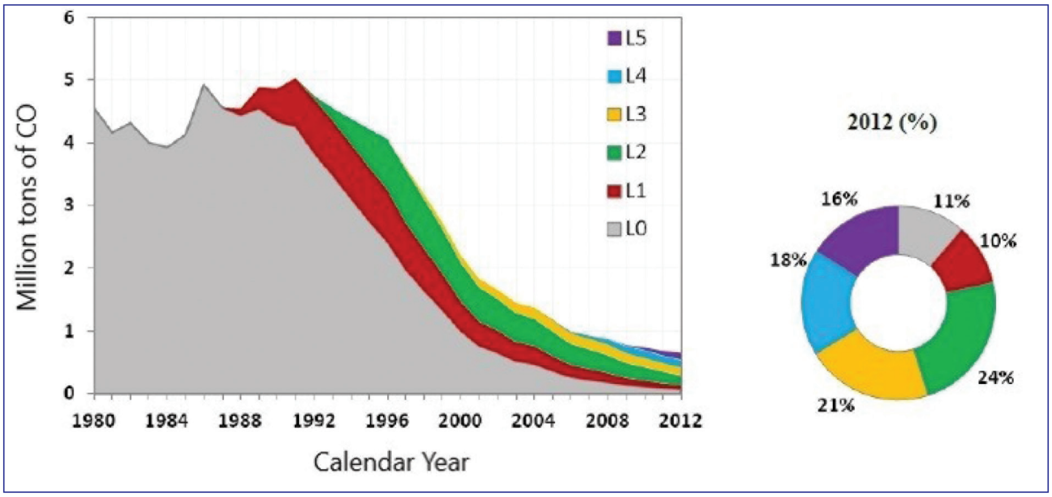
Technologies patented and introduced in cars coming from the US, Europe and some Asian countries complied with the regulations of these regions, and in a following step they equipped Brazilian vehicles, thus meeting PROCONVE emission standards. Some of these technologies can be associated with the different phases of this program. In L-1 phase, cars started to have evaporative emission control, which includes crankcase emission control. Between phases L-2 and L-3 there was the introduction of the highest number of devices in engines, such as fuel dosage control, fuel injection system, oxygen sensors and catalyst. During regulation of L-4 and L-5 phases, engines received the OBD II electronic monitoring, accredited in Brazil as "OBDBr-1" (2007 to 2009) and "OBDBr-2" (2010 and 2011), which equips 100% of the national vehicles produced since 2011 (CONAMA, 2004).

Figures 1, 2 and 3 present the results of regulation until 2012, showing the reduction of emissions of CO, NO_x and non-methane hydrocarbons (NMHC) from cars and light commercial vehicles, regarding the five phases established by PROCONVE.

Figure 1 shows the reduction of CO emissions by cars and light commercial vehicles, with SI engine, of the national fleet, according to PROCONVE phase. Values are in CO thousands of tons, with emphasis on the 2012 percentage distribution of emissions in each phase, and show the reduction since the beginning of Phase L-2, with a more significant fall from Phase L-3, in 1997.

Figure 1

CO emissions from automobiles and light commercial vehicles with SI engine, by PROCONVE phase

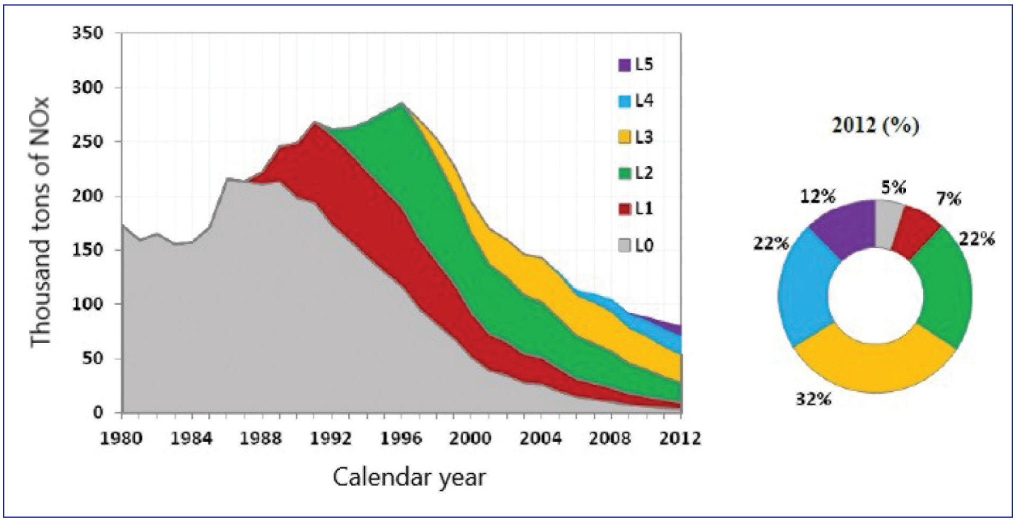


Source: Translated from MMA (2013).

Figure 2 shows the reduction of NO_x emissions by cars and SI light commercial vehicles of the national fleet, per PROCONVE phase. Values are in NO_x thousands of tons, highlighting the 2012 percentage distribution of emissions in each stage, and show the reduction from 1997 as a result of the introduction of Phase L-3.

Figure 2

NO_x emissions from automobiles and light commercial vehicles with SI engine, by PROCONVE phase

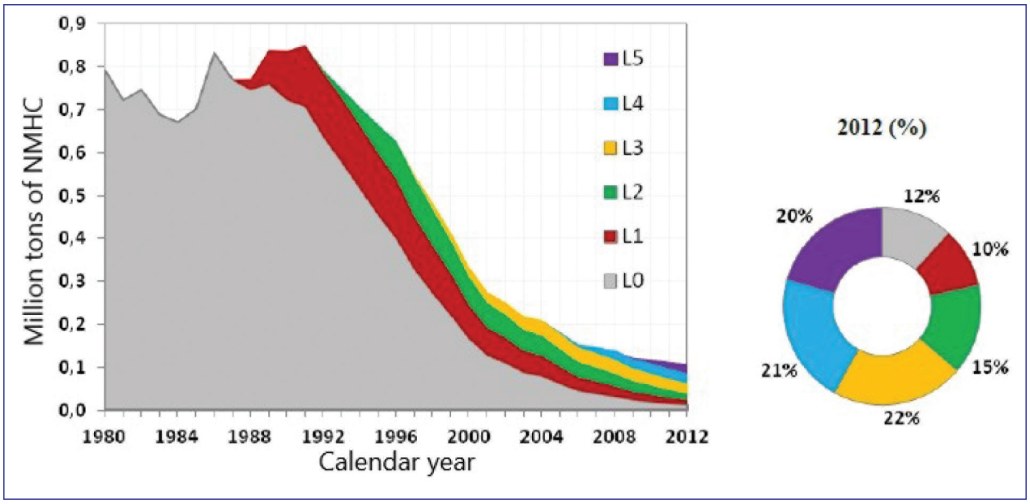


Source: Translated from MMA (2013).

Figure 3 shows the reduction of NMHC emissions by cars and SI light commercial vehicles of the national fleet, according to PROCONVE stage. Values are in NMHC thousands of tons, with emphasis on the 2012 percentage distribution of emissions in each PROCONVE's phase; in the figure we can observe the reduction of these emissions from 1992, after the beginning of Phase L-2.

Figure 3

NMHC emissions from automobiles and light commercial vehicles with SI engine, by PROCONVE phase



Source: Translated from MMA (2013).

To ensure the introduction of new technologies in Brazilian vehicles, local industry began to receive investments to meet the new demand. Changes include the development of new specialties and R&D in Brazil, and the local production of components and assemblies that were previously imported, aiming to reach the production volume for technologies of electronic fuel injection, catalyst and components related to emission control. Prior to 1992, vehicles had the carburetion system (mechanical system) for mixture control, but since 1997, all vehicles with SI engine (Otto cycle) were produced with electronic fuel injection and catalyst (IBAMA, 2011). To meet the pollutant emission limits required by legislation, there was a broad technological diffusion in Brazil in the automotive sector, thus creating industrial parks and infrastructure to meet the local market demand.

Brazil started PROCONVE in 1986, while Europe introduced the Euro legislation in 1992 (phase E1), evolving to other stages of toxic gas emissions' reduction, through the diffusion of technologies for emission control. In the US, this control began in the 1960s, culminating with the USCAAA, which resulted in the reduction of toxic gases CO, HC and NO_x in 1975 (BERGEK and BERGGREN, 2014). During this period, several technologies on this subject were patented and spread to other countries, such as Brazil, which led to the reduction of automotive emissions through legislation.

ANALYSIS AND DISCUSSION OF RESEARCH RESULTS

Automotive legislation to reduce toxic gas emissions has built its rationale and regulation since the 1960s, in markets such as the United States (BERGEK and BERGGREN, 2014). If we follow the history of Brazilian environmental legislation to reduce toxic gases, over the last three decades, we notice changes due to technological innovations. These changes began in the mid-1980s, with the control of emissions in the fuel supply system and engine vents, according to PROCONVE regulations (IBAMA, 2011).

In the 1990s there was a narrowing of emission limits in several countries, such as Tier 1 in US (BERGEK and BERGGREN, 2014); Euro 1, 2 and 3 in Europe (BERGEK and BERGGREN, 2014; KOUSOULIDOU NTZIACHRISTOS, MELLIOS et al., 2008); and, in Brazil, L-2 and L-3 phases of PROCONVE for light vehicles (IBAMA, 2011). Each market introduced environmental technological innovations in cars to meet its emission limits (KOUSOULIDOU, NTZIACHRISTOS, MELLIOS et al., 2008; IBAMA, 2009). In Brazil, automobiles benefited from the electronic fuel injection system, oxygen sensor - before the catalyst -, and catalyst (IBAMA, 2009), technologies acknowledged by users for eliminating the carburetor and, consequently, the choke lever, allowing to drive the vehicle in cold start.

In the 2000s, legislation continued to reduce emission limits in several countries (BERGEK and BERGGREN, 2014; KOUSOULIDOU, NTZIACHRISTOS, MELLIOS et al., 2008) and, in Brazil, L-4 and L-5 phases of PROCONVE fostered the introduction of environmental innovations for the reduction of ozone precursor gases, with refined technologies in the electronic fuel injection system, in injectors and in engines' combustion chamber to reduce NO_x and HC emissions. These changes are still effective to meet the needs of each period, such as the last phase of the program, L-6, of 2014 and 2015, with increased restrictions on toxic gas emissions (IBAMA, 2009). With all these innovations that reduced emissions, cars received an electronic ally to monitor the conditions of these components during the lifetime use of vehicles, which was the "OBDBr-2" system (CONAMA, 2004). With this system, the propulsion assembly is continuously monitored to identify any failure that could compromise the emissions (CONAMA, 2004). Even with technologies to reduce toxic gas emissions and their electronic monitoring, vehicles still need to be periodically inspected in order to identify any anomalies in these technologies and systems, in order to ensure that vehicle emissions remain within factory standards.

To improve the environmental performance of light vehicles in Brazil, the main instrument has been regulation, such as PROCONVE (IBAMA, 2011), also known as command and control. This instrument imposes goals for each automaker, which favors the diffusion of incremental innovations (BERGEK and BERGGREN, 2014) in the automotive industry.

Technologies to improve environmental performance are called *eco-innovation* (IVM, 2006; CARRILLO-HERMOSILLA, DEL RÍO and KÖNNÖLÄ, 2010; BOCKEN FARRACHO, BOSWORTH et al., 2014), and are introduced in Brazilian vehicles to reduce pollutants emission, with optimization of fuel consumption. The development of technologies to comply with regulations (KNELLER and MANDERSON, 2012) followed some paths, depending on the application of each element involved in the process. In order to comply with the legislation on pollutants emission (BERGEK and BERGGREN, 2014; KOUSOULIDOU, NTZIACHRISTOS, MELLIOS et al., 2008), established by PROCONVE, it was necessary to introduce new components in the propulsion system and technological changes in engines. Technological development methods can be carried out through closed innovation, internally, or through collaboration between companies, through open innovation. The innovation process for L-2 and L-3 phases, which received the most significant changes, took place internally in automakers during the 1990s. They acquired systems from suppliers, such as the electronic fuel injection system and catalyst (MMA, 2013), working together to adjust these technologies to their engines. The development of the "flex fuel" technology (vehicles that run on gasoline and/or ethanol) resulted from the first research partnership between automakers through open innovation, in the national automotive sector (LOPES, FERRARESE and CARVALHO, 2017).

CONCLUSION

The objective of this research was to analyze the role of legislation as an inducer of automotive environmental technologies for the reduction of toxic emissions from light vehicles manufactured in Brazil. We found that technologies for the control of pollutant emissions began to equip domestic vehicles in the 1990s, and from then on they have continuously reduced toxic gases from exhaust and evaporation. Technologies implemented to comply with the legislation to reduce pollutants from cars were disseminated in the fleet according to the established limits. Technological changes are still under way aiming to improve air quality by reducing emissions. These actions are necessary to ensure public health and are continuously monitored in order to make the necessary adjustments, in the case of increase in pollutants.

The results show that regulation fostered environmental technological innovation, with the introduction of electronic fuel injection and catalyst, and improved motorization. All environmental technological innovations introduced in Otto cycle vehicles are directly related to the accomplishment of one phase of PROCONVE. These environmental technologies are disseminated in Brazil by European, American and Asian carmakers' headquarters, because legislation makes it mandatory to mitigate toxic emissions. Some technologies, like the catalyst, reduce several toxic gases, while others only reduce emissions from one kind of gas, such as exhaust gas recirculation, which only reduces NO_x.

The regulation of toxic gas emissions in Brazil follows the changes that occurred in other countries, by adjusting their experience to the Brazilian scenario. Comparing the PROCONVE stages to European regulations, we noticed that the technology introduced in European vehicles in 1992 (Euro 1) is equivalent to the technological standard applied to Brazilian vehicles in 1997, the third stage for light vehicles (L-3), with the introduction of the MPFI system and three-way catalyst. This lag can also be identified in the introduction of OBD II, which started in US in 1994, in Europe in 2000, and arrived in Brazil in 2010. The process of introduction of these technologies in Brazilian subsidiaries occurred in different ways, according to each company. Most of the time, technologies were developed in partnership with suppliers or by the automaker itself in headquarters.

For future studies that wish to investigate how the process took place in different companies, and the drivers and barriers to innovation, we recommend a field research based on interviews with the following people: managers of innovation areas in companies; industry experts; government representatives; and representatives of the implemented programs. We also suggest a research on regulation as a determining factor of environmental technological innovation for the mitigation of greenhouse gases from cars, both in Brazil and in other countries, as well as a research on electric cars and fuel cells. These technologies, already consolidated in other markets, arrive in Brazil through imported electric cars and create new business models, such as shared cars. Therefore, there is an opportunity for a new research agenda on disruptive automotive technologies that go beyond the incremental technological innovations of the Otto cycle.

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