Multiple Injection Strategy for Ethanol Port Fuel Injection Engine

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ABSTRACT

Renewable fuels, such as ethanol, are a fundamental lever for decarbonization in the mobility sector, mainly because they act directly on the circulating fleet. On the other hand, local emissions of pollutants are still an important barrier for the long life of internal combustion engines (ICE). The development of powertrain systems needs to overcome this challenge, even more when countries and regions are adopting Real Drive Emission (RDE) targets. In Brazil the PROCONVE L8 legislation, starting in 2025 with biannual updates, has very stringent targets, especially for cold conditions under RDE. As the PFI engine shows a relevant share in entry-level vehicles in the coming years, new technologies are mandatory to support the future relevance of the PFI engine, mainly with ethanol. This paper presents the evaluation of a new feature for the Engine Control Unit (ECU) that fits in this scenario: the Multi-Injection Strategy (MIS). This feature focuses on splitting fuel injection within the same engine cycle. Through the distribution of fuel mass in multiple parts, the injection can be optimized. It makes possible to reduce emissions and the oil dilution at the same time. This novelty was integrated into a PFI Flex Fuel software for the first time during this study.

INTRODUCTION

The mobility is demanding new technologies and energy sources towards the decarbonization and reduction of pollutant gases. Electrification and hydrogen are pointed in prognosis to be the future solutions, but the internal combustion engines (ICE) will remain playing an important role [1]. To better guarantee the future of ICE the usage of a renewable fuel is the key, mainly when we analyze the well-to-wheel basis, it can be as clean as the new technologies [2]. In Brazil, the ethanol is the main biofuel, extensively used for many years, which brought a lot of savings in CO_2 emissions [3], being the easier short-term solution for our market for the next years.

Looking ahead for the Brazilian scenario, it foresees a large usage of ICE engines still in 2035 so the usage of ethanol can support the decarbonization path in the meanwhile. However, ethanol increases the emission of some pollutant gases in cold conditions, conflicting with the upcoming stringent Proconve L8 legislation. Therefore, local solutions to overcome this challenge are highly demanded.

Ethanol as a fuel is a highly flammable, knock-resistant with an octane number of at least 104 RON. The fuel consumption with Ethanol (E100) fuel is distinctly higher compared to gasoline. This higher ethanol consumption is mainly caused by the lesser Lower Heating Value (LHV) of the fuel as compared to gasoline. One liter of E100 has an energy density value of about 20.09 MJ/l while Brazilian gasoline has about 28.99 MJ/l, which results in a theoretical increase in consumption of approx. 30% [4].

When the engine is at the ordinary operating temperature, the exhaust emissions of ethanol fuel show lesser HC, NOx, and soot than those of gasoline. The reason for these lower HC emissions is that E100 fuel can evaporate much better and therefore better mixture preparation is achieved. Increasing content of ethanol, the enthalpy of vaporization also increases, which is released during the evaporation of the injected fuel. Thereby, the intake air becomes cooler, which in turn increases the density of the inlet gas. For the same intake manifold pressure, the charge increases with increasing ethanol content (approx. 2-4%). Since ethanol fuel has higher heat absorption behavior, in general it leads to colder combustion chamber and less knocking phenomena compared to gasoline. This results in lower combustion peak of temperature and thus also in lower NOx emissions. The better evaporation behavior of E100 also leads to better evaporation of wall-applied films in the combustion chamber or of piston wettings, which thus results in less soot being emitted. Nonetheless, the HC emissions during cold start, the HC emissions are higher as those for gasoline. The reason for this increased amount is the vapor pressure, which is much lower than for gasoline (ethanol vapor pressure is 15 KPa, while gasoline is 45 to 62 KPa at 20°C) [5]. It leads to very bad vaporization of ethanol in lower start temperatures and the counter measured is to increase the amount of injected fuel. Also, ethanol suddenly starts to evaporate from a temperature of about 78.4°C, since is composed mainly by one chemical compound. This behavior is important mainly in case of several cold starts in a row when the engine oil sump is significantly contaminated by the fuel. When this temperature is crossed, ethanol suddenly evaporates, flowing through the crankcase ventilation and strongly influencing the combustion chamber mixture.

Analyzing the emission characteristics of ethanol in cold start it is noticeable the bad vaporization of the fuel which leads to wall wetting, poor fuel mixture in cylinder and unburned ethanol, producing largely number of hydrocarbons [6]. A technology largely used in ICE is splitting the injection in the same cycle, but it was so far applicable only for direct injection engines. Now with evolution of hardware and software it can also be used in port fuel injection systems. This paper has the intention of study this new functionality and assess the benefits it can bring for ethanol vehicles.

MIXTURE PREPARATION - Spark-ignition engines operate by burning a premixed mixture of fuel vapor and air. The task of the engine air intake and fuel systems are to prepare such a mixture inside the cylinder from ambient air, and fuel in the tank, that satisfies the requirements of the engine over its entire operating regime. In principle, the optimum fuel-air mixture ratio for a spark-ignition engine is that which gives the required power output with the lowest fuel consumption, consistent with smooth and reliable operation. In practice, the constraints of emissions control may dictate a different mixture composition from this ideal and may also require a fraction of the exhaust gases to be recycled (EGR - exhaust gas recirculation) into the intake system. The relative proportions of fuel and air that provide the lowest fuel consumption, smooth reliable operation, and satisfy the emissions requirements, at the required power level, depend on engine speed and load. Mixture requirements and preparation are usually discussed in terms of the air/fuel ratio and percent EGR [7]. For PFI engines, mixture preparation is affected by vaporization and fuel injection angle [8].

WALL WETTING OR WALL FILM EFFECT - The fuel mass injected into the intake manifold does not remain entirely in the air in the form of fuel droplets or fuel vapor, but a certain portion is deposited on the inner manifold walls in form of a wall film. This portion varies according to temperature, engine speed and load. The amount of fuel which accumulates and is bound in the manifold wall film increases considerably as load and injection time increase. When the throttle valve opens further, a certain portion of the injected fuel is needed to contribute to the formation of the wall film. To prevent the fuel-air mixture from being enleaned during the acceleration process, a certain fuel mass needs to be added (acceleration enrichment). While the load is being reduced, the fuel mass bound in the wall film turns available again and is partially added to the air flow, i.e., during any deceleration, the injection time needs to be reduced by a corresponding fuel mass (deceleration enleanment) [9]. For ethanol, due to its high heat of vaporization, during cold start, high amount of injected fuel will form wall film in the inlet and in cylinder [10].

OIL DILUTION - To create or compensate wall film effects or insufficient vaporization properties during cold starts, additional fuel quantities are injected through start, after start and warm-up-factors. Liquid fuel which does not participate in the combustion does partially reach the exhaust system due to accelerator variations. The remaining fuel stays in the combustion chamber and gets into the engine oil through the piston rings [11]. Comparing to gasoline, this additional amount of injected fuel for ethanol is bigger as demonstrated in the below image.

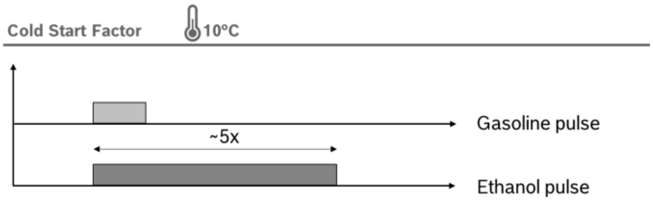

Figure 1. Injector pulse.

FUEL VAPORIZATION – The colder the start worse the ethanol vaporization, so more fuel is necessary to be injected. The difference in vapor formation based on temperature while using ethanol can be seen in the Figure 2. Higher is the amount of fuel large will be the pulse of injection, which enables splitting the injection pulse in some steps without reaching the non-linearity region of the injector. Additionally, PFI engines presents challenges that are not faced in GDI as injection windows [12].

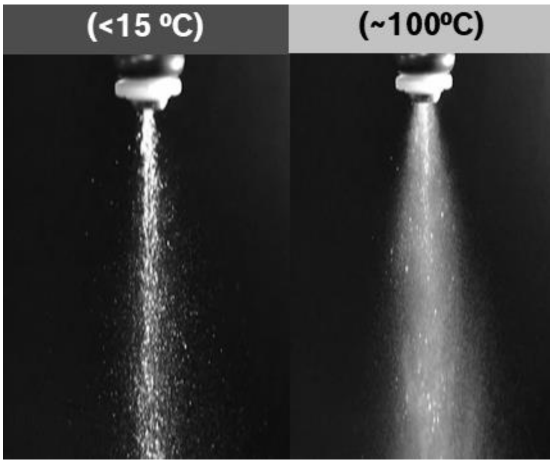

Figure 2. Fuel spray

Based on the theory and on Flex Fuel vehicles experience, this study intends to bring a new feature enhancing PFI engines fueled with ethanol to achieve the emission target and be more efficient. Other important point is the total cost of ownership (TCO): the entry segment vehicle demands cost-optimized solutions, being which, this proposal is aligned to this path as it case is only based on SW. Injection systems allow greater freedom to control the fuel injection process, and thus combustion. The functions of fuel pressure generation and fuel injection are separated by a fuel rail. A low-pressure pump pressurizes and fills the fuel rail, which feeds each of the injectors. The control of this system can readily be integrated with other engine parameters as indicated. Injection pressures from 4bar to 10 bar can be achieved. By repeated activation of the fast-acting solenoid valve within the injector, multiple injection pulses in each injection cycle can be realized. Multiple pulsed injections, represented in Figure 3, can help control emissions, and improves fuel atomization inside the cylinder.

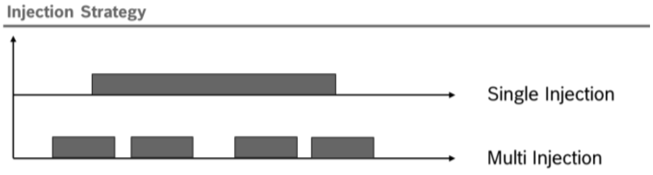

Figure 3. Injection pulse strategy

Fuel-injection technology has advanced to the point where multiple injection pulses are feasible also in PFI engines. Multiple Injection Strategy (MIS) is presented and evaluated in this paper to study the challenges and understand the benefits while using ethanol. For better comprehension, cold start condition was used as test boundaries, because we can have more freedom in the calibration parameters.

METHODOLOGY

A Brazilian market vehicle with a Flex Fuel PFI engine was chosen to perform the tests. A vehicle with 1.6L naturally aspirated engine with 81 kW, being compliant with PL7 legislation and having the new ECU platform from Bosch has been chosen to evaluate the proposed feature of this paper.

To evaluate the proposed technology, an experimental assessment was performed to confirm the theory and find the benefits under the test conditions. To identify, measure, and comprehend the implications of the MIS on a PFI engine, a sequence of tests on vehicle were proposed and divided into four distinct phases with different objectives.

The objective of the first test phase was to validate the integration of the MIS function into the Flex Fuel PFI software. During this test phase, every injection parameter was swept with the aid of an external hardware with a high sampling rate, so injection pulses were measured and compared to the commands sent by the software.

Once the integration was validated, the second phase was focused on identifying a combination of parameters that could enhance engine behavior when compared to a single injection. The MIS function allows variation in the number of injections, injection ratio, pause time, and end of injection. To cover all these parameters, many tests would be required, making the methodology unfeasible. Therefore, to optimize the number of tests, a first set of tests using DoE was conducted to find which function parameters would be the best levers for this study.

In this test phase, the following procedure was proposed. Starting from an initial calibration, the vehicle starts at an oil temperature of 10°C and remain idle until the engine temperature reached 80°C. The process was repeated several times until the best two function parameters were identified. Between each test, data would be evaluated based on start time, start profile, idle stability, and hydrocarbon emissions, and a new enhanced calibration would be proposed.

In the third phase, the two best test parameters obtained in the second phase were utilized, in addition to two other factors, to further enhance the results. Combined with fuel heating the start and post start injection factors were varied and optimized. Based on these new inputs, a new round of testing was conducted using the same procedures as the previous phases.

The evaluation has being carried out targeting the PL8 regulations, and one of the challenges for ethanol engines is to achieve low emissions during cold start in extended RDE conditions. Considering this challenge, the final set of tests were conducted in a FTP75 cycle at a temperature of 10°C, using the best calibration obtained in the previous tests.

RESULTS

Based on described experimental methodology it was possible to evaluate the feature, understanding its possibilities and limitations as well as the benefits in emissions related to this specific engine and test conditions.

As first results, based on the PFI system characteristics, the boundaries conditions for each function parameter have been defined. Since it has a smaller injection window when compared to GDI system, it is necessary to understand the total time, regarding the injections and pause times and compare to the available range. The first discover found was, the pause time between the injections had less impact in results and can lead to injection after valve close during engine admission phase. In this way, the minimum pause time related to the injector was defined. Additionally, it is important to consider the end of injection (EOI) when defining the injection window, because it will define either the pulses won’t be lost, such that they are not too early or not too late in the cycle.

Other evaluated parameter was the fuel mass distribution between the pulses, allowing to choose more fuel with closed valve or opened valve and so enabling a better mixture inside cylinder. This parameter brings a huge possibility in calibration. Nevertheless, based on initial tests, the study starts applying an equal mass between all pulses for first understanding.

At last, the number of injections per cycle. This parameter is considered to have more influence in results and was the focus during the tests. First conclusion was that the limitation due the injection window and the low engine speed during crank allowed the injections to be splitted up to 5 pulses, although after engine start and stabilization in idle condition, the maximum possible number are 3 pulses and during the warmup this number drops to 2. At the end, the best combination found for this study was 5 injections during start and 2 after start, which were used for emission tests. Also, important to point out that this conclusion was for 10°C measurements. New possible split combination might be applied for different engine start temperatures it can have other combinations.

After all those tests and parameters optimization the next step was to perform emission tests to validate the benefits. A baseline with series calibration and a MIS optimized calibration were measured in an INMETRO homologated emission laboratory inside Bosch. Following is presented the results comparison for both conditions.

The figure 4 shows the integrated hydrocarbons result. As can be seen, in the beginning of the cycle, first 100 seconds, there is a faster increase in the baseline curve compared to MIS. After both conditions behaved similarly. As mentioned, the proposed injection strategy operates in this phase where having more fuel being injected. Since it helps to reduce the injected fuel amount, promote better fuel mixture, and reduce wall wetting this HC emission reduction can be explained.

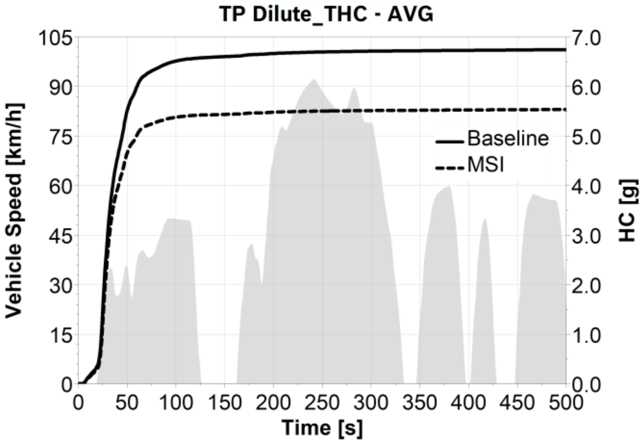

Figure 4. Tail Pipe THC emissions.

The figure 5 shows the integrated NOx result. The same behavior can be notice for this gas, but even in a shorter window of 50 seconds. However, in this case, the reduction is presented only after catalyst converter, it means, the benefit comes from reach faster the light off condition. Anyway, it was possible to correlate it to the lower amount of unburned fuel in the catalyst, what retard the heating process.

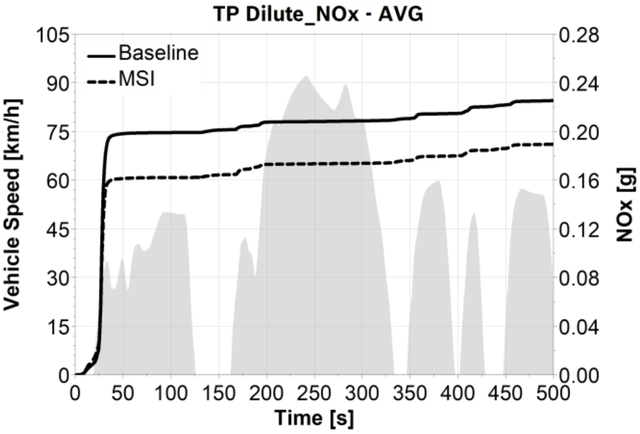

Figure 5. Tail Pipe NOx emissions.

The figure 6 shows the integrated CO result. The small variation of carbon oxide can be neglected. A fine-tuning adjustment of the engine calibration parameters, during dynamic variation of load and speed, can be done specially to adjust the fuel film in combination with multiple injections, with the intention of mitigating any disturbance in the emission of this specific pollutant. A second mechanism that can be used is the transition from multiple to single injection in a dynamic regime.

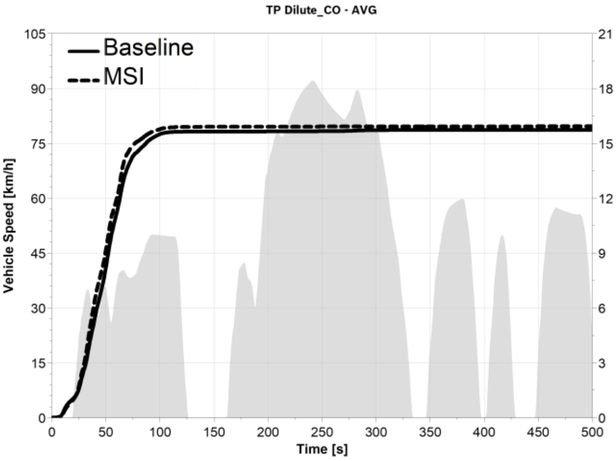

Figure 6. Tail Pipe CO emissions.

CONCLUSION

The upcoming L8 legislation in 2025 with RDE extended conditions of 10°C will bring additional challenges for ICE. Due to ethanol properties as its high heat of vaporization value, it is necessary to inject more fuel to have a suitable startability, which generates more pollutants. New technologies need to be developed to overcome this challenge. This study presents a promising new feature that can support on enabling the emission targets achievement. Through this multi-injection strategy (MIS), it is possible to split the injection in several parts in the same cycle for PFI engines.

The proposed benefit of this strategy is to reduce the wall wetting, to promote better mixture preparation and to reduce the unburned ethanol. In this way it can generate less hydrocarbons during the cold start. To prove this concept several tests were performed in the vehicle to compare the baseline and MIS optimized calibration. The following results are based on a PFI 1.6L vehicle running in a FTP75 cycle at 10°C. As presented in the figures 2 to 4, it shows an emission reduction in HC and NOx, although a minor increase for CO, leading to the conclusion that follows:

As presented in the Figure 7, there was a reduction in HC and NOx, despite of a slight increase for CO.

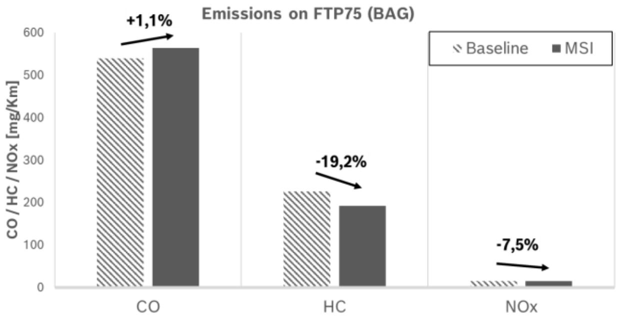

Figure 7. Emission results.

- The highest improvement was in hydrocarbons with a reduction up to 19,2% when compared baseline with series production calibration. The reason is that with the MIS is possible to reduce the amount of injected fuel during the start keeping the same starting quality.

- A considerable decrease in the NOx was also noticed, up to 7,5% comparing both conditions. A reason for this reduction is based on the faster light off in catalyst heating, that could be promoted by the reduction of unburned ethanol in the exhaust gases.

- For CO a slightly increase up to 1,1% was observed. It could be observed a necessity for optimization during dynamic variation of load and speed, mainly where we have the injection mode transition.

The aim of the feature was to bring a solution for NMOG + NOx, the biggest challenge for the next years in Brazil for ethanol. The Figure 8 shows the result of this study, up to 18% can be reduced only through SW optimization.

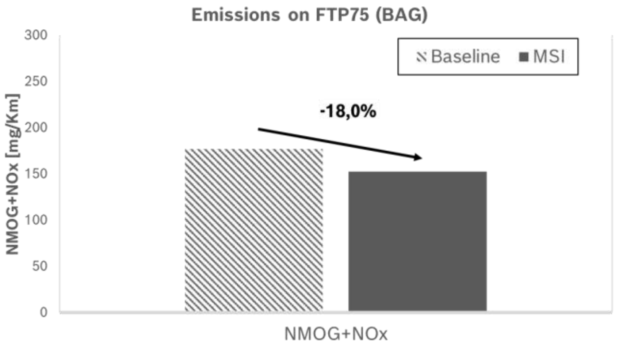

Figure 8. NMOG + NOx emission results.

In summary, the study proposal of integrating, optimizing, and testing the feature was successfully concluded. Regarding the results, for this respective engine and conditions, was found considerable HC and NOx emissions reduction. Therefore, it can be concluded that this feature can support the PFI engines running with ethanol to achieve the Brazilian emission targets in the future.

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