COMPARATIVE EVALUATION OF BIOMETHANE AND NATURAL GAS USE IN A HEAVY-DUTY VEHICLE

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Abstract:
Although there is a growing trend toward electrification of the vehicle fleet, this is not evident in the case of heavy-duty vehicles. It is therefore urgent to find a way to ensure the sustainability of the use of heavy vehicles using other forms of energy, such as natural gas, biofuels, and hydrogen.
Knowing that the use of natural gas is a solution that still corresponds to the emission of high quantities of CO2, due to its fossil origin, we intend to analyse the use of biomethane in heavy-duty vehicles. This fuel is obtained from household waste, which, besides having a renewable character, also allows for avoiding the emission of this biogas into the atmosphere, corresponding to very critical effects of global warming. Thus, this work aims to evaluate the effects of the use of biomethane in a heavy-duty vehicle, compared to the use of compressed natural gas in the same vehicle and under the same conditions, both on a chassis dynamometer and on the homologous road trips analyzed.
Regarding the results obtained in the laboratory experiments, it is revealed that the use of biomethane in an engine implies a slight increase in consumption when compared to the use of compressed natural It should be noted that the increase in consumption is not very significant, with differences of between 2 % and 10 %. The differences in performance are very little, both in terms of torque and power, with a maximum difference of 7.4% for power. Indeed, while measuring specific consumption, which reflects engine efficiency, compressed natural gas helps the engine to slightly improve its efficiency. The data obtained when monitoring the vehicle on the road are in line with the results obtained in the laboratory tests, particularly regarding an increase in consumption corresponding to the use of biomethane. It was also possible to identify a reduction in NOx emissions with biomethane, but there were no significant differences with other pollutants.
An examination of the lubricating oil was also performed, and it was possible to find some indicators of increased lubricating oil degradation with the use of biomethane, which should be considered.

Keywords:
Transport sustainability, biomethane, energy, biofuel, vehicles.

1. Introduction

The transport sector has played a substantial part in contributing to greenhouse gas (GHG) emissions and the diesel dependence of the Heavy-Duty Vehicles (HDV) is difficult to replace. One important problem related to Heavy-Duty Vehicles (HDV) is the limited electrification alternatives available for long-haul applications. Biomethane, a renewable fuel made from organic waste, exhibits great potential as a replacement for fossil fuels and so, the research about the use of biomethane as energetic source for HDVs is needed to find its full potential in this path for decarbonization.

Considering the actual scenario, where HDV presents a smashing dependence of diesel fuel the possible replacement of this fossil fuel by a renewable fuel source becomes evident. Compared to diesel, Biomethane delivers a considerable reduction in greenhouse gas emissions. Depending on the feedstock and production techniques, studies indicate that lifecycle emissions may be reduced by 50% or more [1]. Biomethane is generally presented as a drop-in renewable substitute for fossil natural gas in compressed or liquefied form, with the main advantage being much lower life-cycle greenhouse gas emissions when produced from wastes or residues. For heavy-duty road transport, the literature consistently finds that biomethane can preserve the same basic vehicle and refueling architecture as CNG/LNG, which makes it attractive for fleet transition without major drivetrain changes [2].

Another significative advantage, mainly considering the comparison with electrification, is the possibility of using the current HDV refueling infrastructure, where it also be mixed with natural gas or utilized straight in compressed (Bio-CNG) or liquefied (Bio-LNG) form [3]. When compared to diesel, the combustion of biomethane emits fewer pollutants such as nitrogen oxides and particulate matter, which helps to reduce the environmental impacts, lowering the pollutant emissions [3].

Lastly, the generation of Biomethane makes use of organic waste streams, such as manure, agricultural wastes, and wastewater sludge, which encourages resource recovery and waste management. This possibility allows to have 2 major gains. It gives an added value to a residue and also avoids the emissions of methane and other harmful substances to the atmosphere, which has tremendous potential to damage the atmosphere and to increase the GHG effects. According to the realistic estimates presented in the European Biogas Association (EBA) report, biomethane could supply at least 20% of the total gaseous fuel demand for transport [3]. With the right infrastructure and incentives, biomethane producers could quickly make the transition to the transport sector in just a few years. After 2030, the share of biomethane will probably increase to more than 20% in order to meet the strategic objective of decarbonizing all transport by 2050, along with other alternative fuels such as electricity and hydrogen from renewable sources.

Notwithstanding these benefits, there are still unanswered questions about the widespread use of biomethane in HDVs.

The necessary equilibrium when it comes to sustainable feedstock management has some issues, primarily with feedstock production optimization that maximizes biomethane yield while limiting rivalry with food production and land use. To appropriately account for the environmental impact of biomethane production and usage across various feedstocks and production paths, certain improved Life Cycle Assessment approaches are also required [4].

Concerns regarding the optimization of engines to run on biomethane are another pertinent problem. In order to achieve the greatest technological design for biomethane fuel performance and efficiency, engines must be developed and tested [3]. Biomethane fuel is the best solution for solid organic waste, is the best alternative to gasoline fuel, and is eco-friendly. The obtained results obtained by suggest that it has the best results among all fuels in terms of engine performance, combustion, and emissions [5]. Lastly, there's the requirement to create appropriate research plans to pursue lowered biomethane production costs to make it economically competitive with fossil fuels [4].

To guarantee biomethane's sustainable and efficient use in HDVs, extensive research is needed. Overcoming these research gaps will enable biomethane to reach its full potential as a primary decarbonization approach for the transport sector, especially for heavy-duty vehicles that are difficult to electrify. Biomethane could support these efforts by offering a low-carbon alternative to utilize current technologies and avoid investing in potentially stranded assets, as certain transport applications are currently investing in fossil natural gas as a transition solution. To verify the benefits in various applications, more study will be required. This research should use genuine case studies' monitoring data, which can offer impartial support for policy decisions [6].

In order to have a better and deeper knowledge about the possibility of using biomethane a vehicle powered by a 6-cylinder spark-ignition engine was used, and the work was structured around a comparative analysis of the vehicle's operation when fuelled by CNG and when fuelled by purified biomethane.

The work plan established was based on the fundamental assumption that the comparative assessment between the use of CNG and purified biomethane should be carried out guaranteeing that the vehicle would be subjected to similar conditions in terms of use and testing. To do this, care was taken to establish a standard initial state that should characterize the vehicle before using each of the fuels, changing the lubricating oil and evaluating the power and torque at the beginning and end of each period, which should correspond to a similar distance travelled.

In this comparative process, after using the vehicle with each of the fuels, it was possible to assess the variation in the vehicle's performance, the impact in terms of fuel consumption, possible changes in wear and tear directly or indirectly on the engine components and the level of emissions resulting from the combustion of these fuels.

Heavy-duty power applications, such as rail, maritime, backup power production, off-road construction equipment, and on-road heavy-duty automobiles, have been dominated by diesel-fuelled compression ignition engines. A key review of biomethane in transport reports that biomethane can substantially reduce GHG emissions and that its best fit is often long-distance or high-duty transport, where energy density and refueling speed matter more than in light-duty applications. Another review of biogas-based transport fuels notes that LNG is especially relevant for heavy-duty use because of its higher storage density, and it identifies biomethane-derived LNG as one of the most mature renewable options for trucks [7,8].

In the last decades alternative fuels have emerged as an attractive alternative to conventional fossil fuels in search for a balance between the demand for more energy and the reduction of carbon dioxide (CO_2) emissions. Methane has become a popular alternative fuel in the transportation industry because of its benefits, which include lower greenhouse gas emissions, improved combustion efficiency, appealing pricing, renewability through biomass production techniques, etc. System-level studies also support this view [7]. A Finnish case study found that biomethane could power roughly half of heavy-duty transport by 2030 under plausible supply assumptions, with emissions roughly 50% lower than diesel in the modeled scenarios [8]. A more recent environmental and economic assessment concluded that biomethane used in heavy goods vehicles can deliver notable reductions in climate impact and air-pollution categories, while also highlighting that network constraints and fuel logistics strongly affect the real-world pathway [9].

The main limitation is not vehicle compatibility but supply, infrastructure, and upstream emissions. Studies emphasize that the climate benefit depends heavily on feedstock choice, methane leakage control, upgrading efficiency, and whether biomethane displaces fossil natural gas in the grid or diesel in transport. Overall, the literature supports biomethane as one of the most practical low-carbon fuels for heavy-duty vehicles, especially where gas infrastructure already exists and renewable feedstock supply is strong [10].

Because of its comparatively clean burning, natural gas has long been seen as a possible alternative fuel for automotive uses. The use of methane emits less NOx because it burns at a lower temperature than most liquid hydrocarbons. Its use in engines causes the least amount of carbon dioxide (CO_2) emissions per unit of energy generated because it has the lowest carbon-hydrogen ratio of any stable hydrocarbon fuel. The two main sources of methane are BioMethane (BioM) and Natural Gas (NG), and the fundamental difference between the two fuels in question is their origin. The NG referred to here is a fossil fuel, while biomethane is obtained from organic matter, usually through the anaerobic digestion of organic waste. Strictly speaking, NG also comes from organic material, but its life cycle is several orders of magnitude longer than that of biomethane. If the constitution of these two energy sources is similar, biomethane can be used as a renewable alternative to NG consumption, while avoiding the emission of methane from the decomposition of the organic matter that gives rise to it into the atmosphere, which translates into significant gains in terms of the greenhouse effect [11].

Another important aspect of distinction between the two fuels is that the methane content of biomethane is usually lower than that of NG, which translates into lower calorific value. This effect can lead to increased fuel consumption and some loss of power and torque when biomethane is used. The existence of sulphur compounds in biomethane, namely H_2S, can also cause problems in terms of engine reliability and maintenance, given the acidification of lubricating oil and potential corrosion of some engine components. One of the problems also mentioned in some of the literature is the existence of microparticles that manage to pass the filters during the biomethane production that can enter the crankcase of the engine, causing wear to the cylinders and valve seats, as well as the valves themselves.

This work aims to evaluate the use of purified biomethane, which is expected to reduce the concentration of undesirable substances such as microparticles, sulphur compounds and even the percentage of other substances such as CO_2, increasing the concentration of methane, which in addition to reducing the possibility of engine reliability problems, it is predicted that it will increase the performance and efficiency of the engines.

To accomplish the objective of obtaining a comparative evaluation of the usage of NG and pure biomethane was conducted, the work plan considers the use of one vehicle through comparable testing and on-road circumstances. A standard initial state was defined in the vehicle before using each fuel, changing the lubricating oil, and assessing the power and torque at the start and finish of each time period, which should match the distance travelled. In this comparative process, after using the vehicle with each of the fuels, it was possible to assess the variation in the vehicle's performance, the impact in terms of fuel consumption, possible changes in wear and tear directly or indirectly on the engine components and the level of emissions resulting from the combustion of these fuels.

2. Experimental Methodology

The experimental methodology was planned and carried out involved instrumenting the vehicle and performing several laboratory and real on-road tests to monitor and store the following parameters in the respective situations in which the two fuels mentioned were used:

a. Fuel Consumption:

a.1. Installation, in the vehicle's engine intake line, of a Coriolis-type mass flow sensor for reading and storing the respective consumption data.

a.2. Installation, inside the passenger compartment, of equipment for reading and storing parameters read directly from the Electronic Engine Control Unit (ECU), including the respective fuel consumption.

a.3. Reading and storing the parameters referred to in a.1. and a.2. in experimental tests carried out on a chassis dynamometer and in road tests, the repeatability of which was guaranteed by means of a global positioning sensor - GPS, also installed in the vehicle. The results of vehicle geographical position and time during its usual operation were also acquired and stored in the equipment referred to in a.2.

b. **Emissions:**

b.1. Measurement of the gaseous components of the exhaust gases in the tests carried out on the power bench, using equipment and sensors designed for this purpose.

b.2. Measurement of the gaseous components of the exhaust gases during road tests, namely by reading the respective parameters in the Engine Electronic Control Unit (ECU) and storing the respective data in the same equipment referred to in a.2;

c. **Torque and Power - Performance tests:**

c.1. Performance tests - Torque and Power as a function of speed - using a chassis dynamometer.

c.2. Monitoring and recording various performance parameters obtained from the vehicle's ECU and through the instrumentation installed in it, namely the global positioning sensor - GPS, in the circuits of its usual operation.

2.1. Vehicle Characteristics and Data Acquisition

The vehicle used is equipped with a factory-prepared engine that uses natural gas (CNG). This spark-ignition engine works according to the Otto cycle and allows 100% natural gas to be used. The characteristics of the engine and the vehicle are shown in the table below (Table 1).

Table 1: *Vehicle Characteristics*

Cylinder volume	**7800cm^3**
Nº Cylinders	**6**
Nominal Power	**200kW at 2000 rpm**
Max Torque	**1100 Nm** **from 1100 to 1735 rpm**
Engine type	**Otto Cycle** **prepared to use NG**
Age	**Nov. 2012**
Max Weight	**19000kg**
Min Weight	**13320kg**

It should be noted that this vehicle has a three-way catalytic converter (oxidation-reduction) installed in the exhaust system, which considerably reduces emissions of carbon monoxide (CO), hydrocarbons (HC) and nitrogen oxides (NOx) during operation.

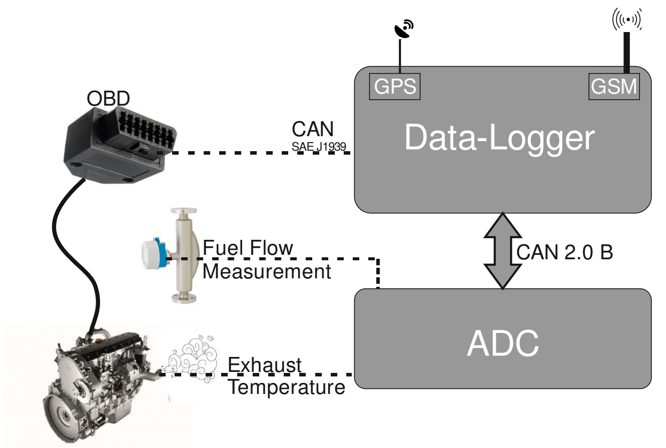

Figure 1: *Schematic representation of the systems for acquiring vehicle operating data.*

In order to ensure continuous data collection during normal use, a set of data acquisition and storage systems was installed in the vehicle: a *data-logger, connection to the vehicle's ECU, via the On-Board Diagnostic (OBD),* a GPS (G*lobal Positioning System*), a temperature sensor in the exhaust pipe to acquire the exhaust gas temperature information, and a Coriolis-type flow sensor, installed in series in the engine's gas supply line, to measure the flow of fuel consumed by the engine. The data logger records vehicle operating data by acquiring information from the ECU via the Controller Area Network (CAN), along with additional inputs from onboard instrumentation, including a Coriolis-type flow sensor and GPS. This enables continuous monitoring and storage of vehicle performance during operation. The positions of the measurement and acquisition systems are shown in figure 1 and figure 2.

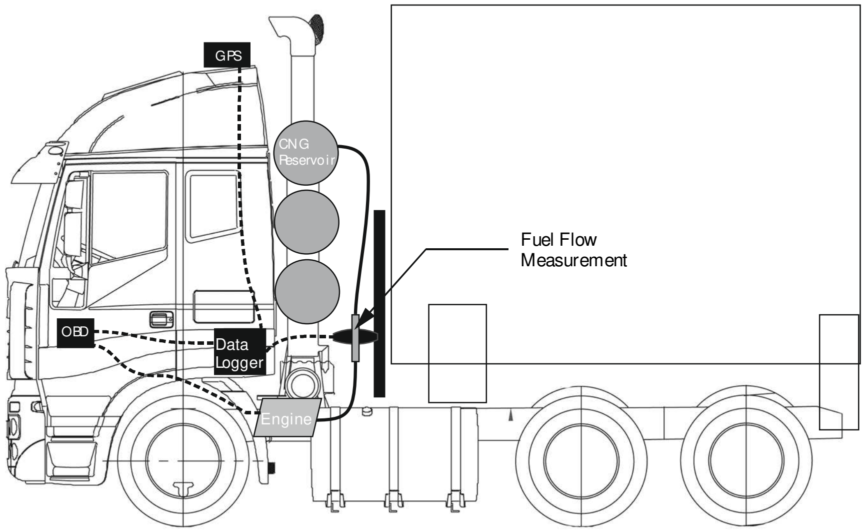

Figure 2: *Representation of the assembly of systems for acquiring vehicle operating data.*

2.2. Experimental Laboratorial Tests

The experimental tests repeatability was assured by comparing the results of the first phase of tests, with the vehicle fuelled with CNG, with the results of the second phase, with the vehicle fuelled with purified biomethane, in addition to monitoring the aforementioned parameters during the usual operation of the vehicle on road courses, tests were carried out on a power bench for heavy-duty vehicles.

Considering the use of a chassis power test bench, it was possible to obtain the engine's power and torque curves at maximum load, and a series of tests were carried out at constant load and constant rotational speed in order to replicate real road operating conditions. These tests were therefore repeated for various values of engine load and rotation speed, so that the test points were representative of the vehicle's use on ordinary routes. The conditions programmed into the power bank for the respective tests were at full load (100%) at different engine rotation speeds from 850rpm to 2250rpm with increased steps of 100rpm, defining 15 points of operation with stabilized operation through 5 seconds in each point.

2.3. Experimental On-Road Tests

With the equipment installed in the vehicle during ordinary use, typical routes were selected, in which the vehicle was fueled with CNG and biomethane on the same route at different times, for which the respective parameters were monitored and stored.

Regarding the road tests, it is important to note that there are several factors which are difficult to duplicate, that have a direct influence on the fuel consumption of the heavy-duty vehicle and, consequently, on the set of parameters monitored. Examples include environmental conditions (wind speed and direction, ...), the state of vehicle maintenance (tires, steering alignment, transmission system condition, ...), the vehicle's own load condition (weight, ...) and the driver's driving profile. For the purposes of this report, a particular route was selected for analysis whose conditions showed the least variability, particularly when considering the data obtained via GPS for the various routes analyzed.

3. Results

The results obtained in different tests were representative of different conditions of operation of the vehicle allowing for a comparison of the engine fuelled with natural gas (NG) and BioMethane (BioM).

3.1 Chassis dynamometer results

The engine power and torque curves obtained during the performance tests on the power bench, with the vehicle fueled with biomethane and CNG presenting the maximum obtained values from the tests carried out with the respective fuels in table 2.

The environmental conditions at the test site were similar on both test days, with atmospheric pressure values of 954 mbar and 957 mbar and air temperatures of 22ºC and 24ºC respectively, and the results allow to make the graph presented in figure 3.

Table 2: *Maximum engine Power and Torque results*

	Natural Gas		BioMethane		Difference
Max. Power	**185,0** [kW]	**1750** [rpm]	**184,0** [kW]	**1830** [rpm]	**- 0.5** [%]
Max. Torque	**1095** [Nm]	**1440** [rpm]	**1059** [Nm]	**1360** [rpm]	**- 3.2** [%]

Considering all the test points recorded, it can be observed that, in the speed range between 850 rpm and 1350 rpm, the nominal power and torque values are slightly lower than those specified by the manufacturer. The same can be seen in the speed range between 1750 rpm and 2150 rpm. These differences are considered normal, resulting from the use of the vehicle and do not raise any question considering the objectives of the present work, that is comparing the same engine fueled by the two different fuels, and since the engine is working in regular conditions, the required conditions are good to perform the required comparative analysis.

It is possible to note a difference (of 1 kW) in terms of maximum engine power is not significant. The maximum torque measured when using biomethane was 3.2% lower than when using compressed natural gas.

However, looking at the entire engine speed range, as shown in the graph in figure 13, it can be seen that in the 850 to 1780 rpm speed range, the nominal power of the engine using biomethane is lower by a maximum of 7.4% compared to compressed natural gas. At 1850 rpm and above 2150 rpm, there was an increase in the nominal power available of between 0.2% and 2.75% using biomethane.

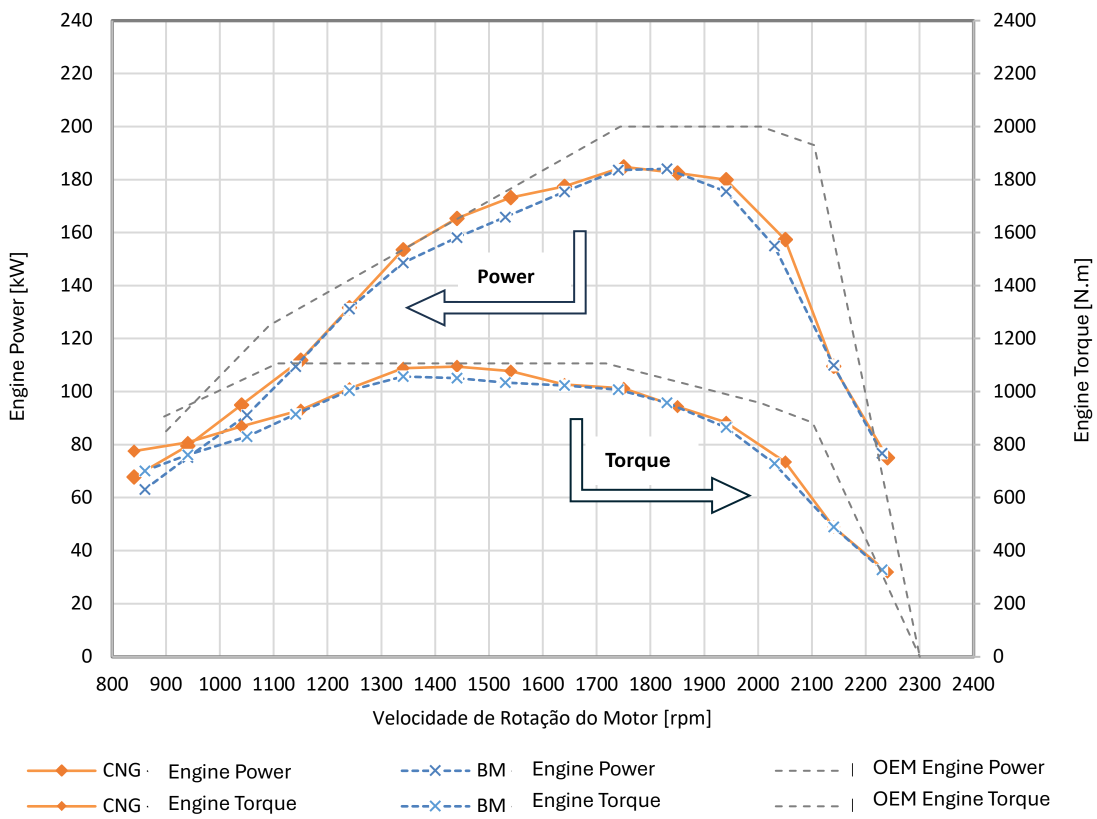

Figure 3: *Power and Torque results for NG and BioM.*

These data demonstrate that engine performance reaches levels that are closely approaching original specifications. Considering all recorded test points, it is observed that within the rotational speed range of 850–1350 rpm, both nominal power and torque values are marginally below those specified by the manufacturer. A similar pattern is observed in the 1750–2150 rpm range. These deviations are considered within normal limits, attributable to cumulative vehicle usage, and do not compromise the validity of the findings presented in this report.

Comparing the results obtained with the two fuels under analysis, the difference in maximum engine power (1 kW) is not statistically significant. The maximum torque measured when using biomethane was 3.2% lower relative to compressed natural gas.

However, examining the full engine speed range, as illustrated in Figure 13, it is notable that within the 850–1780 rpm band, nominal engine power using biomethane is reduced by up to 7.4% compared to compressed natural gas. Conversely, at 1850 rpm and above 2150 rpm, an increase in available nominal power of between 0.2% and 2.75% was recorded when using biomethane.

3.2. Fuel Consumption

Analysis of the results presented in Figures 3 and 4 reveals that biomethane utilization results in increased fuel consumption compared to compressed natural gas (CNG). This difference is clearly illustrated in Figure 3, where both consumption curves corresponding to biomethane consistently lie above those for CNG, whether considering instantaneous consumption or specific fuel consumption.

This trend becomes more pronounced upon examination of Figure 4, which demonstrates that the increase in instantaneous consumption exceeds 2% across the entire engine speed range evaluated, reaching values of 8–10% at operating points between 1200 rpm and 1500 rpm. At higher engine speeds, this differential is slightly attenuated; however, biomethane consumption remains consistently elevated relative to CNG throughout all operating conditions. In absolute terms, maximum CNG consumption values are approximately 38 kg/h within the 1700–2000 rpm range, whereas biomethane reaches a maximum consumption of approximately 40 kg/h over the same rotational speed range. This corresponds to an increase of approximately 2 kg/h of fuel at these operating regimes.

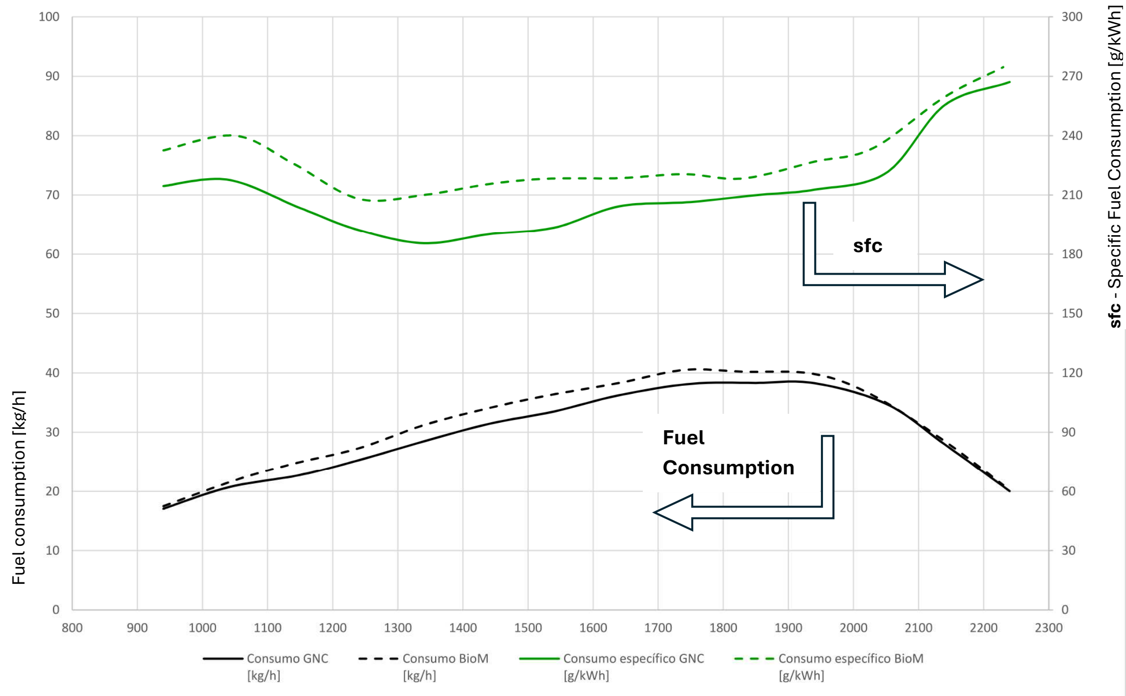

Figure 4: *Fuel Consumption Results*

The integration of work output into this analysis, through an evaluation of specific fuel consumption that considers the quantity of fuel required to achieve equivalent energy delivery at the wheel, yields even more pronounced differences. Given the observations previously described, namely that greater quantities of biomethane were required despite obtaining marginally lower power and torque value. It was anticipated that specific fuel consumption would increase significantly, corresponding to a reduction in engine efficiency when fueled with biomethane. This expectation is confirmed by the data.

This analysis demonstrates that engine efficiency is reduced by approximately 7–13% at engine speeds between 950 and 1750 rpm, decreasing to a minimum reduction of 2.6% under operating conditions where the engine reaches higher rotational speeds, as evidenced by the values presented in Table 3.

As previously noted, the maximum vehicle speed is attained at approximately 1650 rpm. Consequently, while no appreciable performance losses are observed with biomethane utilization at this operating point, fuel consumption increases by approximately 6% under conditions requiring maximum engine load output.

Table 3- *Comparative analysis of the results in chassis dynamometer for Biomethane and Natural Gas*

Engine Speed [rpm]	Power Variation Biom vs GNC [kW]	Torque Variation Biom vs GNC [Nm]	Fuel Consumption Variation [%]	Specific Fuel Consump. Variation [%]
840	-6,9	-9,5		
940	-5,4	-5,8	2,5	8,4
1040	-4,1	-4,5	5,7	10,2
1150	-2,2	-1,7	8,5	11,0
1240	-0,3	-0,7	7,9	8,2
1340	-3,2	-2,8	9,6	13,2
1440	-4,4	-4,0	8,5	13,4
1540	-4,3	-4,0	8,0	12,8
1640	-1,2	-0,4	5,7	7,0
1750	-0,6	-0,5	6,1	6,8
1850	0,9	1,6	4,9	4,0
1940	-2,4	-2,1	4,0	6,6
2050	-1,5	-0,8	4,0	5,7
2140	0,3	0,2	1,9	1,6
2240	2,3	2,8	5,1	2,8

3.3. On road test results

A 112 km route was selected, representative of typical vehicle usage and characterized by significant topographic elevation variability. This route was traversed on separate days using the same vehicle, fueled with compressed natural gas on one occasion and biomethane on the other. The route exhibits a maximum elevation differential of 637 m, comprising 54% positive gradient (ascent) and 46% negative gradient (descent).

Analysis of this route demonstrates that the vehicle completed the identical distance approximately 4 minutes faster when fueled with compressed natural gas (CNG) compared to biomethane. Has presented in table 4, on average, biomethane utilization resulted in an additional 2 seconds per kilometer travelled, corresponding to a reduction in mean velocity of 2.8 km/h. The cumulative fuel consumption differential was 2.5 kg/100km. It is therefore essential to determine whether the observed differences are attributable solely to fuel properties or to additional contributing factors.

Table 4. *Results of the road tests*

Trip date	Fuel used	Total distance [km]	Time travel[1] [h:m:ss]	Average speed[1] [km/h]	Fuel Consumption[1] [kg/100km]
30-august	Biomethane	114,325	01:38:42	68,04	30.7
27-september	Natural Gas	113,813	01:34:49	70,87	28.2

[1] Travel time, average speed and fuel consumption were obtained between reference points.

Although the routes in question are highly similar, the various sources of uncertainty associated with how the vehicle traverses the circuit necessitated a rigorous analysis of zones where the vehicle could be considered to have operated under closely comparable conditions. This analysis identified two route segments of significant spatial extent where the influence of external factors is minimized, thereby enabling observed differences in vehicle behavior, in terms of fuel consumption, to be attributed solely to the fuel serving as the energy source for propulsion. These zones are identified in Figure 5.

As can be observed, the two selected zones correspond to two distinct operating typologies. Route segment A exhibits a significant downward gradient, representing a route with relatively low power demand. Conversely, route segment B is characterized by a steep upward gradient, resulting in substantially higher engine load compared to route segment A.

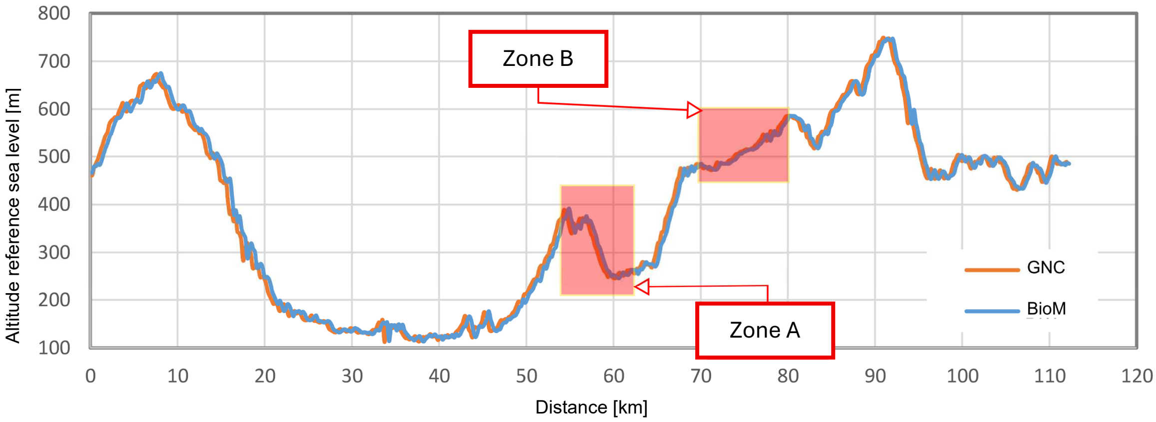

***Figure 5** – Identification of selected zones for fuel consumption evaluation.*

The selection of the identified route segments resulted from detailed examination of the graphs presented in Figure 5, in which engine rotational speed and vehicle velocity are similar across both journeys under study, corresponding to the utilization of the two fuels under consideration.

Analyzing the complete route, despite the power demand being entirely analogous, it is observed that in certain sections, even where velocity is similar for both journeys, engine rotational speed differs. This is attributable to the use of different gear ratios in these zones. Furthermore, although mean velocity is highly similar, instantaneous velocity exhibits significant differences in certain sections of the route. These variables are not fully controllable and may introduce variations in the final results.

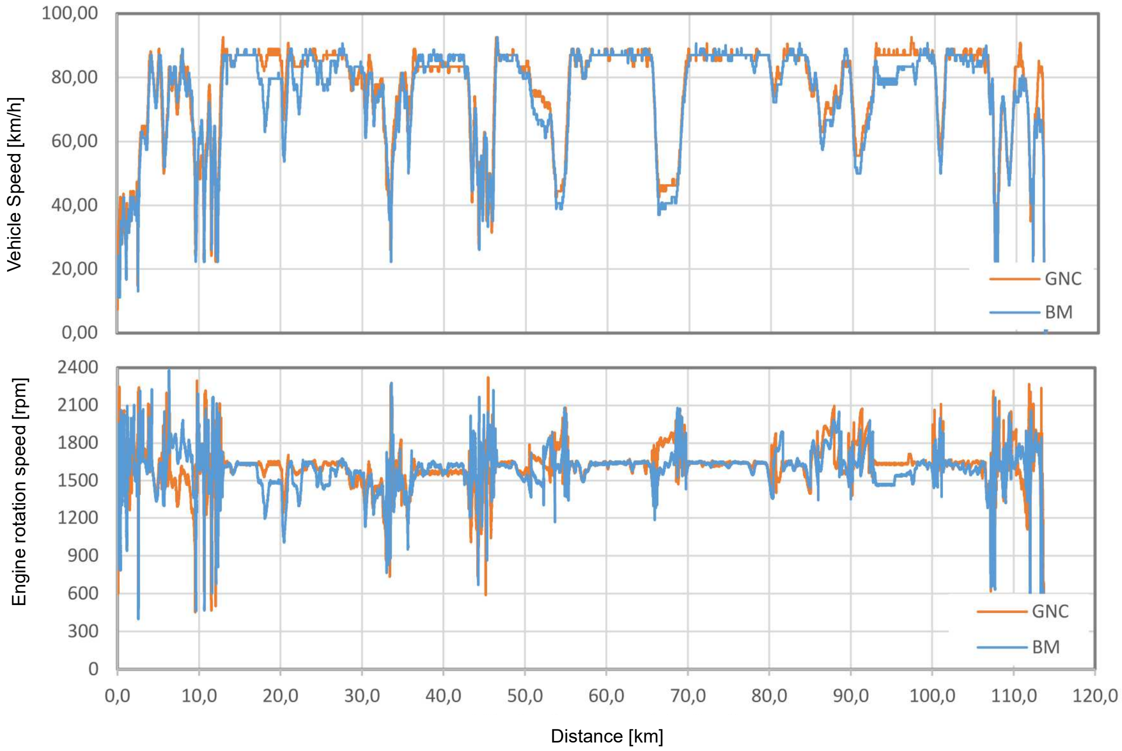

***Figure 6** – Representation of vehicle speed and engine rotation in trip considered.*

Accordingly, as can be verified, two segments were selected (route zone A and route zone B) where vehicle velocity and engine rotational speed remain closely matched in both cases, at approximately 86 km/h and 1620 rpm respectively. It should be noted that this engine speed is the most frequent occurring during the journey, corresponding to nearly 45% of the relative frequency of engine utilization (Figure 6).

Table 5 presents the mean values of velocity and engine rotational speed which, when considered in conjunction with the corresponding graphs presented in Figure 6, validate the similarity between route segments A and B when traversed by vehicle fueled with CNG and biomethane respectively. It is observed that in route zone A, the variation in velocity is negligible (0.01%) and the disparity in engine rotational speed is also entirely residual (0.12%), corresponding to a difference of 2 rpm. Analysis of the graphs in figure 6, supplemented by the data presented in Table 4, demonstrates that biomethane utilization corresponds to increased fuel consumption. This increase is less pronounced in the less demanding circuit (route segment A), but is considerably more significant in route zone B, where the gradient to be overcome requires the vehicle to operate at very high load levels exceeding 60% for most of the route.

The increased load associated with biomethane utilization corresponds to the necessity for greater throttle position sensor (TPS) opening, enabling the vehicle to meet the demands of the circuit. Greater throttle opening permits increased air intake, which in turn corresponds to elevated gas consumption, as observed with biomethane utilization. A direct relationship exists between increased load and the elevated consumption observed when the vehicle is fueled with biomethane. In route zone A, a 0.9% increase in fuel consumption is associated with a 1.34% increase in load, whereas in route zone B, a 6.98% increase in load corresponds to an 11.5% increase in fuel consumption.

Table 6. *Overall comparison of the values correspondent to zone A and B*

Zone A (km 55 a 62)

	BioM	GNC		Variation	
consumption	5.3	5.23	kg/h	1.34	%
Engine rotation	1619	1621	rpm	-0.12	%
Vehicle Speed	86.2	86.2	km/h	-0.01	%
Load	36.0	35.6	%	0.90	%

Zone B (km 70 a 80)

	BioM	GNC		Variation	
consumption	6.9	6.5	kg/h	6.98	%
Engine rotation	1633	1637	rpm	-0.24	%
Vehicle Speed	86.7	87.0	km/h	-0.34	%
Load	80.5	72.2	%	11.50	%

Average values

These results are consistent with those obtained from the dynamometer testing, where a 7% increase in specific fuel consumption was recorded when the engine operates at 1640 rpm. This value precisely corresponds to the consumption increase observed in route segment B, where the demands of the route require the engine to operate under high load conditions.

4. Conclusions

The execution of the initially planned programmed enabled completion of the intended evaluation, yielding the results necessary to assess the effects of purified biomethane utilization in a heavy-duty vehicle, compared to compressed natural gas utilization in the same vehicle under identical conditions, both in dynamometer testing and on the analyzed homologous road routes.

In the initial dynamometer tests, in which the engine was fueled with compressed natural gas as per normal operation, it was observed that power and torque values were significantly below those specified by the vehicle manufacturer. These results were determined to be attributable to a turbocharger malfunction, which was subsequently rectified through replacement. To ensure repeatable and comparable results, the vehicle tests using compressed natural gas, both on the dynamometer and on road, were repeated, thereby guaranteeing equivalent normal operating conditions for both the compressed natural gas tests and the subsequent biomethane tests.

For the analysis of on-road results, two route segments were selected where it could be ensured that results were not affected by external conditions. Each route segment corresponded to different engine demand scenarios, thereby enabling evaluation of distinct engine operating modes. The data obtained from these route segments are consistent with the dynamometer test results, particularly regarding the increased fuel consumption associated with biomethane utilization. However, when compared with the dynamometer tests, the most notable difference lies in the consumption values under these normal on-road vehicle operating conditions, where the increased biomethane consumption was found to be more pronounced.

Regarding the dynamometer results, these are consistent with expectations and with findings commonly reported in the literature—namely, that biomethane utilization in an engine entails a slight increase in fuel consumption relative to compressed natural gas. However, it should be noted that the observed consumption increase is not highly significant, with recorded differences ranging between 2% and 10%. The purification of the biomethane employed thus appears to attenuate the consumption differentials compared to those reported in other studies evaluating biomethane utilization.

With respect to performance, the recorded differences are marginal, both in terms of torque and power, with a maximum difference of 7.4% observed for power output. It should further be noted that when engine speed is within the 1625–1675 rpm range—corresponding to the vehicle's maximum cruising speed—no performance penalty is anticipated with biomethane utilization, given that under these operating conditions the available nominal power is only 1.2% lower than when compressed natural gas was used. When all operating regimes are considered, the aforementioned differences indicate a performance penalty for the engine when fueled with purified biomethane. Indeed, when evaluating specific fuel consumption which indicates engine efficiency level through the relationship between fuel consumption and energy effectively utilized for vehicle propulsion—it is observed that compressed natural gas enables enhanced engine efficiency.

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