PROJECTING THE ENVIRONMENTAL IMPACT OF DIESEL CARS ON GASEOUS POLLUTANTS, $PM_{2.5}$ AND CO_2 IN A METROPOLITAN AREA

ANDRÉ LUIZ SILVA FORCETTO & RUI DE ABRANTES
CETESB, Environmental Company of Sao Paulo State, Brazil

ABSTRACT

Almost all passenger cars (PC) in Brazil are flex fuel (can run any proportion of petrol and ethanol) and diesel fuel is prohibited to these cars; diesel is available for vans and pickup trucks, as well petrol and ethanol. However, there is a proposal under discussion to introduce diesel PC in Brazilian market, arguing that they have better autonomy and emit less CO_2 and pollutants. The goal of this paper is to show the impact on pollutants and CO_2 emissions from diesel PC being offered as a main option; it will be discussed also an alternative scenario, the environmental impact if Internal Engine Combustion (ICE) vehicles are banned in favor of electric ones. Data analysis was performed on type-approval tests of petrol / flexfuel light duty vehicles (LDV). For the first case, the projection for introducing PC diesel in SPMR market shows a significant increase in NO_x emission, small rise for fine particulate matter ($PM_{2.5}$) and little reduction for HC, CO and total CO_2, although with significant rise for fossil CO_2. The alternative scenario, replacing ICE PC with electrics, shows high reduction for NO_x, some gain for CO_2 and $PM_{2.5}$ and small decrease for CO and HC. Thus, the use of diesel PC will lead to NO_x increase; by other hand, biofuels can reduce CO_2 but will increase NMHC and CO emissions. Electric PC may be a good option but requires time to replace ICE vehicles and bringing effective environmental gain.
Keywords: diesel cars, NO_x, $PM_{2.5}$, air pollution, biofuels.

1 INTRODUCTION

In Brazil, commercial fuels are petrol containing between 20 to 25% ethanol, 100% ethanol, petroleum-derived diesel with 8% biodiesel and compressed natural gas (CNG). Since early 1980s it was available, in the Brazilian market, vehicles moved for 100% ethanol and in the 2000s the sales of the so-called flexfuel vehicles began, which are able to burn petrol and ethanol in any proportion [1]. Diesel fuel is prohibited by law for passenger cars (PC) because this fuel receives a lower tax, which reduces the price of trucks freight and bus fares [2], as a consequence, almost all PC in Brazil are flexfuel. Commercial light duty vehicles (LDV), such as vans, SUVs and light pickup trucks may have either petrol or diesel internal combustion engines (ICE). Usually heavy-duty vehicles (HDV) have only diesel ICE.

However, a proposal to introduce diesel PC in Brazilian market is under discussion, arguing that a modern diesel ICE has better autonomy and emits less CO_2 and pollutants than petrol ICE. Thus, this paper aims to project what would be the impact on the emissions of NO_x, $PM_{2.5}$, NMHC (hydrocarbons except CH_4) and CO_2 if diesel PC would be offered as main purchase option; an alternative scenario will also be discussed, what would be the environmental impact if ICE vehicles would be banned in favor of electric ones.

This study is based on the Brazilian methodology for vehicular emissions inventory and is focused in the Sao Paulo Metropolitan Region (SPMR), the biggest Metropolitan Region in Brazil. Data analysis was performed based on type-approval laboratorial tests of LDV models offered in Brazilian market with both petrol/flexfuel and diesel engines.

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2 VEHICLES AS POLLUTANTS SOURCE

SPMR is one of the largest metropolitan areas of the world, with 39 cities, about 20 million people and 7.4 million vehicles [3]. The main sources of SPMR atmospheric pollutants are vehicles and industries, aside from biomass burning, particulate resuspension and emissions from fuel production and distribution [4]. Fig. 1 shows the relative proportion in mass of atmospheric pollutants emissions by sources in SPMR.

There is a federal program in Brazil that works since late 1980s for pollutants from vehicles, called Program for Control of Air Pollution from Automotive Vehicles (PROCONVE) [5]. PROCONVE is based on similar programs from Europe and USA, where the principle is to set emissions limits for new vehicles which are periodically reduced and compliant to these standards being demonstrated through standardized type-approval tests in laboratory and statistic control of production [5].

These efforts reach positive outputs, due to the introduction of new technologies for automotive pollution control. So, despite the rise in car usage, it was achieved significant reduction of SO_2, CO and MP_{10} emissions and consequently an improvement in air quality [5], [6]. However, tropospheric ozone (O_3) and $PM_{2.5}$ are still a concern in SPMR; their precursors, such as NO_x and volatile organic compounds (VOC), come mainly from vehicles [4]. O_3 level frequently exceeds Sao Paulo State standard of 140 mg/m^3 for 8-hours average, as shown in Fig. 2 and 3.

Ozone formation is highly influenced by the presence of CO, NO_x and VOC as well as ultraviolet radiation level, air humidity and winds [4], [7], [8]. NO_x is responsible not only for ozone formation but as a pollutant itself, that can cause irritation to nose, eyes and mucous membranes with capacity to cause respiratory diseases, such as emphysema and cancer [9]. Other effects for high concentration of NO_x are formation of $PM_{2.5}$ and nitric acid (HNO3) [10], [11]. The issue of Greenhouse Gases (GHG) should not be discarded either; SPMR vehicular fleet corresponds to more than 13,000 metric tons per year of Equivalent CO_2 and PC alone are responsible for 54% of this amount [3].

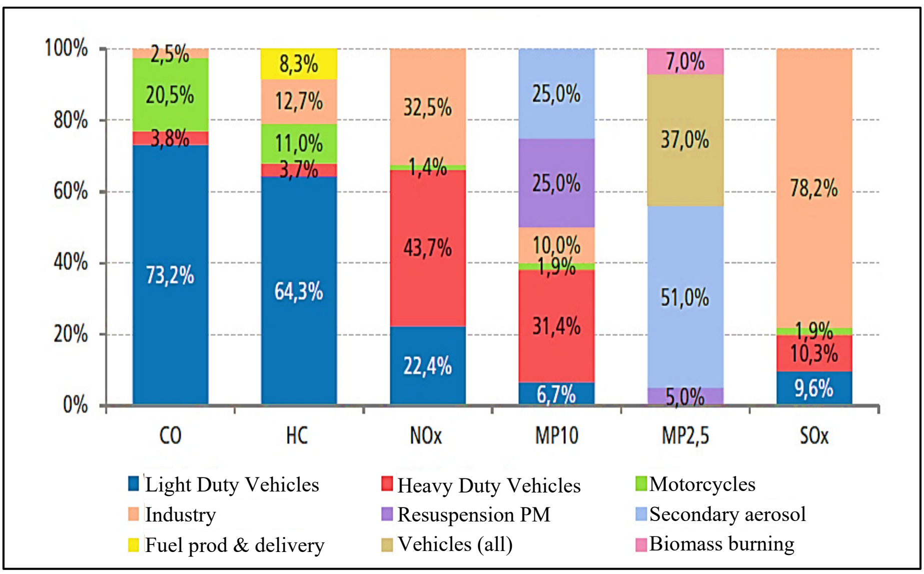

Figure 1: Air pollutants: relative contribution by source in SPMR [4].

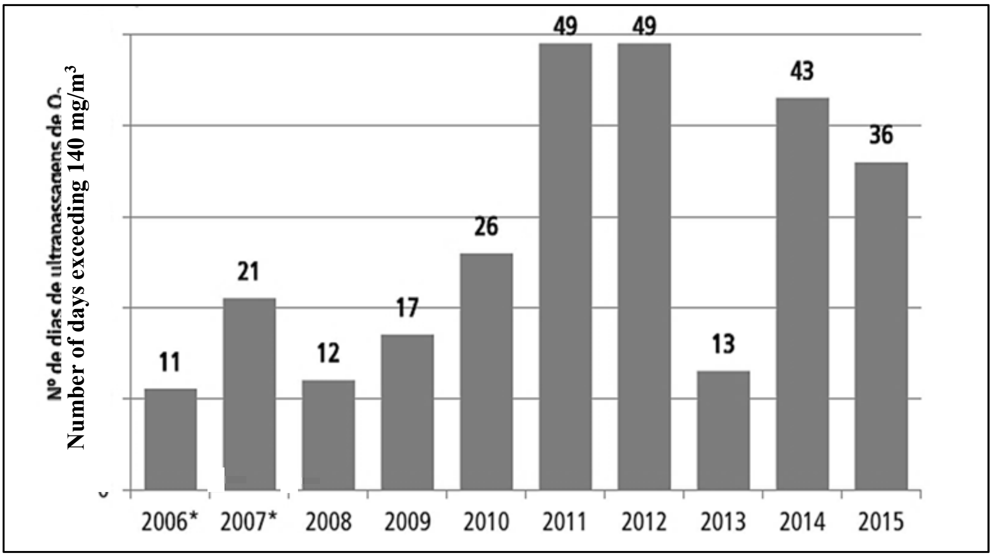

Figure 2: Number of days exceeding ozone standard in SPMR [4].

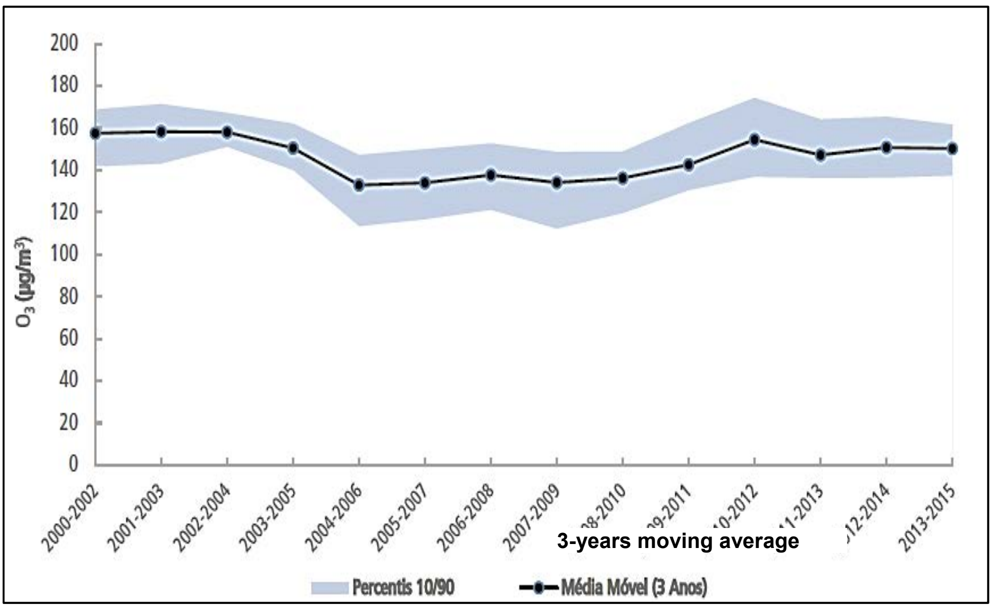

Figure 3: Ozone concentration 3-years moving average in SPMR [4].

3 METHOD

This analysis was focused in SPMR, which has a significant part of Brazilian's fleet. About 30% of all Brazilian vehicles are in the Sao Paulo State [12] and approximately half of the state fleet is running in SPMR [3].

3.1 Database

CETESB, besides its role as the Environmental Sao Paulo State Agency, is a technical agent for vehicular type-approval purposes for the Brazilian Environmental Protection Institute (IBAMA), therefore it has a large database from homologation laboratory tests. To this study it was selected results from tests made between 2011 and 2016, so under PROCONVE regulation L5 and L6 (PC and LDV Phase 5 and Phase 6), close equivalent to Euro 4 and Euro 5 standards [13].

The vehicles were chosen under the criteria of similarities, i.e., the requirements for the same model are: available diesel and petrol/flexfuel engines, same number of cylinders and approximately same cubic capacity and power. This research results in typical emission factors for NO_x, CO, $PM_{2.5}$, NMHC, total CO_2, fossil CO_2 and fuel consumption for diesel, petrol and ethanol. The difference between "total CO_2" and "fossil CO_2" is because Brazilian petrol contains in average 22% ethanol and diesel has 8% biodiesel; for fossil CO_2 is not taken in account the CO_2 from biofuels.

3.2 Actual NO_x emission

For the calculations of emissions inventory projections, it was also considered the actual NO_x emission, which is the typical NO_x emission for Real Driving Emission (RDE). Many studies point to RDE NO_x emissions up to 25 times above the legal limits [14]–[19]. According to results found in CETESB research developed for IBAMA evaluation of some Brazilian diesel LDVs in the case known as "Dieselgate" [20], it was adopted as Actual NO_x Factor an index of 4 times the average of NO_x laboratory results.

3.3 Emissions Inventory projection

The first scenario is when diesel cars are offered as main purchase option. Considering that 50% of European fleet are diesel cars [21], to project the same proportion in SPMR, 90% of PC sales will have to be diesel PC, in a period of 6 years. This projected fleet is evaluated in the SPMR Vehicular Pollutants Inventory and the results are compared to actual inventory.

3.4 Alternative scenario

It was also projected this alternative scenario: what would be the impact in a fleet where diesel cars represent 50% of all PC – the European proportion – and half of them are replaced for Zero Emission Vehicles (ZEV), carried on the same projection for 6 years.

4 RESULTS AND DISCUSSION

4.1 Characteristics of the vehicles in the database

It was analyzed 147 tests from 16 different models of LDV, mainly SUVs, vans and light pickup trucks, powered by diesel and petrol/flexfuel. Table 1 shows a summary of the main characteristics of these vehicles.

The averaged emissions factors from type-approval tests database are shown in Table 2. In all cases, the proportion of ethanol in petrol was 22% and 8% of biodiesel in the diesel.

An important point must be highlighted here about CO_2 emission: the average difference between Otto (petrol/ethanol) and diesel engine is very small, just 5.5%, quite different from

Table 1: Main characteristics of the samples.

	Petrol	Ethanol	Diesel
Number of tests evaluated	59	33	55
Cubic capacity (average - cm3)	2,630	2,336	2,743
Maximum Power (average - kW)	169.1	128.6	155.1

Table 2: Averaged emission factors (g/km). *(Source for $PM_{2.5}$ for petrol/ethanol engines: SILVA [22].)*

	Petrol	Ethanol	Diesel
Total CO_2	245.5	221.4	231.9
Difference:	Baseline	-9.8%	-5.5%
Fossil CO_2	191.5	0	224.9
Difference:	Baseline	-100%	+17.5%
Consumption (km/liter)	8.84	6.78	11.4
Difference:	Baseline	-23.3%	+29.5%
NO_x	0.033	0.041	0.281
Difference:	Baseline	+26.6%	+760.0%
Actual **NO_x** (4x lab emission factor)	0.033	0.041	1.124
Difference:	Baseline	+26.6%	+3,306.1%
$PM_{2.5}$	0.002	0.002	0.096
Difference:	Baseline	0%	+381.7%
CO	0.316	0.451	0.059
Difference:	Baseline	+42.8%	-81.5%
NMHC	0.016	0.022	0.011
Difference:	Baseline	+33.2%	-36.1%

what is promoted by manufacturers in order to incentive diesel PC as solution for reducing CO_2 emission. Aside from that, when the portion of CO_2 from renewable fuels is discounted, diesel fuel is in a clear disadvantage, producing 17.5% more fossil CO_2 than the Brazilian petrol. It is important to keep in mind that a diesel vehicle saves fuel (+29.5%) in relation to petrol PC, but produces almost the same CO_2 per kilometer. One possible explanation for these results can be given by the amount of carbons atoms per molecule: in diesel fuel there are typically 8 to 16 atoms of C, in petrol 4 to 12°C and in ethanol only 2 carbons (C_2H_6O) [23]–[25].

4.2 Projections for emissions inventory

When these emissions factors are applied in the calculations for emissions inventory, it is possible to have a better view of diesel PC influence in the environment, as can be seen in

Table 3, 4 and 5. Here, "Equivalent CO_2" means that in the calculations is weighted the carbon footprint from fossil CO_2, CH_4 and N_2O, CO_2 emission from biofuels is considered as zero [3].

Although PC represents 71.5% of SPMR fleet [3], its actual contribution is not proportional, especially for NO_x and $PM_{2.5}$, because HDV are the main source of these pollutants, but its CO and NMHC emission are significant.

Observing Table 5, we can see that when the proportion of diesel PC increases in the fleet, the weight of NO_x emissions grows significantly and there is some increment for $PM_{2.5}$; Equivalent CO_2 has a negligible reduction and CO and NMHC participation reduces but remains significant. When is considered the "actual" NO_x emission, it will add 24.2 thousand metric tons/year and will answer for 42% of the vehicular NO_x with a small reduction for GHG.

Table 3: PC contribution for actual emissions from SPMR fleet (metric tons/year).

	PC emission	**Total emission**	**% from PC**
Equivalent CO_2	5,163	13,117	39.4%
NO_x	8,989	54,355	16.5%
$PM_{2.5}$	67	1,434	4.7%
CO	82,203	127,157	64.6%
NMHC	20,029	29,031	69.0%

Table 4: PC contribution in SPMR – 50% of the fleet as diesel PC (metric tons/year).

	PC emission	**Total emission**	**% from PC**
Equivalent CO_2	5,094	13,048	39.0%
NO_x (laboratory factor)	14,413	59,799	24.1%
Actual NO_x	33,238	78,605	42.3%
$PM_{2.5}$	143	1,509	9.5%
CO	72,703	117,657	61.8%
NMHC	17,155	26,158	65.6%

Table 5: Comparison Actual x Projected: Total emissions (metric tons/year).

	Actual (No diesel PC)	**Projection (50% fleet diesel PC)**	**Difference**
Equivalent CO_2	13,117	13,048	-0.5%
NO_x (laboratory factor)	54,355	59,799	+9.1%
Actual NO_x	54,355	78,605	+30.9%
$PM_{2.5}$	1,434	1,509	+5.0%
CO	127,157	117,657	-8.1%
NMHC	29,031	26,158	-11.0%

It is possible to affirm for this projection that NO_x itself tends to become a critical pollutant that could worsen the secondary formation of $PM_{2.5}$ (not estimated here), on the other hand, the reduction for CO and NMHC emission can result in some improvement for O_3 issue. For $PM_{2.5}$, the expected influence of diesel PC was not found in the projections. Two factors could explain this, among others: firstly, PC and LDV make use of diesel particulate filters (DPF) in the exhaust system, so the mass of $PM_{2.5}$ from diesel PC is very lower than HDV, which, in Brazil, this technology is still not applied; second, the mass of fine particulate is very low, even at high particle number, so a small increment in $PM_{2.5}$ mass can represent a huge emission in number of particles.

4.3 Alternative scenario

When the alternative of no more selling ICE PC is analyzed, it must be considered that replacement for new electric vehicles does not happen immediately but requires some time to be done, meanwhile old PC will still be running and burning petrol, diesel and ethanol, along with motorcycles and HDV, all these emitting pollutants and CO_2.

Thus, the 6-years projection for this scenario, as summarized in Table 6, shows a large reduction in NO_x emission but only some reduction for CO_2 and $PM_{2.5}$ and negligible influence for NMHC and CO.

5 CONCLUSIONS

All projections go against the idea of diesel cars as a low pollutant vehicle which reduces CO_2 emission significantly but adopting diesel PC as the main choice leads to a huge NO_x increase, making the air pollution even worse in metropolitan areas.

On the other hand, the use of biofuels, which is nowadays available in many countries [26], can bring a short time reduction in GHG, although with some increase for NHMC and CO, which are ozone precursors.

Electric PC, however, may be a good solution for air pollution, but the projection shows that the environmental gain is not immediate, but it will take some time to be effective. There are side questions about electric cars, not discussed here, but should be considered, among others, as higher electric vehicles prices, final disposal for weak batteries and availability of energy supply and overcharge of the grid.

Table 6: Comparison: 50% fleet w/diesel PC x no sales for ICE PC (metric tons/year).

	Baseline: 50% fleet diesel PC	**Projection (no ICE PC sales)**	**Difference**
Equivalent CO_2	13,048	11,710	-11.4%
Actual NO_x	78,605	53,409	-47.2%
$PM_{2.5}$	1,509	1,413	-6.8%
CO	117,657	115,107	-2.2%
NMHC	26,158	25,999	-0.6%

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REFERENCES

[1] História da legislação sobre o etanol; Nova Cana, Online. https://www.novacana.com/etanol/historia-legislacao/. Accessed on: 27 Feb. 2018.
[2] Composição de preços ao consumidor – óleo Diesel, Petrobras, Online. http://www.petrobras.com.br/pt/produtos-e-servicos/composicao-de-precos/diesel/. Accessed on: 6 Apr. 2017.
[3] Bales, M. (coord.), *Emissões veiculares no estado de São Paulo 2015,* CETESB: Sao Paulo, p. 214, 2016, Online. http://veicular.cetesb.sp.gov.br/wp-content/uploads/sites/35/2013/12/Relatorio-Emissoes-Veiculares-2015-subst-011116.pdf. Accessed on: 23 Nov. 2016.
[4] Arroio, R. (ed.), *Qualidade do ar no estado de São Paulo 2015,* CETESB: São Paulo, 167 pp., 2016, Online. http://ar.cetesb.sp.gov.br/publicacoes-relatorios/. Accessed on: 20 May 2016.
[5] Instituto Brasileiro do Meio Ambiente e Recursos Naturais Renováveis (IBAMA), *Proconve/Promot – Air Pollution Control Program By Motor Vehicles*, 3rd ed., IBAMA/DIQUA: Brasilia, 584 pp., 2011, Online. http://www.ibama.gov.br/areas-tematicas-qa/programa-proconve. Accessed on: 24 Jun. 2015.
[6] Qualidade do Ar, CETESB, Online. http://ar.cetesb.sp.gov.br/. Accessed on: 26 Nov. 2016.
[7] Alvim, D. et. al., Estudo dos compostos orgânicos voláteis precursores de ozônio na cidade de São Paulo. *Engenharia Sanitária e Ambiental*, **16**(2), p. 13, 2011. Accessed on: 21 Jan. 2017. DOI: 10.1590/S1413-41522011000200013.
[8] Martins, L., Sensibilidade da formação do ozônio troposférico às emissões veiculares na Região Metropolitana de São Paulo, Universidade de São Paulo – Instituto de Astronomia, Geofísica e Ciências Atmosféricas: São Paulo, p. 219, 2006. Thesis (Doctorate at Atmospheric Sciences).
[9] Castro, A.H.S., Araújo, R.S.E. & Silva, G.M.M., Qualidade do ar – parâmetros de controle e efeitos na saúde humana: uma breve revisão. *Holos*, year 29, **5**, pp. 107–121, Oct. 2013. ISSN: 1807-1600i.
[10] Search results for Nitrogen Oxides; United States Environmental Protection Agency (USEPA), Online. https://ofmpub.epa.gov/sor_internet/registry/termreg/searchandretrieve/termsandacronyms/search.do?matchCriteria=Contains&checkedTerm=on&checkedAcronym=on&search=Search&term=Nitrogen%20Oxides#. Accessed on: 4 Apr. 2017.
[11] Albuquerque, T.T.A., *Formação e transporte das partículas finas inorgânicas em uma atmosfera urbana: o exemplo de São Paulo*, Universidade de São Paulo – Instituto de Astronomia, Geofísica e Ciências Atmosféricas: São Paulo, p. 189, 2010. Thesis (Doctored in Meteorology).
[12] Frota de veículos, por tipo e com placa, segundo as Grandes Regiões e Unidades da Federação - DEZ/2016; Departamento Nacional de Trânsito (DENATRAN), Online. http://www.denatran.gov.br/estatistica/261-frota-2016. Accessed on: 15 Feb. 2018.
[13] Delphi, *2016–2017 Worldwide Emissions Standards, Passengers Cars and Light Duty,* Troy, Michigan, 104 pp., 2017, Online. http://delphi.com/docs/default-source/worldwide-emissions-standards/delphi-worldwide-emissions-standards-passenger-cars-light-duty-2016-7.pdf. Accessed on: 21 Jan. 2017.

[14] Franco, V. et al., Real-world exhaust emissions from modern diesel cars – A meta-analysis of PEMS emissions data from EU (EURO 6) and US (Tier 2 bin 5/ULEV II) Diesel passenger cars. Part 1: aggregated results; International Council on Clean Transportation Europe (ICCT), Online. http://www.theicct.org/sites/default/files/publications/ICCT_PEMS-study_diesel-cars_20141010.pdf. Accessed on: 4 Jan. 2017.
[15] Kadijk, G. et al., TNO 2016 R10083 NO_x emissions of Euro 5 and Euro 6 diesel passenger cars – test results in the lab and on the road; TNO – Netherlands Organization for Applied Scientific Research, Online. http://publications.tno.nl/publication/34620046/H95fkX/TNO-2016-R10083.pdf. Accessed on: 23 Sep. 2016.
[16] German, J., The emissions test defeat device problem in Europe is not about VW; International Council on Clean Transportation Europe (ICCT), Online. http://www.theicct.org/blogs/staff/emissions-test-defeat-device-problem-europe-not-about-vw. Accessed on: 25 Nov. 2016.
[17] Kodjak, D. et al., An international perspective on vehicle emissions compliance, testing and enforcement. *US EPA Compliance Summit*, p. 22, 2016.
[18] Marner, B., Emission of nitrogen oxides from modern Diesel vehicles; Air Quality Consultants, Online. http://www.aqconsultants.co.uk/getattachment/Resources/Download-Reports/Emissions-of-Nitrogen-Oxides-from-Modern-Diesel-Vehicles-210116.pdf.aspx. Accessed on: 23 Sep. 2016.
[19] Thompson, G. et al., *In-Use Emissions Testing of Light-Duty Diesel Vehicles in the United States – final report*. Center for Alternative Fuels, Engines & Emissions (CAFEE) – West Virginia University: Morgantown, United Sates of America, pp. 133, 2014, Online. http://www.theicct.org/sites/default/files/publications/WVU_LDDV_in-use_ICCT_Report_Final_may2014.pdf. Accessed on: 11 Jan. 2017.
[20] Auto de infração nº 9082389-E – Procedimento 02001.007032/2015-46 – Decisão de 1ª instância 191/2017 – Parecer DIQUA 000207/2017 – Relatório de avaliação de emissões de poluentes de veículos Amarok Diesel, CETESB, 01.2017; IBAMA – Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais, Online. http://www.ibama.gov.br/phocadownload/noticias/noticias2017/oficio_volkswagen_e_anexos_.pdf. Accessed on: 6 Apr. 2017.
[21] New passenger car registrations breakdown by share of diesel 1990-2016; European Automobile Manufacturers Association (ACEA), Online. http://www.acea.be/statistics/tag/category/share-of-diesel-in-new-passenger-cars. Accessed on: 9 Feb. 2018.
[22] da Silva, M.F., *Emissão de metais por veículos automotores e seus efeitos à saúde pública*. Universidade de São Paulo – Faculdade de Saúde Pública: São Paulo, p. 156, 2007. Dissertation (Master degree in Public Health).
[23] Gasolina, Agência Nacional do Petróleo, Gás Natural e Biocombustíveis (ANP), Online. http://www.anp.gov.br/wwwanp/petroleo-derivados/155-combustiveis/1855-gasolina. Accessed on: 19 Feb. 2018.
[24] Óleo Diesel, Agência Nacional do Petróleo, Gás Natural e Biocombustíveis (ANP), Online. http://www.anp.gov.br/wwwanp/petroleo-derivados/155-combustiveis/1857-oleo-diesel. Accessed on: 27 Feb. 2018.
[25] Etanol; Agência Nacional do Petróleo, Gás Natural e Biocombustíveis (ANP), Online. http://www.anp.gov.br/wwwanp/biocombustiveis/etanol. Accessed on: 27 Feb. 2018.
[26] 60 países já adotam a mistura obrigatória de biocombustíveis aos combustíveis fósseis; União das Indústrias de Cana de açúcar (UNICA), Online. http://www.unica.com.br/noticia/27251092920325965467/60-paises-ja-a. Accessed on: 17 Jan. 2018.