Incremental Cost of Emission Reduction Technologies for A- and B- Segment Vehicles Equipped with PFI/TGDI Flex Fuel 1.0L Engines to Meet Brazilian Emissions Standard PROCONVE L8

Guilherme Neves
Maurilio Cassiani
Frederico Weissinger
Vincent Bigliardi
Eugenio Coelho
AVL South America, Powertrain Engineering

ABSTRACT

This paper evaluates worldwide available and proven standard emission reduction technologies, from both technical and cost perspectives, for in-cylinder, after-treatment and evaporative control systems to meet PROCONVE L8, the most stringent light vehicles Brazilian emissions legislation to come, which will enter into force in 2025.

If, on the one hand, more advanced in-cylinder control technologies, such as turbocharging and flex-fuel direct injection, are already available and successfully introduced in the Brazilian market, on the other hand they represent a cost increase. Traditionally, the Brazilian market is characterized by the profile of acquisition of low-cost vehicles in segments A and B, in which PFI (Port Fuel Injection) flex-fuel 1.0L engine equips most of them. Flex fuel technology allows the engine to run on either gasoline or ethanol, or in any blend in-between. Nevertheless, in recent years the market observed the introduction of TGDI (Turbocharged Gasoline Direct Injection) flex fuel 1.0L engine for these segment vehicles. Such low engine displacement TGDI technology is forecast to keep increasing its share due to ROTA 2030, Brazilian automotive program with one branch based on fuel efficiency. Both technologies currently available in Brazil are generally downsized inline-three cylinders engines to aid automakers attending fuel efficiency targets.

Some scenarios for technological packages, encompassing in-cylinder, after-treatment and evaporative control systems, for both PFI and TGDI flex fuel 1.0L engines are built with the most promising technologies to attend emissions target of level 50, which is the corporate emission level at the beginning of PL8. Incremental cost impact is evaluated for each solution identified for moving from current PL6 to PL8. Such analysis considers both variable and indirect costs.

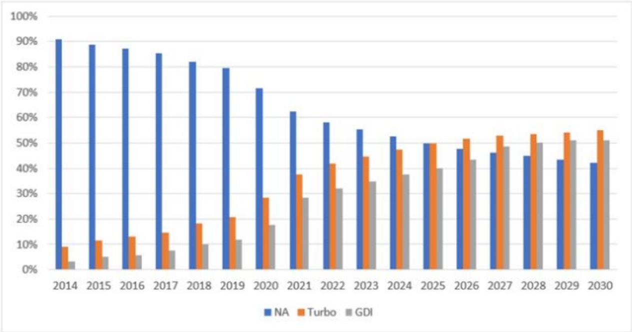
Results indicate PFI flex fuel 1.0L engine-based solution as the most cost driven pathway. Nevertheless, according to automaker's strategy, TGDI engines may also be considered as an option.

INTRODUCTION

The definition of the vehicle after-treatment system is no longer solely guided by increasingly stringent emissions legislations and on-board diagnostic (OBD) system requirements. The right cost of ownership over the product life is a major competitive advantage, which can only be achieved through optimized integration of the after-treatment system with the powertrain definition in early stages of development. In a cost sensitive market like Brazil, such integration is even more decisive, especially for the automaker's A- and B-segment vehicles, which are the top sellers, as presented by Automotive World [1] in Table 1, and generally equipped with a PFI (Port Fuel Injection, also known as Indirect Injection) flex fuel 1.0L engine, even though in recent years the market has observed the introduction of TGDI (Turbocharged Gasoline Direct Injection) flex fuel 1.0L engine in these segment vehicles. The forecast presented in Automotive Business [2] is that TGDI engines will increase their share in the Brazilian market, overcoming PFI engines on 2028, as shown in Figure 1, extracted from IHS Markit report [3]. This high market share for TGDI engines will be mainly leveraged by A- and B- segment vehicles, likely to be equipped with a TGDI flex fuel 1.0L engine. Such low engine displacement TGDI technology will continuously increase its share due to ROTA 2030, Brazilian automotive program based on fuel efficiency, safety and R&D (Research and Development). In Brazil most of the engines are flex-fuel, which is a technology that allows the engine to run on either gasoline or ethanol, or in any blend in-between.

Table 1. Light vehicles (LV) shares by segment in Brazil. Mini (A), Small (B) segments. Source: Research: Brazil's new vehicle market: prospects to 2024 and beyond [1]

Segment	2001	2005	2010	2015	2016	2017	2018	2019
Mini	1.1	7.0	7.3	10.7	9.6	9.8	11.1	11.9
Small	66.0	63.9	56.0	45.2	44.2	41.0	41.3	39.8
Lower Med.	13.7	11.8	14.6	15.4	14.7	15.3	12.1	11.4
Medium	3.7	0.8	0.8	1.2	0.9	0.9	0.8	0.7
SUV	3.6	5.3	7.6	14.0	16.2	19.1	20.6	22.2
Pickup	7.1	7.1	9.3	10.5	11.9	11.5	11.9	12.0
Other	4.8	4.1	4.5	2.9	2.5	2.4	2.1	2.0
Total LVs	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**



Source: IHS Markit VPaC: Vehicle Performance and Compliance – September 2019

Figure 1. Market share increase forecast for TGDI engines in the Brazilian market. Source: IHS Markit VPaC – Vehicle Performance and Compliance – September 2019 [3]

The future phases of pollutant emission control for light vehicles in Brazil, namely PROCONVE L7 and PROCONVE L8 or shortly PL7 and PL8, will be implemented, respectively, in 2022 and 2025, including the new demands for the OBD-Br3 on-board diagnostic system. PROCONVE stands for Motor Vehicles Air Pollution Control Program, while L7 and L8 stands for light vehicles phases 7 and 8. These upcoming phases will require emission reduction technologies, which are already successfully implemented in more advanced emissions legislation markets, such as the USA (United States of America) and EU (European Union).

PL7 and PL8, as well OBD-Br3, are briefly presented with their associated challenges and compared against American and European norms. Available and proven standard emission reduction technologies are described. Some technological packages, based on AVL's expertise acquired over several emission development projects and likely to meet PL8, the most stringent Brazilian emissions legislation to come, are presented for both PFI and TGDI flex fuel 1.0L engines powering vehicles in A- and B- segments.

For each technological package proposed, evaluation of the cost increase based on "Estimated Cost of Emission Reduction Technologies for Light-Duty Vehicles, 2012" [4] is provided in respect to the current PL6 standard. Such estimate comprises variable costs, related to additional hardware with associated ECU (Engine Control Unit) control functions development and indirect costs, related, e.g., to vehicle calibration development, tooling and certification. Cost comparison is then carried out to identify the most cost-effective pathway to meet PL8. For achieving the objective of this paper, in-cylinder control for engines, after-treatment and evaporative systems are analyzed. This means that no other powertrain component, e.g., as transmission and tires, are considered. This choice is made to keep a fair cost comparison on the same basis between solutions, once, e.g., in Brazil TGDI powered vehicles are commonly equipped with a more expensive AT (Automatic Transmission) when compared to PFI powered vehicles with MT (Manual Transmission). It is also important to emphasize that the higher performance of a TGDI flex fuel 1.0L engine when compared to a PFI flex fuel 1.0L engine is not relevant for this cost-driven study.

PL7, PL8 AND OBD-BR3 LEGISLATIONS

Historically, the pollutant emission control for light vehicles in Brazil has always been based on the legislation applied in the USA. It presents several adaptations, both in terms of implementation time, procedures and limits, mainly due to specificities, such as higher ethanol content in gasoline [5].

PL7 and PL8 are scheduled to begin, respectively, in 2022 and 2025. Besides the historical alignment with the American standard, here based on US Tier 3 (United States National Vehicle Emissions and Fuel Standards Phase 3), PL7 and PL8 also present elements from European norm Euro 6. Below main changes in respect to current PL6 are highlighted, as well from either US Tier 3 or Euro 6 they come from. Such information is based on the Resolution Nº 492, from 20th of December of 2018 [6] and it is worth mentioning that there are still open topics being discussed in technical groups.

PL7, PL8: CHANGES FROM PL6 BASED ON US TIER 3 – The main pollutant control change is related to hydrocarbons emission. The prior NMHC (Non-Methane Hydrocarbons), which could be discounted by the unburned ethanol for PL6, is replaced by NMOG (Non-Methane Organic Gases), which besides NMHC also includes the organic gases ethanol and aldehydes. Specific NMOG calculation for PL7 and PL8 considers photochemical reactivity adjustment coefficients to account for different ozone formation potential between gasoline and ethanol fuels, as detailed in Normative Instruction N°22, from 24th of September of 2020 [7]. Furthermore, for PL6, NMHC and NOx (Nitrogen Oxides) were controlled separately, while for PL7 and PL8 they are combined as NMOG + NOx with more stringent limits when compared to NMHC + NOx for PL6. The reason for changing to NMOG + NOx is to limit the pollutants that contribute to the formation of ozone in the lower atmosphere, which are harmful to the respiratory system. Ultimately this means that different emission control systems may be used to further reduce NMOG, NOx or both at the same time, once the emission limit may be achieved by different NMOG/NOx shares, as shown in Figure 2.

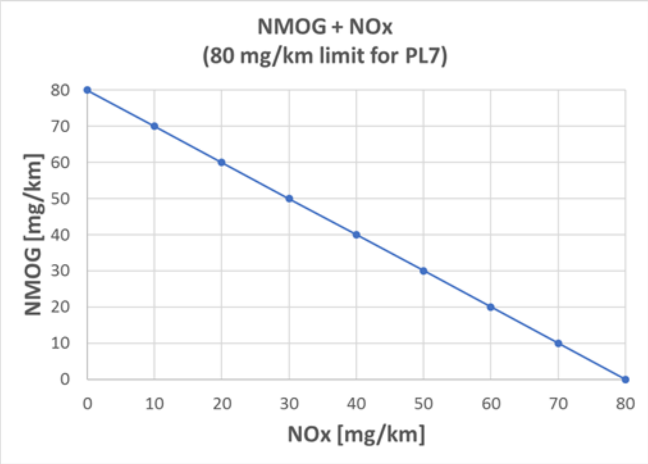


Figure 2. NMOG + NOx combined limit for PL7.

CO (Carbon Monoxide) and HCHO (aldehydes) are further reduced for PL7 and PL8, while PM (Particulate Matter) is now regulated for GDI (Gasoline Direct Injection) engines only.

New test and procedure are available for evaporative control emission. The prior 2h testing at SHED (Sealed Housing for Evaporative Determination) is increased to 48h with lower HC (Hydrocarbons) emissions limit. Also, a new test accounts for the evaporative emission during tank fueling, which additionally requires an ORVR (Onboard Refueling Vapor Recovery), system responsible for trapping fuel vapors at this event and routing them to the canister. No emission limit change is expected for evaporative between PL7 and PL8.

Compliance with emission limit over useful vehicle life was increased from current 80,000 km or 5 years to 160,000 km or 10 years, thus directly impacting all emission relevant hardware, which must comply with more severe aging.

Besides more stringent emission limits presented above, PL8 also introduces the concept of a single emission limit at the corporate level, regardless of the vehicle category. This allows the automaker to draw up strategies according to its portfolio to meet the standard. It also establishes the generation and use of emission credits.

Table 2: Light vehicle exhaust and evaporative emissions limits for Brazilian, US and EU legislations.

					Exhaust					Evaporative		
	Legislation	Level	Date	Cycle	NMOG+NOx [mg/km]*	PM [mg/km]	CO [mg/km]	HCHO [mg/km]	RDE	HS+D** [HS: h; D: number of tests / D: h per test]	HS+D Worst Case** [g]	Refueling Onboard [mg/l]
Brazil	PL6	-	2014-2022	FTP-75	130	-	1300	20	No	1;1/1	1,50	-
	PL7	-	2022-2025	FTP-75	80	6	1000	15	Monitor	1;2/24	0,50	50
	PL8	80	2025-	FTP-75	80	6	1000	15	Yes	1;2/24	0,50	50
	PL8	70	2025-	FTP-75	70	4	600	10	Yes	1;2/24	0,50	50
	PL8	60	2025-	FTP-75	60	4	600	10	Yes	1;2/24	0,50	50
	PL8	50	2025-	FTP-75	50	4	600	10	Yes	1;2/24	0,50	50
	PL8	40	2025-	FTP-75	40	4	500	10	Yes	1;2/24	0,50	50
	PL8	30	2025-	FTP-75	30	3	500	8	Yes	1;2/24	0,50	50
	PL8	20	2025-	FTP-75	20	2	400	8	Yes	1;2/24	0,50	50
	PL8	0	2025-	FTP-75	0	0	0	0	Yes	1;2/24	0,50	50
US	Tier 3	Bin 160	2017-2025	FTP-75	99,4	1,9	2609,8	2,5	No	1;3/24	0,35	53
	Tier 3	Bin 125	2017-2025	FTP-75	77,7	1,9	1304,9	2,5	No	1;3/24	0,35	53
	Tier 3	Bin 70	2017-2025	FTP-75	43,5	1,9	1056,3	2,5	No	1;3/24	0,35	53
	Tier 3	Bin 50	2017-2025	FTP-75	31,1	1,9	1056,3	2,5	No	1;3/24	0,35	53
	Tier 3	Bin 30	2017-2025	FTP-75	18,6	1,9	621,4	2,5	No	1;3/24	0,35	53
	Tier 3	Bin 20	2017-2025	FTP-75	12,4	1,9	621,4	2,5	No	1;3/24	0,35	53
	Tier 3	Bin 0	2017-2025	FTP-75	0	0	0	0	No	1;3/24	0,35	53
EU	Euro 6	-	2014-2025	WLTC	138	4,5	1000	-	Yes	1;2/24	1,00	-

* For PL6 and Euro 6 NMOG + NOx is estimated from NMHC and NOx individual limits
Obs: NMHC = NMOG for comparison purpose

** Hot Soak + Diurnal (D+HS) test has specificities between Brazil, US and EU standards.
Obs: limits are presented as Hot Soak + Diurnal Worst Case for comparison purpose in respect to evaporative system capability.

PL7, PL8: CHANGES FROM PL6 BASED ON EURO 6 – RDE (Real Driving Emission) is important to reduce the gap between type-approval vehicle emissions results, outputted by FTP-75 (Federal Test Procedure Number 75) standard cycle at Chassis Dyno for PROCONVE legislation, and those in the real-world. For such, vehicles driving on real conditions must present, within a factor, low emissions as is meant by PL7 and PL8. RDE will be launched in monitoring phase during PL7 and with CF's (Conformity Factor) for PL8, which determines how many times the pollutants may be above emission limits. For 2025, CF will be 2. Two years later, on 2027, CF will be reduced to 1,5. For RDE testing, only CO, NOx, THC (Total Hydrocarbons) and CO_2 (Carbon Dioxide) will be measured.

Table 2 summarizes the exhaust and evaporative emissions limits for passenger vehicles for Brazilian (PL6, PL7, PL8), American (Tier 3) and European (Euro 6) legislations. It is important to note that even with similar levels of NMOG + NOx between PL7 and US Tier 3 Bin125 (as for PL8, Bin is related to emission level; in this case 125 refers to NMOG + NOx = 125 mg / mi), these standards are not directly comparable in relation to technological solutions due to different fuels. While the Brazilian standard uses E22, E61 and E100 as reference fuels, the American standard adopts E10. The number refers to the percentage of ethanol in volume that is mixed with gasoline. NMOG + NOx is the most critical limit to be met for PL7 and PL8. This is mainly due to ethanol, which has the hydroxyl functional group (-OH), in addition to the low vapor pressure that makes it difficult to burn in cold conditions. It is also important to highlight that Hot Soak + Diurnal evaporative test has specificities between markets/standards and are presented with the sole intent of better understanding the severity level of each legislation.

Figure 3 shows the evolution of corporate limits over time for the US Tier 3 and PL8. The latter one establishes a gradual reduction every 2 years, with values to be reviewed according to global technologies and international experiences in force at the time. For matter of comparison, US Tier 3 enforced corporate level of 50, here represented as NMOG + NOx = 50 mg/km, in 2018, while Brazilian emissions legislation will require such emission level only in 2025, at the beginning of PL8.

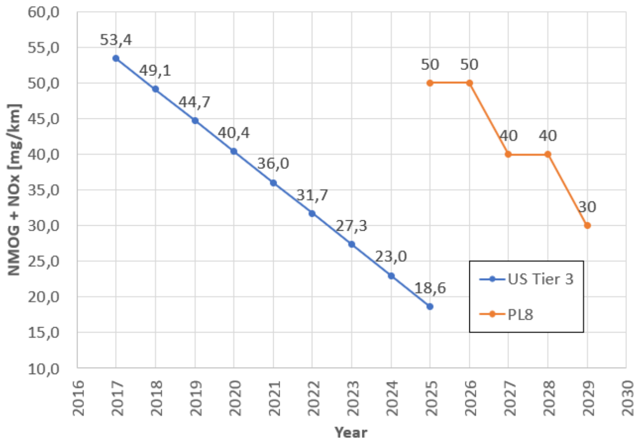


Figure 3. Emissions corporate level, considering NMOG + NOX, for US Tier 3 and PL8.

OBD-BR3 – Regarding the on-board diagnostic system, new requirements are set for OBD-Br3, both for alignment with the PL7 and PL8 standards and for obtaining a more robust system in which efficiency is increased at the same time as fraud is restrained. OBD-Br3 will be divided into two phases, the first one to be implemented with PL7 in 2022 and the second one with PL8 in 2025. Table 3 lists the new monitors, to be added to the current OBD-Br2+ valid for PL6, and in which phase they will enter into force. The final text for the officialization of OBD-Br3 is written in the Normative Instruction N°23, from 24th of September of 2020 [8].

Table 3. OBD-Br3 new monitors.

OBD Br3 New Monitors	2022	2025
Lower malfunction limits	✓	✓
NMOG + NOx Limit	✓	
Secondary Air System Monitor	✓	
Downstream-Catalyst Oxygen Sensor Monitor		✓
Fuel System Monitor * excess fuel when the vehicle is filled with E22-E30, or lack of fuel when filled with E90-E100.	✓ Gasoline vehicles only	✓ Flex fuel vehicles (extremes only *)
In Use Monitor Performance Ratio (IUMPR)	✓ Gasoline vehicles only (w/o % factor)	✓
Evaporative System Monitor (Ø1mm / E19-E30)		✓
Catalyst Heating System Monitor	✓	
Valve Time Variation System Monitor		✓
EGR System Monitor	✓	
Time recording with MIL On (PID 0x93)	✓	
PCV System Monitor		✓
Cold start auxiliary system monitor Electrical continuity when the system is active	✓	

ANALYSIS OF POTENTIAL TECHNOLOGICAL SOLUTIONS FOR EMISSION CONTROL OF FUTURE LEGISLATIONS PL7 AND PL8

Technological solutions for controlling tailpipe emissions in gasoline engines generally focus on the precise control of the air-fuel mixture around the stoichiometric ratio, a combustion process in which all fuel and oxygen molecules are consumed, and on improvements in after-treatment system. Specific emission control systems are required to limit evaporative emissions. In this section the main technologies used worldwide are described. The most relevant and feasible technologies for fulfilling the purpose of this work are detailed to obtain a greater understanding of their principle of operation and their importance for meeting more restrictive emissions.

The precise control of the air-fuel mixture is highly dependent on the injection system, which traditionally can be PFI or GDI. While PFI engine benefits with a more homogeneous air-fuel mixture, proper GDI injection pattern tuning may better perform in cold conditions due to stratification and high-pressure injection that help to vaporize the fuel and mix it with air. Several studies as the ones performed by Rosenblatt, D., Karman, D. (2020) [9] and Winklhofer, E. (2014) [10] indicate the potential benefits of better controlling mixture formation with a GDI engine for reducing gaseous tailpipe emissions while improving fuel economy. As drawback particulate emissions may increase due to stratified charge with locally rich zones within combustion chamber, which can be reduced by the use of oxygenated fuels like ethanol. For Brazilian Market, under cold conditions, PFI engines are nowadays equipped with fuel heating system, which significantly improves combustion during cold phase. O_2 sensors, both upstream and downstream catalyst, also play an important role, once they feedback the O_2 concentration to the ECU to correct the injection time in order to have high catalyst conversion efficiencies under different engine operating points. Injection systems also allow different engine operating strategies to reduce emissions.

Another measure on the engine level to reduce emissions is the combustion chamber design, which can be improved by reducing crevices that generate hydrocarbons and by increasing turbulence through swirl and tumble for better mixing air and fuel. There are studies, like "The Effects of Crevices on the Engine-Out Hydrocarbon Emissions in SI Engines, 1994" [11], showing how sensitive engine-out HC is depending on where the crevice is located in the combustion chamber.

EGR (Exhaust Gas Recirculation) is used to reduce NOx by decelerating the flame front in the combustion process and consequently reducing temperatures inside the combustion chamber, as researched by Vianna, J. N. de S. et al (2005) [12]. It can be obtained internally through the trapping of residual gases from the VVT (Variable Valve Timing) or externally through the recirculation of the exhaust gases to the intake. Latter solution is not standard for engines that equip A- and B- segment vehicles in Brazil.

For gasoline engine TWC (Three-Way Catalyst) is the standard after-treatment system for controlling emissions. It receives this name due to its capability of controlling THC, CO and NOx. Main parameters and components are described for better understanding the process of selecting a TWC. Both engine operating point towards higher loads, as well catalyst positioned closer to engine-out are key factors for emission control, as stated by Singer, B.C. et al (1999) [13]. More stringent THC and CO emissions require CC (Close-Coupled) catalyst, which is integrated to the exhaust manifold to allow it to faster achieve operating temperature for maximum conversion. UF (Under-Floor) catalysts are used as buffer for further emission reduction. TWC itself is composed of substrate, a cylinder with honeycomb structure that is defined by its material, volume, CPSI (Cells Per Square Inch), thickness between cells. Such substrate is impregnated with PGM (Platinum Group Metals), commonly palladium (Pd) and rhodium (Rh), which will be responsible for the catalytic conversions. Then a metallic housing is bounded to the substrate through a mantle that has several functions, as sealing, thermal insulation, fixation and mechanical protection against impact. A heat shield provides extra thermal insulation to keep catalyst at the proper operating temperature.

The main drawback of conventional TWC is that it needs exhaust heat provided by the combustion by-products to achieve its operating temperature. Meanwhile it can only partially reduce emission on cold phase, thus may prolonging the period of high exhaust emission rates, as observed by Yusuf, A.A., Inambao, F.L. (2019) [14]. As countermeasure some technologies were developed to faster warm-up the catalyst, such as SAI (Secondary Air Injection), which injects air in the exhaust to have post-combustion (extra fuel is needed), and EHC (Electrically Heated Catalyst), which utilizes electrical power for heating.

Below boundary conditions are assumed for selecting technological packages that are likely to meet PL8:

- PFI/TGDI flex fuel 1.0L engines with standard technology that generally equip automaker's A- and B-segment vehicles
- Emission target to be achieved with proposed technological packages is level 50 (NMOG + NOx = 50 mg/km) with a CF=2 for RDE (check Table 2 for more information)

For evaporative emissions, it is common sense that vehicles will require evaporative control system upgrade to ORVR for attending PL8. There are different architectures, but the main modifications are larger canister to increase its capacity to adsorb fuel vapors, reduced filler pipe to prevent tank vapors from scaping to atmosphere while refueling and proper layout to force the vapors through the canister. In this work, ORVR system is considered as detailed by Martini, G. et al (2012) [15] and shown in Figure 4.

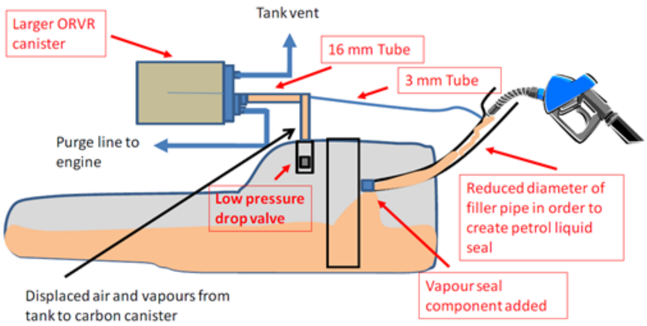


Figure 4. Evaporative control system updated to ORVR – modifications in red. Source: Martini, G. et al (2012) [15]

From first assessment on technologies for exhaust emissions reduction and setting of emission targets, further details on following hardware are provided:

- Fuel heating system (only for PFI engines)
- O_2 sensors, both upstream and downstream catalyst
- TWC, including EHC

FUEL HEATING SYSTEM – Ethanol fuel has some characteristics that makes its cold operation more challenging when compared to gasoline. The main ones are related to its composition, a simple molecule with a well-defined evaporation point, and its low vapor pressure, mainly during cold phase (see graphics extracted from Nigro, F. (2011) [16] for gasoline and ethanol in Figure 5).

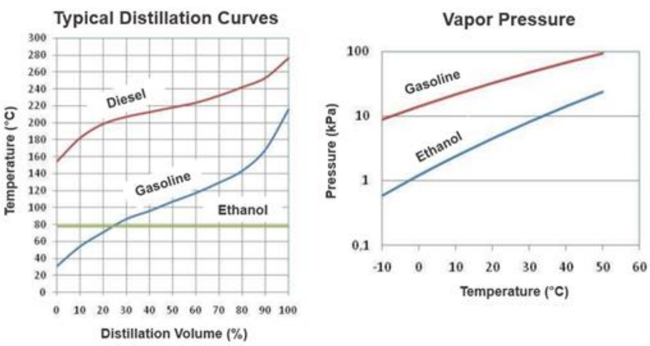


Figure 5. Distillation and vapor pressure curves for gasoline and ethanol. Source: Nigro, F. (2011) [16]

The low vapor pressure of ethanol can be increased by heating the fuel, thus resulting in a more favorable air-fuel mixture likely to have more robust combustion. 1st generation fuel heating systems, currently on market, has as main objective to enable cold start with ethanol and to improve the driveability at those temperatures, typically below 20°C, which are non-relevant for Brazilian emissions legislation. 2nd generation systems will extend its operation to emission relevant temperatures above 20°C during engine start and its warm-up phase, thus resulting in lower HC and CO emissions, in sync with PL8 limits. Further details on thermodynamic and heat transfer phenomena while heating the fuel, as well its positive impact on reducing emissions can be found in studies performed by Oliveira A.V.S. et al (2016) [17] and Sales L.C.M, Sodré J.R. (2012) [18].

The most common systems have heating elements in the fuel rail, such as the one from Robert Bosch GmbH [19] presented in Figure 6, or directly in the injector nozzle, a solution implemented by Delphi Technologies [20] and shown in Figure 7.

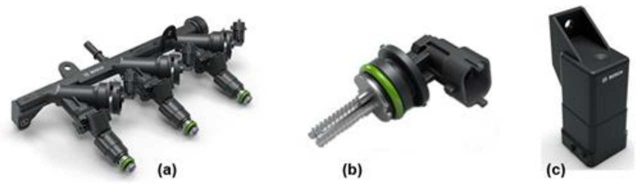


Figure 6. Fuel heating system by fuel rail from Robert Bosch GmbH – (a) fuel rail; (b) heating element; (c) HCU (Heating Control Unit). Source: extracted from https://www.bosch-mobility-solutions.com.br/br/destaques/sistemas-de-transmiss%C3%A3o-e-mobilidade-el%C3%A9trica/flexstart/ [19]

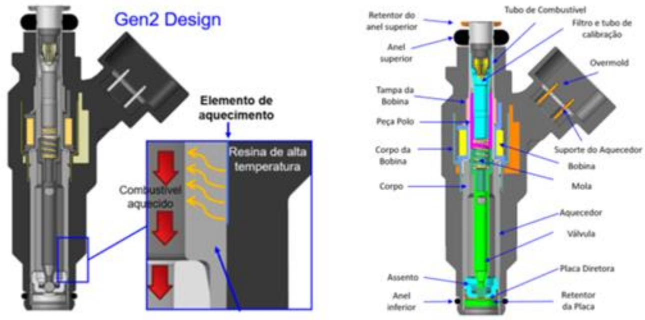


Figure 7. Fuel heating system by injector nozzle from Delphi Technologies. Source: extracted from https://omecanico.com.br/injetores-aquecidos-auxiliam-a-reduzir-emissoes/ [20]

O2 SENSOR – Oxygen sensor, also known as lambda sensor, is an electronic device that measures the concentration of oxygen in the exhaust gases. Such information is the basis for several functions, both for controlling the formation of the air-fuel mixture and for the treatment of exhaust gases. Currently, every vehicle has at least two of these sensors as standard configuration. The 1st one is located between the engine's outlet and the catalyst's inlet. Its primary function is to adjust the engine's air-fuel mixture, ensuring that after-treatment systems operate in optimal compositions for emissions conversion. The 2nd one is usually close to the TWC outlet. Its main functions are to monitor and verify that after-treatment system is properly working and to fine-tune the air-fuel mixture considering the catalyst state. The 2nd probe was implemented as an OBD 2 requirement, in which the functionality of relevant systems for reducing emissions is monitored.

Figure 8, extracted from Brady R. (1988) [21], shows an overview of the engine's air-fuel mixture control system and exhaust gas treatment with its main sensors and actuators. Oxygen sensors are at the heart of these features and are therefore essential in meeting increasingly stringent emissions legislations. Basically, the 1st sensor sends information about the air-fuel mixture (excess fuel, lack of fuel, ideal mixture - stoichiometric) to ECU, which is responsible for adjusting the amount of fuel to be injected. Once the injection is adjusted, the catalyst is expected to efficiently reduce the pollutants. Such monitoring is then performed by the 2nd sensor, which in turn influences the control of the 1st sensor and, consequently, the amount of fuel injected. This way, it is possible to simultaneously guarantee that engine's air-fuel mixture and the exhaust after-treatment are operating at their optimum points.

Figure 9, which is extracted from Lambda Training by ETAS [22] shows the schematic diagram of the sensor with the zirconia membrane (zirconium dioxide) and the sensor voltage vs output ratio, λ, in which the precision of the sensor is verified only for $\lambda = 1$. For this reason, HEGO, also known as binary or alternating sensor, is suitable for controlling air-fuel mixture, within a tolerance, for enhancing after-treatment systems and allowing OBD monitoring.

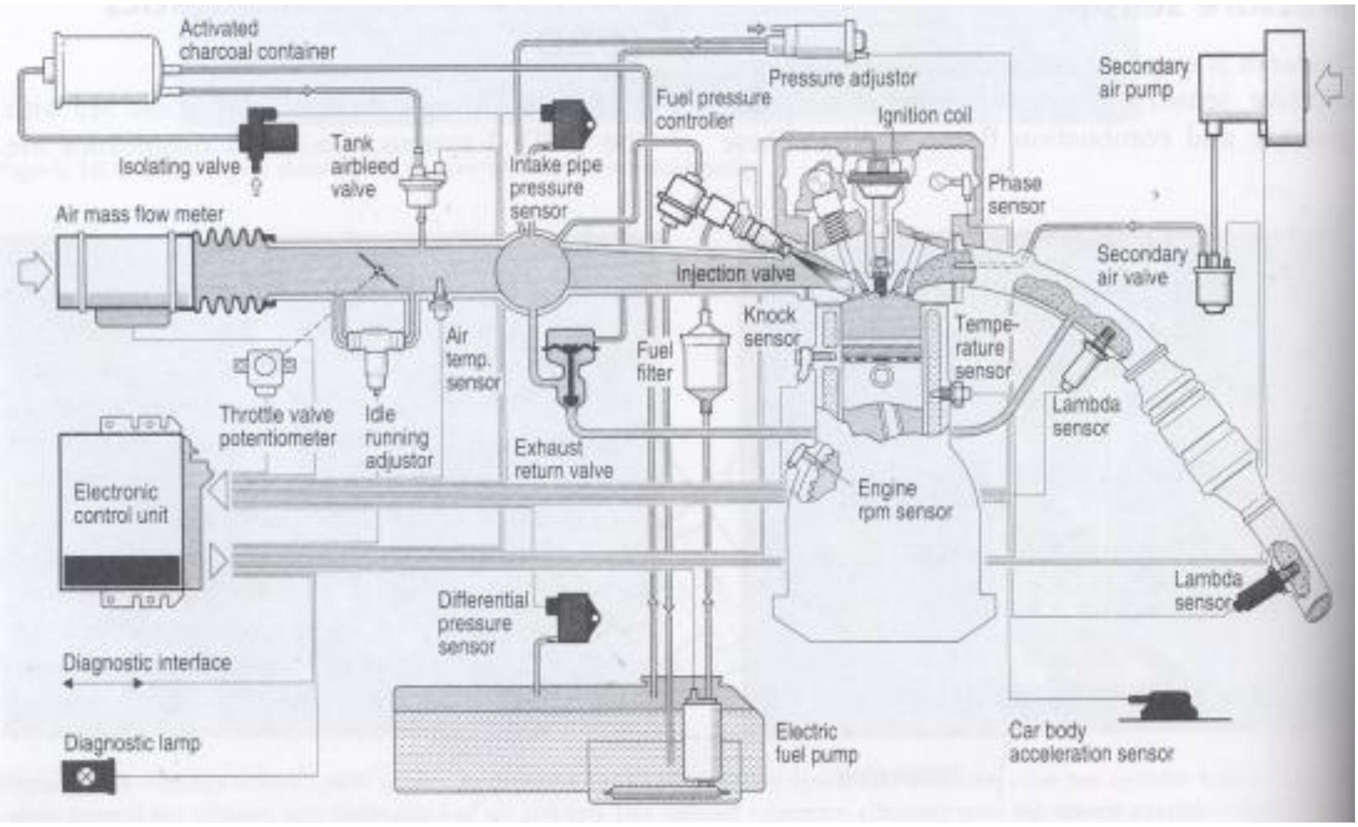


Figure 8. Overview of the engine's air-fuel mixture control system and exhaust after-treatment. Source: Brady R. (1988) [21]

The working principle of the oxygen sensor is based on the Nernst sensor, which uses a zirconium dioxide membrane that allows electrolytic transfer of oxygen ions at high temperatures (~ 650 °C) resulting in a voltage. From this property it is possible to measure the difference in oxygen concentration between two different gases. One side of the sensor membrane is exposed to exhaust gases while the other one is exposed to the reference air from the atmosphere. There are two main types of sensors: HEGO and UEGO.

HEGO (Heated Exhaust Gas Oxygen sensor) is used to determine $\lambda = 1$ (air-fuel mixture in stoichiometric ratio). It does not have precision for $\lambda \neq 1$, since it is only able to compare the oxygen concentration in the exhaust gases with reference air. However, it manages to capture the transition from air-fuel mixture between rich-poor and poor-rich.

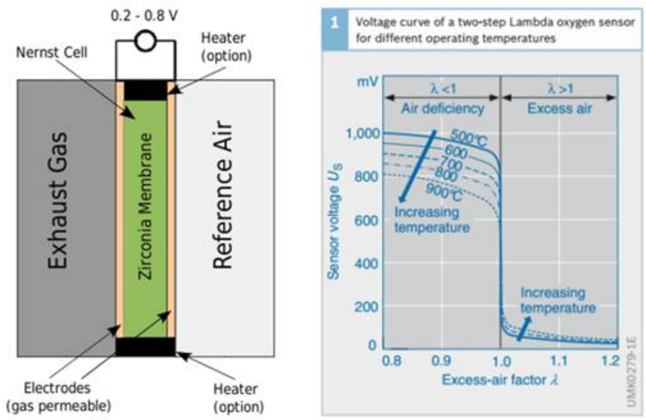


Figure 9. HEGO - schematic diagram and voltage vs lambda curve for different operating temperatures. Source: Lambda Training by ETAS [22]

UEGO (Universal Exhaust Gas Oxygen sensor) has the same working principle as HEGO, but with improvements. It has two zirconium dioxide cells incorporated by an electrochemical gas pump. Such system allows a precise correlation of required pumping current to keep the monitoring chamber at $\lambda = 1$ for different oxygen concentrations and, consequently, with a wide operating range of air-fuel mixture and not only at $\lambda = 1$ as in the case of HEGO. Figure 10, which is extracted from Lambda Training by ETAS [22], shows the schematic diagram of the sensor - including the two zirconia membranes (zirconium dioxide) and the monitoring chamber, and the pumping current vs λ, in which a wide band of air-fuel mixtures can be captured. Due to this reason, UEGO is also known as wideband or proportional and is used for more precise control of the air-fuel mixture (probe located between the engine and after-treatment system) to meet more advanced emissions legislations.

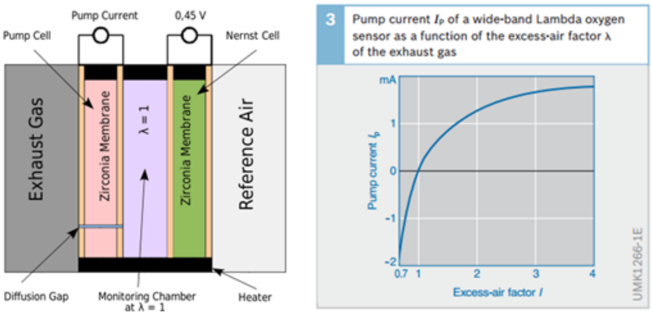


Figure 10. UEGO - schematic diagram and current pumping curve vs Lambda. Source: Lambda Training by ETAS [22]

Oxygen sensors need to operate at a high temperature in order to function properly. Modern sensors are equipped with two devices to minimize pollutants by precisely controlling the engine's air-fuel mixture as soon as the engine starts: heating element and TSP (Thermal Shock Protection).

Heating element inside the ceramic allows early operation and faster response times. Heating strategies must be implemented to ensure both the readiness of operation and the reliability of the sensor, for example against thermal shocks caused by water droplets present in the exhaust at colder temperatures and which could destroy the sensor ceramic if the maximum heating power is provided. Classic strategy has dew point recognition to, from such information, define the heating power of the sensor according to the identified event (cold start with / without dew point identification, restart, sensor temperature below / above the optimum operating temperature, etc.).

Thermal shock protection layer allows the sensor to work even more quickly, since heating can usually occur at full power at the time the engine starts, before dew point is reached.

Vehicles that meet advanced emissions legislations such as US Tier 3 and Euro 6 and have the ICE (Internal Combustion Engine) as the main tractive force use UEGO as 1st probe and HEGO as 2nd one. Both generally also have thermal shock protection to enable correct operation as quickly as possible. In this way, it is possible to fine-tune the air-fuel mixture to meet the requirements of the after-treatment system resulting in high pollutant conversion efficiency, even during critical cold operation.

THREE-WAY CATALYST – The three-way catalyst is a component widely used to control exhaust emissions from gasoline engines. It is a catalyst due to its properties, which increases the speed of a chemical reaction, participates in it, but is not consumed as a reagent or product. And it is so called three-way for being able to convert 3 pollutants that are regulated, directly or indirectly, by emissions legislations: HC, CO and NOx.

Catalytic agents are precious metals that are part of the PGM group, composed by ruthenium (Ru), rhodium (Rh), palladium (Pd), osmium (Os), iridium (Ir) and platinum (Pt). The electronic structure of PGM group is unique and it generates chemical properties that are not matched by any other element of the periodic table nor by compounds which can remain stable for a long time in the conditions of high temperature of automotive catalytic converters. Automotive applications, however, mainly use Pt, Pd and Rh, which exist in a limited supply - Bardi, U., Caporali, S. (2014) [23].

Currently most automotive applications have reduced or eliminated the use of Pt, replacing it by Pd for the oxidation of HC and CO. The reduction of NOx, in turn, is performed by Rh. The global chemical reactions are shown by Equations 1, 2 and 3.

$$HC + O_2 \rightarrow CO_2 + H_2O \tag{1}$$

$$CO + {}^{1}/_{2}\, O_2 \rightarrow CO_2 \tag{2}$$

$$NO_x + CO \rightarrow CO_2 + {}^{1}/_{2}\, N_2 \tag{3}$$

This means that HC, CO and NOx are controlled through the three-way catalyst, which at its maximum efficiency consumes the above-mentioned pollutants (chemical reaction reagents) to produce CO_2, H_2O (water) and N_2 (nitrogen), as illustrated in Figure 11, extracted from Nanotechnology Products Database [24]. The substrate is generally honeycomb shaped and is defined by CPSI and the wall thickness of adjacent cells. PGM is impregnated in each cell to maximize the useful area for catalytic reactions.

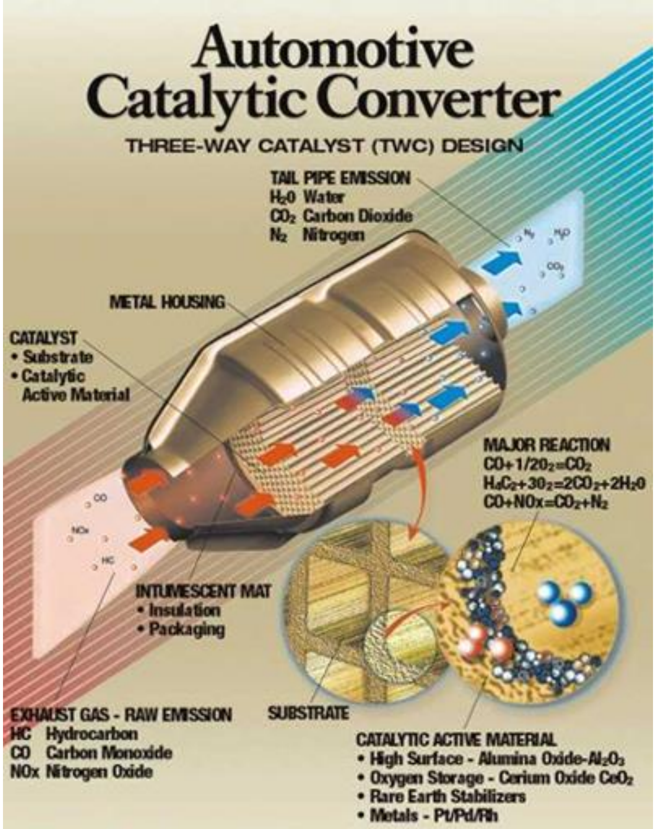


Figure 11. Three-way catalyst working principle and main components. Source: extracted from https://product.statnano.com/product/7867/ptrh-only-three-way-catalysts [24]

For the catalytic conversion to be maximized, it is necessary that the catalyst operates at an appropriate temperature and that the air-fuel mixture is controlled in a narrow band around stoichiometric ratio. Figure 12, adapted from Lassi, U. (2003) [25], shows the impact of catalyst aging on the light-off temperature, temperature at which the catalyst presents 50% conversion efficiency, in this case to CO. Catalyst aging can occur due to different phenomena, such as, for example, a mechanical impact that detaches the mantle between substrate and encapsulation or the agglutination of PGM by thermal stress, thus reducing the useful area. Catalyst aging requires longer time and higher temperatures to reach the light-off temperature.

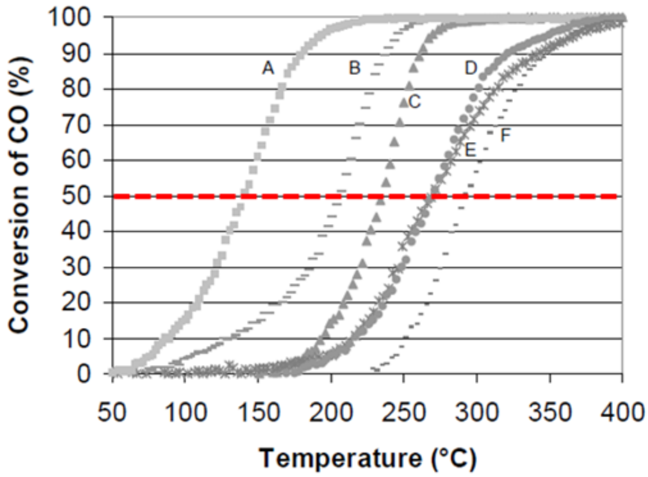


Figure 12. Comparison of the light-off curves of CO after the reductive and oxidative agings: A) H_2 (Hydrogen)/800°C/3h-aged; B) air/800°C/3h-aged; C) H_2/1000°C/3h-aged; D) H_2/1200°C/3h-aged; E) air/1000°C/3h-aged, and F) air/1200°C/3h-aged; lean reaction conditions. Adapted from Lassi, U. (2003) [25]

Figure 13, which is extracted from https://ac.umicore.com/en/technologies/three-way-catalyst/ [26], shows the conversion efficiency of HC, CO and NOx as function of air-fuel ratio, as well as the operating range for optimum conversion efficiency of the 3 gases. Such range is typically between $\lambda = 1 \pm 2\%$.

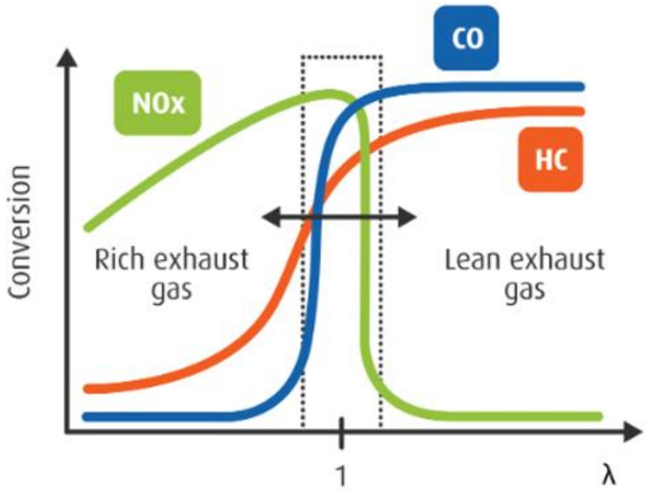


Figure 13. Characteristic curves of HC, CO and NOx conversion as function of λ. Source: extracted from https://ac.umicore.com/en/technologies/three-way-catalyst/ [26].

Another important feature of the three-way catalyst is its ability to store and release oxygen. Such property is known as OSC (Oxygen Storage Capacity) and is enabled by cerium oxide, which captures excess oxygen when the mixture is poor and uses it to oxidize HC and CO when the mixture is rich. In this way it works as an oxygen buffer, maximizing the conversion of HC, CO and NOx.

Several parameters of the three-way catalyst must be analyzed to ensure compliance with emissions legislation, both for new and aged components. Its working principle has been detailed to bring basic knowledge about the topic and to show how complex the selection of a catalyst is. The current work is not intended to develop all the possibilities of a catalyst to meet PL8, but rather to base the selection on more mature emissions legislation markets, such as the US and EU.

Another feature considered to attend PL8 is the EHC, which utilizes electrical power for heating the TWC. Vehicles powered with ICE, as only tractive force or as in a hybrid powertrain, will likely need to have an EHC to meet more stringent emissions. This happens, for example, because catalyst is always below its light-off temperature during a cold-start and engine warm-up. And even after light-off is reached exhaust temperature could drop causing TWC to operate out of its optimum range, e.g., during a long deceleration or when the engine is off due to start-stop system. EHC associated with ECU control functions allows efficient TWC thermal management to have as soon as possible, under different conditions, TWC at its optimum temperature to convert pollutants. According to EMITEC (2011) [27], the additional costs for EHC can be more than offset. The greater efficiency of systems consisting of a close-coupled TWC with an attached EHC allows the volume and PGM loading to be substantially reduced. Figure 14, from EMITEC (2011) [27], shows an example of EHC available in market. Firstly, introduced in premium vehicles, such technology is likely to be implemented in A- and B-segment vehicles to cope with more stringent emissions legislations.

Figure 14. Electrically Heated Catalyst from Emitec. Source: EMITEC (2011) [27].

EVALUATION AND DEFINITION OF TECHNOLOGICAL PACKAGES FOR MEETING PL8

Technological packages are evaluated and defined based on previous assessment of potential technological solutions for attending PL8. Packages are proposed for both PFI and TGDI flex fuel 1.0L engines that commonly equip vehicles in A- and B-segments. They are stated as potential technological packages, once their definitions are based on AVL's expertise acquired over several emission development projects for more stringent emissions legislations and therefore are also likely to meet PL8. As reminder, the emission target to achieve is level 50 (NMOG

Table 4: Reference, auxiliary reference for PL6 and technological packages proposed for PL8.

	Reference	Auxiliary Reference	Technologial Packages proposed for PL8		
	PFI Flex Fuel 1.0L Standard TWC for PL6	TGDI Flex Fuel 1.0L Standard TWC for PL6	PFI Flex Fuel 1.0L TWC Euro6dFull for PL8	PFI Flex Fuel 1.0L TWC with EHC for PL8	TGDI Flex Fuel 1.0L TWC for PL8
In-Cylinder Control					
Engine	PFI with Fuel Heating 1st Gen	TGDI	PFI with Fuel Heating 2nd Gen	PFI with Fuel Heating 2nd Gen	TGDI
Upstream O_2 Sensor	HEGO	UEGO with TSP	UEGO with TSP	UEGO with TSP	UEGO with TSP
Downstream O2 Sensor	HEGO	HEGO	HEGO with TSP	HEGO with TSP	HEGO with TSP
Faster Microprocessor	No need for PL6	No need for PL6	Higher ECU SW demand	Higher ECU SW demand	Higher ECU SW demand
After-Treatment					
Three-Way Catalyst (TWC)	TWC (CC) Spec from PFI PL6	TWC (CC + UF) Spec from TGDI PL6	TWC (CC + UF) Spec from Euro 6dFull	TWC (CC + UF) Spec in-between PFI 1.0L PL6 and Euro6dFull	TWC (CC + UF) Spec in-between PFI 1.0L TWC with EHC and Euro6dFull
Electricaly Heated Catalyst (EHC)	-	-	-	EHC	-
Alternator (Alt) + Battery (Bat)*	Alt100A + Bat45Ah	Alt100A + Bat45Ah	Alt100A + Bat45Ah	Alt180A + Bat65Ah	Alt100A + Bat45Ah
Evaporative					
Canister	Standard Canister for PL6	Standard Canister for PL6	Higher Canister Volume for PL8	Higher Canister Volume for PL8	Higher Canister Volume for PL8
Canister Valve (CV)	Standard CV for PL6	Standard CV for PL6	Bigger and more Precise CV for PL8	Bigger and more Precise CV for PL8	Bigger and more Precise CV for PL8
Onboard Refueling Vapor Recovery (ORVR)**	-	-	Standard ORVR for PL8	Standard ORVR for PL8	Standard ORVR for PL8
Engine Applied Vacuum System	-	-	Standard for OBD-Br3	Standard for OBD-Br3	Standard for OBD-Br3

* Alternator and battery are only updated due to EHC and for this reason are included in the after-treatment system

** ORVR system without considering canister

+ NOx = 50 mg / km) with a CF=2 for RDE (check Table 2 for more information).

Reference technological package, which meets current PL6 norm, is composed by PFI flex fuel 1.0L engine with 1st generation fuel heating system. The O_2 sensors, both upstream and downstream catalyst, are HEGO without TSP. TWC-CC has standard technology with typical PGM loading for this emission phase. Evaporative system mainly consists of canister and purge valve. An auxiliary reference technological package, also attending PL6, is set by replacing the PFI flex fuel 1.0L engine by a TGDI flex fuel 1.0L engine for easiness on following the paper development.

Add-ons to the reference technological package are considered. In this paper, an add-on is defined as a technology upgrade in respect to the reference technological package. In this sense, a TGDI flex fuel 1.0L engine is an add-on to the PFI flex fuel 1.0L engine. Such concept is important for the cost comparison evaluation to identify the most cost-effective pathway to meet PL8, considering A- and B- segment vehicles.

Table 4 details reference and auxiliary reference technological packages (PL6 related), as well potential technological packages considered in this paper for attending PL8. The hardware is subdivided into in-cylinder, after-treatment and evaporative control systems. In-cylinder control encompasses engine technologies as well measures to improve emissions at engine level, including air-fuel mixture control enhanced by O_2 sensors. Faster microprocessors were also included in the in-cylinder control reflecting that for PL8 a higher ECU demand will be required for controlling, e.g., fuel heating strategy and exhaust thermal management for keeping TWC at its optimum temperature operating range. After-treatment mainly copes with TWC, but for cost comparison, battery and alternator are also included once an upgrade is required for the scenario with EHC. Its electrical power consumption demands a higher capacity battery, as well a higher current alternator. For this paper, no vehicle electrics and electronics dimensioning is evaluated. For sake of simplicity, battery capacity is increased from 45 Ah to 65 Ah, while alternator is increased from 100 A to 180 A. Both hardware upgrades have as objective to reflect on integration cost of EHC. Evaporative will also change for PL8, requiring ORVR system for coping with refueling emissions limit and an engine applied vacuum system for monitoring system leakage. The latter component is OBD-Br3 related.

Both PFI and TGDI flex fuel 1.0L engines are inline-three cylinders. Only small modifications, such as material change and redesign, are foreseen for PL8. Lower power consumption of fuel heating systems, for PFI engines only, does not require any alternator/battery update. O_2 sensors present the same technology level between proposals, either UEGO or HEGO, only differentiated by including TSP capability. EHC has 1,5 kW, which allows the maintenance of standard 12V architecture, but demanding higher current alternator and battery capacity to keep vehicle electrics and electronics well dimensioned. From the evaporative system, canister is expected to increase its volume and to require carbon type with higher adsorption efficiency. Bigger canister valve with more aggressive purging strategy is likely to be needed for attending more stringent PL8 limits. Other components for a implementing an ORVR system, as shown in Figure 4, are also included to cope with HC limit during tank fueling event. First assessment on potential technological packages cope with above analysis.

Table 5. TWC specification for reference, auxiliary reference and technological packages proposed for PL8.

		Reference	Auxiliary Reference	Technologial Packages proposed for PL8		
		PFI Flex Fuel 1.0L Standard TWC for PL6	TGDI Flex Fuel 1.0L Standard TWC for PL6	PFI Flex Fuel 1.0L TWC Euro6dFull for PL8	PFI Flex Fuel 1.0L TWC with EHC for PL8	TGDI Flex Fuel 1.0L TWC for PL8
Catalyst Specification (average values from AVL's experience)						
Configuration		CC	CC	CC + UF	CC + UF	CC + UF
Substrate		Ceramic	Ceramic	Ceramic + Ceramic	Metallic + Ceramic	Ceramic + Ceramic
Pd	g/l	1,6	1,4	1,9	1,6	1,7
Rh	g/l	0,2	0,15	0,3	0,3	0,35
Vd	l	1	1	1	1	1
SVR	-	1,5	1,5	3	2	2
CV	l	1,5	1,5	3	2	2
Pd	g	2,4	2,1	5,7	3,2	3,4
Rh	g	0,3	0,23	0,9	0,6	0,7

The hardware to achieve stringent PL8 emissions are similar between proposals. The main differences are the after-treatment system and the engine technology, PFI or TGDI, which are considered mature for PL6 and no significant changes are expected for PL8. TWC plays a major role because its cost is highly sensitive to PGM loading, which are commodities sold in the international market that are becoming scarce, in contrast with even higher demand from automotive industry to attend more stringent emissions. Table 5 presents TWC technical specification, providing configuration (CC, UF) substrate material (ceramic, metallic) and PGM loading (Pd and Rh only) for PL6 scenarios, for both PFI and TGDI flex fuel 1.0L engines, and prospects for PL8 according to the pathway chosen to attend such emissions level. SVR (Swept Volume Ratio) is the ratio between CV (Catalyst Volume) and Vd (engine displacement), which is highest for Euro6dFull due to more stringent emissions when compared to PL8. PGM loading figures are averaged according to AVL's experience and are only intended to provide reference values for better understanding on PGM increase for more stringent emissions, e.g., based on Euro 6, as well as basis for cost comparison to identify the most cost-effective pathway to meet PL8.

COST ANALYSIS OF TECHNOLOGICAL PACKAGES FOR MEETING PL8

Incremental cost impact of the potential technological packages proposed to attend PL8 is based on Posada, F., Bandivadekar, A., German, J. (2012) [4]. Some changes are implemented to reflect the Brazilian market and to be able to compare those incremental costs to the reference hardware, PFI flex fuel 1.0L engine with standard TWC spec to attend PL6.

This methodology estimates the increase in costs associated with the implementation of technologies to reduce emissions, moving from PL6 to PL8. Its main points are detailed by Posada, F. (2014) [28] and shown in the flowchart of Figure 15 and explained below to support the modifications, updates and extrapolations necessary to fulfill the objective of this work:

1. Cost of technologies based on RIA (Regulatory Impact Analysis).
2. Update of technologies through academic sources and technical papers.
3. The cost of each technology is converted to USD (US Dollars), considering average price in 2019, pre-pandemic, as USD1 ~ BRL4 (BRL stands for Brazilian currency, real).
4. Costs reviewed and consolidated by key people in the industry, considering all inputs to create a solid database.

Costs of emission reduction technologies can be divided into two groups. The first one considering variable costs, related to the hardware update itself, and the second one including indirect costs, which in this paper encompass vehicle calibration development, tooling and certification.

Indirect costs of tooling and certification are fixed and based on Posada, F., Bandivadekar, A., German, J. (2012) [4]. Estimate for vehicle calibration development, which encompasses vehicle application and software development for ECU control functions related to hardware update, is provided and kept constant per emission phases PL6 and PL8 for the sake of simplicity. Variable costs, mainly in relation to the selection of the catalyst, are in-depth analyzed, updated and extrapolated.

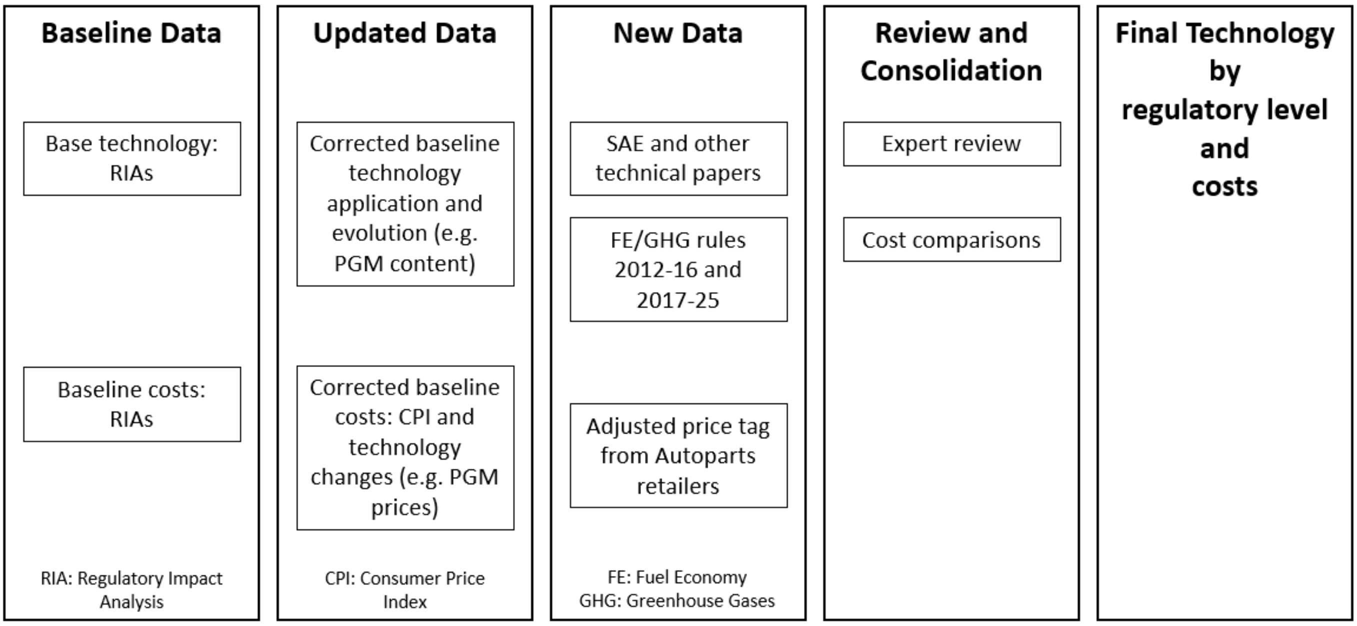


Figure 15. Methodology used to estimate cost increases for more restrictive legislation. Source: Posada, F. (2014) [28].

TRL (Technological Readiness Level) is considered at its maximum level, TRL9, for each component of the proposed technological packages. This means all potential solutions are market mature and, therefore there is no significant cost reduction due to the product's learning curve and / or increased production volume.

The component price estimate was carried out based on research in the aftermarket, considering a factor of 5 between the retail price and the automaker's cost for a given component. This means the aftermarket has more expensive products, 5x in this work, because it does not benefit from large volumes as the automaker, and it is positioned towards the end of the supply chain (after-sales directly to the final customer). The prices reflect the database built from auto parts retailers' websites, as well with inputs and reviews from key people in the industry. Only exceptions for this cost assessment methodology are the evaporative control system update, which is based on Martini, G. et al (2012) [15], and the TWC, for which a detailed calculation is performed based on Posada, F., Bandivadekar, A., German, J. (2012) [4] considering that PGM has the highest share for the component's price. In this paper, conservative values for PGM are used, with Pd being marketed at 80 USD/g and Rh at 320 USD/g. Both values tend to their historical maximum, which are aligned with the shortage of these metals, as well as their high demands in vehicle after-treatment systems. Further details on PGM price and its market analysis can be found in [29] and [30]. All prices are converted to 2019 USD.

Table 6 includes the estimate for variable costs (hardware associated) of emission reduction technologies for current PL6 and potential technological package for PL8, considering both PFI and TGDI flex fuel 1.0L engines. Estimated cost for each component is given by a single average value and it may differ according to each automaker. For instance, PFI and TGDI estimated prices are highly dependent on automaker's strategy, such as how high is volume production and whether it's locally or abroad manufactured and assembled. For this paper several sources were considered and averaged to estimate the cost of locally producing 100.000 engines per year. From Table 6 is inferred a difference of USD750 between a PFI flex fuel 1.0L engine and a more expensive TGDI flex fuel 1.0L engine, both with 3 cylinders. Other components are likely to be less sensitive to price variation. Furthermore, variable costs are responsible for more than 98% of the total costs. Main drivers for such increase are related to the engine technology, whether is PFI or TGDI, and the TWC, specially on how high is PGM loading.

Indirect costs of tooling and certification are based on EPA (1999) [31]. From Posada, F., Bandivadekar, A., German, J. (2012) [4] they are inferred with a fixed cost of USD12. Such estimate is increased to USD15 for PL6 - considering there are 3 reference fuels for certification, E22, E61 and E100, and further increased to USD25 for PL8 due to RDE and new procedure for evaporative. Vehicle calibration development is also included in the indirect costs.

Table 6. Variable costs for reference, auxiliary reference for PL6 and technological packages proposed for PL8.

	Reference		Auxiliary Reference		Technologial Packages proposed for PL8					
	PFI Flex Fuel 1.0L Standard TWC for PL6		TGDI Flex Fuel 1.0L Standard TWC for PL6		PFI Flex Fuel 1.0L TWC Euro6dFull for PL8		PFI Flex Fuel 1.0L TWC with EHC for PL8		TGDI Flex Fuel 1.0L TWC for PL8	
	Comments/ Description	Estimated Cost	Comments/ Description	Estimated Cost	Comments/ Description	Estimated Cost	Comments/ Description	Estimated Cost	Comments/ Description	Estimated Cost
		USD		USD		USD		USD		USD
Variable Costs		**909**		**1621**		**1472**		**1292**		**1944**
In-Cylinder Control		**520**		**1275**		**567**		**567**		**1287**
Engine	PFI with Fuel Heating 1st Gen	500	TGDI	1250	PFI with Fuel Heating 2nd Gen + Engine Modification	530	PFI with Fuel Heating 2nd Gen + Engine Modification	530	TGDI	1250
Upstream O_2 Sensor	HEGO	10	UEGO w/ TSP	15	UEGO w/ TSP	15	UEGO w/ TSP	15	UEGO w/ TSP	15
Downstream O_2 Sensor	HEGO	10	HEGO	10	HEGO w/ TSP	12	HEGO w/ TSP	12	HEGO w/ TSP	12
Faster Microprocessor	No need for PL6		No need for PL6		Higher ECU SW Demand	10	Higher ECU SW Demand	10	Higher ECU SW Demand	10
After-treatment		**377**		**334**		**838**		**658**		**590**
Three-Way Catalyst	TWC (CC)	324	TWC (CC + UF)	281	TWC (CC + UF)	785	TWC (CC + UF)	500	TWC (CC + UF)	537
Electricaly Heated Catalyst	No need for PL6		No need for PL6		Not considered for this proposal		EHC 1,5 kW	65	Not considered for this proposal	
Alternator + Battery*	100A + 45Ah	53	100A + 45Ah	53	100A + 45Ah	53	180A + 65Ah	93	100A + 45Ah	53
Evaporative		**13**		**13**		**68**		**68**		**68**
Canister	Standard for PL6	8	Standard for PL6	8	Higher Volume for PL8	13	Higher Volume for PL8	13	Higher Volume for PL8	13
Canister Valve	Standard for PL6	5	Standard for PL6	5	Higher Precision for PL8	10	Higher Precision for PL8	10	Higher Precision for PL8	10
ORVR**	No need for PL6		No need for PL6		Standard for PL8	30	Standard for PL8	30	Standard for PL8	30
Engine Applied Vacuum System	No need for PL6		No need for PL6		Standard for OBD-Br3	15	Standard for OBD-Br3	15	Standard for OBD-Br3	15

* Alternator and battery are only updated due to EHC and for this reason are included in the after-treatment system

** ORVR system without considering canister

It encompasses vehicle application and software development for ECU control functions related to hardware update. The costs provided per vehicle are distributed along 5 years with annual production of 100.000 vehicles totaling 500.000 vehicles.

Table 7 provides gross estimate for vehicle calibration with the sole intention to highlight required resources during both PL6 and PL8. Such costs may vary according to specific demands and they are only marginal when compared to variable costs (tens of dollars vs thousands of dollars).

The total estimated costs of emission control technologies are presented on Table 8 for reference and auxiliary reference technological packages for PL6, as well for the potential technological packages considered in this paper for attending PL8. Such costs may vary according to the automaker's strategy and market positioning and is considered within the range of ± USD50 for each technological package. This means that, for a certain technological package, a maximum increase of USD200 is expected from its minimum delta cost in respect to the reference PFI 1.0L Standard TWC for PL6. The cost's spectrum for both PL6 and PL8 scenarios, with the fore mentioned range, are also shown graphically in Figure 16.

From previous graph it's clear that in-cylinder control and after-treatment push the costs for meeting current and future legislations. Competitive advantage is possible by selecting technological packages that can mitigate such inherent cost's increase for attending PL8. For this paper technological package PFI flex fuel 1.0L engine with TWC EHC presents the lowest cost increase from current reference PFI 1.0L Standard TWC for PL6, which is in the range USD296-496, for attending PL8 level 50 (NMOG + NOx = 50 mg / km) with a CF=2 for RDE.

According to automaker's strategy, e.g., high share of TGDI flex fuel 1.0L engines equipping A- and B-segment vehicles, the hardware update, mainly on after-treatment system, is also feasible and ranges from USD236 to USD436, which is close to the incremental cost of the lowest cost technological package proposal. Figure 17 highlights, from cost assessment performed, most cost driven technological packages for both PFI and TGDI flex fuel 1.0L engines.

Table 7. Vehicle calibration costs for PL6 and PL8.

PL6	Vehicle Application	Development Vehicle Cost	Additional Equipment	Development Total Cost	Distributed Over	Total per Vehicle
	USD (Thousand)	USD (Thousand)	USD (Thousand)	USD (Thousand)	100.000 cars*5years	@USD 2019
SW Development	0	0	0	0	500000	0,00
Project Development	750	140	25	915	500000	1,83
						1,83

PL8	Vehicle Application	Development Vehicle Cost	Additional Equipment	Development Total Cost	Distributed Over	Total per Vehicle
	USD (Thousand)	USD (Thousand)	USD (Thousand)	USD (Thousand)	100.000 cars*5years	@USD 2019
SW Development	250	35	100	385	500000	0,77
Project Development	1750	175	50	1975	500000	3,95
						4,72

Table 8. Total estimated costs of emission control technologies for reference, auxiliary reference for PL6 and technological packages proposed for PL8.

	Reference	Auxiliary Reference	Technologial Packages proposed for PL8		
	PFI Flex Fuel 1.0L Standard TWC for PL6	TGDI Flex Fuel 1.0L Standard TWC for PL6	PFI Flex Fuel 1.0L TWC Euro6dFull for PL8	PFI Flex Fuel 1.0L TWC with EHC for PL8	TGDI Flex Fuel 1.0L TWC for PL8
	Estimated Cost	Estimated Cost	Estimated Cost	Estimated Cost	Estimated Cost
	USD	USD	USD	USD	USD
Variable Costs	909	1621	1472	1292	1944
In-Cylinder Control	520	1275	567	567	1287
After-treatment	377	334	838	658	590
Evaporative	13	13	68	68	68
Fixed	17	17	30	30	30
Vehicle Application	1,83	1,83	4,72	4,72	4,72
Tooling + Certification	15	15	25	25	25
Total [-50 +50] USD	926 876-976	1638 1588-1688	1502 1452-1552	1322 1272-1372	1974 1924-2024
Delta from PFI PL6 [-50 +50] USD	0 876-976	712 612-812	576 476-676	396 296-496	1048 948-1148

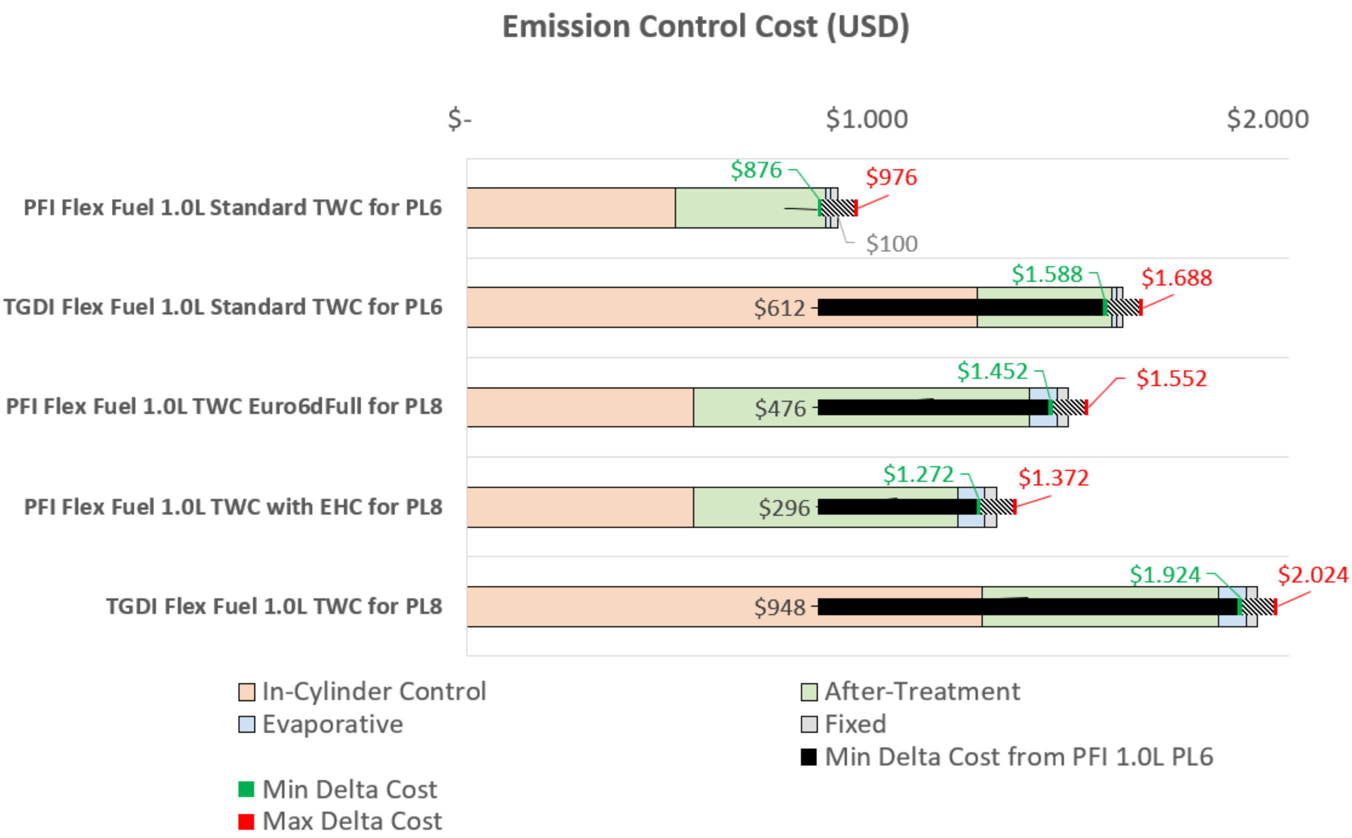


Figure 16. Total estimated costs of emission control technologies for reference, auxiliary reference for PL6 and technological packages proposed for PL8.

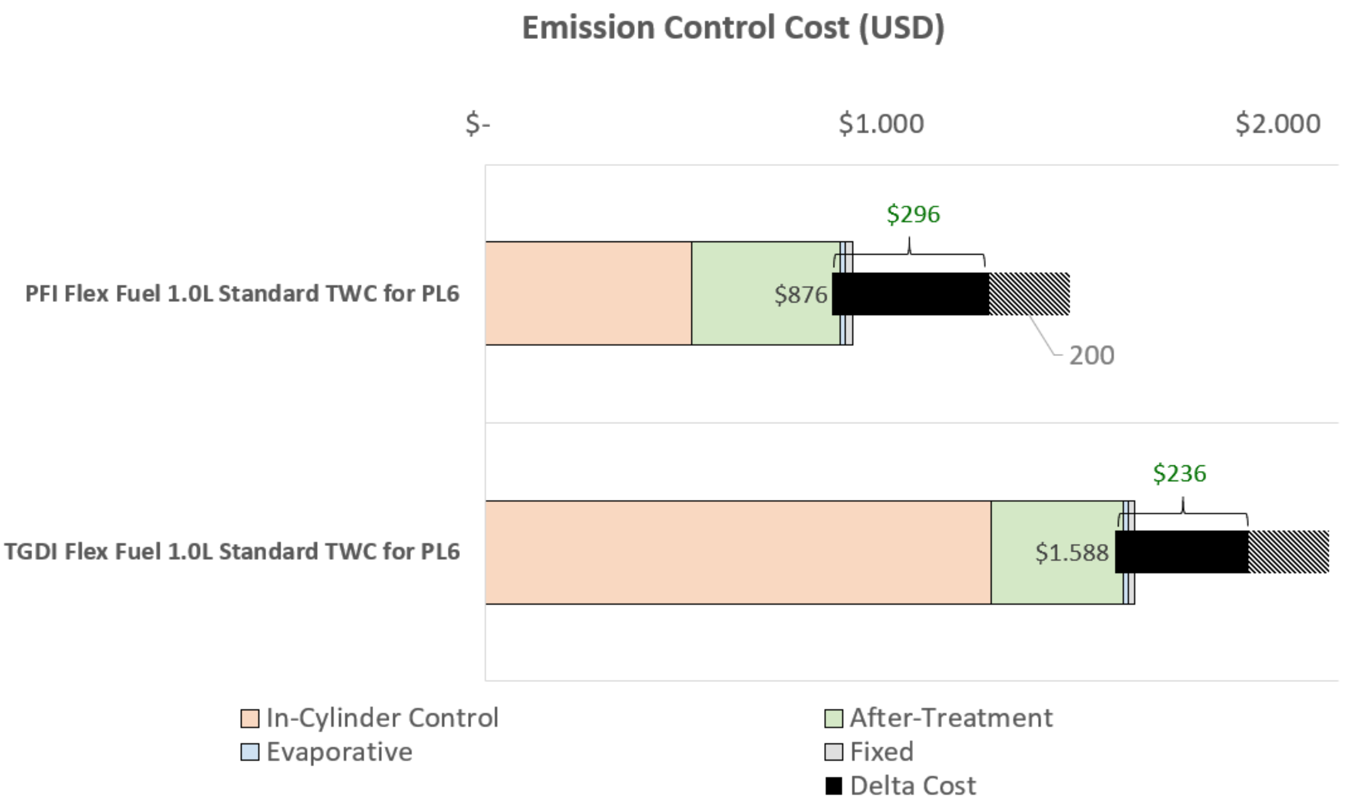


Figure 17. Total estimated cost of emission control technologies for most cost driven technologies for PFI and TGDI engines.

SUMMARY, CONCLUSION AND FUTURE PERSPECTIVE

PL7 and PL8 pose challenges to the automotive industry, once they will enter into force with new limits and procedures. PL7 will likely not require significant hardware update in respect to current PL6. Nevertheless, it will be a transition phase to the more stringent PL8 legislation and therefore should strategically position the automaker through the technological pathway chosen to attend in a structured way ever lower corporate emission levels in the years to come. This paper presented a detailed analysis of PL7 and PL8, Brazilian emissions legislation to come in the next years, respectively, in 2022 and 2025. The focus was to identify potential emission reduction technologies to equip A- and B- segment flex-fuel vehicles to specifically attend PL8, the most stringent Brazilian emissions legislation to come. Emissions target is set to level 50 (NMOG + NOx = 50 mg / km) with a CF=2 for RDE, which is the corporate emission level to attend at the beginning of PL8. After identifying such technologies, they were combined in some scenarios, here so-called technological packages, for both PFI and TGDI engines. Once A- and B- segment vehicles are more cost sensitive to final costumer, commercial feasibility of proposals is verified by analyzing the incremental cost impact of each potential technological package proposed to attend PL8 when compared to standard solutions found for current PL6. The cost analysis comprises both variable costs, related to the hardware update itself, and indirect costs, which in this paper encompass vehicle calibration development, tooling and certification.

All proposed technological packages for PL8 have some common components, like UEGO and HEGO with TSP, Fuel Heating System 2nd Generation (only for PFI) and evaporative system encompassing updated canister and purge valve, as well new components/layout for ORVR system. The main differences between them lies on the engine technology, PFI or TGDI, and on the TWC, whose cost is mainly associated with PGM loading. Such loading is composed by commodities sold in the international market that are becoming scarce, in contrast with even higher demand from automotive industry to attend more stringent emissions. In this paper PGM was marketed for Pd at 80 USD/g and Rh at 320 USD/g. Both values tend to their historical maximum and reflect the pressure on finding alternative solutions for decreasing PGM dependency on after-treatment systems.

An incremental cost ranging from USD296 to USD496 is identified for the technological package encompassing PFI flex fuel 1.0L with TWC EHC. In absolute value this is the most cost driven pathway for attending PL8 (Figure 16) once it has the lowest cost for the engine, while mitigating the cost increase for the after-treatment system. According to automaker's strategy TGDI engines must also be considered for A- and B- segment vehicles. Despite the base cost difference to PFI engines, in this paper considered as USD750, technological package with similar incremental cost was identified to TGDI flex fuel 1.0L engines ranging from USD236 to USD436.

It is important to mention that this work focused only on the emissions perspective. There are other important players, such as ROTA 2030 energy efficiency program, that will impact on the selected technological package and consequently on the cost. Therefore, conclusions may differ. Common point is that technologies will be introduced to reduce both engine-out and tailpipe emissions, thus decreasing the need of the very expensive and scarce PGM for the after-treatment systems.

REFERENCES

[1] Automotive World (2020). Research: Brazil's new vehicle market: prospects to 2024 and beyond.

[2] Automotive Business. (17th of August of 2020). O caminho do downsizing no Brasil. Source: https://www.automotivebusiness.com.br/artigo/1814/o-caminho-do-downsizing-no-brasil

[3] IHS Markit (2019). IHS Markit VPaC – Vehicle Performance and Compliance – September 2019.

[4] Posada, F., Bandivadekar, A., German, J. (2012). Estimated Cost of Emission Reduction Technologies for Light-Duty Vehicles. Washington DC: ICCT.

[5] CETESB (2018). Análise da proposta de Resolução CONAMA para as novas fases de controle de veículos leves do Proconve (L7 e L8) aprovada em reunião Plenária do CONAMA em 28 de novembro de 2018. São Paulo: CETESB.

[6] MMA/CONAMA. (20th of December of 2018). Resolução Nº 492, de 20 de Dezembro de 2018. Diário Oficial da União, p. 141.

[7] MMA/IBAMA (24th of September of 2020). Instrução Normativa nº 22, de 24 de Setembro de 2020. Diário Oficial da União.

[8] MMA/IBAMA (24th of September of 2020). Instrução Normativa nº 23, de 24 de Setembro de 2020. Diário Oficial da União.

[9] Rosenblatt, D., Karman, D. (2020). Annex 54-1: A Report from the Advanced Motor Fuels Technology Collaboration Programme - GDI Engines and Alcohol Fuels. AMF

[10] Winklhofer, E. (2014) Modern Spark Ignition Engines: Why Ethanol can become the Better Fuel and How This is Accomplished

[11] Min, K., Cheng, W., & Heywood, J. (1994). The Effects of Crevices on the Engine-Out Hydrocarbon Emissions in SI Engines. SAE Transactions, 103, 371-385.

[12] Vianna, J. N. de S. et al (2005). Reduction of pollutants emissions on SI engines: accomplishments with efficiency increase. J. Braz. Soc. Mech. Sci. & Eng. [online]. Vol.27, n.3, pp.217-222.

[13] Singer, B.C. et al (1999). A fuel-based approach to estimating motor vehicle cold-start emissions, J. Air Waste Manag. Assoc. 49

[14] Yusuf, A.A., Inambao, F.L. (2019). Effect of cold start emissions from gasoline-fueled engines of light-duty vehicles at low and high ambient temperatures: Recent trends, Case Studies in Thermal Engineering,Volume 14.

[15] Martini, G. et al (2012). Review of the European Test Procedure for Evaporative Emissions: Main Issues and Proposed Solutions. Luxembourg: JRC.

[16] Nigro, F. (2011). O Etanol como Combustível: Características e Oportunidades. São Paulo: USP.

[17] Oliveira A.V.S. et al (2016). Fenômenos de termodinâmica e transferência de calor em sistemas de aquecimento de combustível para partida a frio de motores de combustão interna, XXIV Simpósio Internacional de Engenharia Automotiva, Blucher Engineering Proceedings, Volume 3, 2016, Pages 189-201

[18] Sales L.C.M, Sodré J.R. (2012). Cold start emissions of an ethanol-fuelled engine with heated intake air and fuel, Fuel Volume 95, 2012, Pages 122-125.

[19] Bosch. (20th of November of 2020). FlexStart. Source: Bosch Web Site: https://www.bosch-mobility-solutions.com.br/br/destaques/sistemas-de-transmiss%C3%A3o-e-mobilidade-el%C3%A9trica/flexstart/

[20] O Mecânico. (20th of November of 2020). Injetores aquecidos auxiliam a reduzir emissões. Source: https://omecanico.com.br/injetores-aquecidos-auxiliam-a-reduzir-emissoes/

[21] Brady R. (1988). Automotive Electronics and Digital Instrumentation, New Jersey: Printice Hall, Inc.

[22] ETAS. (2011). Lambda Training. ETAS.

[23] Bardi, U., Caporali, S. (2014). Precious Metals in Automotive Technology: An Unsolvable Depletion Problem?. Minerals. 4. 388-398.

[24] Nanotechnology Products Database (27th of November of 2020). Pt/Rh-only three-way catalysts. Source: https://product.statnano.com/product/7867/ptrh-only-three-way-catalysts

[25] Lassi, U. (2003). Deactivation Correlations of Pd/Rh Three Way Catalysts Designed for Euro IV Emission Limits. Dissertation - University of Oulu, Linnanmaa.

[26] Umicore. (23rd of April of 2020). Three-way catalyst (TWC). Source: Umicore Web Site: https://ac.umicore.com/en/technologies/three-way-catalyst/

[27] EMITEC (2011). Heated catalysts, the solution to future emission problems. 64th IAA September 2011.

[28] Posada, F. (2014). Costo de la Tecnología para el Control de Emisiones en Vehículos Ligeros y OBD. Washington DC: ICCT.

[29] Johnson Matthey (10th of July of 2020). PGM Prices. Source: http://www.platinum.matthey.com/

[30] Market Watch (7th of June of 2020). Why palladium prices keep hitting new highs and rhodium has already rallied by over 40% this year. Source: https://www.marketwatch.com/story/why-palladium-prices-keep-hitting-new-highs-and-rhodium-has-already-rallied-by-30-this-year-2020-01-17

[31] EPA (1999). Control of Air Pollution from New Motor Vehicles: Tier 2 Motor Vehicle Emissions Standards and Gasoline Sulfur Control Requirements (Regulatory Impact Analysis). Washington: US Environmental Protection Agency.

CONFLICTS OF INTEREST

There were no potential conflicts of interest on this research.

CONTACT INFORMATION

Guilherme Neves
AVL South America
Ria Antonio Utrilla, 315
Cidade Industrial Satélite de São Paulo
07230-650 – Guarulhos – SP
Brazil
Guilherme.Neves@avl.com

ACKNOWLEDGMENTS

The author would like to acknowledge the contributions from the powertrain engineering team/AVL South America and key people of the industry to this paper. Helpful and insightful discussions on the potential technological packages and the cost analysis methodology were invaluable for the outcome of this work.

DEFINITIONS/ABBREVIATIONS

A- Segment (Vehicle): Also known as city car or mini compact; smallest category of vehicles

AT: Automatic Transmission

B- Segment (Vehicle): Also known supermini or subcompact; next larger category of vehicle when compared to A- segment vehicle

BRL: Brazilian currency, real

CC: Close-Coupled

CF: Conformity Factor for RDE

CO: Carbon Monoxide

CO_2: Carbon Dioxide

CPSI: Cells Per Square Inch

CV: Catalyst Volume

ECU: Engine Control Unit

EGR: Exhaust Gas Recirculation

EHC: Electrically Heated Catalyst

EPA: Environmental Protection Agency

EU: European Union

Exx: gasoline with xx percent of ethanol in volume

Flex Fuel: technology that allows the engine to run on either gasoline or ethanol, or in any blend in-between

FTP-75: Federal Test Procedure Number 75

GDI: Gasoline Direct Injection

H_2: Hydrogen

H_2O: Water

HC: Hydrocarbons

HCHO: Aldehydes

HEGO: Heated Exhaust Gas Oxygen sensor

ICE: Internal Combustion Engine

Ir: Iridium

LV: Light Vehicle

MT: Manual Transmission

N_2: Nitrogen

NMHC: Non-Methane Hydrocarbons

NMOG: Non-Methane Organic Gases

NOx: Nitrogen Oxides

OSC: Oxygen Storage Capacity

OBD: On-Board Diagnostic

OBD-Br2+: On-Board Diagnostic Brazil Phase 2+

OBD-Br3: On-Board Diagnostic Brazil Phase 3

OH: Hydroxyl Functional Group

ORVR: Onboard Refueling Vapor Recovery

Os: Osmium

Pd: Palladium

PFI: Port Fuel Injection

PGM: Platinum Group Metals

PL8 Level 50: Level is related to emission level; in this case 50 refers to NMOG + NOx = 50 mg / km

PM: Particulate Matter

PROCONVE: Motor Vehicles Air Pollution Control Program in Brazil

PROCONVE L6, PL6: Brazilian Emissions Standard for Light Vehicles Phase 6

PROCONVE L7, PL7: Brazilian Emissions Standard for Light Vehicles Phase 7

PROCONVE L8, PL8: Brazilian Emissions Standard for Light Vehicles Phase 8

Pt: Platinum

RDE: Real Driving Emission

R&D: Research and Development

Rh: Rhodium

RIA: Regulatory Impact Analysis

ROTA 2030: Brazilian automotive program based on fuel efficiency, safety and Research and Development

Ru: Ruthenium

SAI: Secondary Air Injection

SHED: Sealed Housing for Evaporative Determination

SVR: Swept Volume Ratio

TGDI: Turbocharged Gasoline Direct Injection

THC: Total Hydrocarbons

TRL: Technological Readiness Level

TSP: Thermal Shock Protection

TWC: Three-Way Catalyst

UEGO: Universal Exhaust Gas Oxygen sensor

UF: Under-Floor

USA: United States of America

USD: US Dollars

US Tier 3: United States National Vehicle Emissions and Fuel Standards Phase 3

US Tier 3 Bin125: Bin is related to emission level; in this case 125 refers to NMOG + NOx = 125 mg / mi

Vd: Engine Displacement

VVT: Variable Valve Timing