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FUGITIVE EMISSIONS IN MOBILE SOURCES - AN EXPERIMENTAL ANALYSIS IN DIESEL-POWERED VEHICLES REGULATED BY THE EURO V STANDARD

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Abstract. *Changes have stood out among the global issues of greatest interest in recent decades. Among the classes of pollutant emissions, fugitive emissions are responsible for 5% of Greenhouse Gas (GHG_s) emissions in Brazil. In 2015, 195 countries gathered at the United Nations Conference on Climate Change (COP21) where each member nation, through the Intended Nationally Determined Contributions ($INDC_s$), stipulated its own goals and commitments for the climate agreement, whose central focus is to limit the increase in global average temperature by up to 2°C. Brazil is a signatory to this agreement and its proposed emission reduction targets are 37% by 2025 and 43% by 2030. In this context, fugitive emissions began to be extensively studied in industrial plants. However, there are no records of studies on mobile sources, even taking into account that the aging of couplings and exhaust pipes in vehicles can cause gas leakage. Thus, this work proposes to elucidate, in an unprecedented way, through experimental investigation, the existence of fugitive emissions in buses regulated by Euro V standards. For this, statistical methods were used to define the minimum representative sample. Along the exhaust, fugitive gases were enclosed and channeled to begs, which were later sent for analysis in the laboratory. Chemiluminescence and infrared methods and a Horiba PG-300 analyzer were used to analyze the samples. The results were compared with the parameters of the current legislation, where it was observed a direct relationship between vehicle age and increased fugitive gas emissions.*

Keywords: *Euro V, Mobile sources, Greenhouse gases, Exhaust pipe, Leakage gases.*

1. INTRODUCTION

In 7^{th} among the countries that emit the most Greenhouse Gases (GHG_s), Brazil contributed 2.9% of total global emissions of pollutants in 2019. Land use change and forestry were dominant activities in the emissions process. Alone, these two activities contributed 44% of the emissions (CO_2), Albuquerque *et al.* (2020).

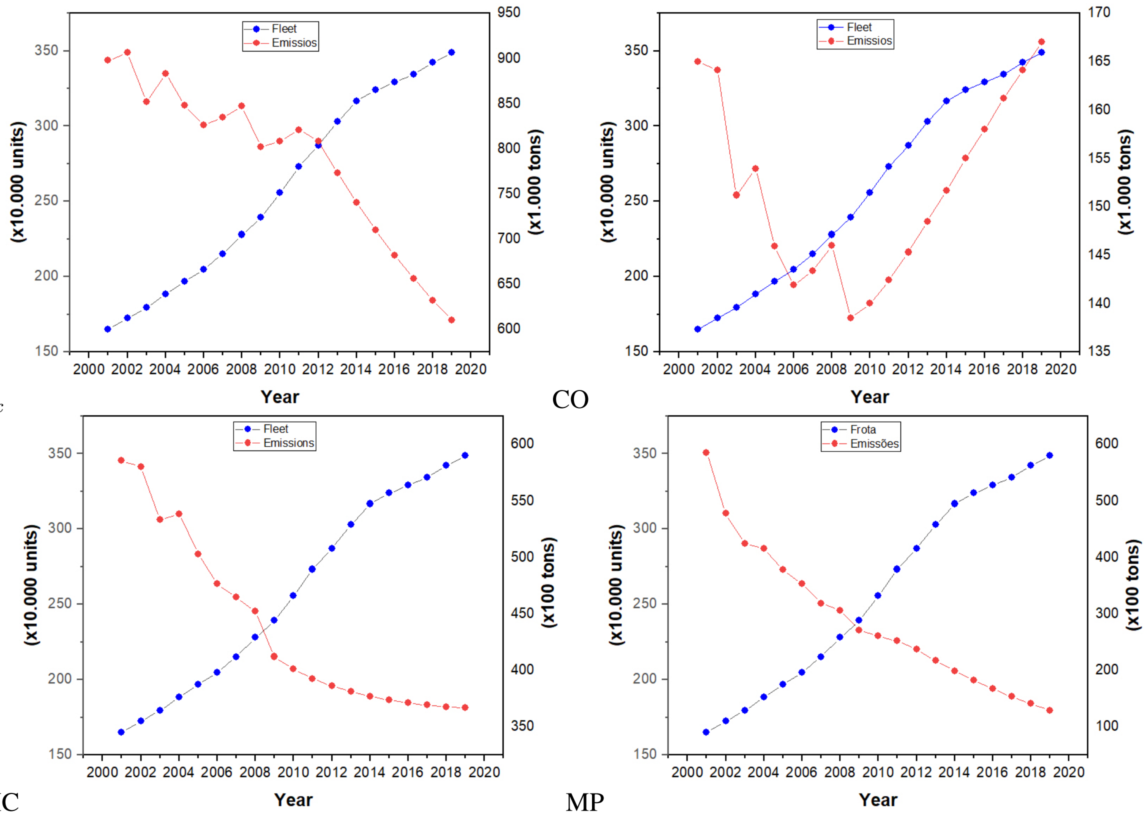
Considering exclusively the pollutants object of this investigation, in the last two decades, the energy sector was the biggest polluter, contributing with 55,3% and 91,3% of (CO) and (NO_x) emissions, respectively. Of this total, the transportation segment, a subgroup of the energy sector, emitted 40,2% of (CO) and 55,1% of (NO_x), and, among the modals that divide the transportation segment, the road activity was dominant with emission of 70,1% of (NO_x) and 97,7% of (PM)., do Meio Ambiente (2011).

To control emissions of pollutants in the automobile industry in Brazil, resolution 18/1986 was published starting the cycle of regulations. In 2008, Conama's resolution 403/2008 gave life to one of the most important phases of Proconve.

The 7^{th} phase brought significant advances, with stringent restrictions on pollutant emission levels. In this sense, the truck and bus industry was forced to develop new engine technologies. The most efficient of these technologies is the Selective Catalytic Reduction System (SCR), which uses the reducing agent $ARLA_{32}$ in its operation and presents an efficiency between 80% and 90% in the reduction of pollutants according Guan *et al.* (2014) Carslaw *et al.* (2015) and Preble *et al.* (2019).

The technological advances imposed by the regulations led to more stringent emission limit tolerances. The reduction proposed by the 7^{th} phase of Proconve was 28,5% for (CO), 30,3% for (HC), 60% for (NO_x) and 80% less emission of (PM). In January 2022 the 8th phase of Proconve will go into effect with the implementation of Euro VI standard technologies.

The practical effects of the 403/2008 resolution present good consistency with the proposed objectives. In the year 2000, the truck and bus fleet represented 184 thousand units and was responsible for the emission of 904 thousand tons of (NO_x) and 610 thousand tons (PM). With the implementation of emission control technologies, even with 89,6% growth in the truck and bus fleet in the last two decades, the reduction in emissions of (NO_x) was 32,5% in 2019 compared to the year 2000. Following the same trend, but with even greater expressiveness, the reduction in (PM) emissions was 78,8% in the same period. In Fig. 1 it is possible to observe the clear relationship between the selective catalytic reduction technologies, with emphasis on the (NO_x) that has a direct relationship with the technologies of gas control in the post-treatment.



NO_x CO NMHC MP

Figure 1. Behavior of pollutant emissions in trucks and buses in the last two decades as a function of fleet growth and the influence of selective catalytic reduction technologies on after-treatment

2. EXPERIMENTAL PROCEDURE

2.1 Sample Size Definition

Considering the complexity of measurement and the need to understand the behavior of fugitive emissions over the lifetime of the vehicle, the concept of stratified sampling that is based on dividing populations into sub-populations or strata is more appropriate for defining the sampling model in this investigation. In this format, the sample is selected and separated independently within each stratum and the data collected for each sample is used to develop the estimates within the same axis. Free software G*Power3 was used to define the minimum representative sample size. Data were entered into the program considering minimum power of 80%, with null hypothesis at (H_0) and alternative hypothesis (H_1) at 0.7, Tab. 1.

Table 1. Linear bivariate regression: One group, size of slope.
Analysis: A priori: Compute required sample size

Input:	Tail(s)	One
	Slope H_1	0.7
	α err prob	0.05
	Power (1- err prob)	0.80
	Slope H_0	0
	Std dev α_x	1
	Std dev α_y	1
Output:	Noncentrality parameter δ	2.9405882
	Critical t	1.8945786
	Df	7
	Total sample size	9
	Actual power	0.8404212

2.2 Sample Collection and Preparation

To conduct the experiment, technical visits were made within 6 days to 3 urban and road transport companies in the city of Manaus/Amazonas, where 10 buses were selected and separated into 3 distinct groups according to year and model, being the Volvo B270F, B12M and B11R. The first two groups in the urban transport category and the third in the road category, Fig. 2:

Figure 2. Representation of the vehicles used for sample collection. Both from the same brand, varying the models and applications, being Fig. (a) for the B270F model, Fig. (b) for B12M and Fig. (c) B11R.

2.3 Performing the experimental procedure

We used the enclosure system as shown in, Fig. 3. A copper pipe 500 mm long and 6 mm in diameter was connected to the exhaust pipe of the vehicle. An Aramid tape that has high thermal resistance was used as thermal insulation.

Overlapping the Aramid, another tape (Torofita) was used to assist in the process of barrier and escape of the gases. The collected fugitive gases were stored in a beg with a capacity of 1 dm^3 and sent for laboratory analysis.

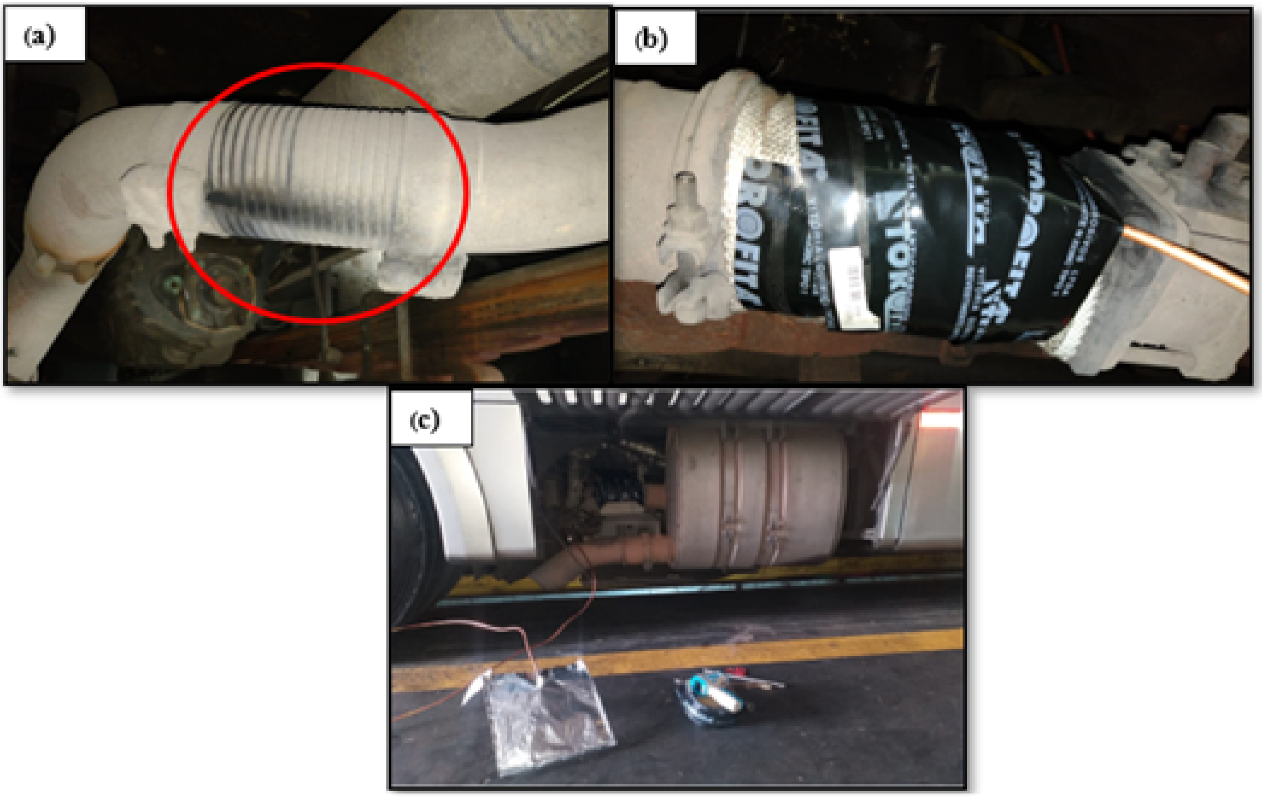


Figure 3. Experimental apparatus for collecting the gases by encapsulation and piping to the begs. Fig. (a) represents the leak point in the exhaust pipe, Fig. (b) the junction copper pipe to the leak point and Fig. (c) the beg at the moment of filling.

2.4 Gas collection method

For the collection of gases and storage in bags with a capacity of 1 dm^3 three tables were prepared, relating the mileage values of each vehicle, engine rotation, collection time, exhaust pipe temperature and engine working temperature, Tab. (2-4).

Table 2. Engine operating parameters and conditions at the time of gas sampling. Considered to be steady state with temperature similar to load state - Volvo B12M vehicle

Year of manufacture	**round mile (km)**	**Engine speed (RPM)**	**Engine power (CV)**	**timing collection (min)**	**all exhaust temperature** ($^\circ C$)	**engine working temperature** ($^\circ C$)	**exhaust gas temperature** ($^\circ C$)	**Application**
2014	518.640	1.700	340	13,8	178	93,1	175	Urban
2014	367.100	1.700	340	9,03	165	92,4	155	Urban

2.5 Gas Analysis Method

The 10 samples collected were sent to the laboratories of the company White Martins where they were analyzed in an analyzer (Horiba PG-300) that can simultaneously measure up to five gas components separately. To analyze the (NO_x) concentrations the Cross-Flow Modulation Chemiluminescence detection method was used while to analyze (SO_2) and (CO) the Cross-Flow Modulation Non-Dispersive Infrared Absorption Method was applied.

In possession of the experimentally acquired collection time variables and the mass of gases measured in the laboratory, the fugitive gas flow rate in each of the analyzed vehicles was calculated, Eq.1, whose results were used for the elaboration of the Tab. 5.

Table 3. Engine operating parameters and conditions at the time of gas sampling. Considered to be steady state with temperature similar to load state - Volvo B270F vehicle

Year of manufacture	round mile (km)	Engine speed (RPM)	Engine power (CV)	timing collection (min)	all exhaust temperature ($^{\circ}C$)	engine working temperature ($^{\circ}C$)	exhaust gas temperature ($^{\circ}C$)	Application
2012	846.694	1.700	270	10,2	105	87	110	Urban
2012	367.100	1.700	270	12,1	106,7	86	103,7	Urban
2013	518.640	1.700	270	11,4	124	88	106	Urban
2013	367.100	1.700	270	13,1	138	85	104,6	Urban

Table 4. Engine operating parameters and conditions at the time of gas sampling. Considered to be steady state with temperature similar to load state - Volvo B11R vehicle

Year of manufacture	round mile (km)	Engine speed (RPM)	Engine power (CV)	timing collection (min)	all exhaust temperature ($^{\circ}C$)	engine working temperature ($^{\circ}C$)	exhaust gas temperature ($^{\circ}C$)	Application
2015	670.803	1.700	450	11,8	97	96	137	Roadway
2016	856.794	1.700	450	10,5	81	92	104	Roadway
2018	938.933	1.700	450	12,1	107	94	152	Roadway
2020	93.449	1.700	450	11,39	115	91,8	132	Roadway

Table 5. Flow rate collected experimentally as per Fig. 3 and calculated by the mass flow equation using the variables gas mass and collection time.

Vehicle	Massa (kg)	Tempo (s)	Vazão (kg/s)
A	0,011	788	$1{,}396\times10^{-5}$
B	0,017	540	$3{,}148\times10^{-5}$
C	0,027	602	$4{,}485\times10^{-5}$
D	0,015	781	$1{,}921\times10^{-5}$
E	0,029	664	$4{,}637\times10^{-5}$
F	0,023	721	$3{,}190\times10^{-5}$
G	0,024	605	$3{,}967\times10^{-5}$
H	0,090	664	$1{,}355\times10^{-5}$
I	0,011	660	$1{,}667\times10^{-5}$
J	0,012	721	$1{,}664\times10^{-5}$

$$V_i = \left(\frac{m_i(kg)}{t_i(s)}\right)(kg/s) \tag{1}$$

where:

V_i Flow (kg/s)

m_i Mass of gas (kg)

t_i Collection time (s)

3. RESULTS AND DISCUSSION

For the study of the analysis of the results found in the concentration of gases collected in 10 different samples the Tab. 6 of permissible values of Conama 7 for the control of gas emissions from motor vehicles.

With the analysis of the 10 samples from the gas collection, we generated the Tab. 7 and Fig. 4 representing the ratio between the mileage traveled by each vehicle and the total emission of each gas released into the atmosphere through the tailpipe leak.

3.1 Comparison between reference values and measured values

Vehicle exhaust emissions are typically measured using a gas analyzer and reported in parts per million (ppm) and percent volume (vol%), Heseding and Daskalopoulos (2006). It is important to compare these emissions to European ve-

Table 6. Maximum parameters for the emission of pollutants based on the Conama resolutions and the Brazilian Ministry of the Environment - Emphasis on P7, the phase currently in effect. (CO) Carbon monoxide, (THC) Total hydrocarbons (NO_x) Nitrogen oxide, (PM) Particulate matter.

Standard Brasilian	Standard European	CO (g/kWh)	THC g/kWh)	O_X (g/kWh)	MP (g/kWh)	Resolution (Conama)	Effective Date
P1	-	14	3,5	18	0	Res. 18/1986	1987 the 1989
P2	Euro 0	11,20	2,45	14,40	0,6	Res. 08/1993	1994 the 2002
P3	Euro I	4,90	1,23	9,00	0,70 the 0,4	Res. 08/1993	1994 the 2002
P4	Euro II	4,00	1,10	7,00	0,15	Res. 08/1993	1994 the 2002
P5	Euro III	2,10	0,66	5,00	0,10 a 0,3	Res. 315/2002	2003 the 2011
P6	Euro IV	1,50	0,46	3,50	0,02	Res. 315/2002	2003 the 2011
P7	**Euro V**	**1,50**	**0,46**	**2,00**	**0,02**	**Res. 403/2008**	**2012 the 2021**
$P8^5$	Euro VI	1.50	0,13	0,40	0,01	Res. 490/2018	from 2022

Table 7. Concentration of raw gases analyzed in the laboratory with cross-modulation chemiluminescence detection method and Cross-Flow Modulation Non-Dispersive Infrared Absorption.

Vehicle	model	Year of manufacture	round mileage (km)	Carbon monoxide (g/kWh)	nitrogen oxide (g/kWh)	Carbon dioxide (g/kWh)
A	B12M	2014	518.640	0,3537	0,0212	0,1460
B	B12M	2014	367.100	0,3487	0,0133	0,1434
C	B270F	2012	846.694	0,4974	0,0186	0,1745
D	B270F	2012	528.923	0,4575	0,0179	0,1714
E	B270F	2013	595.771	0,3806	0,0153	0,1707
F	B270F	2013	210.814	0,3555	0,0265	0,1473
G	B11R	2015	670.803	0,3232	0,0199	0,1390
H	B11R	2016	856.794	0,3077	0,0173	0,1358
I	B11R	2018	938.933	0,3049	0,0232	0,1314
J	B11R	2020	93.449	0,0215	0,0332	0,0190

hicle emission standards that are generally reported in (g/kWh) for heavy duty vehicles and (g/km) for light duty vehicles. In previous research, Pilusa *et al.* (2012) has described an interesting relationship between vehicle emission concentration and specific fuel consumption. This relationship is defined by Eq.2

$$EP_i = EV_{i,d}\left(\frac{M_i}{M_{Exh,d}} \times \frac{m_{Exh,d}}{P_{eff}}\right) = EV_{iw}\left(\frac{M_i}{M_{Exh,w}} \times \frac{m_{Exh,w}}{P_{eff}}\right) \tag{2}$$

where:
EP_i Pollutant mass, i, referenced to Peff (g/kWh).
$EV_{i,d}$ Exhaust emission value of components on dry basis, i, as volume share (ppm).
$EV_{i,w}$ Exhaust emission value of components on wet basis, i, as volume share (ppm).
M_i Molecular mass of the components, i, (g/mol).
$M_{Exh,d}$ Molecular mass of the exhaust gases on dry basis (g/mol).
$M_{Exh,w}$ Molecular mass of the exhaust gases on wet basis (g/mol).
$m_{Exh,d}$ Exhaust mass flow (kg/h).
P_{eff} Power output (kW).

Likewise the empirical constants also reported by Pilusa *et al.* (2012) are represented by the Eqs. 3 and 4.

$$K_d = \left(\frac{m_{Exh,d}}{P_{eff}}\right) = 3.873\ g/kWh \tag{3}$$

$$K_w = \left(\frac{m_{Exh,w}}{P_{eff}}\right) = 4.160\ g/kWh \tag{4}$$

Is important to note that (CO) is measured on a dry basis and should be estimated using the Eq. 5 while the rest of the gases are measured on a wet basis and can be calculated using the Eq. 6. The Eqs. 4 and 5 were derived from Eq. 2 taking into account the empirical constants of Heseding and Daskalopoulos (2006). Under this assumption, the Eqs. (7-10) were used to convert the ppm results obtained by laboratory analysis to g/kWh.

$$EP_{i,d}(g/kWh) = \frac{EV_{id}(ppm)}{1x10^6} \times \left(\frac{m_i}{30,21\ g/mol} \times 3873\ g/kWh \right) \tag{5}$$

$$EP_{i,w}(g/kWh) = \frac{EV_{iw}(ppm)}{1x10^6} \times \left(\frac{m_i}{28,84\ g/mol} \times 4160\ g/kWh \right) \tag{6}$$

The overall conversion from emission gas concentration in (ppm) to specific fuel consumption in (g/kWh) for heavy duty vehicles is summarized through the Eqs: (7-10).

$$CO(g/kWh) = 3,592 \times 10^-3 \times CO(ppm) \tag{7}$$

$$NO_x(g/kWh) = 6,636 \times 10^-3 \times NO_x(ppm) \tag{8}$$

$$HC(g/kWh) = 2,002 \times 10^-3 \times HC(ppm) \tag{9}$$

$$CO_2(g/kWh) = 63,470 \times 10^-3 \times CO_2(ppm) \tag{10}$$

The Fig. 4 shows the relationship of the concentration of the fugitive gases Carbon Monoxide, Carbon Dioxide and Nitrogen Oxides according to the emission content of each vehicle listed in the table above. It can be seen that vehicles C and D had the highest emission concentration of the three gases analyzed, varying year and mileage.

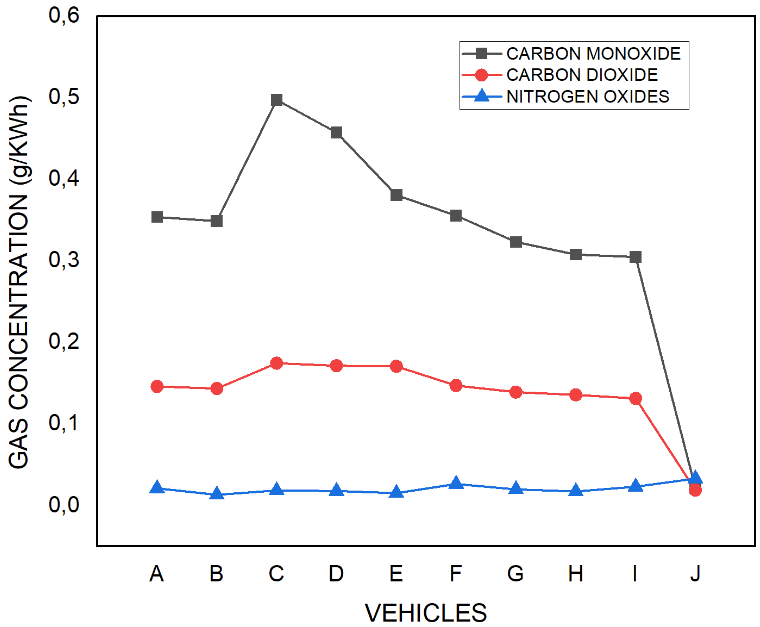


Figure 4. Representation of the raw gas concentrations (CO), (CO_2) and (NO_x) in Volvo B12M, B270F and B11R vehicles showing the behavior and evolution in emission intensity.

The Fig. 5 of the concentration of gases emitted by Volvo B12M model vehicles, both from the year 2014, it was found that there was little variation between mileages A and B which justifies the presentation of a concentration analysis of the three gases evaluated with linear values, highlighting carbon monoxide as the gas with the highest concentration. In this case, the natural wear conditions of the engine's internal components are directly related to the increase in the mileage traveled by the vehicle. This result is consistent with the research objectives.

Showing even more coherence between the objectives and results analyzed, the behavior of the concentrations presented in Fig. 6 clearly shows a direct relationship between the increase in mileage, or the useful life of the vehicle, and the concentration of raw gases emitted by Volvo vehicles model B270F. The significant variation in gas concentration values at different mileages explains the degradation of parts and components of the engine and exhaust system.

For the B11R model vehicles, the results presented, Fig. 7, indicate a 15-fold increase in pollutant concentration between the vehicles with manufacturing years 2020 and 2015. When comparing the difference between the mileage traveled by the same vehicles, the one with the highest concentration of pollutants traveled 7 times more. With these results it can be concluded that the increase in the concentration of pollutants is directly related to the increase in the mileage traveled and consequently more worn engine components.

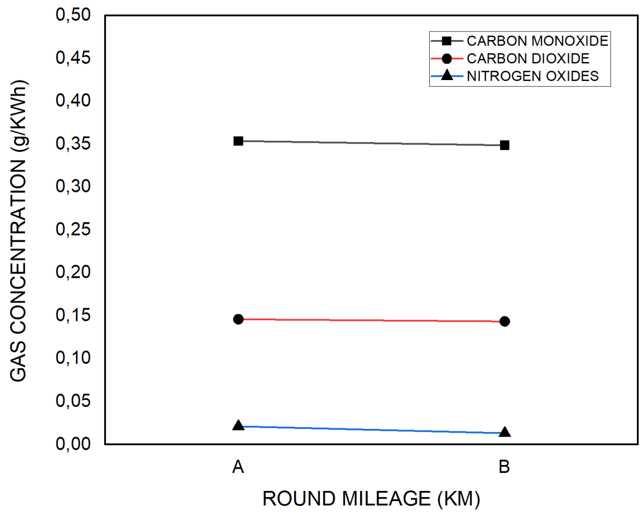


Figure 5. Representation of the concentrations of raw gas (CO), (CO_2) and (NO_x) in the Volvo B12M. Behavior and evolution of emissions for the same year and model varying the mileage.

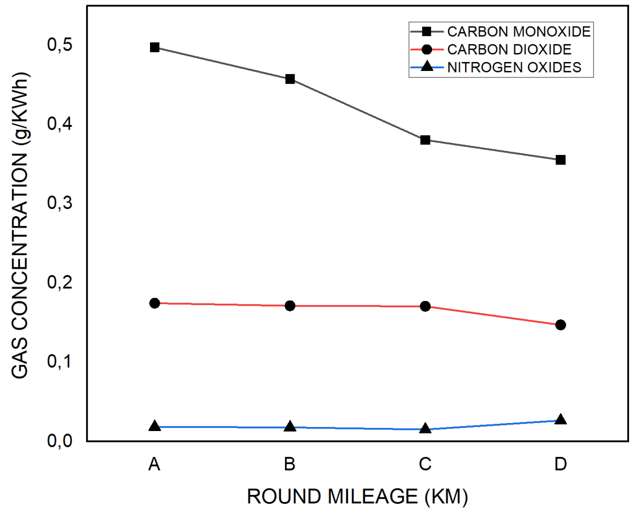


Figure 6. Representation of the concentrations of raw gas (CO), (CO_2) and (NO_x) in the Volvo B270F. Behavior and evolution of emissions for the same year and model varying the mileage.

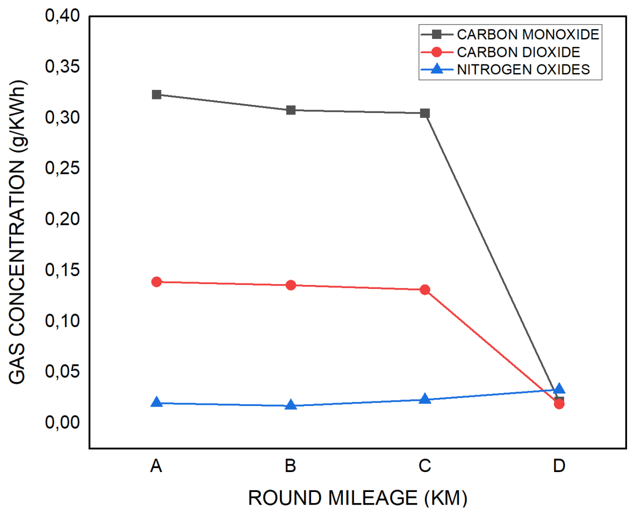


Figure 7. Representation of the concentrations of raw gas (CO), (CO_2) and (NO_x) in the Volvo B11R. Behavior and evolution of emissions for the same year and model varying the mileage.

4. Conclusion

Considering the complexity of the analysis whose availability of resources available for research has great limitations, the general objective was clearly achieved, evidencing the existence of fugitive emissions, Tab. 7, although the concentrations analyzed in the samples are within the maximum tolerance limits,Tab. 6.

With the results obtained in this study, the presence of the concentration of the main gases in the emission of urban and road vehicles of the Volvo model that are inserted in the Euro V category was scientifically analyzed, which are based on the reduction of pollutant gaseous particles to the earth's atmosphere. It was found that Carbon Monoxide was the largest gaseous concentrator of pollutants among the three models of vehicles evaluated, which demonstrates the need for regular preventive maintenance in vehicles with longer manufacturing date, even if the percentage of concentration is within the regulated by the agency CONAMA.

All samples were taken with the engine at steady state. Thus, further studies considering engine load are recommended. It is understood that the collection of fugitive gases in this condition may present higher concentration amounts.

We also disregarded, in this study, the estimates of fugitive emissions of pollutants because we consider that the concentrations identified in the samples present quantities consistent with the Brazilian standards that regulate the emissions of pollutants in motor vehicles.

5. Congratulation

I thank God for the opportunity to be developing the study of the concentration of gas emissions of pollutants in urban and road vehicles in the city of Manaus, the State University of Maringá together with Professor Dr. Leonel R. Cancino to my peers Nayara Caetano and Kethlen Caetano, Daniel Ferreira and the whole team from the Laboratory of the company White Martins responsible for technical and scientific support, and the companies of the group Eucatur Urbano, Viação São Pedro and Asatur Turismo who provided their vehicles for collection of gas samples.

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7. RESPONSIBILITY NOTICE

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