

Challenges and Techniques to Meet PROCONVE L7 Emissions Limits with Low Displacement PFI Flex Fuel Engines

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ABSTRACT

One of the main challenges for OEMs to reduce tailpipe emissions is to meet emissions regulation at minimum costs, keeping the vehicle at affordable price to the final customer. Starting in January 2022, all vehicles sold in Brazil will need to comply with PROCONVE L7 (PL7) emissions regulation. PL7 imposes more stringent emissions limits and new procedures to be followed such as the NMOG (Non-Methane Organic Gases) determination. This paper details the NMOG calculation with ozone formation potential corrections. The PL7 NMOG + NO_x emissions limit is one of the biggest challenges when running tests with EHR fuel (reference hydrous ethanol) mainly due to aldehydes and unburned ethanol generation prior to engine warmup. The majority of NMOG is generated during the cold phase of ABNT NBR 6601 emissions cycle. This paper aims to detail potential actions to reduce NMOG and meet the PL7 emissions limit when running a light passenger vehicle with low displacement PFI (Port Fuel Injection), normally aspirated, three cylinders engine and fueled with EHR fuel. The emissions tests were run at Ford Tatuí Development Center.

INTRODUCTION

In December of 2018, by means of the Resolution nº 492, the Brazilian National Environmental Council (CONAMA) approved PROCONVE L7 and L8 Emissions standards for new Light-Duty Vehicles (LDVs) [1]. Besides the tighter emissions limits, new procedures need to be followed and additional engineering work will be required from OEMs and suppliers. Table 1 shows the main differences between PROCONVE L6 (PL6), emissions regulation in force until December 2021, and the new PL7 regulation for light passenger vehicles, which will be effective starting in January 2022. PL7 requires NMOG + NO_x legal limit instead of separated limits for NMHC (Non-Methane Hydrocarbons) and NO_x (Nitrogen Oxides) [2].

Table 1. Differences between PROCONVE L6 and PROCONVE L7 for passenger vehicles with spark ignition engines.

	PROCONVE L6	PROCONVE L7
NMHC limit	50 mg/km	-
NO_x limit	80 mg/km	-
NMOG⁽¹⁾ + NO_x limit	-	80 mg/km
Ethanol deduction from NMHC	Allowed	Not Allowed
CO limit	1300 mg/km	1000 mg/km
Particulate Mass limit	-	6 mg/km ⁽²⁾
Aldehydes limit	20 mg/km	15 mg/km
Real Driving Emissions	Not Required	Monitor Phase
Emissions Durability	80,000 km	160,000 km
Evaporative Emissions	1h + 1h, 1.5 g/test	1h hot soak + 48h, 0.5 g/test

⁽¹⁾ NMOG calculation is based on MIR (Maximum Incremental Reactivity) weighting factors for hydrocarbons, ethanol and aldehydes.

⁽²⁾ direct injection only.

The increase in difficulty is greater than the simple comparison of NMHC, NO_x and NMOG + NO_x limits may suggest, especially for Flex Fuel vehicles, which can be fueled with gasohol, hydrous ethanol or any blend between them, and comprise 96% of all new licensed passenger vehicles (spark ignition engines) according to ANFAVEA – Brazilian National Association of Motor Vehicle Manufacturers [3]. The new NMOG calculation will consider the ozone formation impact of ethanol and aldehydes, and the emission of that pollutant with ethanol will be much higher when compared to NMHC

measurements in PL6 phase, from which the complete deduction of ethanol was allowed.

Table 2 shows properties differences between A22 (reference gasohol fuel) and EHR fuels.

Table 2. Properties comparison between EHR and A22 fuels.

Property	Hydrous Ethanol (EHR)	Gasohol (A22)
Ethanol Content (% volume)	94.5 min.	21 - 23
Water Content (% mass)	7.5 max.	0
Stoichiometric Air Fuel Ratio	8.4	13 – 13.3
Latent Heat of Evaporation (kJ/kg)	955	510
Net Heat of Combustion (MJ/kg)	24.5	40.1
Flash Point (°C)	13	-43

Because of its physical properties, such as fixed boiling point (78.5 °C), larger latent heat of evaporation and higher flash point [4], [5], ethanol fuel causes combustion stability difficulties during the cold engine operation phase and contributes with a large amount of NMOG emissions. Most of it is generated during the engine startup and warmup, prior to catalyst light off during the ABNT NBR 6601 emissions cycle. Therefore, an additional effort is required to reduce NMOG emissions. It is crucial to identify solutions to improve EHR fuel vaporization and combustion quality prior to engine warmup, avoiding misfires and poor combustion events occurrence [6], [7].

METHODOLOGY

The “Equivalent NMHC” calculation, developed by the Unburned Ethanol Work Group at Brazilian Association of Automotive Engineering (AEA) in 2012-2013, was used as a surrogate for NMOG, as its determination procedure had not been published by IBAMA (Brazilian Institute of Environment and Renewable Natural Resources) by the time this paper was written. “Equivalent NMHC” accounts for the ozone formation potential of ethanol, as well as aldehydes, and eliminates its deduction from NMHC, as allowed by PL6. Equation 1 shows the adopted NMOG calculation, which is essentially the same as the “Equivalent NMHC” calculation developed by the AEA work group. An official Brazilian procedure to calculate NMOG for PL7 is awaiting publication by IBAMA after being developed by another work group at AEA, and through new edition of ABNT NBR 6601 Annex D, but it is not expected to differ significantly from this:

$$NMOG_{EHR} = NONMHC_{EHR} \cdot \frac{MIR_{NONMHC_{EHR}}}{MIR_{NMOG_{A22}}} + ETOH \cdot \frac{MIR_{ETOH}}{MIR_{NMOG_{A22}}} + HCHO \cdot \frac{MIR_{HCHO}}{MIR_{NMOG_{A22}}} + CH_3CHO \cdot \frac{MIR_{CH_3CHO}}{MIR_{NMOG_{A22}}} \quad (1)$$

where:

- $NONMHC_{EHR}$ is the Non-Oxygenated Non-Methane Hydrocarbons weighted emission when

running tests with EHR (in g/km), detailed in equation 2;

- MIR (Maximum Incremental Reactivity) is a measure of the ozone formation potential for a specific compound, estimating the mass of ozone produced from a mass of the compound [8], [9] (see Table 3);
- $MIR_{NONMHC_{EHR}}$ is the NONMHC ozone formation potential for EHR fuel;
- MIR_{ETOH} is the unburned ethanol (ETOH) ozone formation potential;
- MIR_{HCHO} is the formaldehyde (HCHO) ozone formation potential;
- MIR_{CH_3CHO} is the acetaldehyde (CH₃CHO) ozone formation potential;
- $MIR_{NMOG_{A22}}$ is the NMOG ozone formation potential of the hydrocarbons and oxygenates from A22 reference fuel combustion.

Table 3 shows the MIR values (ozone formation potential) used for each compound, obtained from California Air Resources Board (CARB) [10], for single compounds, and from Graner, L. *et al* study [9], for NMOG with A22 and for NONMHC with EHR.

Table 3. Reference ozone formation potential (MIR) values (g O₃/g chemical compound) used in this study [10], [9].

Oxygenated Organic compounds	
Unburned Ethanol (ETOH)	1.53
Formaldehyde (HCHO)	9.46
Acetaldehyde (CH ₃ CHO)	6.54
Non-Oxygenated Non-Methane compounds	
NONMHC _{EHR}	3.16
Non-Methane Organic Gases from A22 reference fuel	
NMOG _{A22}	4.86

The Non-Oxygenated Non-Methane Hydrocarbons with EHR ($NONMHC_{EHR}$) weighted emissions was obtained through equation 2 (in g/km):

$$NONMHC_{EHR} = NMHC_{EHR} - d_{THC} \cdot \left(2 \cdot \frac{ETOH}{d_{ETOH}} \cdot Rf_{ETOH} + \frac{HCHO}{d_{HCHO}} \cdot Rf_{HCHO} + 2 \cdot \frac{CH_3CHO}{d_{CH_3CHO}} \cdot Rf_{CH_3CHO} \right) \quad (2)$$

where:

- $NMHC_{EHR}$ is the Non-Methane Hydrocarbons weighted emission when running tests with EHR in g/km;
- d_{THC} is the total hydrocarbons mass density (576.8 g/m³);

- $ETOH$ is the unburned ethanol weighted emission, determined through gas chromatography in g/km;
- d_{ETOH} is the ethanol mass density (1915.12 g/m³);
- Rf_{ETOH} is the Flame Ionization Detector (FID) response factor for ethanol measurement;
- $HCHO$ is the formaldehyde weighted emission, determined through liquid chromatography in g/km;
- d_{HCHO} is the formaldehyde mass density (1249.2 g/m³);
- Rf_{HCHO} is the Flame Ionization Detector (FID) response factor for formaldehyde measurement;
- CH_3CHO is the acetaldehyde weighted emission, determined through liquid chromatography in g/km;
- d_{CH_3CHO} is the acetaldehyde mass density (1832.9 g/m³);
- Rf_{CH_3CHO} is the Flame Ionization Detector (FID) response factor for acetaldehyde measurement.

ACTIONS FOR NMOG EMISSIONS REDUCTION

In order to reduce NMOG emissions, this paper will detail the following opportunities when running EHR fuel:

- Fuel heating combined with open loop fueling calibration optimization (crank and post-crank fueling);
- Injection phase calibration optimization during engine startup;
- Strategies for emissions reduction during cold idle.

FUEL HEATING + OPEN LOOP FUELING CALIBRATION – Initial emissions tests in low displacement port fuel injection engine showed that NMOG results are influenced by open loop fuel (crank and post-crank fueling). The higher the fuel mass, the higher the NMOG emissions.

When compared to A22 fuel, a larger amount of EHR needs to be injected to start the engine. Besides the EHR stoichiometric Air Fuel Ratio (AFR) of 8.4, this is needed because a significant portion of the startup fuel does not vaporize and bypasses the combustion process without burning. The unburned fuel can follow two paths: leak down into crankcase or discharge from the cylinder during the exhaust cycle [11].

Applying an auxiliary cold start system, the startup and warmup injected fuel can be heated above the flash point to get a better vaporization and consequently better combustion quality. There are two main fuel heating technologies currently available: heaters in the fuel rail and heated injectors [12], [13], [14]. The test vehicle was equipped with the first type of technology.

Combining the auxiliary cold start system with ECU calibration, the injected open loop fuel can be adjusted to

deliver a closer to stoichiometric AFR without jeopardizing startup time and drivability, considering that only the vaporized fuel burns in the combustion chamber. Excessively lean actual mixtures of air/vaporized fuel can cause poor idle control, longer crank times and engine stalls, which are not acceptable. The heated fuel provides a richer mixture for the same mass of injected fuel due to the higher fraction of vaporized fuel.

In case of using heaters in the fuel rail, there is a difficulty to heat the fuel inside the injectors and injector cups. It is important to optimize the fuel rail design to minimize the unheated fuel volume and, through calibration, purge this cold fuel as fast as possible to allow the heated fuel to be injected into the combustion chamber during the engine startup process.

Another important aspect related to cold start auxiliary system is the pre-heating time, which is the period from starting fuel heating until fuel target temperature is achieved, when engine crank is enabled. To avoid engine startup complaints, it is important to identify the best tradeoff between fuel target temperature and pre-heating time.

INJECTION PHASE DURING ENGINE STARTUP –

The quality of fuel preparation in port fuel injection engines is known to have a significant impact on engine behavior [15]. There are three main parameters that can impact fuel preparation: fuel targeting, injection phase and injected fuel droplet size. The injection phase calibration optimization can be used to improve startup time and emissions without engine hardware changes. There are two injection phase strategies for PFI engines:

- Closed Valve Injection (CVI): fuel is injected when the intake valve is closed. It is the most traditional method with low backfire risk;
- Open Valve Injection (OVI): fuel is injected when the intake valve is open.

Experimental tests with EHR fuel were done with CVI, OVI and a combination of OVI + CVI. Table 4 shows the engine startup time impact and Hydrocarbons (HCs) emission level for each kind of strategy. The same fuel mass was considered for each tested strategy.

Table 4. Injection phase strategies and impacts on engine startup time and emissions when running EHR fuel.

	Engine Startup Time	Hydrocarbons Emissions Level
OVI*	Faster	Higher
CVI	Longer	Lower
OVI + CVI**	Faster	Lower

*OVI is applied until the end of the first cold idle;

**OVI is applied during crank then CVI takes place forward.

The OVI strategy presented higher HCs emission and more difficult AFR control during the post-start phase, which can be explained by:

1. Increased in-cylinder liquid fuel with open valve injection, which does not have the aid of valve and port heating for vaporization [15];
2. Part of injected fuel going directly to the exhaust during the valves overlap;
3. Part of injected fuel directly impinging on the cylinder's walls. The oil on the walls is known to be capable of adsorbing HCs and essentially shields them from burning during the combustion process. The oil desorbs part of HCs during the exhaust stroke. Another portion of the fuel hitting the walls leaks down to the crankcase and this is the reason why OVI strategy, besides increasing emissions, causes high oil dilution.

While OVI delivered faster startup times, the CVI delivered lower HCs emission. The combined strategy OVI + CVI was the best one. Figure 1 shows an example of engine startup with the combined strategy.

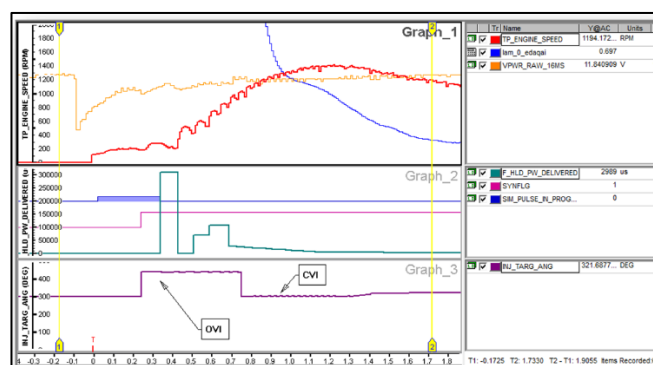


Figure 1. Combined injection phase strategy for faster engine startup and lower emissions.

STRATEGIES FOR EMISSIONS REDUCTION DURING COLD IDLE – An exhaust gases conversion rate of 95% is not achieved while the catalyst is not hot enough. For the system under study in this paper, the catalyst needed midbrick temperatures over 370 °C for a high conversion rate. Catalyst light off takes longer when running small displacement engines due to lower gas flow at idle after engine startup. Increasing idle speed can provide increased gas flow to achieve faster catalyst light off, but it may also increase the total mass of HCs emissions, so a careful analysis is required for best tradeoff.

Besides the catalyst light off itself, it is also essential to minimize Hydrocarbons feedgas (HC_FG which means the HCs emission prior to catalyst conversion) during cold idle. With this objective, the following parameters were studied in engine dynamometer in a Design of Experiments (DoE) study: engine speed (identified as “Eng Spd” in Figure 2), spark plug electrode type (“Spk Plug”), injection phase strategy (“OVI”), exhaust camshaft positioning (“VCT Exh”) and fuel rail pressure (“Fuel Press”). The engine coolant and oil temperatures were kept at 20 °C during the evaluations. All the parameters had influence in HC_FG, however the injection phase strategy and exhaust camshaft

positioning presented higher importance for HCs emission. Figure 2 shows the statistical significance of each parameter in the DoE model.

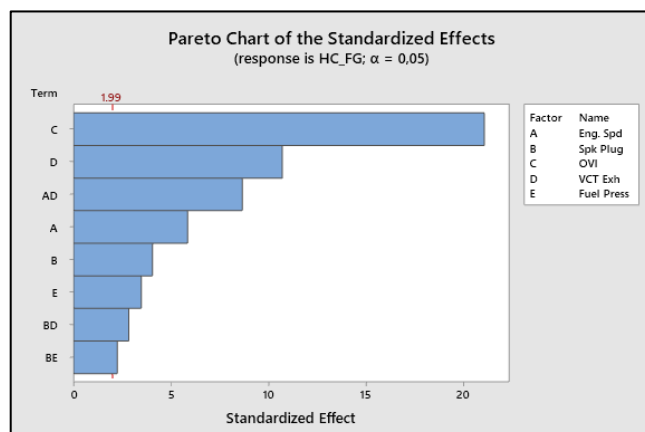


Figure 2. Parameters effect on HCs emission.

Figure 3 shows engine speed and exhaust camshaft positioning influence in HCs feedgas emission. Engine speed of 1070 rpm presented lower HCs emission when running exhaust camshaft position with valve opening at 0 degrees before top dead center (BTDC). Both 1070 rpm and 1250 rpm had statistically similar HC emission levels for 0 degrees BTDC exhaust camshaft positioning.

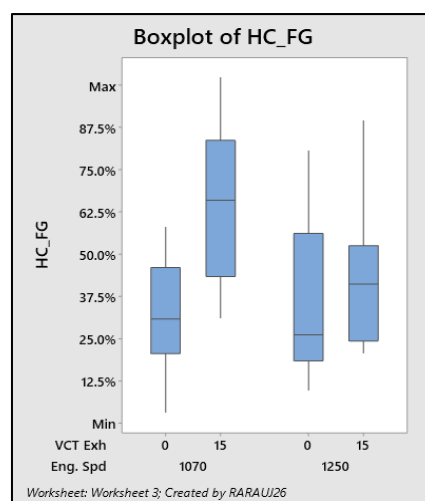


Figure 3. HCs feedgas (HC_FG) emission statistical analysis for engine speed and exhaust camshaft positioning parameters.

Figure 4 shows the effect of spark plug electrode type, injection phase strategy and fuel rail pressure to HCs emission. Iridium spark plug, CVI (OVI off) and 3.8 bar fuel rail pressure presented the best results for HCs feedgas emission during cold idle.

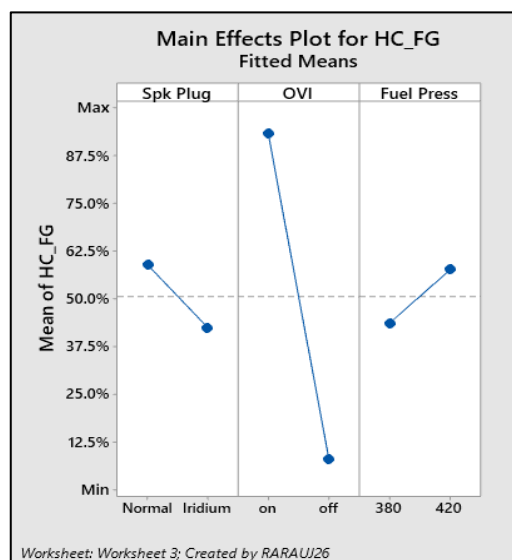


Figure 4. HCs feedgas emission statistical analysis for spark plug electrode type, injection phase strategy and fuel rail pressure.

Table 5 shows the compiled results for cold idle HC_FG reduction when running EHR fuel.

Table 5. Tests and best setup for feedgas HCs emission during cold idle with EHR fuel.

	Range under study	Best HC_FG Emission
Idle speed sweep [rpm]	1070 to 1250	both were statistically similar with 0 deg Exhaust Camshaft position
Spark plug electrode material	Nickel / Iridium	Iridium
Fuel rail pressure [bar]	3.8 / 4.2	3.8
Injection phase strategy	OVI / CVI	CVI
Exhaust camshaft positioning [degrees BTDC]	0 / 15	0 (lowest overlap)

EXPERIMENTAL SETUP

The following facilities and resources were used:

- Chassis dynamometer with Horiba gas analyzers;
- Chemical laboratory:
 - Agilent 7890B GC (Gas Chromatograph) for unburned ethanol determination;
 - Agilent 1200 Series HPLC (High Performance Liquid Chromatograph) for aldehydes determination.
- Engine dynamometer test bench with AVL AMA I60 S2 gas analyzers;
- Flex fuel vehicle with: auxiliary cold start system (heaters in the rail), 160,000 km catalyst, non-linear oxygen sensor, nickel spark plug electrode type,

port fuel injection, normally aspirated and small displacement engine.

A total of eight ABNT NBR 6601 emissions tests with EHR fuel were raised for analysis. A same vehicle ran three tests without any emissions reduction actions and other two tests with a set of proposed changes. In order to increase the sample size and verify robustness for vehicle-to-vehicle variation, each of the configurations was tested in one additional vehicle each, adding two tests results to the baseline and one test to the proposed set. Unfortunately, it was not possible to keep the same second sample for both configurations, therefore the graphs will be based on the common vehicle. However, the additional results confirmed all the conclusions and the numbers related to all the tests will be shown in parenthesis following the corresponding data from the common vehicle.

The configuration with proposed actions focused on PL7 emission targets comprised the following changes:

- Fuel rail design change with cold fuel volume reduction of 62% to allow heated fuel to reach the cylinders faster during crank;
- Pre-heating of the fuel was adjusted;
- Heating of the fuel was extended and ramped down until the end of engine warmup phase;
- Crank and post-crank injected fuel amount was reduced to deliver a closer to stoichiometric AFR;
- Target cold idle speed was calibrated to 1130 rpm because it was already a mapped point in the ECU calibration and the HCs feedgas emissions did not show significant difference in the range of 1070 to 1250 rpm;
- Exhaust camshaft positioning during cold idle was set to 0 degrees BTDC (lowest possible overlap with best combustion stability);
- Combined injection phase strategy OVI + CVI was calibrated: OVI is applied during crank then CVI takes place forward.

These proposed actions for tailpipe emissions, mainly for NMOG reduction, met the PL7 emissions targets. The average results are shown on next section.

In addition to the cold phase actions above, the closed loop AFR control was optimized to improve the catalytic conversion with warmed-up engine and catalyst.

It is important to highlight that improvements shown in this paper are applicable for the experimental engine under study and the results may be different for another engine hardware.

RESULTS

In order to avoid disclosing absolute values, for confidentiality reasons, all results in this paper will be shown as a percentage of a reference value. The reference value is described in Figure titles.

Figure 5 shows the average emissions for final NO_x and NMOG results. Both pollutants were reduced when the proposed actions were applied, particularly NMOG due to better EHR fuel vaporization and AFR control during engine startup and post-startup. NMOG was reduced by 18% (17% considering additional vehicles) and NO_x was reduced by 36% (33%), the latter being explained by closed loop fuel calibration optimization and cold steady state feedgas improvements.

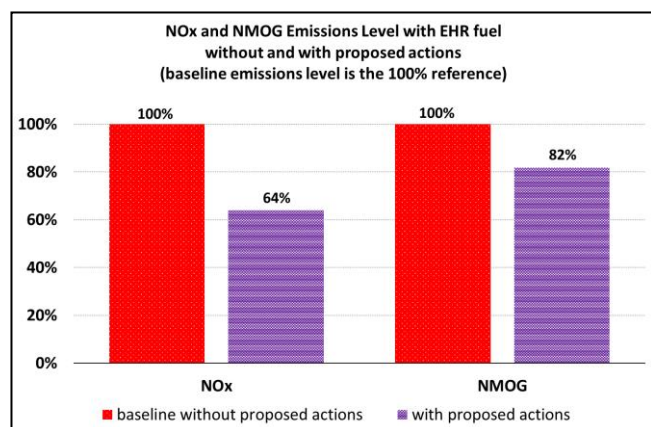


Figure 5. Effect of proposed actions on NO_x and NMOG emissions level.

Figure 6 shows the contribution of the NMOG emissions constituents to the final result, with 100% being the total weighted NMOG emissions of the baseline configuration without the proposed improvement actions. It is possible to see that, in the baseline, a little more than half of the final result, 52% (52%) was from ethanol emission, and a little less than one third, 30% (30%) came from non-oxygenated hydrocarbons. Acetaldehydes accounted for 15% (15%), and formaldehydes were only 3% (3%) of the final NMOG.

After applying the improvement actions, contributions of NONMHC and ethanol were significantly reduced relative to the baseline total NMOG value, while the changes in acetaldehyde and formaldehyde contributions were negligible. NONMHC was reduced by 43% (47%), representing a reduction of 13 percentage points (p.p.) in the final NMOG result (14 p.p.). Ethanol was reduced by 12% (10%), resulting in a reduction of 5 p.p. in NMOG (6 p.p.). Acetaldehyde, in absolute value, was reduced by 6% (9%), but due to its low emission, represented only 1 p.p. reduction in NMOG (also 1 p.p. considering additional vehicles). Formaldehyde increased 65% in absolute value (39%), and despite its high MIR, due to its extremely low absolute emission compared to the other constituents, contributed with only 1 p.p. increase in NMOG (2 p.p.).

The different variation levels in each compound type changed the contribution of each one to the final reduced NMOG result. NONMHC, the most reduced constituent, represented only 21% (19%) of the final NMOG, from 30% (30%) in the baseline. Ethanol, although considerably reduced in absolute value, was less reduced than NONMHC

and thus accounted for a higher share of the reduced result, with 56% (58%) compared to the 52% (52%) of the baseline. With almost no change in absolute value, acetaldehyde had a slightly higher participation in a final lower value, with 17% (17%) of the final NMOG, versus 15% (15%) in the baseline. Finally, with an increased absolute value, formaldehyde accounted for a higher share of 6% (6%), while it originally was only 3% (3%) of the baseline NMOG emission.

The lower ethanol and NONMHC levels, which are the most significant contributors of final NMOG result, can be attributed to lower injected amount of fuel and better combustion stability when the proposed actions were applied. The greater reduction in NONMHC than in ethanol suggests that, more than reducing the amount of lost fuel (which would bypass the combustion and leave the exhaust as unburned ethanol), the adopted measures improved the combustion quality, resulting in less partially burnt hydrocarbons in the exhaust gas, or in compounds that were easier to convert in the catalyst.

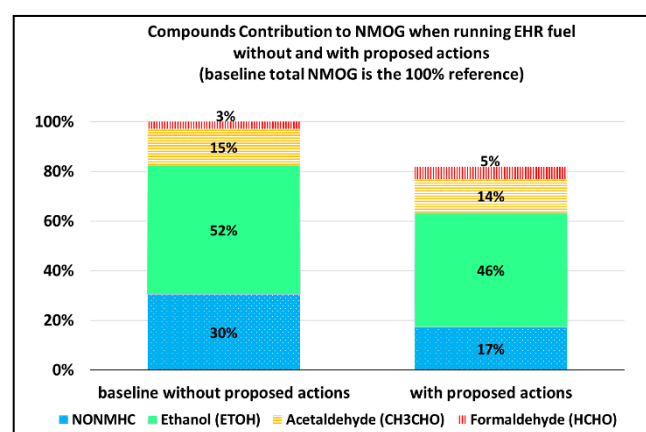


Figure 6. Effect of proposed actions on NMOG compounds.

Figure 7 shows the impact of the proposed actions on phase by phase NMOG emissions in ABNT NBR 6601 test cycle. Most of NMOG came from 1st phase (cold phase), which presented a reduction of 19% (20%), yielding an improvement of 18 p.p. in the final NMOG result (19 p.p.). Both phase 2 and phase 3 presented negligible influence on final NMOG results with very similar values regardless of the proposed actions. This result is expected since the actions were focused on emissions improvements during engine startup and warmup.

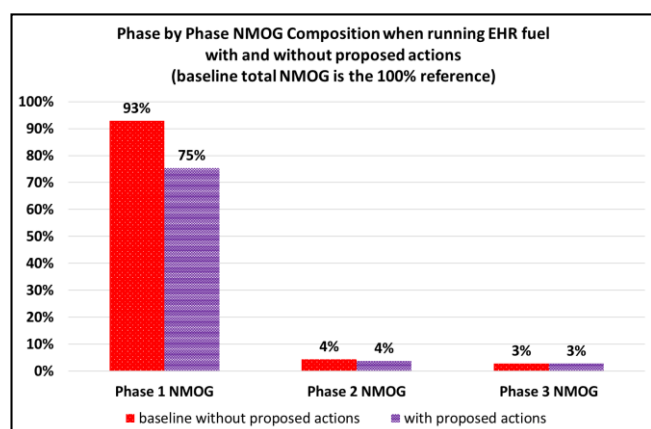


Figure 7. Effect of proposed actions on phase by phase NMOG in ABNT NBR 6601 cycle.

Figures 8 to 11 depict further breakdowns of the phase by phase NMOG emissions into its different constituents. Figure 8 shows the contribution of each compound in each phase relative to the total NMOG baseline emission without the proposed actions. Figures 9, 10 and 11 show the share of each compound in the NMOG emission of each phase. In those figures, the outer ring is the breakdown of the baseline NMOG emission, and the inner ring is the breakdown of the improved NMOG emission.

Phase 1 NMOG compositions for both baseline and improved conditions showed a quite similar pattern compared to the overall test results. This is expected, as this phase represents the great majority of the NMOG weighted result. In the baseline, ethanol from the first phase alone represented 52% (52%) of the final NMOG emission. Of the NMOG emission in that phase, ethanol had a share of 56% (55%). NONMHC, acetaldehyde and formaldehyde emissions in the first phase were respectively 24% (25%), 14% (15%) and 2% (3%) of the final NMOG value. From the first phase NMOG emission, they represented 26% (26%), 15% (16%) and 3% (3%) respectively. Those shares were quite similar to the ones analyzed in Figure 6 for the total weighted result of each constituent. The same similarity between the first phase and overall result occurred with the improvement actions. Ethanol, NONMHC, acetaldehyde and formaldehyde in the first phase represented, respectively, 46% (47%), 14% (12%), 13% (13%) and 3% (3%) of the baseline total NMOG emission, or 56% (58%), 17% (15%), 16% (17%) and 3% (4%) of the improved NMOG weighted emission. Relative to the first phase NMOG, ethanol contributed with an even higher share of 61% (62%), while the contributions of NONMHC, acetaldehydes and formaldehydes were respectively 18% (16%), 17% (18%) and 4% (4%) of the first phase NMOG.

However, the second and third phases showed very different compositions. Ethanol went from largest contributor in the first phase to no contribution at all in the two phases that started with fully warmed-up engine. All second and third phases of all tests, before and after the changes, presented non-detectable emission of ethanol. On the other hand, NONMHC went from small shares in the first

phase to 88% (77%) of the second phase NMOG and 81% (73%) of the third phase NMOG in the baseline, or 62% (74%) of the second phase and 64% (65%) of the third phase in the improved configuration. Nevertheless, due to the low absolute values, NONMHC in the second and third phases represented only 4% (3%) and 2% (2%), respectively, of the weighted NMOG in the baseline. In the improved condition, NONMHC in each of those phases represented 2% (2%) of the total baseline NMOG. Acetaldehyde and formaldehyde had non-negligible shares in each of the phases, but the contribution of their second and third phase emissions to the final NMOG results were close to zero.

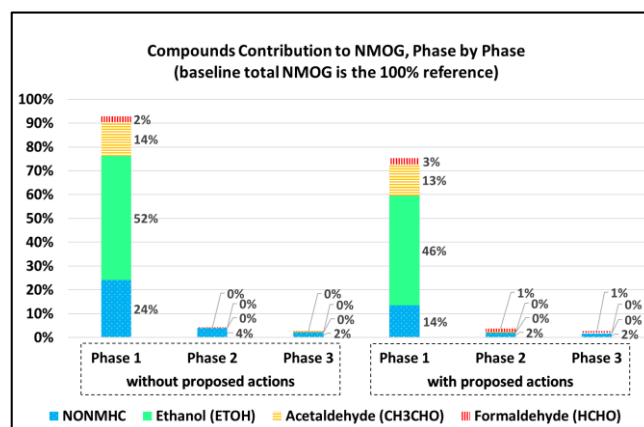


Figure 8. Breakdown of NMOG constituents, phase by phase.

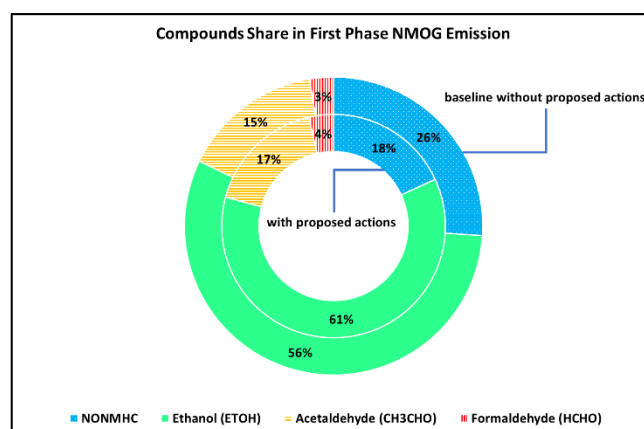


Figure 9. Share of each compound in first phase NMOG emission.

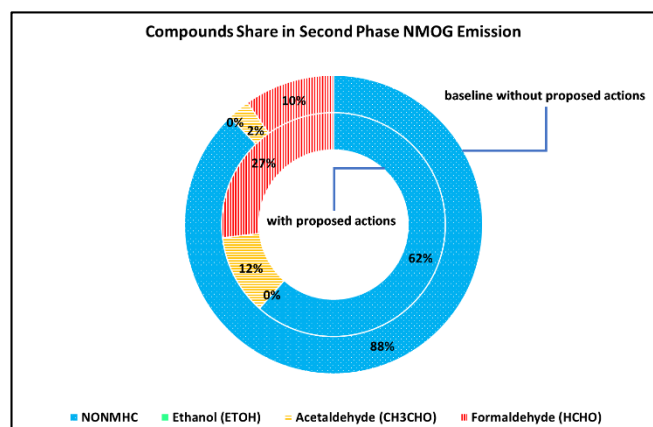


Figure 10. Share of each compound in second phase NMOG emission.

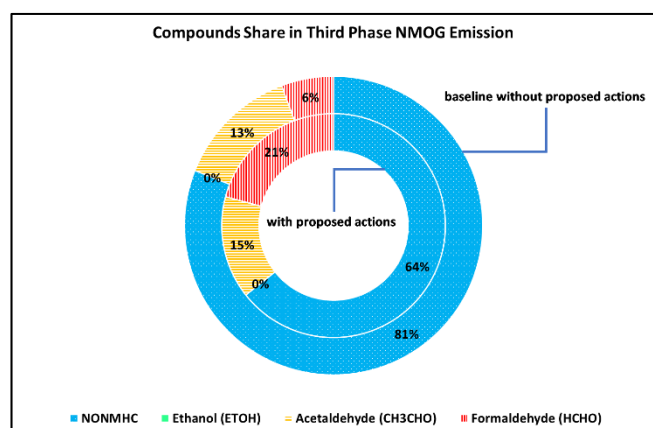


Figure 11. Share of each compound in third phase NMOG emission.

SUMMARY / CONCLUSIONS

This paper detailed the challenges and opportunities to meet PL7 limits with a flex fuel PFI engine, considering NMOG calculation. In order to achieve low NMOG emissions, it is crucial to assure a satisfactory EHR fuel vaporization, closer to stoichiometric AFR control and good combustion events during the cold phase of ABNT NBR 6601 cycle. An auxiliary fuel heating system with optimized rail design, combined with ECU calibration actions such as reduction in crank and post-crank fuel injection, optimization of exhaust camshaft timing and open valve injection during crank, can be implemented to successfully reduce NMOG emissions and meet PL7 emissions limits.

In the experimental tests described in this paper, a significant reduction of 18% in NMOG was obtained in the emissions of a vehicle with EHR fuel with those actions. NO_x was also reduced by 36% with the combined action of closed loop fuel control optimization. From the baseline emissions, of the NMOG constituents, NONMHC was reduced by 43%, Ethanol by 12%, Acetaldehyde by 6%, and Formaldehyde increased 65%. Their contributions to the final reduction of 18% were -13 percentage points (p.p.), -5 p.p., -1 p.p. and +1 p.p. respectively. Virtually all the improvement was obtained in the first phase of the NBR

6601 cycle, as the focus of the actions were on cold engine operation. Changes in second and third phases NMOG emissions were negligible.

For further investigations, the synchronization time can be influenced by engine stop position, which could be optimized for better repeatability in crank fuel injection mass. Another opportunity could be related to fuel rail pressure and spark plug electrode optimization for better combustion quality during engine startup. Both studies showed promising results, which could be verified for the future PROCONVE L8 phase.

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ACKNOWLEDGEMENTS

The authors gratefully acknowledge Ford Motor Company Brazil, which provided all resources and support for the accomplishment of this work at Tatuí Development Center. Also, acknowledgements to José Roberto Moreno Junior and Samantha Nataly Hermógenes e Silva, Powertrain Calibration Engineers who participated on this project development and raised most of data presented in this paper during the period of work for Ford.

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DEFINITIONS / ABBREVIATIONS

A11H50	Reference fuel with 50% A22 and 50% EHR in volume
A22	Brazilian reference gasohol fuel with 78% gasoline and 22% anhydrous ethanol
ABNT	Brazilian Association of Technical Standards
AEA	Brazilian Association of Automotive Engineering
AFR	Air Fuel Ratio
CH₃CHO	Acetaldehyde
CO	Carbon monoxide
CO₂	Carbon dioxide
CVI	Closed Valve Injection
DoE	Design of Experiments
ECU	Engine Control Unit
EHR	Brazilian reference hydrous ethanol fuel
ETOH	Unburned ethanol
Feedgas	Emission prior to catalyst conversion
FID	Flame Ionization Detector
Flash point	Lowest temperature at which vapors above a volatile combustible substance ignite in air when exposed to flame
Flex fuel	Able to be fueled with gasohol, hydrous ethanol or any mixture between both
FTP	Federal Test Procedure

Gasohol	Gasoline with 18 – 27% anhydrous ethanol	NOx	Nitrogen Oxides
		OEMs	Original Equipment Manufacturers
HC_FG	Hydrocarbons feedgas	OVI	Opened Valve Injection
HCS	Hydrocarbons	PFI	Port Fuel Injection
HCHO	Formaldehyde	PL6	PROCONVE L6
Lambda	Actual AFR to stoichiometry ratio	PL7	PROCONVE L7
MIR	Maximum Incremental Reactivity (ozone formation potential)	VCT	Variable Camshaft Timing
ABNT NBR 6601	Emissions test procedure based on United States Federal Test Procedure FTP-75	TDC	Tatuí Development Center
		THC	Total Hydrocarbons
NMHC	Non-Methane Hydrocarbons		
NMOG	Non-Methane Organic Gases		
NONMHC	Non-Oxygenated Non-Methane Hydrocarbons		