National University of Science and Technology "POLITEHNICA" Bucharest
University Center of Pitesti
Faculty of Mechanics and Technology

SCIENTIFIC BULLETIN
AUTOMOTIVE series
year XXXI, no. 35

FMT 50

On the use of natural gas in a diesel engine retrofitted for spark ignition operation

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Article history
Received 01.05.2025
Accepted 14.06.2025
DOI https://doi.org/10.26825/bup.ar.2025.001

Abstract: The problem of global warming is becoming an increasingly intense concern for all industries. In order to limit the increase in temperature to 1.5°C by 2030, according to the Paris agreement of 2015, humanity should reach zero CO_2. Among the alternative fuels available now, methane gas is considered to be one of the best substitutes for fossil fuels.The main problem in using the methane gas as fuel is missing of an exclusive optimisation of the engines due to compromise in bi-fuel operations.The paper will present the engine prototype, its adaptation on a vehicle, aiming to be tested on the roller bench for emissions, as well as experimental results obtained at the engine test bed showing a comparison with a standard commercial gasoline engine.
Keywords: Natural gas, methane, CO_2 emissions, spark ignition, sustainability

INTRODUCTION

The problem of global warming is becoming an increasingly intense concern for all industries, the important fact being that from the industrial revolution until 2017, the warming due to human activities has reached the value of approximately 1°C[1]. Therefore, in order to limit the increase in temperature to 1.5°C by 2030, it is necessary to reduce greenhouse gas(GHG) as stated the Paris Agreement[2], [3]. EC Directive no. 443/2009 [4] stipulates that, with effect from 2021, passenger vehicles with an inertia class of 1380 kg must meet a value of 95g CO2/km, which corresponds to a fuel consumption of approximately 3.8l/100km [5]. Consequently, the automotive industry invests in the electrification of vehicles, but in the transition to full electrification, alternative fuels may be used to reduce CO_2 emission with respect to the fossil fuels.

Out of the currently available alternative fuels, natural gas (NG) is considered to be one of the best substitute for fossil fuels because, on the one hand, it's fully compatible with conventional spark ignition (SI) engine and, on the other hand, it's eco-friendly due to its clean nature of combustion, [6], [7]. Natural gas is mainly composed of methane (more than 90%), whose favorable ratio of hydrogen to carbon (1:4) help gain lower CO_2 emissions up to 30% compared to gasoline, [8]. As mentioned in [9], [10], NG combustion produces the lowest CO_2 emissions of fossil fuels. Another positive aspect of NG is its wide availability, as pointed out by the CIA World Factbook [11] in its comprehensive country comparison from NG production. In conclusion, NG seems to be a good alternative for SI engines.

Currently, on the market there are only bi-fuels or bi-valent engines, gasoline and NG. However, these engines are not meant to show the full potential of NG for CO_2 reduction because there are important differences between the two fuels the engines are designed to operate with: gasoline has a lower octane number (ON) than NG, which means that the compression ratio (CR) of such engines is chosen so that they can operate knock-free in wide-open throttle (WOT) conditions, i.e., smaller than what could be used in the case of only operating with NG. Consequently, to fully exploit the NG potential for reducing the CO_2 emission, it must be used in a high compression SI engine. Indeed, its octane number (ON) being around 130, it can withstand high CR without the risk of knock occurrence for the sake of the thermal efficiency. Consequently, it is not the usual bi-fuel engine, gasoline and methane, which will show the full potential of NG, but the so-called mono-valent engine, designed and calibrated only for NG, [8].

Considering all the above, the paper will present a high compression SI engine prototype specially developed for NG operation. After the presentation of the engine prototype, the paper also shows some preliminary experimental results obtained at the engine test bed (ETB), underlining the NG potential for CO_2 reduction.

THE PROTOTYPE AND THE EXPERIMENTAL INVESTIGATION

Engine prototype presentation

Since developing a completely new engine featuring a compression ratio appropriate for the NG is very expensive and time-consuming, this prototype is based on a turbocharged compression ignition (CI) engine from a European manufacturer, which was adapted for SI operation. The main advantages of using this engine are: (1) it is designed to withstand the high pressures generated by the high CR specific to the CI engine; (2) it is a very common engine; therefore, it can be easily found in case of damage during research. The main characteristics of the prototype engine are presented in the table below:

Table 1. Engine prototype characteristics

Characteristics	Value
Displacement [cm^3]	1461
Bore [mm]	76
Stroke [mm]	80.5
Number of cylinders [-]	4
Compression ratio [-]	18.25
Number of valves [-]	8 (2/cylinder)

Given the difficulty to handle the cold starting with NG, the engine was also adapted to be able to operate with gasoline port-fuel injection (PFI). Indeed, as mention in [12], in the case of NG use, while starting the engine, it is very easy to go beyond its superior flammability limit, therefore, very precise control of the injectors is needed; consequently, at this stage, to avoid any inconvenience during the starting procedure of the prototype, it was decided to use gasoline. Besides the adaptation of the PFI of gasoline and NG, a throttle was mounted, and the injectors of the base CI engine were replaced with spark plugs. This conversion is carried out entirely at the cylinder head level. After several iterations, the final mounting solution is shown in Figure 1, which shows the digital twin of the real prototype. The reason for choosing this solution depended on several constraints: space considerations but also, thermal constraints given by mounting the exhaust manifold and the variable geometry turbine on the same side as the intake manifold.

Besides mechanical adaptation, electrical adaptation was also necessary. As already briefly described in [13], to successfully fire the engine, mechanical top dead center (TDC) should be synchronized with electrical TDC. Simply adapting the SI-specific components mechanically is not enough to start and run the engine. A control unit (ECU) is required to control both the ignition timing and the gasoline or natural gas injection. Therefore, a specific SI engine wiring had to be adapted together with the ECU.

First of all, in order to know to which cylinder to inject the fuel and then to ignite it, the ECU has be fed with the positions of the camshaft and the crankshaft. For this, the two shafts are equipped with various marks and sensors, but these are specific to each engine. So, the adaptation of the camshaft and crankshaft sensor marks specific to a SI engine whose displacement is close to the prototype's had to be adapted.

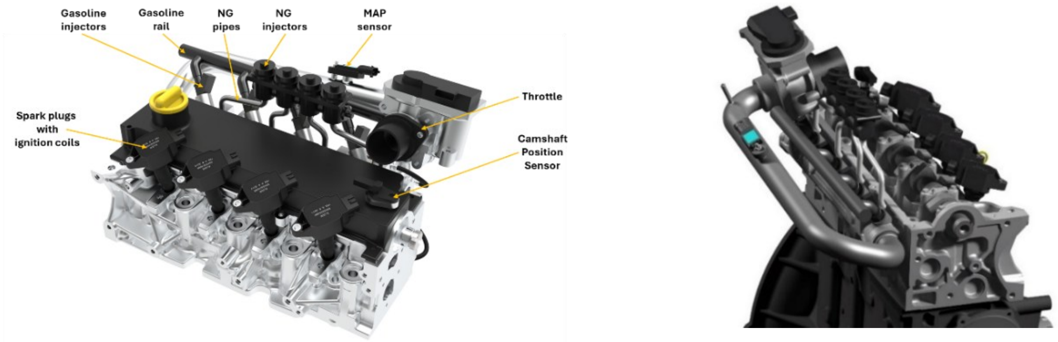


Figure 1. Prototype engine. Cylinder head adaption

The SI engine signal chronograph has been extracted from the engine manufacturer's specifications and will be used as a reference for camshaft and crankshaft signal synchronization (Figure 2). From this chronograph, ECU knows, depending on which tooth is in front of the crankshaft sensor, which tooth the camshaft sensor synchronizes with and vice versa.

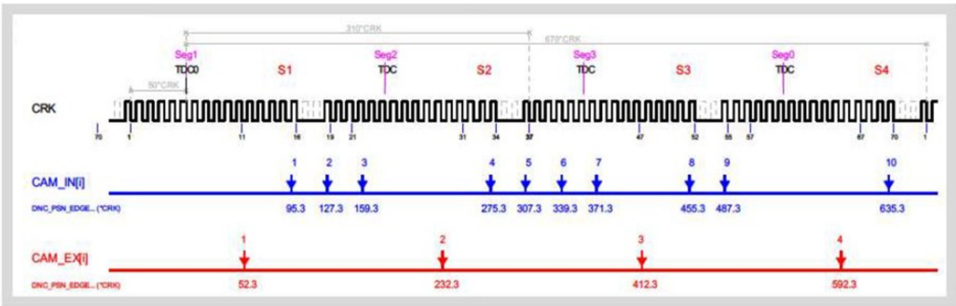


Figure 2. Reference chronograph from a SI engine

First to adapt was the camshaft's tooth-ring. Figure 3*a* presents the physical prototype's ring as well as its digital twin. It had to be adapted to new dimensions to fit in with the prototype, but it must maintain its identical functionality as in the original SI engine ring The prototype engine ring is larger in terms of inner diameter (where it mounts on the camshaft) and smaller in terms of outer diameter (where the angular references are found). A mounting tool was also manufactured in order to help mount the ring as correctly as possible. Finally, the ring was fixed using two opposite welding spots. Obviously, the next step was to adapt the camshaft position sensor as seen in Figure 3*b*.

a) prototype camshaft ring *b)* camshaft position sensor

Figure 3. The setup for the camshaft position measurement

Next, it was necessary to adapt the angular position sensors and the crankshaft marks. The part that will help to attach the crankshaft tooth-ring to the prototype engine pulley was designed to allow a free 360° CA rotation to easily position the wheel and synchronize the mechanical TDC with the electronic one. The final step was the adaptation of the angular position sensor (Figure 4).

Figure 4. The setup for the crankshaft position measurement

The final setup was done when all the sensors, the starter and the alternator were mounted. After several attempts, the engine started, and it was mounted on the test bed.

The main goal of the whole enterprise is to have a vehicle equipped with an optimised NG fuelled engine, which should be tested at the roller bench on the current homologation procedure (WLTP) and in real driving conditions (RDE) via a portable emissions measurement system (PEMS). Consequently, beside the adaptations briefly described above, the prototype engine should be fitted on a car. Thus, all the necessary elements of the NG fuelling system should be on board. Consequently, gas tank (in our case, a total of 80 litres in two cylindrical tanks designed to store approximatively 11 kg of gas at 200 bar), ducts, sensors, wiring and reducers were firstly adapted in CATIA software on the vehicle for a better understanding of further steps and for time saving. In Figure 5 the digital twin of the car prototype equipped with the compressed natural gas (CNG) fuel system and the prototype engine is presented. Regarding the gas storage, the tanks can be mounted either before or after the rear axle. Until completely optimisation of the engine at the test bed and benefits exploration, the car will remain a virtual prototype.

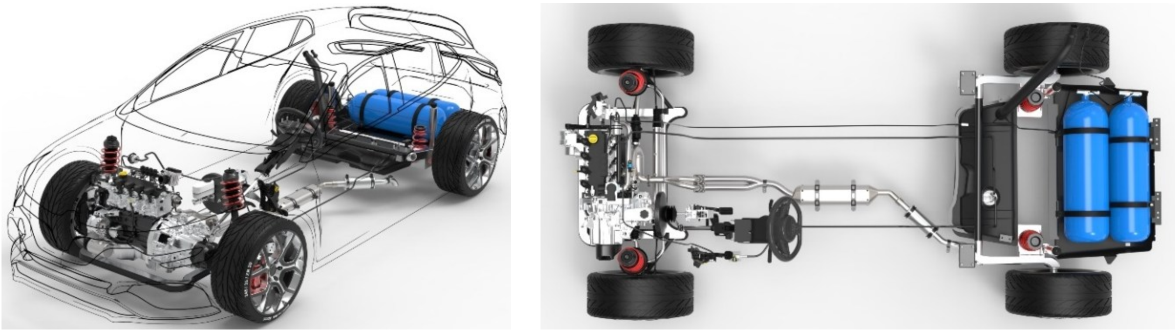


Figure 5. CNG car prototype

Experimental setup and testing methodology

The prototype engine was investigated in a stationary test bed equipped with an Eddy-current brake. The layout and the instrumentation of the engine test bed is shown in Figure 6.

The purpose of this investigation at the engine test bed (ETB) is to make a comparison between the results obtained with the NG engine prototype and the ones issued from a commercial gasoline engine, which has relatively close displacement (1600 cm^3).

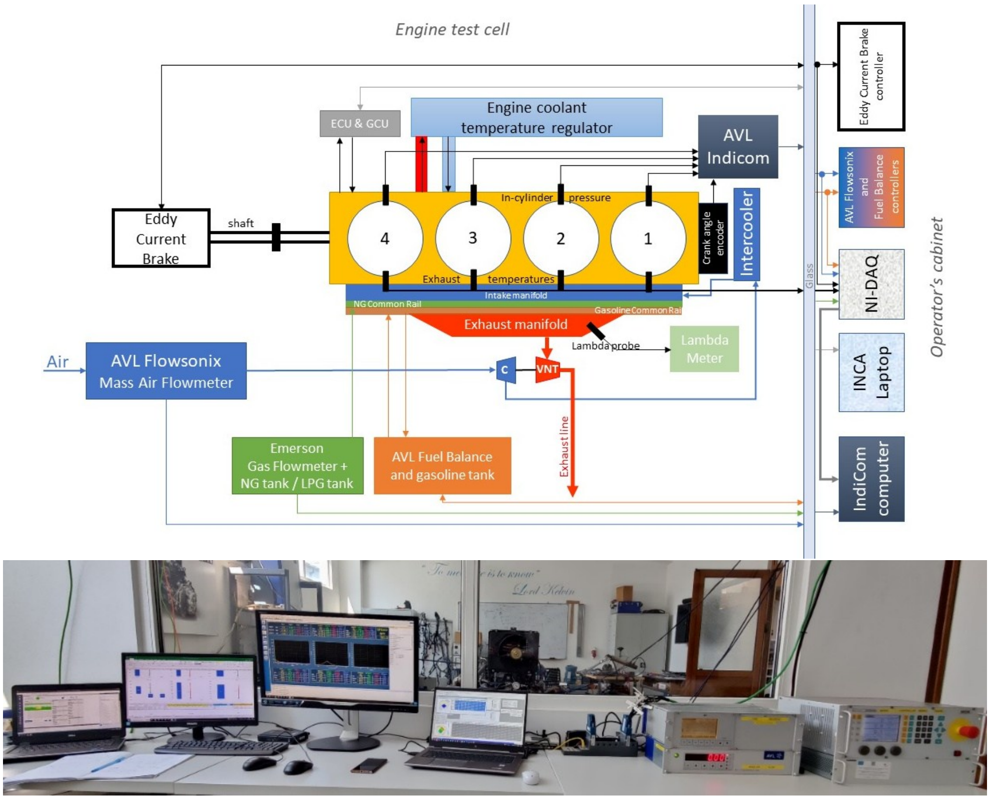


Figure 6. Engine test bed

The operating point chosen was 2300 rpm engine speed and 30.5 Nm of effective torque. The tests were carried out in (quasi)iso-conditions: ambient temperature 25°C ± 5, engine coolant temperature 80°C ± 1, and with stoichiometric mixture (i.e., equivalence ratio equal to 1). In order to avoid any influences from the mechanical efficiency standpoint, the alternator was disconnected, and the battery was charged with a separate power supply. In-cylinder instantaneous pressure acquisition was performed with AVL's IndiCom™ dealing with pressure signals coming from instrumented glow-plugs (i.e., false glow-plugs), while the combustion-related parameters were obtained with Concerto™ software based on the first law of thermodynamics. Data acquisition was conducted over 500 complete engine cycles for each sampling session, thus, resulting in a relevant indicated diagram for each case based on averaging the 500 acquired engine cycles. As access to the ECU was available via ETAS-INCA™ software, the procedure started with a spark ignition sweep in order to find the optimum spark advance (SA) values, i.e., the ones which gives the minimum fuel consumption (or best efficiency).

Mass air flow (MAF) and NG mass flow were measured with an AVL Flowsonix™ mass air flowmeter and with a Coriolis effect-based flowmeter produced by Emerson™ featuring a ±0.25% of rate accuracy, working with gas supplied at 5 bar reduced from the high-pressure tank causing a freezing at the lower pressure outlet pipe, as shown in Figure 7.

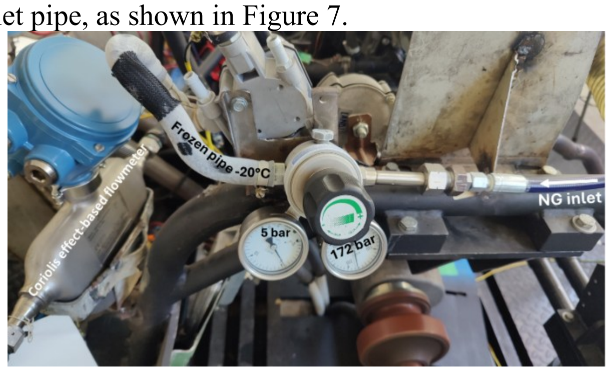


Figure 7. Gas supply system

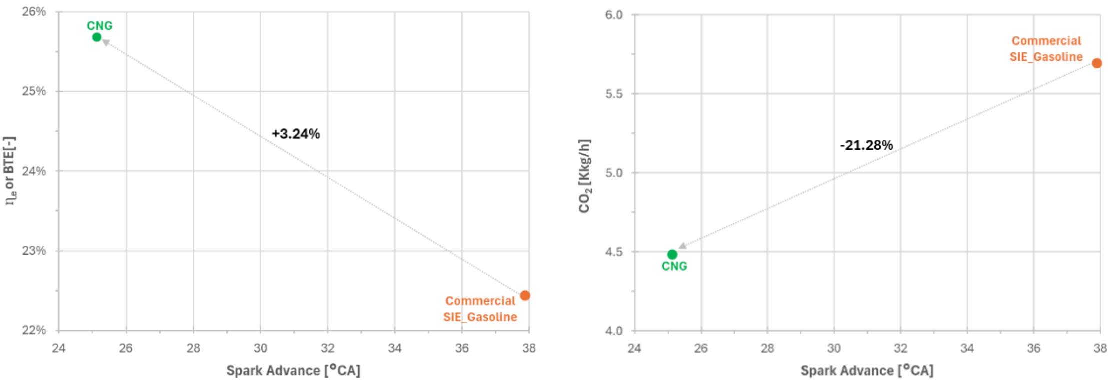
Regarding the gas analysis, the usual PEMS from AVL was used (Figure 8). Consequently, the following gaseous species were available: carbon monoxide and dioxide (CO and CO_2), nitric oxide and dioxide ($NO + NO_2 = NO_x$). Thanks to the usual particle counter from the AVL's PEMS, the number of those particles with diameter larger than 23 nm was also acquired.

Figure 8. Portable Emission Measurement System connected to the ETB

EXPERIMENTAL RESULTS

On the brake thermal efficiency (BTE), as shown in Figure 9*a*, the reference commercial gasoline engine features a 22.40% BTE for an optimum spark advance (SA_{opt}) of 37.875°CA, while the NG prototype achieved a BTE of 25.68% for a SA_{opt} of 25.125°CA: thus, an absolute increase of 3.24% percentage points, which is reflected in the CO_2 emissions, as can be seen in Figure 9*b*.

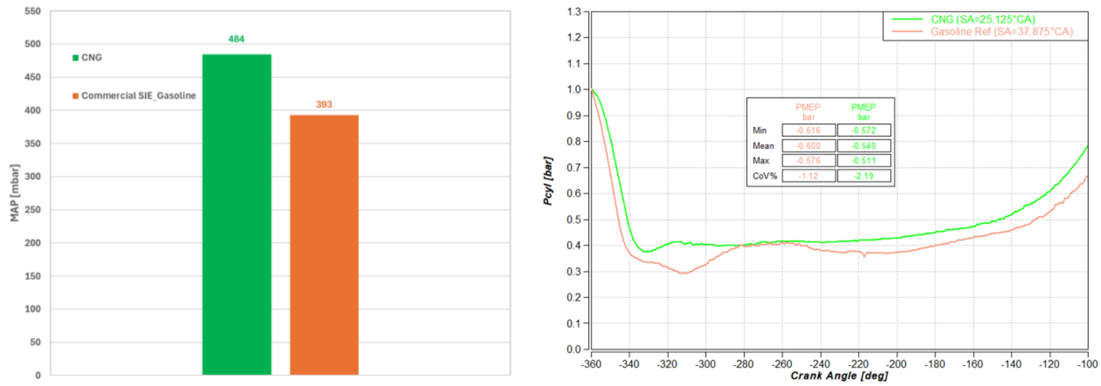
The fact that the prototype engine achieves maximum effective efficiency at lower spark advance values is due to internal aerodynamics specific to the CI engine, as presented in [13]. Therefore, an iso-spark advance comparison was impossible to achieve.



a) BTE *b)* CO_2

Figure 9. Efficiency and CO_2 emissions comparison

Of course, the decrease in the CO_2 emission for the NG case is also due to the favorable H/C ratio of its main component – the methane. Indeed, the CO_2 reduction is influenced by two main factors: the decrease in fuel consumption and the increase of the ratio between hydrogen and carbon in the case of natural gas (NG: 4/1 = 4 if considering only methane; commercial gasoline: 18/8 = 2.25 if considering the octane). Returning to fuel consumption, the commercial SI engine had 2.643 kg/h, which corresponds to 9.839 mg/stroke (i.e., milligrams per each cycle and each cylinder) while the NG prototype had 2.249 kg/h, which means 8.149 mg/stroke. This is the result of a different air-fuel ratio between these two fuels, making it another reason for the energy improvement generated using NG (besides the CR, which in the case of the commercial gasoline engine is almost half of the one of the NG prototype: 9.25 vs. 18.25). The fact that the stoichiometric air for the NG (i.e., L_{min} - the minimum mass of air that theoretically generates complete combustion of a unit mass of fuel) is higher than that specific to gasoline (16.72 kg of air for NG and 14.5 kg of air for gasoline) translates into a higher air requirement for the gaseous fuel, which means a higher absolute pressure in the intake manifold (MAP) and, ultimately, a lower pumping work (PMEP), as shown in Figure 10.



a) MAP *b)* lower loop of the indicated diagram and PMEP

Figure 10. Influence of air fuel ratio of NG over MAP

The effect of the higher CR and MAP is seen also in the indicated diagram (Figure 11). As can be seen, the maximum pressure inside the cylinder is much higher for the prototype (32.28 bar vs. 16.38 bar for commercial SI engine). Higher in-cylinder pressure translates into a higher rate of heat release (RoHR), as also seen in Figure 11. Regarding the combustion stability, it can be seen that over the 500 acquired cycles, the coefficient of variation (CoV) applied to the IMEP is 1.187% for the prototype and 2.890% for the commercial engine. This means that the variation of IMEP around an average value is much smaller, so much stable in the NG case.

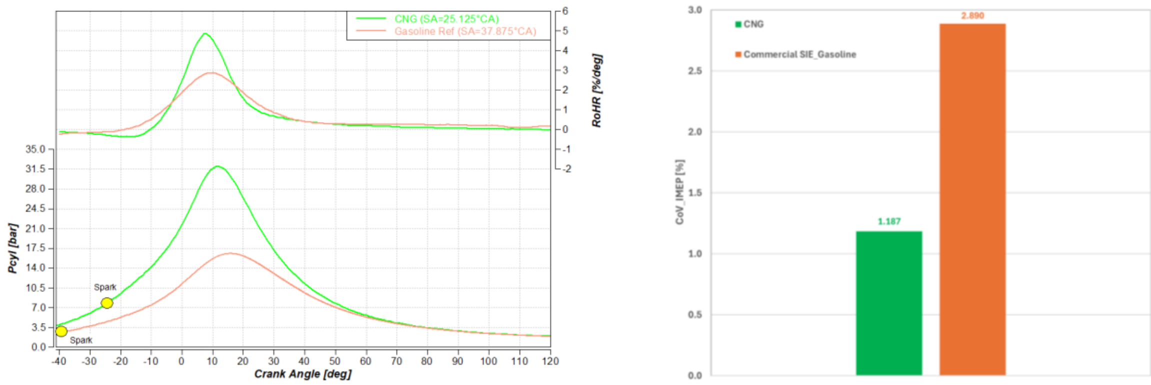


Figure 11. Indicated diagram and combustion stability

On the knock phenomenon, the knock pressure peak parameter (kp_pk) was used to assess its intensity. Figure 12 shows the evolution of this parameter over the 500 acquired cycles, as well as its average value and CoV. Being an operating point characterized by a low load, high knock peaks should not appear. The influence of the higher ON of the NG can be seen in Figure 12: lower average kp_pk and CoV (i.e., smaller scattering around the average value) with respect to the commercial gasoline SI.

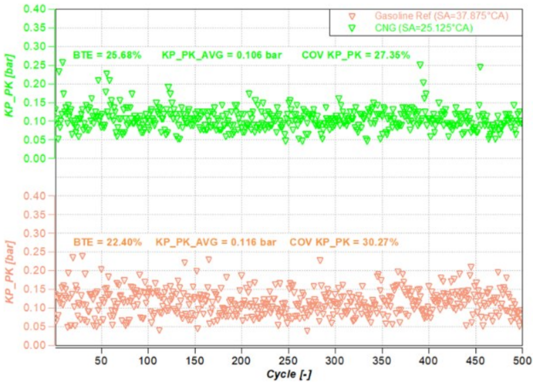


Figure 12. kp_ kp of the prototype vs commercial engine

Regarding the pollutant emissions of the prototype, the trade-off between nitrogen oxides (NO_x) and carbon monoxide (CO) can be observed in Figure 13. It is noticeable that in the CO case, the reduction is 30.55% when using gaseous fuels. This can be explained by the incomplete vaporization of gasoline because being a liquid fuel, first, it needs to be injected (i.e., sprayed, thus, atomized), then evaporated and mixed during the intake stroke. In the NG case, the vaporization process is missing because it is already gas and, of course, there is a higher change of a better mixing. Moreover, the higher air fuel ratio of NG means a higher oxygen value in cylinder, which increases the chances of a complete combustion of carbon resulting in less CO. Another reason is the fuel itself, NG having only one carbon atom in composition, which cumulated with the previous details about the air-fuel ratio, results in a decreased CO emissions. Regarding the NO_x emission, it is known that it appears in conditions of high temperature and oxygen excess. As expected, increased CR of the engine means a higher temperature in cylinder. Moreover, having in mind the higher need of air for burning NG, so increased oxygen, this leads to an unavoidable fact: increased NO_x by 87.33%. If there is no room for optimization (such as Exhaust Gas Recirculation (EGR) which was not available), this increased NO_x should be treated in the exhaust line using an optimized catalyst for this type of engine or dedicated systems such as SCR (Selective Catalyst Reduction) or NO_x trap.

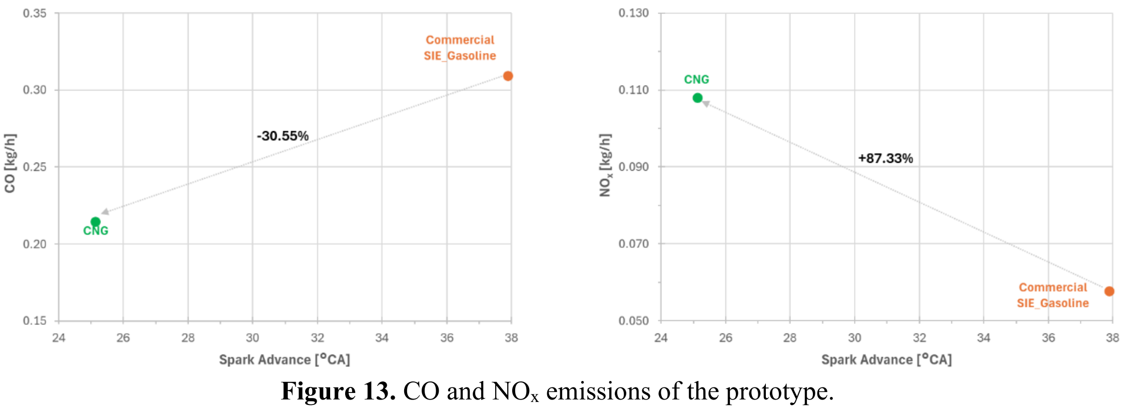


Figure 13. CO and NO_x emissions of the prototype.

Last point discussed is the particulate number (PN) emissions, which could not be compared with the commercial SI engine because there is no data available. The CNG prototype yielded an $PN = 6.514 \cdot 10^{14}$. Bearing in mind that gaseous fuels generally have less particles than liquid fuels, we can say that our prototype has at least equal PN emissions as serial engine.

CONCLUSION

In conclusion, methane has a big potential, at least for short and medium term, to reduce emissions and help car manufacturers comply with the actual and future regulations. It is the friendliest with the environment among fossil fuels and actual engine technologies can be easily adapted to work with it. Obviously, the SI engine can be operated either with gasoline or with NG (as is the case for the LPG) providing to the client a great satisfaction related to the range. However, this kind of application (bi-valent ones) is not fully optimised to work with methane fuel, being designed and calibrated to work in bi-fuel configurations, which means compromises; hence, the full potential of methane is not exploited in such applications.

The prototype created has a high compression ratio, because of the methane's higher octane number (around 130), thus, knock-free operation. Making a side-by-side comparison with a commercial gasoline engine, the prototype has many advantages: increased efficiency by 3.24% percentage points, reduced CO_2 by 21.28% and a more stable operation seen in the variation of the IMEP. In terms of emissions, CO is reduced by 30.55% and NO_x increased by 87.33%, which implies additional optimisations (e.g., EGR, SCR, NO_x trap). PN could not be compared due to missing information for the commercial gasoline engine but knowing that gaseous fuels has less PN emissions, one can say that the prototype should not exceed the PN of the commercial gasoline engine.

Abbreviations

BTE	Brake Thermal Efficiency	NG	Natural Gas
CA	Crank Angle	NOx	Nitrogen oxide
CI	Compression Ignition	ON	Octane Number
CNG	Compressed Natural Gas	PC	Passenger Car
CO	Carbon monoxide	PEMS	Portable Emissions Measurement System
CO2	Carbon Dioxide	PFI	Port Fuel Injection
CoV	Coefficient of Variation	PMEP	Pumping Mean Effective Pressure
CR	Compression Ratio	PN	Particulate Number
ECU	Electronic Control Unit	RoHR	Rate of Heat Release
EGR	Exhaust Gas Recirculation	SA	Spark Advance
ETB	Engine Test Bed	SA_{opt}	Optimum Spark Advance
GHG	Greenhouse Gases		
IMEP	Indicated Mean Effective Pressure	SCR	Selective Catalyst Reduction
LPG	Liquified Petroleum Gas	SI	Spark Ignition
MAF	Mass air Flow	TDC	Top Dead Center
MAP	Manifold Air Pressure	WOT	Wide Open Throttle

References

[1] IPCC, "Framing and Context," in *Global Warming of 1.5°C*, Cambridge University Press, 2022, pp. 49–92. doi: 10.1017/9781009157940.003.

[2] IPCC, "Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development," in *Global Warming of 1.5°C*, Cambridge University Press, 2022, pp. 93–174. doi: 10.1017/9781009157940.004.

[3] R. J. Detz and B. van der Zwaan, "Transitioning towards negative CO2 emissions," *Energy Policy*, vol. 133, Oct. 2019, doi: 10.1016/j.enpol.2019.110938.

[4] European Parliament and Council of the European Union, "Regulation (EC) no. 443/2009," *Official Journal of the European Union*, vol. 140, no. 1, pp. 1–15, 2009.

[5] ICCT, "EU CO2 EMISSION STANDARDS FOR PASSENGER CARS AND LIGHT-COMMERCIAL VEHICLES," 2014.

[6] M. I. Khan, T. Yasmin, and A. Shakoor, "Technical overview of compressed natural gas (CNG) as a transportation fuel," *Renewable and Sustainable Energy Reviews*, vol. 51, no. December 2017, pp. 785–797, 2015, doi: 10.1016/j.rser.2015.06.053.

[7] EU, *DIRECTIVE 2014/94/EU OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on the deployment of alternative fuels infrastructure*. Official Journal of the European Union, 2014.

[8] M. Westerhoff, "Natural gas. A chance to be grabbed," *MTZ*, vol. 76, no. February, pp. 9–13, 2016.

[9] G. Chala, A. Abd Aziz, and F. Hagos, "Natural Gas Engine Technologies: Challenges and Energy Sustainability Issue," *Energies (Basel)*, vol. 11, no. 11, p. 2934, Oct. 2018, doi: 10.3390/en11112934.

[10] R. Tilagone, S. Venturi, and G. Monnier, “Natural Gas - an Environmentally Friendly Fuel for Urban Vehicles: the Smart Demonstrator Approach,” *Oil & Gas Science and Technology*, vol. 61, no. 1, pp. 155–164, Jan. 2006, doi: 10.2516/ogst:2006010x.
[11] ***, “Country comparison: natural gas production,” The CIA world factbook. Accessed: Jan. 31, 2021. [Online]. Available: https://www.cia.gov/the-world-factbook/field/natural-gas-production/country-comparison
[12] R. Popa, A. Clenci, R. Chiriac, R. Niculescu, V. Iorga-Simăn, “Experimental and Numerical Investigation on The Effects of Using Natural Gas in a Monovalent Spark Ignition Engine INTRODUCTION AND LITERATURE OVERVIEW.”
[13] R. Popa, J. Berquez, A. Clenci, V. Iorga-Simăn, M. Niculae, and R. Niculescu, “Sustainable road mobility with methane gas. Preliminary results of a monovalent spark ignition engine fueled with methane,” pp. 13–17, 2021, doi: 10.46720/F202N-XXX-NNN.