Exploratory research analysis on emissions generated in internal combustion engines.

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Abstract:

It is common knowledge that internal combustion engines have the function of transforming thermal energy into useful mechanical work. During the combustion process of the fuel and air mixture (heat generation) a quantity of gases are produced and released into the environment by the exhaust system of these engines. When these machines were invented, their creators might not have had the notion that the generated gases would be aggressors to nature. The constant population growth, the increasing demand for the use of these engines and observations of the impact in nature, among them the health and greenhouse effects, evidenced mainly from the end of the last century, led scientists to study the problem related to gaseous emissions from these machines. The present work aims to study and evaluate the emissions of internal combustion engines, their consequences both to the human health and to the environment, the evolution of government legislation and also the control mechanisms implemented to reduce these pollutants. The applied methodology is a qualitative and exploratory study of bibliographic character of theoretical and experimental works that were presented in master's dissertations, doctoral theses, scientific articles and websites of companies specialized in the subject.

Keywords:

Internal combustion engines; Emissions; Environment; Human health, Legislation.

1. Introduction

There is evidence that the invention of combustion engines has brought great benefits to mankind. These machines are used in electric power generation units, agricultural equipment, ships, trains, airplanes and automotive vehicles to transport people and/or cargoes.

While operating these engines admit a certain amount of air and fuel that undergoes a transient combustion process, resulting in the discharge into the atmosphere of numerous gaseous substances, liquid and also solid material. Depending on the composition of the fuel, the chemical reaction will generate carbon dioxide (CO_2), carbon monoxide (CO), water, nitrogen oxides (NO_x), hydrocarbons (HCs), formaldehyde (HCHO) and particulate matter (PM).

According to the European Environment Agency [1] the road transport sector was the largest contributor to total NO_x emissions and the second largest emitter of black carbon (BC) in 2015, though emissions from the road transport sector have been reduced considerably (by more than 25 %) since the year 2000.

"Emissions from diesel cars cause about 5,000 premature deaths annually in the European Union, Norway and Switzerland" was the conclusion of a recent study conducted by the Norwegian Meteorological Institute in cooperation with the International Institute of Applied Systems Analysis of Austria and the Chalmers University of Technology in Sweden [2].

The graph shown in Fig. 1 illustrates the contribution percentage of emissions by sector in the European Union in the year 2015. We note that about 78% of emissions released into the environment originate from fuel combustion and the transportation sector where combustion engines are widely used.

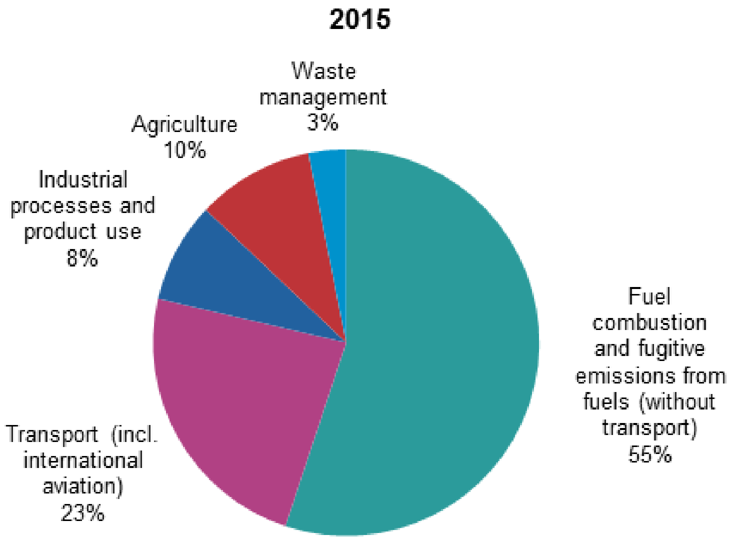

Fig. 1: Greenhouse gas emissions, by source sector. Adapted from EUROSTAT [3]

While on the one hand the engines have brought benefits, on the other hand problems have arisen as in the case of emissions. In view of this, we propose to study and evaluate the emissions of internal combustion engines, their consequences for the human being and the environment, the evolution of government legislation and the control mechanisms implemented in these machines to reduce these agents.

2. Methodology

It is a bibliographical research where analyzes will be made, both qualitatively and quantitatively, to theoretical and experimental works described in master's dissertations, doctoral theses, scientific articles and government websites and to reports of specialized companies related to environmental and emissions issues.

The bibliographic research [4] is made with the intention of raising the available knowledge about a subject, in order to analyze, produce or explain the object being investigated. The bibliographic research aims to analyze the main theories of a theme and can be carried out for different purposes.

According to [5], the main advantage of bibliographical research is that it allows the researcher to cover a range of phenomena much broader than that which he could directly research. The bibliographical research is also indispensable in historical studies. In many situations, there is no other way of knowing the facts of the past then by using secondary data.

3. A Brief History

The UN Conference on the Human Environment, known as Stockholm-72, was the starting point for debates on global environmental issues. Exploitation of natural resources, devastation of forests, degradation of ecosystems, use of fossil fuels, industrialization and production of waste in the big cities were problems addressed in the conference. It was followed by the United Nations Environment Program (UNEP) which stipulated actions for the protection of the environment in the context of sustainable development.

In 1987 the World Commission on Environment and Development, led by the Norwegian Prime Minister Gro Harlem Brundtland, presented the document *Our Common Future*, better known as the Brundtland Report. The document came to use the term "sustainable development" with the following definition: how current generations meet their needs, yet without compromising the ability of future generations to meet their own needs [6].

In 1992 the United Nations Conference on Environment and Development was held in Rio de Janeiro and became known as Rio-92. The aim of the final statement [7] was to establish a new and just global partnership by creating new levels of cooperation among States, key sectors of society and individuals, working towards the conclusion of international agreements that respect the interests of all and protect the integrity of the global environment and development system, recognizing the Earth's integral and interdependent nature.

Deriving from Rio-92, the Kyoto Protocol established standards to reduce gas emissions that aggravate greenhouse effect and which are considered to cause the planet's abnormal warming. Secondly, [8] the Kyoto Protocol determined the reduction rates for developed industrialized countries, with percentages differentiated according to each country's emissions. Underdeveloped countries were also engaged for a reduction in the use of fossil fuels, although without defined goals.

The United Nations Framework Convention on Climate Change (UNFCCC) was established during the Rio-92 summit, with the goal of stabilizing concentrations of greenhouse gases (GHGs) in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. The Convention of the Parties (COP) was created in this period. It is the supreme body of the UNFCCC [9] to keep regularly under exam the evolution of the main targets and take the necessary decisions to promote the effective implementation of the Framework Convention. The COP performs annual meetings since 1995 and since then significant meetings have included the COP3, when the Kyoto Protocol was adopted, the COP11 with the implementation of the Action Plan of Montreal and the COP17 in Durban, with the creation of the Green Climate Fund.

Held in Johannesburg in 2002, the World Summit on Sustainable Development (Rio +10), discussed mechanisms to implement the Kyoto Protocol guidelines. According to [10] the purpose of the conference was to obtain a doable action plan. Rio + 10 stood out more for mentioning the problems of globalization and for detailing an implementation plan that, although almost without bringing quantitative targets, initiated a collective action toward environmental protection combined with economic and social development.

The Climate Conference (COP21) held in Paris in 2015 represented a historic milestone. After 21 years of studies and attempts to formalize a global agreement, the first global consensual agreement on the subject was finally signed. The 195 countries agreed to halt emissions and control the increase in global average temperature by limiting it to +1.5 °C by 2100. It is worth pointing out that this agreement did not specify how much each country should reduce its own emissions, but each one of them should define their national contribution and set their own goals and targets to slow the growth of emissions. A good summary was the speech presented by UK Prime Minister David Cameron [11]: “Today is an important day. The talks at the COP21 conference in Paris have culminated in a global deal, with every country in the world now signed up to play its part in halting climate change. In other words, this generation has taken vital steps to ensure that our children and grandchildren will see that we did our duty in securing the future of our planet”.

The most recent Convention of the Parties was the COP23 held in November last year in Bonn, Germany. Its main objective was to discuss the next steps for implementing the Paris Agreement prior to 2020. Delegates from 190 countries focused on the following questions to chart these next steps: Where are we? Where do we want to go? How do we want to get there?

According to [12] the Prime Minister of Fiji and President of COP 23, Bainimarama, listed the main results: the formation of the Grand Coalition, the Ocean Pathway and the Gender Action Plan and the Indigenous People's Platform. And yet, a global partnership has been launched to provide millions for the most vulnerable people on the planet.

4. Gaseous Emissions

Air pollutants may be categorised as primary (directly emitted to the atmosphere) or secondary (formed in the atmosphere from precursor pollutants) [1]. Key primary air pollutants include primary PM, BC, sulphur oxides (SO_x), NO_x (which includes both NO and NO_2), NH_3, CO, methane (CH_4), non-methane volatile organic compounds (NMVOCs), Benzene C_6H_6, certain metals, and polycyclic aromatic hydrocarbons (PAHs, including Benzo[a]pyrene BaP). Secondary air pollutants include secondary PM, O_3 and NO_2.

In this research we restrict only to explore vehicular emissions. According to [13] there are three known modes of gaseous of pollutant emissions from IC engines: a) by evaporation of the fuel in the tank or in the supply circuit elements; b) the emission into the atmosphere of the gases contained in the sump; c) by the exhaust gases.

Gaseous emissions may include:

Carbon monoxide (CO): odorless and colorless gas that joins with hemoglobin, causing headache and reduced respiratory capacity. At high concentrations, it causes asphyxiation and may even kill.

Carbon dioxide (CO_2): it is a primary product of the combustion of hydrocarbons and does no harm to man, but is the main causer of the greenhouse effect. Its production is directly related to fuel consumption.

Hydrocarbons (HC): are compounds that have in their composition Carbon and Hydrogen atoms such as methane, ethane, acetylene, aldehydes, toluene, benzene and other polycyclic aromatic hydrocarbons PAHs. Most are considered carcinogenic, cause irritations, respiratory problems and contribute to global warming. According to [14] they are formed near the walls of the combustion chamber where the temperature is not sufficient to complete the reaction or in regions where the mixture is excessively rich or poor.

Nitrogen oxides (NOx): are hazardous gases that contribute to the formation of smog and form oxidants such as tropospheric ozone (O_3), which causes irritation to the eyes and sever problems to the respiratory system. In contact with the water vapor forms the nitric acid that also contributes to the formation of acid rain. Still according to [14] there are two generation sources: fuel NOx, formed by the nitrogen present in the fuel and the oxygen of the air; air NOx, formed by the thermal and immediate mechanisms. Reduced flame temperature, blend control and of the ignition advance, combustion chamber geometry and exhaust gas recirculation designs are technologies currently employed to reduce their emission.

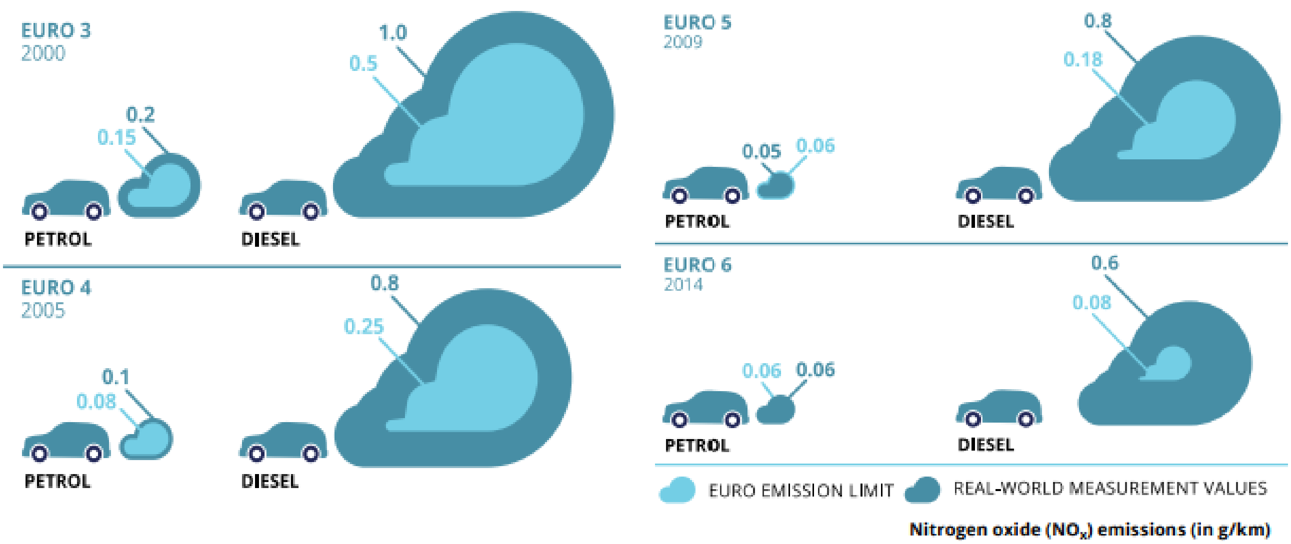

Fig. 2: EU limits and real-world nitrogen oxide (NOx) emissions (in g/km): comparison between gasoline and Diesel cars, according to the European Environmental Agency [15].

Figure 2 illustrates a comparison between the EURO limit values and actual measured values for NOx emissions in gasoline (petrol) and diesel engines.

Sulfur compounds (SO_2 and H_2S): results from the burning of the sulfur existing in the fuel that is in the highest concentration in the diesel. Reduces visibility and causes acid rain, which causes corrosion of buildings and destruction of vegetation.

Particulate matter (PM): also known as particle pollution, refers to a complex mixture of extremely small particles of solid or liquid material that are suspended in the air in the form of dust, fog, smoke, soot and other, mainly generated by the diesel engine. Its size range is between 0.002 and 100μm. They are formed in incomplete combustion by either low temperature and/or excess fuel. The effects on the human body are soon evident in the alteration of the respiratory system's ability to remove particles of inhaled air, causing infections such as pharyngitis, rhinitis, bronchitis and pneumonia and other lung and heart diseases.

Emissions may vary depending on the fuel used, engine load, type of combustion, the air/fuel mixture and the physical conditions of the engine. In Diesel cycle engines, with compression ignition of a poor mixture, emissions are composed of gases and vapors consisting of carbon dioxide, carbon monoxide, nitrogen oxides, sulfur oxides and various hydrocarbons and some volatile organic compounds. These air pollutants can still interact with one another or undergo photolysis, giving rise to pollutants substances such as ozone, peroxyacetyl nitrates, among others. They also form particulate material that includes soot, dust, smoke and all suspended material in the air. According to [16] the use of biodiesel in a diesel engine used in its investigation showed that the higher the biodiesel content in the mixture with diesel and the reduction of the load applied to the engine, the lower the emissions of CO_2, NO_2, CO, NO and hydrocarbons (HCs).

In Otto cycle engines that use gasoline, alcohol, blends of alcohol and gasoline (Flex), liquefied petroleum gases (LPG) or natural gas (NG), where ignition is controlled by a spark, the main released pollutants are hydrocarbons, carbon oxides and aldehydes. Nevertheless, due to the stoichiometric combustion, these pollutants are easily eliminated by the Catalytic Converter located in the exhaust pipe. The burning of the alcohol emits fewer amounts of carbon monoxide and nitrogen oxide compared to gasoline. Studies carried out by [17] showed that the use of NG and also of biomethane in a vehicular engine obtained excellent results related to the aspects of emissions when compared with alcohol and mainly to gasoline being the worst.

Tests performed by [18] on dual-fuel technology engines using biogas, NG and ethanol showed significant reductions in NOx, HC and CO emissions when compared to the same single-fuel engine. It was also observed an increase in the combustion efficiency in dual-fuel mode.

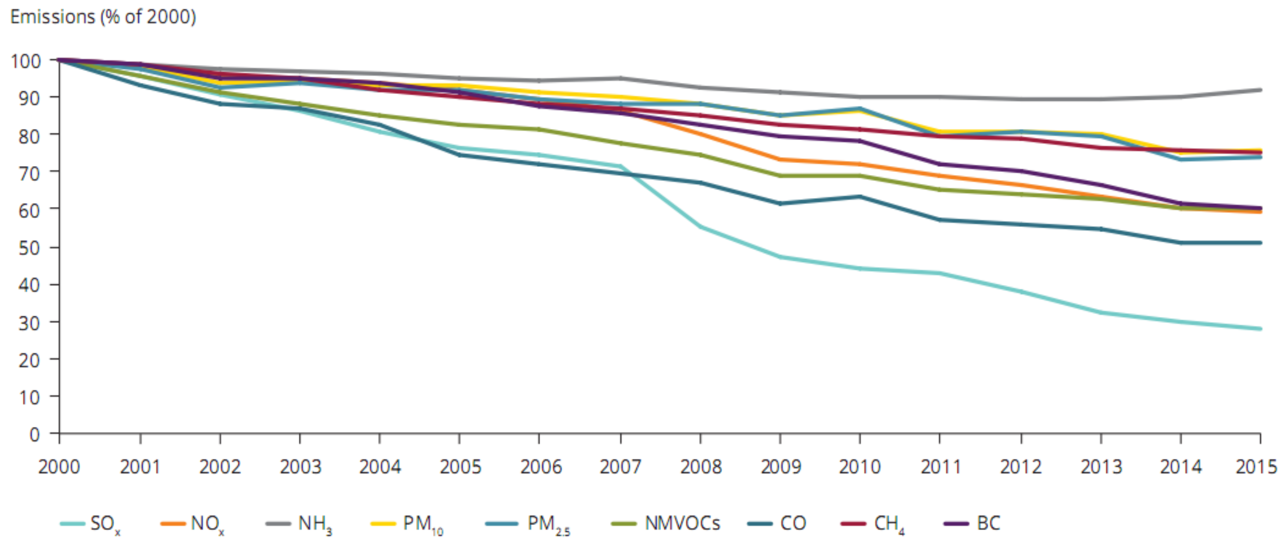

Fig. 3: Total emissions in the EU-28, from 2000-2015 (% of 2000 levels), according to [1].

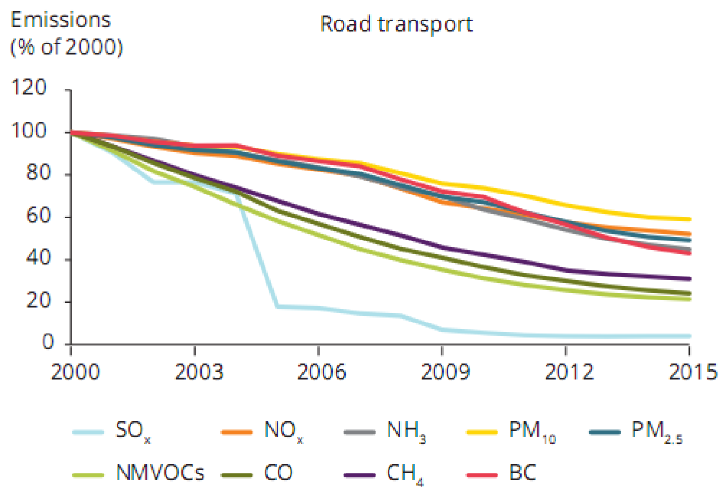

Fig. 4: Emissions from road transport in the EU-28, from 2000-2015 (% of 2000 levels),[1].

Figure 3 shows the evolution in EU-28 global emissions while Fig. 4 shows the contribution to the emissions by the transport sector both registered between the years 2000-2015 (% of 2000 levels).

We can observe that there has been a decrease in the emission values during this period. The transport sector has contributed significantly to this reduction through more stringent legislation that has forced manufacturers to implement technological changes in their vehicles seeking greater energy efficiency and reduction of emissions aimed at environmental and life preservation on our planet.

5. Standards

5.1 European

The Directive 70/220 / EEC of the Council of 20 March 1970 is relative to the approximation of the laws of the Member States to measures to be taken against air pollution by emissions from vehicles. This was the first Directive to limit values in emissions from passenger cars (light vehicles) and was based on US standards.

The Directive 88/77 / EEC of the Council of 3 December 1987 on the approximation of the laws of the Member States was on measures to be taken against the emission of gaseous pollutants from diesel engines for use in heavy vehicles.

In 1991, the emission figures were applied to passenger cars of any cylinder capacity. One year after was implemented the norm Euro-1 in which differentiated emission values were determined for gasoline and diesel engines.

More stringent values were adopted from Directive 94/12 / EC which came into force in 1996. Cars complying with these values were listed in Euro-2. In 2000 and 2005 Euro-3 and Euro-4, respectively, were implemented, further increasing the stringency for the values of CO, NOx and PM emissions.

In 2007, the Parliament and the European Council published the Regulation[1] (CE) n.715/2007, concerning the approval of motor vehicles with regard to emissions from passenger light vehicles and commercials (Euro-5 and Euro-6) and access to vehicle repair and maintenance information. Euro-5 was in force from September 2009 regarding the homologation of new types of vehicles and from January 2011 on the registration and sale of new vehicles. The Euro-6, currently in force, was applied from September 2014 to the homologation and in January 2015 regarding the registration

[1] In [26] we can obtain the texts of the Directives and the Regulations cited.

and sale of new vehicles. The Table 1 shows a summary of the emission limits imposed by each Directive and/or Regulation.

Table 1: European Emission Limits for Passenger Vehicles in mg/km [19]

Engine type	classy	Directive or Regulation	Year of Execution	CO	HCT	NMHC	THC+NOx	NOx	PM
Diesel	EURO 1	91/441/CE	1992	2720	-	-	970	-	140
	EURO 2	94/12/CE	1996	1000	-	-	700	-	80
	EURO 3	98/69/CE	2000	640	-	-	560	500	50
	EURO 4	98/96/CE	2005	500	-	-	300	250	25
	EURO 5	n°715/2007	2009	500	-	-	230	180	5
	EURO 6	n°715/2007	2014	500	-	-	170	80	5
Gasoline	EURO 1	91/441/CE	1992	2720	-	-	970	-	-
	EURO 2	94/12/CE	1996	2200	-	-	500	-	-
	EURO 3	98/69/CE	2000	2300	200	-	-	150	-
	EURO 4	98/96/CE	2005	1000	100	-	-	80	-
	EURO 5	n°715/2007	2009	1000	100	68	-	60	5
	EURO 6	n°715/2007	2014	1000	100	68	-	60	5

5.2 United States

According to [20] , in 1963 the first legislation at federal level, with the objective of conformity air pollution was passed in the form of the Clean Air Act; a few years later, in 1968, Congress adopted California's 1965 vehicle emissions standards at federal level. In 1970, the EPA was established for standard-settings and enforcement activities.

New specifications from the National Air Quality Standards (NAAQS) were adopted in 1977 with implications for the future development of vehicle emission standards.

Another set of major amendments to the Clean Air Act occurred in 1990 (1990 CAA Amendments) [21]. The 1990 CAAA substantially increased the authority and responsibility of the Federal Government. New regulatory programs were authorized for control of acid deposition (acid rain) and for the issuance of stationary source operating permits. The National Emission Standards for Hazardous Air Pollutants (NESHAP) was incorporated into a greatly expanded program for controlling toxic air pollutants. The provisions for attainment and maintenance of NAAQS were substantially modified and expanded. Other revisions included provisions regarding stratospheric ozone protection, increased enforcement authority, and expanded research programs.

In 1990, still according to [20], further amendments to the Clean Air Act set Tier 1 standards applicable to all new vehicles, covering CO, NOx, PM and HC. Under Tier 1, a set of different standards for different vehicle categories were defined. In 2000, EPA promulgated Tier 2 standards which were stricter, and in 2014, Tier 3 standards were passed which are in force now and have a phased-in strategy over the period from 2017 through 2025.

Manufacturers must certify their vehicles to one of the seven emission bins shown in Table 2. Vehicles are tested over the FTP-75 test procedure (the NMOG + NOx limits must be additionally met over the HFET cycle). The standards are applicable to all vehicles, regardless of the fuel type.

Table 2: Tier 3 Certification bin standards (FTP; 241,500 km or 150,000 mi) [22]*(Adaptated)*

Bin	NMOG+NOx *mg/km*	PM* *mg/km*	CO *g/km*	HCHO *mg/km*
Bin 160	99.4	1.86	2.60	2.48
Bin 125	77.6	1.86	1.30	2.48
Bin 70	43.5	1.86	1.06	2.48
Bin 50	31.1	1.86	1.06	2.48
Bin 30	18.6	1.86	0.62	2.48
Bin 20	12.4	1.86	0.62	2.48
Bin 0	0	0	0	0

*In MYs 2017-20, the PM standard applies only to that segment of a manufacturer's vehicles covered by the percent of sales phase-in for that model year.

The Tier 3 rule also includes emission standards for heavy-duty vehicles (HDV), such as heavy-duty pick-ups and vans, chassis-certified as complete vehicles. The definitions of vehicle categories, including light-duty vehicles (LDV), light-duty trucks (LDT) and medium-duty passenger vehicles (MDPV) are consistent with the Tier 2 definitions. Table 3 shows that the fleet average Non-Methane Organic Gases NMOG + NOx limit is phased-in starting from 2017, and reaches 18.6 mg/km in 2025.

Table 3: Tier 3 fleet average NMOG+NOx FTP standards (mg/km) [22](Adaptated)

Vehicle Category	2017*	2018	2019	2020	2021	2022	2023	2024	2025
LDV, LDT1	53.4	49.1	44.7	40.4	36.0	31.7	27.3	23.0	18.6
LDT2, LDT3, LDT4, MDPV	62.7	57.1	51.6	46.0	40.4	34.8	29.2	23.6	18.6

*For LDVs and LDTs over 2.72 kg GVWR and MDPVs, the fleet average standard apply beginning in MY 2018.

5.3 Brazil

The Air Pollution Control Program for Automotive Vehicles (PROCONVE) and the Program for the Control of Air Pollution by Motorcycles and Similar Vehicles (PROMOT) were created by the National Council Of The Environment - CONAMA through Resolutions that establish guidelines, deadlines and legal standards of the permissible emission for the different categories of motor vehicles, national and imported [23].

The legislation[2] PROCONVE started in 1988 and was gradually implemented as follows:

5.3.1 Light vehicles (L)

Light passenger vehicles (automobiles) - Motor vehicles designed for transportation of up to 12 passengers or their derivatives for goods transportation; Light commercial vehicles (LCV) - Motor vehicles designed for transportation of goods or for transportation of more than 12 passengers or with special characteristics for off-road use. According to [24] we have:

- PROCONVE L1 limits were phased-in over 1988-1991, followed by PROCONVE L2 emission standards phased-in over 1992-1996. These earliest standards were applicable only to passenger cars (LCV emissions became regulated from 1995). Noise limits for cars and LCVs became effective from 1994.
- PROCONVE L3 emission regulations were adopted in 1993 with implementation from 1997 to 2004. The L3 limits were based on Euro 2 standards.

[2] In [27] are found all the Laws, CONAMA Resolutions, IBAMA Regulations, IBAMA Normative Instructions referring to the steps of the PROCONVE/PROMOT.

- PROCONVE L4 and L5 emission standards were adopted in 2002 with implementation dates over 2006-2009. The L4/L5 standards were based on Euro 3/4, respectively. Because 50 ppm sulfur diesel fuel was not available by 2009, the L4 phase remained in effect for diesel vehicles until the end of 2012.
- OBD requirements for domestically produced and imported Otto cycle light commercial vehicles were adopted in 2004.
- PROCONVE L6 regulations were introduced by resolution CONAMA 415/2009 in 2009 with implementation dates over 2013-2015.

5.3.2 Heavy vehicles (P)

It is the self-propelled vehicle for the transport of passengers and/or cargo, with a maximum mass of more than 3,856 kg or mass of the vehicle in running order of more than 2,720 kg, designed for passenger and/or cargo transport.

- PROCONVE P1 was been in force from 1986 to 1992 and established smoke control with opacity limit "k> 2,5". To achieve the objectives of this phase, the vehicles underwent recalibration of fuel injection systems.
- PROCONVE P2 which was already equivalent to Euro 0. At this stage, CO and NO_x limits were established. Emissions of particulate material were not legally established that year, but were suggested at 0.60 g/kWh. The maximum sulfur content of the fuel was 3,000 to 10,000 ppm (particle per million). To meet these standards, it was necessary to make changes in the combustion chambers, improve the calibration of fuel injection systems and the implementation cooling systems of the admission air.
- PROCONVE P3 came into force in Brazil in 1994 and was equivalent to Euro 1. Settled significantly lower emission limits for CO, NOx and particulate matter. The trucks have been awarded high-pressure, turbocharged and intercooler injection pumps and have been compliant with the new legislation.
- PROCONVE P4 instituted few changes such as improvements in engine designs and fuel injection systems and the multivalve system. Reduction in the maximum levels of CO, NO_x and in the limit of particulate material (0.15 g/kW.h). The sulfur content allowed for diesel oil continued between 3000 and 10000 ppm. The P4 phase was equivalent to European emission standards Euro 2.
- PROCONVE P5 entered into force in 1998 equivalenting the Euro 3 and brought significant changes. The sulfur content was established between 500 and 2,000 ppm, reductions in CO and NOx limits and particulate material. In this phase came the engines arrive with electronic injection of fuel in high pressure.
- PROCONVE P6 there were problems during the implementation of this phase mainly in relation to the supply of fuel with a sulfur content of 50 ppm. That is why this fase did not come into force in Brazil.
- PROCONVE P7, equivalent to Euro 5 and in force since 2012 established a more still rigorous emission level, reducing CO to 1.50 g/kWh, NOx to 2.00 g/kWh, particulate matter up to 0.02 g/kW.h and sulfur content 10 ppm. The manufacturers introduced two technologies to meet the program requirements: exhaust gas recirculation-EGR and selective catalytic reduction-SCR.

6. Conclusion

The problem of emissions in the atmosphere has been a source of concern and of profound study for many researchers. In the face of the warnings evidenced in several research works around the world, the need for debates involving government leaders, government entities, scientists, environmental protection agencies and industry representatives arose.

Rio 92 marked the moment when the international political community clearly admitted that it was necessary to reconcile socioeconomic development with the use of natural resources. Countries have recognized the concept of sustainable development and have begun to shape actions that can aggregate economic, environmental and social components with the aim of protecting the environment and preserving life on the planet.

In the automotive area, governments have implemented programs and guidelines that have been gradually improved over time to reduce emissions of greenhouse gases and hazardous pollutants thus reducing problems related to the human health, nature impact and global warming.

Obligations were imposed on vehicle manufacturers as they had to invest in new research and find the right solutions to achieve the required low levels of pollutants. New technologies have been implemented in vehicles such as electronic injection systems, catalytic converters and selective reduction, exhaust gas recirculation systems, use of fuel vapors and crankcase gases, development of biofuels, among others.

Although the vehicle fleet in the world has increased, all these realized efforts have had an effect and automotive emissions are being significantly reduced. For example in Brazil, according to data from the Ministry of the Environment [25], a sharp drop in CO emissions occurred from around 5.5 million in 1991 to 1.3 million tons in 2012. Very significant reductions of NO_x occurred from 1997, with the entry into force of the L3 phase of PROCONVE and a decrease in emissions of particulate matter, so that in 2012 they corresponded to less than half of that observed in 2000.

In view of this tendency to reduce vehicular emissions and, consequently, to improve human health and quality of life, sound legislation is laudable. Supervisory bodies should act more forcefully and the automotive industry should continue its efforts in the search for effective technological advances to be implemented in the vehicles in the near future.

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