Comparison of Particulate Emissions from Different Categories of Diesel and Otto Engines and Vehicles

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Abstract

Based on the Brazilian vehicles' average certification values, it can be seen that there has been an increase in particulate matter emissions from gasoline and flexfuel cars, due to the introduction of direct fuel injection Otto engines (GDI). This effect was compared to the particulate emission reduction strategies for heavy duty diesel engines, already underway in Brazil since 1986 and with great effectiveness, in order to assess the need for a specific approach for light duty Otto cycle engines.

This study compares the technological standards applied to light and heavy-duty engines, for a strategic assessment of the vehicle particulate emissions control, but since these emissions are expressed in different ways for those vehicle categories, a new analysis method was developed specifically for this purpose.

This is an easy and efficient method, based on energy demand, which converts the emission factors into a common base, more associated with the engine's workload and, consequently, more representative of the activities performed by all vehicles in their fleet, regardless of knowing the usage statistics of each one. The concept is based on converting the apparently non-comparable emission factors, measured in g/km for light-duty vehicles and in g/kWh for heavy-duty vehicles, to a standardized unit in grams of PM per kilogram of fuel burned (or per Mol of Carbon, for more accurate comparisons with oxygenated fuels), which allows the comparison of the "environmental efficiency" of different types of machines.

The comparison made on this new basis allows the identification of whether the technological advances in engines and gas after-treatment systems applied to heavy-duty vehicles already exceed the quality of the current technologies applied to light-duty vehicles, and will indicate the real need to prioritize the latter in the control of particulate matter. If this is the case, the replacement of Otto engines with MPFI indirect injection with the new GDI engines will need to be re-evaluated, so that this market trend can be made viable by applying resources that reduce PM emissions. Such a strategy potentializes the application of ceramic filters in exhaust systems, which is the best alternative, as it provides the most advanced environmental results, with the additional benefit of also reducing the number of particles (NP).

This calculation process is being studied to be applied to the entire history of the particulate emissions control in Brazil, taking into account the average emission factors of each technology and the MPFI/GDI market proportions, in order to effectively compare the downward trend in PM emissions from heavy-duty diesel vehicles, with the new upward trend in light-duty gasoline and flex-fuel engines, in order to precisely define the strategy for its correction.

This same analysis technique was extended to other engines, such as generator sets, and indicated the need to equip them with state-of-the-art technologies, in the

EURO VI standard if possible, so that the emissions induced by electric vehicles, under the "well-to-wheel" concept, are compatible with those of traditional vehicles with internal combustion engines, in cities that depend on the electricity supply produced by diesel thermoelectric plants.

This analysis allows for a very comprehensive assessment, involving all vehicle and engine types in order to rebalance PM emission control strategies that are divorced from each other.

Background

Traditionally, spark-ignition Otto cycle engines have low particulate emissions, even without control devices, because the air-fuel mixture is prepared before it enters the combustion chamber, resulting in a high degree of homogeneity and more complete combustion. This fact significantly differentiates them from diesel engines, in which fuel is injected under high pressure directly into the combustion chamber, forming a spray whose droplets become nuclei for the particulate matter formation, whose emission is naturally high.

However, this fuel injection system offers performance and energy efficiency advantages, and has also been applied to Otto cycle engines, which significantly increases their particulate matter emissions.

In the United States, the introduction of gasoline direct injection (GDI) engines in 2008 increased cars' average particulate matter emissions by about 10 times, leading the country's environmental legislation to set a limit of 0.3 mg/km. Forecasts modeled by its environmental agency in 2014 indicated that this process would take two decades to bring average PM emissions back to acceptable levels[1], as shown in Figure 1.

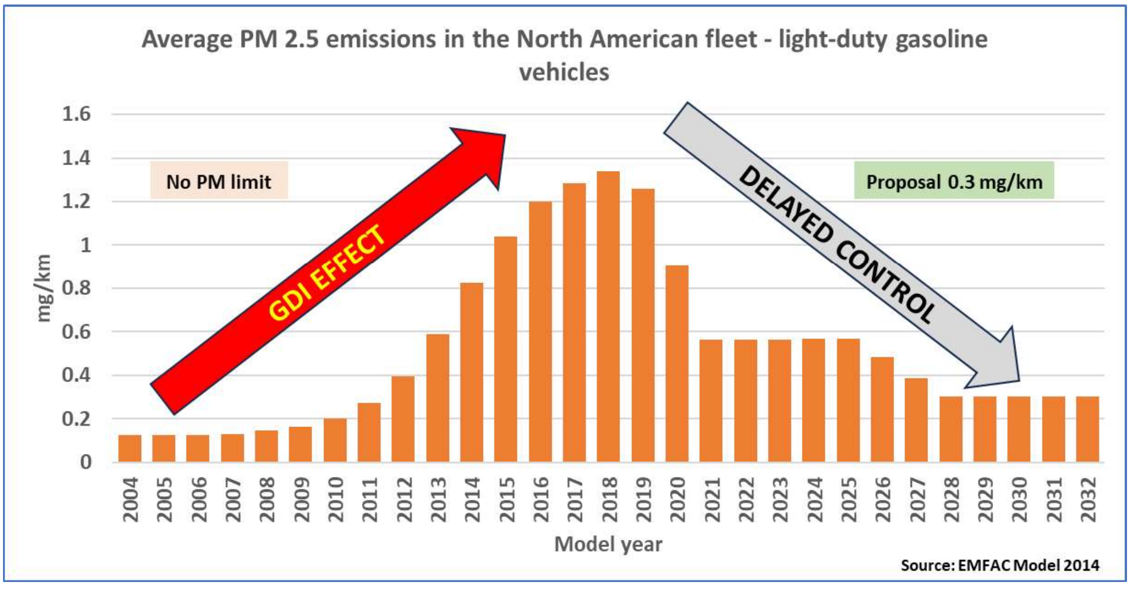
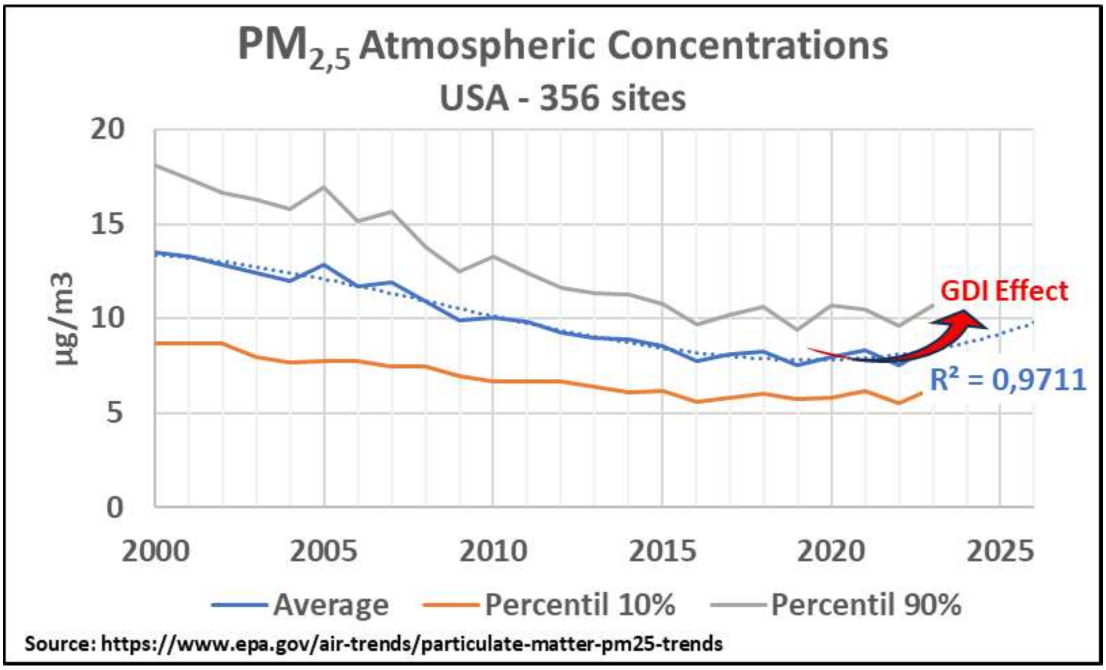


Figure 1 - Average PM emissions from gasoline-powered vehicle fleet - USA

This effect was confirmed in 2023 in emissions surveys conducted by remote sensing for the TRUE Initiative Program, which showed a decline in PM emissions from 2005 to 2015 models and an abrupt reversal of this trend, which was completely lost with the growth observed up to the 2020 model years.[2] This same trend is also detected in the analysis of atmospheric concentrations of PM2.5 in various US regions, which already show a reversal of the decline in this pollutant that had been observed since 2010, with growth resuming from 2020 at the national level, which has already led the annual average to exceed the US standard of 9µg/m3 in several regions, as shown in Figure 2, obtained from EPA data[3].



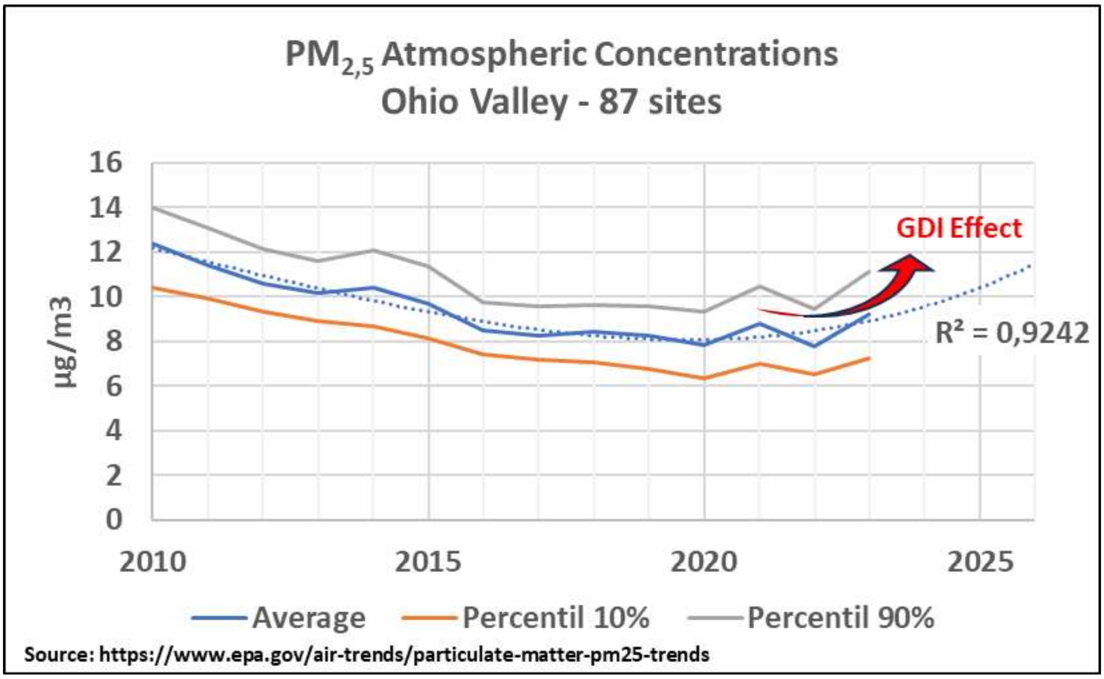


Figure 2: Annual atmospheric averages of $PM_{2.5}$ in the United States

In both diesel and Otto GDI engines, the most effective technology for meeting the strictest MP emission limits is based on filtering exhaust gases and burning the soot accumulated in the filter, using the temperature of the gases themselves. These are ceramic filters that, in addition to reducing particulate mass, also reduce the number of particles present in the exhaust gases by up to 500 times, depending on the filter's technological generation.

This aspect is particularly important because the reduction in PM emissions, based on techniques associated with the combustion process to promote better particle burning, as in the case of oxidation catalysts, comes at the expense of particle size reduction, but maintains the same number of particles per cubic meter of exhaust gas. It is worth noting that, during the in-engine combustion process, soot particles form with diameters of around 0.1 µm ($PM_{0.1}$), which are much smaller than particles known as $PM_{2.5}$, i.e., with diameters of up to 2.5 µm. With this tiny diameter, $MP_{0.1}$ has much higher toxicity, since submicron particles penetrate deeper into the lungs and can only be eliminated by the bloodstream, enhancing the absorption of foreign materials into the tissues, which cause more serious diseases, instead of being expelled by nasal mucus.

The formation of particulate matter in internal combustion engines

In diesel engines, fuel is sprayed directly into the combustion chamber, forming a heterogeneous mixture of air and liquid, whose droplets absorb heat and gasify, producing a cloud of vapor around them, mixed with air in decreasing concentrations as it moves away from the droplet. Combustion occurs in this vapor area, heating the droplet and producing a pyrolyzed carbon core that constitutes the particulate matter, as shown in Figure 3. In other words, each droplet is burned on the outside and “cooked” on the inside, leaving a carbon core from the heavier fractions of the fuel. This process leads to the higher formation of soot, known as typical for Diesel engines, which can be greatly reduced by increasing the fuel injection pressure, aiming to improve its pulverization, and complemented by exhaust gas filtration in the most modern engines.

In spark ignition engines, Otto cycle with indirect injection (Multi Port Fuel Injection - MPFI), the fuel is mixed with air outside the combustion chamber, under better conditions to produce a more homogeneous mixture, with a great part of it being vaporized beforehand. Therefore, the particulate matter emissions from this type of engine are naturally much lower.

However, direct fuel injection into the combustion chamber has also recently been applied to Otto engines (GDI) to improve torque and fuel consumption, similar to diesel engines, which also makes them similar in terms of particulate matter formation, albeit to a lesser extent because the fuels used are more volatile, among other characteristics of this design.

For this reason, the introduction of GDI models on the market raises the average particulate emissions of light-duty gasoline vehicles, traditionally close to 1 mg/km, to 3 mg/km or more. This fact was observed in the US market in the first decade of the

2000's and is now being repeated in Brazil, significantly raising the average for Otto engines from 2021 onwards, including flex-fuel vehicles.

This process is controlled mainly by increasing the injection pressure to produce smaller droplets and by the geometry of the engine components, up to a certain point when gas filtration is necessary to meet more stringent limits.

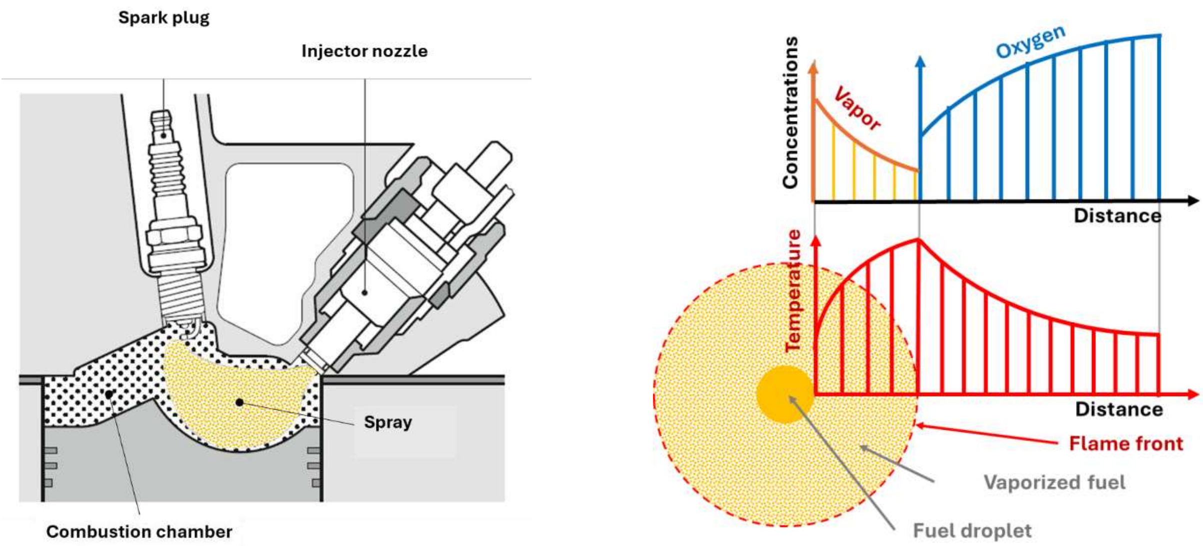


Figure 3 – Vaporization and combustion of fuel in direct injection engines

The evolution of particulate matter emission control in Brazil

Since the beginning of PROCONVE – National Motor Vehicle Air Pollution Control Program, soot emissions from heavy-duty diesel engines have been reduced from 1,500 mg/kWh in the 80's, when diesel fuel was of low quality and contained 10,000 ppm of sulfur, to less than 30 mg/kWh in 2012 with the introduction of phase P7, when Brazil could count on ultra-low sulfur fuel (10 ppm). This process drastically reduced PM emissions, both in the formation of sulfates and by enabling advanced fuel injection technologies in diesel engines.

In 2023, phase P8 (EURO VI standards) consolidated new technologies, reducing PM emissions even further and enabling compliance with the limit of 10 mg/kWh, with the additional requirement of compliance with the limit of 6×10^{11} particles per kWh of engine-generated mechanical energy, which has been achieved through the use of ceramic filters. Table 1, based on historical data from PROCONVE, illustrates this evolution in the emission control of particulate matter in Brazilian heavy-duty engines.

Table 1 - Typical emissions and particulate matter limits for heavy-duty vehicles

HDV Phase	PM mg/kWh	Notes
Pre PROCONVE	1500	Old typical data, converted to equivalent values in the ETC test
P3 - 1996	1100	
P4 - 2000	250	
P5 - 2005	160	Limit - Introduced S500 diesel oil
P6 - 2009	30	Phase canceled due to unavailability of S50 diesel oil
P7 - 2012	30	Limit - Introduced S10 diesel oil
P8 - 2023	10	Mass limit in addition to the limit of 6 x 10^{11} part/kWh

At the same time, certified particulate matter emissions from gasoline, ethanol, and flex-fuel vehicles remained consistently at 1 mg/km until 2021, when the average began to rise, reaching 3 mg/km for gasoline vehicles in 2023, according to average certification data for vehicles with MPFI and GDI engines published by CETESB. It is important to note that light-duty diesel commercial vehicles had much higher values in 2011, but have already reached the level of 1 mg/km since 2023.

Therefore, the same behavior observed in the United States with the introduction of GDI engines has been intensifying in Brazil in recent years, although CETESB has not specified the proportions between the two. In Brazil, there is still a mitigating factor when these engines (MPFI and GDI) use hydrated ethanol, but even in this case, they emit particulates between 1 and 2 mg/km, still below the corporate limits required in phase L8, which are currently 4 mg/km and will be 3 mg/km from 2029 onwards. These limits for phase L8 are lenient and allow for an increase in average PM emissions in the coming years, permitting values above these limits for a particular model to be compensated for by another model from the same manufacturer.

Table 2 - Typical particulate matter emissions from light-duty vehicles [4]

PM Emission Averages - mg/km							
Calendar Year	Passenger Vehicles			Commercial Vehicles			
	Flex -Ethanol	Gasohol	*Flex* -Gasohol	Diesel	*Flex* -Ethanol	Gasohol	*Flex* -Gasohol
1997 a 2011	1,1	1,1	1,1	65	1,1	1,1	1,1
2011 a 2021	1,1	1,1	1,1	13,6	1,1	1,1	1,1
2022 (L7)	1,6	1,3	**3,0**	**2,0**	1,6	**2,3**	**3,0**
2023	**2,4**	1,3	**2,9**	1,1	1,0	1,7	**3,5**
2024	1,7	1,2	**2,4**	0,7	1,0	1,8	**3,5**
2022-24 Ave.	1,9	1,3	**2,8**	1,2	1,2	1,9	**3,3**

GDI EFFECT

Source: CETESB certification data, 2024

Technological comparisons between vehicles of different categories

CETESB provides society with the best information on vehicle activity, publishing annually the average values of certified emission factors for each vehicle category and model year so that society, the scientific community, and public administrators can learn about, evaluate, and propose public policies for maintaining environmental quality[5].

Although it is the most comprehensive publicly available data source, several categories do not present all data in some phases of PROCONVE. However, similar categories can be grouped together to provide an overview of the program's evolution. Thus, the statistical significance is not uniform for all cases, but it accurately describes the history of typical values, especially in terms of their progressiveness and the technological evolution of the Brazilian fleet.

Exhaust emissions and their respective limits set by PROCONVE are expressed in grams per kilowatt hour for heavy-duty vehicles and in grams per kilometer for light-duty vehicles and motorcycles, which makes it difficult to compare emission levels across all categories. These emissions measurement methods are associated with driving cycles characteristic of the engine loads encountered in everyday use of the various vehicle categories. Thus, heavy-duty engines are tested at higher loads than light-duty engines and motorcycles, each in its own way, but in the manner most representative of the actual use of the vehicle category for the determination of emissions and fuel consumption.

Consequently, the ratio between emission factors and fuel consumption under the same test load conditions, which corresponds to emissions per kg of fuel, is also representative of actual use. For this calculation, both are measured and expressed in the same units, either in g/km or g/kWh. It should be noted that this factor is much more stable than the first ones throughout the engine map, i.e., the average results of the test cycle are representative of a wide variety of operating conditions.

The factor obtained in $g_{\_pollutant}/kg_{\_fuel}$ multiplied by the actual total consumption of a given vehicle category, whether in a fleet or in a region, results in a fairly accurate estimate of the total pollutant emissions of that fleet or region.

This technique circumvents the difficulty of comparing emissions from different types of vehicles and engines, categories, sizes, and applications, without the need to create traditional inventories, allowing for a comparison of their “environmental efficiency”.

The same technique can be used for comparisons with remote sensing emissions monitoring, where measurements are expressed directly in g/mol of carbon, easily converted to g/kg of fuel burned.[6]. Based on this technique, Figure 4 compares the certified average emissions as published by CETESB and converted to $g/kg_{\_fuel}$ based on fuel consumption determined in the same certification tests.

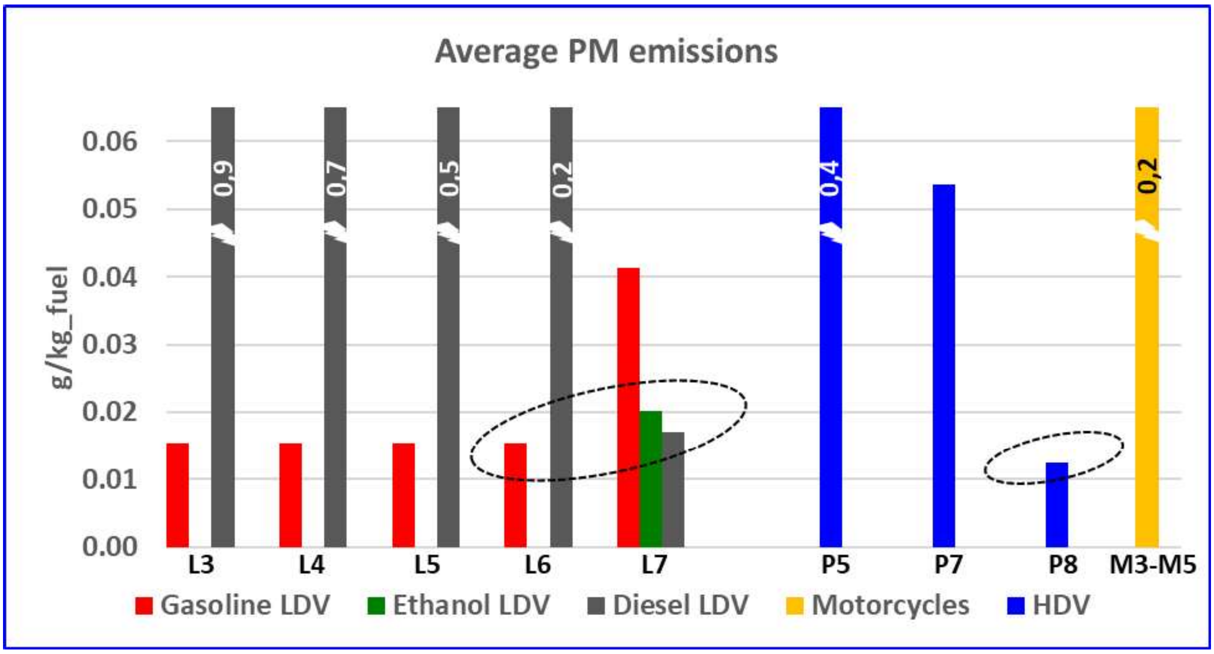


Figure 4 - Certified average emissions expressed in g/kg$_{\text{fuel}}$

From these comparisons, some important findings can be drawn:

a) Light-duty vehicles with Otto cycle engines had the lowest particulate emissions up to phase L6 (data available only for gasoline vehicles, flex-fuel vehicles fueled with gasoline, and diesel vehicles);
b) Starting in phase L7, the significant market share of GDI engines increased PM emissions from gasoline and flex-fuel engines by more than 100%, reaching levels similar to those of heavy-duty engines in the penultimate phase of PROCONVE (P7);
c) Still in phase L7, the first data on flex-fuel vehicles fueled with ethanol appears, showing emissions still compatible with those of traditional gasoline vehicles (MPFI) in previous phases;
d) Since the early stages of the program, particulate emissions from both diesel light-duty and heavy-duty engines have been drastically reduced in stages L7 and P8 (95% to 99%), reaching levels compatible with those of traditional Otto engines (MPFI), which were considered satisfactory until then;
e) Motorcycles still have technologies that allow high PM emissions, at levels almost four times higher than those of the heavy-duty engines of the P7 phase.

Observations “a” and “b” suggest the immediate implementation of technologies that reduce PM emissions from light-duty vehicles with Otto cycle engines. However, observation “c” indicates that the use of ethanol represents a possibility for mitigating this problem.

Observation “d” leads to the conclusion that Brazil already has technological solutions and aftertreatment systems for reducing PM emissions from light duty diesel engines to the required levels, which can also be used for Otto GDI engines.

These facts, already evidenced by the results of new vehicle certifications, indicate the urgent need and feasibility to correct the distortions caused by GDI engines in controlling particulate matter emissions by motor vehicles in general.

It is important to note that, for a long time, Diesel vehicles had by far the highest levels of particulate matter emissions, until the introduction of phase P7 of PROCONVE in 2012, when this was reduced below the emission level of motorcycles, but still well above flex-fuel and gasoline vehicles. In 2023, emissions from heavy vehicles were reduced to ¼ of the P7 limit, equivalent to those of MPFI engine cars, virtually eliminating this problem. However, GDI engines are raising the averages for light-duty vehicles to levels comparable to those of P7 phase heavy-duty vehicles, now outdated. It should also be noted that light-duty diesel vehicles also had their PM levels drastically reduced, well below the established limits, due to the widespread use of ceramic filters, reaching levels of 1 mg/km, compatible with those of traditional gasoline and flex-fuel vehicles.

In technological terms, these figures show that Brazil already has sufficiently clean technologies to return light-duty vehicles with Otto engines, including GDIs, to low emission levels, with the advantage that filters also reduce the number of particles by a factor of 10 to 500 times below current levels, depending on the technology generation to be adopted and the substrate impregnation with catalytic material.

The first recommendation resulting from this analysis is to improve the data used here, based on specific measurements of PM mass and particle number (NP), distinguishing between GDI and MPFI vehicles running on ethanol and the current E30 gasoline, so that a detailed study can be carried out on the feasibility of applying the technologies considered to date and included in the CETESB certification database.

In addition, observation “e” indicates that motorcycle engines do not yet have technologies for stricter control of PM emissions. However, current international regulations for four-stroke engines have not yet prioritized PM control in this category, because these vehicles have limited space for control systems and their PFI engines already reduce this problem. Furthermore, most motorcycles have single-cylinder engines that produce strong mechanical and gas flow vibrations, which reduces the durability of ceramic substrates, hindering their application.

Comparison of environmental impacts

Traditional analyses of the environmental impact of vehicle fleets are based on emissions inventories calculated from the number of existing vehicles, their annual mileage, and their actual emission factors in grams per kilometer, which all need to be obtained for each model year. In the case of heavy-duty vehicles, emission factors are given in grams per kilowatt hour of energy produced, which can be converted to g/km based on fuel consumption measured in the engine and vehicle.

This is an extensive task that depends on various statistics, which are often affected by significant errors. However, with the concept developed above, a comparative inventory between different fuels for a region can be easily and quickly estimated from the total fuel consumption verified in the region, multiplied by the ratio between emission factors in grams per kilogram of fuel burned, which can be weighted by category. This approach reduces some uncertainties in the inventory and is very important for detecting specific flaws in environmental legislation and for planning future strategies, before data is available for a more precise detailed inventory. In addition, it also allows for the analysis of very different types of machinery, such as cars, trucks, trains, generators, etc.

In the case of this analysis, the aim is to compare only the future trends in particulate matter emissions from heavy-duty vehicles with those from light-duty vehicles, grouped only by model year. The analysis of the last two phases of PROCONVE predicts that the evolution of each of these categories will reverse the balance of particulate matter control in the two fleets.

Furthermore, considering that national fuel demand is divided into 50% diesel, 33% gasoline, and 16% ethanol, as shown in Table 3, these fleets will, in the medium term, have half of their fuel consumption (or energy spent on transportation) subject to lower particulate matter emission factors (P8 diesel vehicles) and the other half burning in vehicles powered by Otto cycle engines from the L8 phase, which are less controlled.

Thus, as time passes without a correction of PM limits for gasoline engines in particular, their emissions will approach the characteristics of these two phases, making light-duty vehicles the largest contributors to particulate matter emissions. This effect will completely offset the hard-won benefits of controlling heavy-duty Diesel vehicles as both fleets modernize, as indicated by the overall averages shown in Figure 5.

Table 3 – Fuel consumption by Brazilian region in 2024 – ANP[7]

Base year: 2024	HYDRATED ETHANOL	E27 GASOHOL	DIESEL OIL
BRAZIL	**16%**	**33%**	**50%**
SÃO PAULO STATE	31%	28%	41%
SOUTHEAST REGION	25%	30%	46%
NORTHEAST REGION	8%	44%	49%
SOUTH REGION	7%	40%	53%
CENTRAL-WEST REGION	21%	22%	57%
NORTH REGION	4%	33%	63%

Source: based on ANP data (National Agency for Petroleum, Natural Gas and Biofuels)

In the state of São Paulo, these percentages are even worse, with 59% of fuel demand concentrated in Otto vehicles, and it is likely that this is also the case in larger cities. In other regions, these effects are similar because Otto vehicles still have significant participation, even at the regional average level.

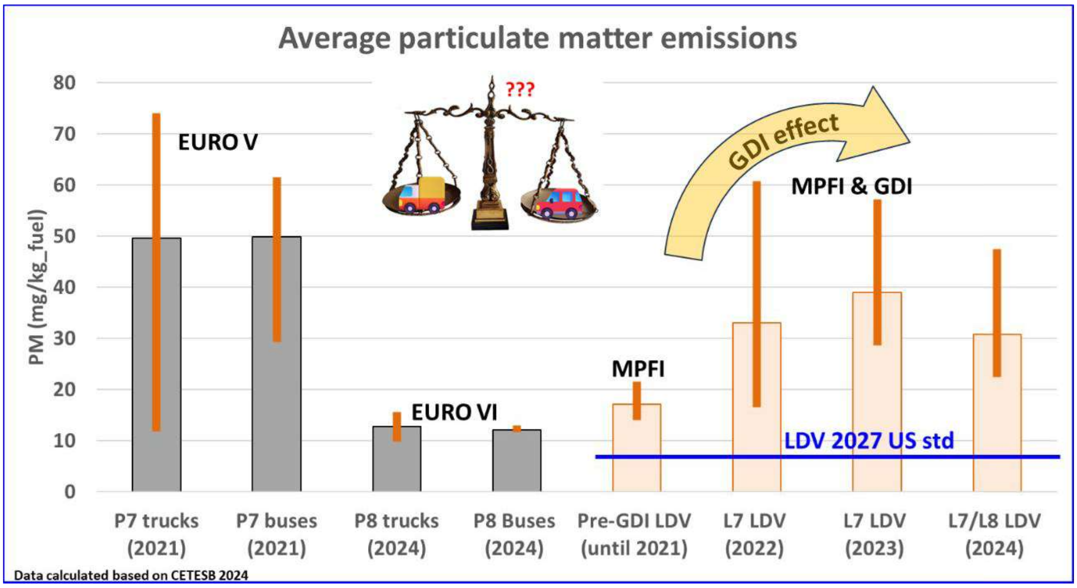


Figure 5 – Average PM emissions expressed in g/kg of burned fuel

In summary, this situation shows the disparity between the PM emission control strategies adopted for light-duty and heavy-duty vehicles, which can be corrected by limiting PM emissions from light-duty vehicles to 0.3 mg/km (0.06 g/kg of fuel), as planned in the US to take effect in 2027.

Health impacts

Traditionally, analyses and regulations on particulate matter emissions have focused on the mass of particles emitted per kilometer traveled, in the case of light-duty vehicles, or per kilowatt hour of power generated, in the case of heavy-duty diesel engines. In the environmental analysis, the parameters for assessing air quality are based on the atmospheric concentrations of PM_{10} and $PM_{2.5}$ measured in $\mu g/m^3$, i.e., the mass of particles with a diameter of less than 10μm or 2.5μm, respectively. However, as mentioned earlier, with the significant increase in fuel injection pressure, initially in diesel engines and more recently in direct injection gasoline engines, particle size has been greatly reduced, leading to the formation of particulate matter with a diameter of around 0.1μm ($PM_{0.1}$), so that even an emission with a small particle mass can contain a very large number of ultrafine particles.

In terms of public health, this fact is extremely important, since these particles penetrate the pulmonary alveoli and can only be eliminated through the bloodstream, always carrying a load of hydrocarbons that can lead to much more serious consequences than coarser particulates, such as the development of various types of cancer.

Figure 6 compares the statistical distributions of particle size for different metrics of number, particle surface area, lung deposited surface area (LDSA), and mass. The areas under the distributions of these variables (C_{total}) were normalized relative to their respective totals. The black line at the top of the figure shows the probability of respiratory deposition based on the ICRP (International Commission on Radiological Protection, 1994) model for light exercise with nasal breathing at 25 L/min. The particles were modeled as spherical, with a density of 1 g/cm³.

It is important to note that the horizontal axis has a logarithmic scale, so that the areas under the aforementioned statistical distribution curves are actually smaller on the left side of the graphs than on the right.

This model highlights three zones of particulate matter emission control associated with particle size, with the following characteristics:

a) Particles with a diameter greater than 1000 nm (red zone) are highly likely to be deposited in the lungs (black curve), given the large amount of mass present in this class, despite the low number of particles. This emission corresponds to the visible range and is generally corrected by combustion process control.

b) Particles with diameters between 23 nm and 1000 nm (yellow zone) still account for a considerable portion of the mass, and their number starts to become significant for diameters below 200 nm. However, larger particles in this range (>200 nm) have a smaller surface area and deposition in the lungs (green and yellow curves) and a low probability of deposition in the lungs (black curve). This intermediate zone is still in the diameter range where mass, rather than particle number, is the control parameter. The use of clean fuels, such as ethanol, or the use of particle filters allows for an intermediate degree of control in this category, even with more restrictive PM mass requirements.

c) Particles with a diameter of less than 23 nm (blue zone) are formed from semi-volatile precursors that have negligible mass but a high number of particles (blue curve) with a large surface area and a high probability of deposition in the lungs (yellow and black curves). In this case, controlling the combustion process is not sufficient and must be carried out by limiting the number of particles, which has been implemented internationally with standards for counting particles larger than 10 nm in diameter (or NP_{10}), possibly due to technological limitations in measurement and process control. This requirement generally leads to the application of ceramic filters, often impregnated with catalysts to facilitate the burning of particles.

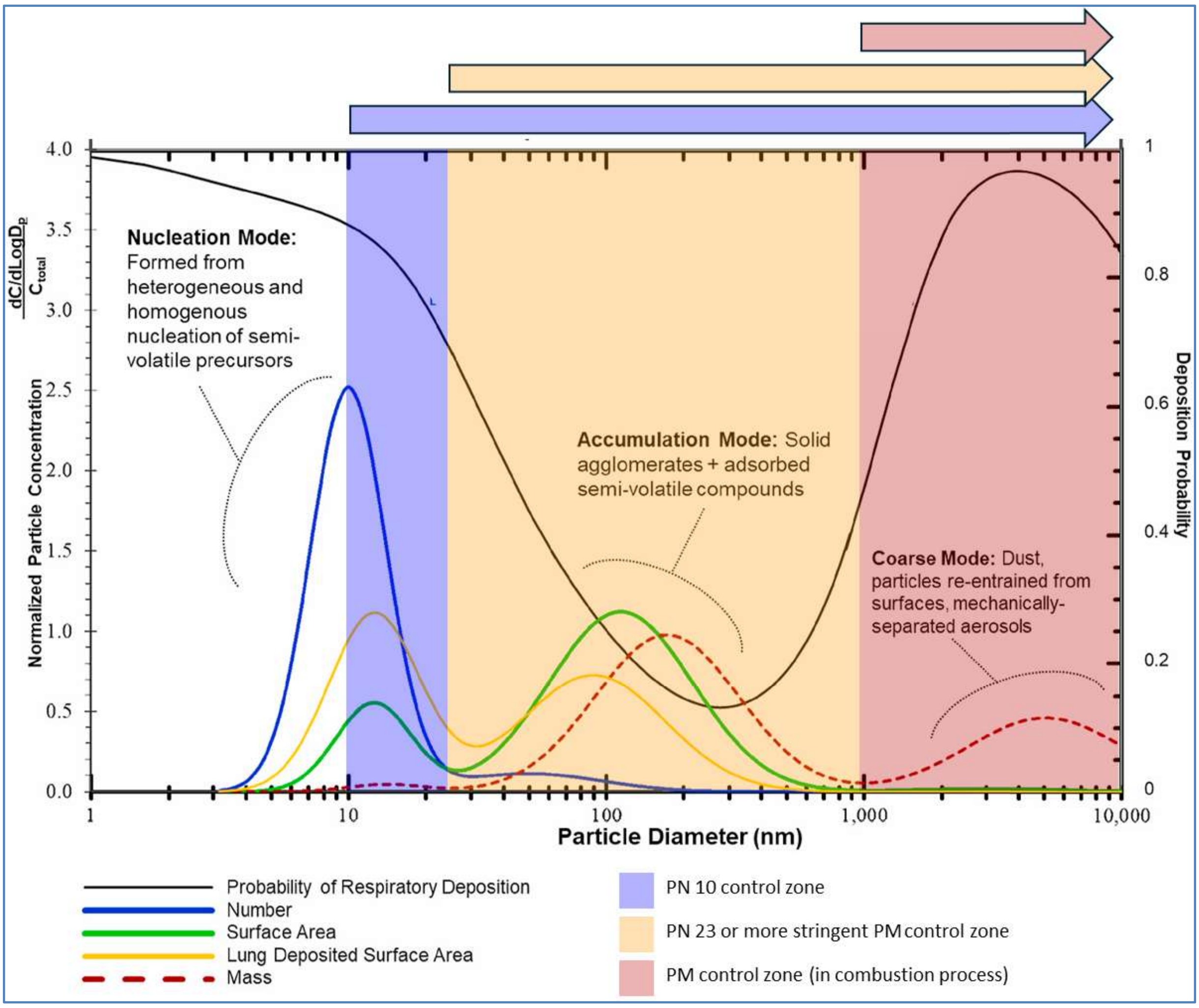


Figure 6: Particle size distribution in exhaust emissions from a typical engine (Adapted from Kassel, 2013) [8]

A correct understanding of the mechanisms that explain particle deposition as a function of their diameter depends on a more in-depth knowledge of the respiratory system's physiology and its modeling. However, from these three characteristics, it can be concluded that controlling mass emissions is important, but controlling the number of particles becomes the focus from a public health perspective as the diameter of the particles is reduced as a result of technological advances in injection systems, although the mass of ultrafine particles tends to be negligible in this case in relation to the total mass of particulates.

It is important to note that, also for 10 nm particles, the surface area again assumes significant values, which is an indicator of the hydrocarbon adsorption capacity of these particles, greatly aggravating their toxicity.

For these reasons, the European Community began to place greater emphasis on controlling the number of ultrafine particles from GDI vehicles, leaving the control of the mass itself in the background, and established a limit of 6×10^{11} particles per kilometer traveled in the Euro 6 regulation, implemented in 2017.

In Brazil, the growing sales of light-duty vehicles with GDI engines means that the European approach must be followed in order to control ultrafine particulate emissions, reducing not only the mass of particles but also their impact on public health.

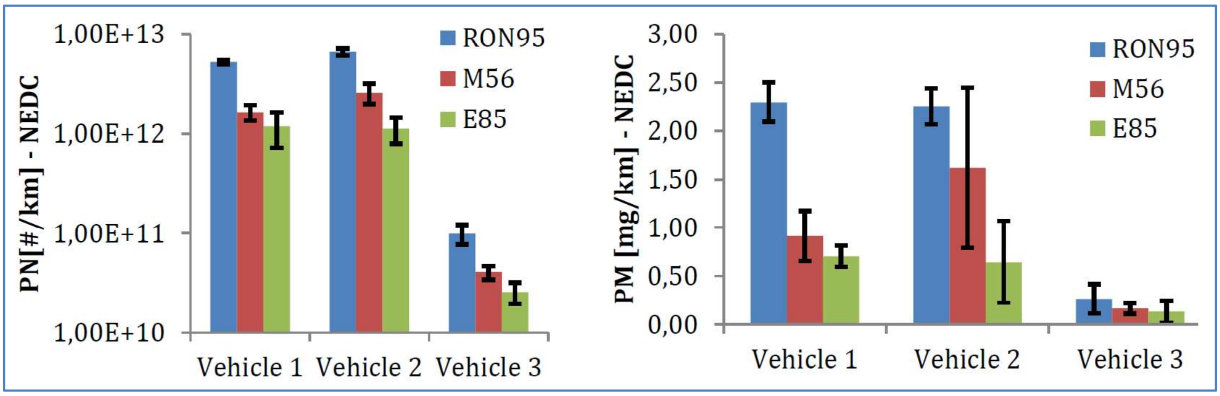
However, as the PM emissions are still very high and increasing, it is important to establish an urgent strategy to halt this effect by reducing mass emissions, returning to the levels seen before GDI engines entered the market, to be complemented by the establishment of particle number limits to effectively solve this problem.

Brazilian fuels are part of the solution

A study conducted by Ford showed that increasing the ethanol content in gasoline reduces particulate matter emissions from GDI engines, so that Brazilian gasoline already provides lower PM values than international standards. This reduction is small up to levels of 20%, but gasoline with ethanol levels above 30% reduces the mass and number of particles by between 30% and 45%, with little influence on particle size and a slight increase in the soot's organic fraction[9]. The low sulfur content of all Brazilian fuels also contributes to the reduction of particulate emissions due to the absence of sulfates.

These factors lead to the recommendation that the reference gasoline be updated to the commercial ethanol contents, currently at 25% and 30% for premium and regular fuels, respectively, so that the results obtained are representative of the Brazilian reality and allow for the most appropriate technology to be chosen for PM and NP control.

In the case of ethanol-fuelled vehicles, the International Energy Agency report[10] presents a comparison of particulate matter emissions, expressed in mass and number of particles, for gasoline (RON 95), ethanol (E85), and methanol (M56), which indicated much higher emissions in GDI engines, but significantly reduced when using E85 fuel, as shown in Figure 7. The tests were carried out following the European NEDC test cycle on two GDI vehicles (2.4 L, US standard, naturally aspirated, 2014, and 2.0 L, Euro 5, turbo, 2011) and one MPFI vehicle (1.6 L, EURO 5, 2012).



Source: Rosenblatt *et al.*(2020)[8]

Figure 7 – PM and PN emissions in three vehicles according to the European NEDC test cycle

These results indicate that using ethanol reduces particulate emissions from GDI engines by 70% for PM and 80% for PN, while in MPFI engines these reductions were 55% and 75%, respectively, despite these being originally an order of magnitude lower than in GDI engines.

Although these measurements were taken according to the European NEDC test cycle, which underestimates them, the relative proportions between the results suggest that ethanol enhances the compliance of GDI vehicles with the 1 mg/km limit, corresponding to current Brazilian MPFI vehicles, at least for flex-fuel engines running on ethanol, in a transition phase to the desired limits of 0.3 mg/km and $6x10^{11}$ part/km, to be progressively implemented in a definitive phase.

Strategy recommendations for light-duty vehicles

Technologically speaking, the best solution for definitively correcting the particulate matter emissions increase in light-duty vehicles, observed in the last few years, is to apply ceramic filters to vehicles with Otto GDI engines, as is already done for light-duty and heavy-duty diesel engines.

Since its first generation, this technology has reduced PM emissions to below 0.3 mg/km, equivalent to 6 mg/kg of fuel, which is compatible with the levels practiced in all Diesel engines currently sold in Brazil, and will be required for all light-duty vehicles in the US Tier 4 phase starting in 2027 and Euro 7 in 2028 as well.

In addition, the application of ceramic filters in GDI engines will simultaneously reduce the number of particles in exhaust gases - PN by about 90%, i.e., typically from (2 to 5) $x10^{12}$ particles/km (for engines without PN control)[11] to $6x10^{11}$ particles/km (currently feasible limit for first-generation ceramic filter technology), with the potential for further reduction to 1 $x10^{9}$ with fourth-generation filters, as show the graphs[a] in Figure 8. This limit corresponds to significantly greater protection of public health due to the reduction in toxicity. It is important to note that the European limit for the number of particles and the American limit for mass are achievable with the same first-generation filter technology.

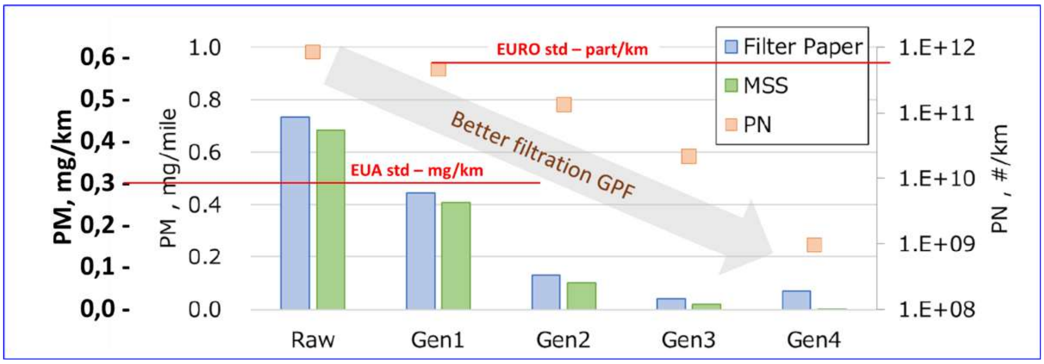


Figure 8 – PM and PN levels after the ceramic filter (1st to 4th generation – FTP driving cycle)[12]

[a] Measurements on filter paper correspond to the official measurement method for certification, which includes soot and organic components, while those performed by MSS (Micro Soot Sensor) measure only the carbon portion and are used for real-time assessments.

Considering that this development involves revising the vehicle and engine design, it will be necessary to consider a minimum timeframe for implementing such modifications. However, it seems reasonable to immediately implement an intermediate stage in the regulation by requiring a standard of 1.0 mg/km to return Otto engines to the usual levels practiced in Brazil until 2021, which will naturally be met by traditional MPFI engines and Diesel utility vehicles. This standard can be considered feasible immediately, since there are existing vehicles with GDI engines that meet it, especially when running on ethanol. It is therefore reasonable for this requirement to come into effect in the very short term for at least 80% of each manufacturer's light-duty vehicle production. The remaining 20% of vehicles may keep their GDI engines unchanged for an additional period until the next phase, when all vehicles must comply with the 0.3 mg/km standard, even if they require more extensive modifications to achieve this reduction.

This strategy has the advantage of imposing immediate action to halt the already observed increase in PM emissions from light-duty vehicles, while not preventing the production of these vehicles with GDI engines, but forcing their progressive development towards stricter control of particulate matter emissions, which can be introduced as each manufacturer's commercial plans prioritize interest in these engines.

It is important to note that the limits of 0.3 mg/km and 6 x 10^{11} particles/km mentioned above can be met simultaneously with first-generation ceramic filters, which are sufficient for the current Brazilian situation, but there exist four generation technologies capable of achieving considerably greater reductions, as shown in Figure 8.

Regarding particle count, this approach was led by Europe, which established particulate matter standards for Otto cycle engines, defined by the joint requirement of limits on mass and particle count. The table below shows the current values in different parts of the world.

Table 4 - Particulate matter standards for light-duty gasoline vehicles

Regulations	mg/km	particles/km
EURO 6/7	4,5	**$6x10^{11}$**
EUA Tier 3	1,9	---
EUA Tier 4 - 2027	**0,3**	---
California - 2023	0,6	---
CHINA 6 - 2023	3	$6x10^{11}$
CHINA 7 - planned	1 a 2	1 a 3 x 10^{11}

In light of the suggestions proposed above, Table 5 presents a summary of the values currently applied in Brazil and the corrections necessary to rebalance particulate matter control requirements for all vehicle categories, to be implemented through the following steps:

a) an urgent adjustment to be applied in the L8 phase to prevent emissions from continuing to increase;

b) a new L9 phase to reduce PM emissions from light-duty vehicles in line with the best available and economically feasible technologies, bringing them into line with those of the most advanced Diesel vehicles.

Table 5 - Typical particulate matter emissions from vehicles and engines

PROCONVE	Category	Particulate Matter Emissions		
		Standards		mg/kg_{fuel}
Phase P8	trucks and buses	10mg/kWh	$6x10^{11}$ part/kWh WHTC	10 a 16 (2024 averages)
Phase L8	cars and pickup trucks	4mg/km	---	29 a 57 (2024 averages)
Phase L8 adjustment	cars and pickup trucks	1mg/km	---	18 (2021 averages)
New Phase L9	cars and pickup trucks	0.3mg/km	$6x10^{11}$ part/km	06 (~ 1/3 of pre-GDI)

In addition, it is necessary to anticipate the growing use of diesel or natural gas generators to supplement the Brazilian energy matrix. In cases where batteries are recharged with electricity generated by thermoelectric sources and small generators used during peak hours, the emissions produced in this generation are induced by electric vehicles. Under the concept of "from the well to wheel", established by the Fuel of the Future Law, these emissions must be considered as being associated to the vehicle and need to be compatible with those of traditional vehicles with internal combustion engines, especially in cities that depend on electricity supplied exclusively by thermoelectric plants.

In these cases, the increased demand for recharging electric vehicle batteries imposes new emission standards on Diesel engines for generator sets, before these emissions become environmentally significant, given that these machines remain in use for several decades. In this sense, it is necessary to establish emission limits equivalent to those of P8 engines, i.e., 10 mg/kWh and 6 $x10^{11}$ particles/kWh (similar to Stage V, already available in Europe).

In addition to these requirements, it is recommended to take advantage of the creation of this new regulation to establish the foundations for the inspection of vehicle and engine emissions by remote sensing, which is a fundamental tool for effectively monitoring the results of PROCONVE to avoid distortions such as those pointed out in this paper. This type of monitoring must rely on "reference values" calculated for all categories, as conceptualized in this study and expressed in grams of pollutant per kilogram of fuel, or per mole of carbon, which is the native unit of measurement for this method and also directly applicable to all fuels, whether oxygenated or not. These reference values should be proposed in accordance with the desired severity of the inspection program, but respecting the minimum limits obtained by dividing the emission values by the fuel consumption values expressed in the same units, both certified according to PROCONVE.[13].

Extension of this analysis to engines of other machines and generators

Environmental impact analysis based on emissions per kilogram of burned fuel also allows comparison with other types of machines whose operation is completely different from that of vehicle engines, but which have an important correlation with them.

In the case of non-road machinery, inventories have shown that this fleet's total emissions are higher than those of the truck fleet, which is much larger. This led to the proposal for a new PROCONVE MAR II phase, with US Tier 4 Final requirements for off-road machinery, which lead to technologies equivalent to those of the P7 phase for trucks and buses. This shows that further development will be necessary to reach the equivalent of phase P8, so that the stringency of machinery controls is brought into line with that of the heavy-duty and light-duty road vehicles currently under discussion.

Similarly, generator set emissions control has been discussed along the same principles as non-road machinery, with a tendency to accept Tier 4 final levels as appropriate for them, as a program start, at least for generators with the greatest environmental impact.

In the case of generators, it is necessary to gradually bring this group of machines to levels equivalent to those of phase P8 for all regulated pollutants, to prevent vehicle electrification from causing greater environmental impacts than vehicles with internal combustion engines. This aspect is particularly important for large generators that supply entire cities and for those frequently used in urban areas, giving them a special class of “low-emission generators” when they are also used to recharge electric vehicle batteries.

Table 6 shows the status of the various types of PM emissions sources currently under discussion, and indicates the cases to be prioritized for the benefit of compliance with air quality standards for particulate matter, considering their consistency and equivalence with the technologies applied for the control of emissions from road vehicles. However, this assessment needs to be extended to other regulated pollutants as well, in order to establish regulatory consistency with Diesel vehicle engines, whose details are beyond the scope of this study.

Table 6 - Typical particulate matter emissions from machinery and generators

PROCONVE	Category	Particulate Matter Emissions		
		Standards		mg/kg_{fuel}
Phase MAR I	non-road machinery	200 to 600 mg/kWh	---	900 to 2400 (average depending on machine type)
Phase MAR II	non-road machinery	20 to 30 mg/kWh	---	90 to 125 (standards) 50 (expected average - equivalent to P7)
Current market (unregulated)	generators	---	---	2200 to 4200 (estimated as Tier 1)
New program	generators	20mg/kWh	---	90 to 125 (standards) 50 (average - equivalent to P7/MAR II)
New program	special generators	10mg/kWh	$6x10^{11}$ part/kWh	10 to 16 (equivalent to average P8, for recharging electric vehicles)

Given this vision, particulate matter emissions could be brought to the same control level in all regions of the country, regardless of the type of vehicle or machine present, such as mixed fleets, segregated corridors, cities in general, highways, power generation, agricultural and construction machinery, road and non-road machinery, locomotives, etc.

Final conclusions

This paper presents a method, based on energy demand, that converts the particulate emission factors of any vehicle or engine category to a common unit, expressed in $g_{pollutant}/kg_{fuel}$, which allows for an assessment in terms of the energy production of engines, that is, the “environmental efficiency” of the various technologies employed. This method is particularly useful for comparing engines of different categories and for monitoring emissions by remote sensing.

This study compared the importance of PM emissions from heavy-duty diesel vehicles with those from light-duty ethanol and gasoline vehicles, both expressed in g_{PM}/kg_{fuel}, and detected a distortion in the particulate matter control strategy for light-duty vehicles, caused by the introduction of direct injection Otto cycle engines on the market, already verified in the United States for over a decade and which has recently been increasingly present in Brazil. It is recommended to extend this analysis to other pollutants, aiming at a complete balance in the control of emissions from all vehicles and machines that use internal combustion engines.

This analysis showed that the technological standard of heavy-duty vehicles in phase P8 already exceeds the features currently applied to light-duty gasoline and flex-fuel vehicles, and suggests the establishment of new emission standards and strategies for controlling particulate matter emissions for light-duty vehicles in two stages to encourage the implementation of the best available and economically viable practices for GDI engines, bringing them up to the same technological level as diesel vehicles.

Thus, the strategy suggested for Brazil should follow the following steps, proving the values through dynamometer tests according to the procedures of US FTP 75 procedures, to be complemented in the future by applicable requirements based on real driving emissions (RDE) tests:

a) **Route Correction:** January 1, 2029 - change in BIN 30 and BIN 20 for light-duty passenger vehicles and acquisition of equipment and expertise for particle number control
   - Correction of the corporate PM emission standard to 1 mg/km (mass);
   - Determination of typical NP_{10} values for vehicles with MPFI and GDI engines, measured in dynamometers.
b) **PM emission standard reduction:** January 1, 2031 - change in BIN 30 and BIN 20 for light-duty passenger and commercial vehicles:
   - PM (mass) standard of 0.3 mg/km;
   - PN_{10} standard of $6x10^{11}$ particles/km

Since the Brazilian data correspond to the certification averages obtained with E22 gasoline and the international data are based on RON95 gasoline, it is recommended to extend this analysis to individual results of specific measurements of PM mass and particle number – NP in current Brazilian vehicles, distinguishing between GDI and MPFI vehicles, using E100 ethanol and E30 gasohol, in order to conduct a detailed feasibility analysis of the technologies considered.

Filtration technologies associated with catalysts have led to significant reductions in particulate matter emissions and provide better protection for public health, as well as helping to meet the Air Quality Standards established by recent legislation. However, the use of ethanol and higher alcohol content blends are important contributing factors in meeting the suggested limits.

In addition, the introduction of the PN limit brings Proconve into line with the most modern international standards (Euro 6 and 7, China 6 and 7, among others), opening doors to new potential markets. Another important aspect is the appreciation of the strategic role of ethanol and Brazil with its biofuels, which already show superior performance in terms of particulate emissions. Thus, controlling particulates by number and mass is a necessary step to reduce environmental and public health impacts and ensure that the Brazilian fleet keeps pace with global best practices.

Furthermore, it is recommended that a program be created for the gradual establishment of emission limits for generator set engines that may eventually be used to power electric vehicle charging systems, so that these do not induce emissions higher than those of traditional vehicles. Such a program should start with the Tier 4F standard and gradually evolve to levels equivalent to the P8 phase limits for heavy-duty vehicles.

The analysis developed in this study focused on the Brazilian case, but it raises some strategic aspects that are important for other countries, such as India, which has already been intensifying the use of ethanol as fuel and may include in its strategies the control of PM and NP in vehicles with GDI engines and the use of ethanol contents of up to 30% in gasoline to benefit this control, taking advantage of the Brazilian experience, which has already reached this proportion.

This study was prepared by EnvironMentality at the request of AFEEVAS in August 2025 to support discussions on rebalancing particulate matter control under PROCONVE, given the growing share of GDI engines in the light-duty vehicle market.

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