

Performance and Emissions Comparison between Biomethane and Natural Gas Fuel in Passenger Vehicles

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Abstract. Bio-methane as fuel in a natural gas engine is a viable solution to reduce greenhouse gas emissions. The present paper illustrates the results of the first set of measurements carried out in the BiomethER project (EU-LIFE). BiomethER aimed to design and build two innovative bio-methane production plants, located in Emilia Romagna region (Italy), fed by different feedstock: the first one with sewage sludge and the other with landfill waste. Biogas extracted by the anaerobic digester was cleaned and upgraded to bio-methane for road vehicles application. To verify the compatibility of bio-methane in conventional compressed natural gas engine (CNG) vehicles, three passenger cars have been tested with two gases: conventional natural gas and bio-methane coming by BiomethER sewage sludge plant. Test concerned dynamic performances and exhaust emissions and was operated on the chassis dynamometer facility, in ENEA Casaccia Research Centre. Preliminary results showed no appreciable deviation was noticeable for fuel consumption and CO₂ emissions between the two fuels, acceleration and maximum power were almost the same for the three vehicles tested. The WTW evaluation of GHG emissions for the biomethane resulted in up to 79% lower in comparison with natural gas provided by the Italian pipeline.

1 Introduction

At present days one of the biggest worldwide challenges is the reduction of environmental impact produced by energy-intensive sectors largely depending on fossil fuels. Anthropogenic CO₂ originating from the combustion of carbon-based fuel is considered responsible for climate change along with other gases (methane, fluorinated gases, nitrous oxide). More efforts are underway to contrast the increase of average earth temperature and Conference of Parties (COPs) agreements stated in 2 °C the “red line” of maximum temperature increase beyond which an irreversible climate change will take place. In later

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years, the European Union (EU) launched several initiatives to contrast climate change and some were addressed to decrease the CO₂ emissions caused by the transport sector. It is recognized that almost a quarter of CO₂ emissions is originated by transport and that it is the main source of air pollution in urban areas. Within the transport sector, road transport is the biggest emitting source accounting for almost three-quarters of GHG emissions. EU strategies for transport decarbonisation includes a large set of measures to support the transition toward green mobility. Among them stand out an acceleration in deployment of low-emissions alternative fuel for transport, such as electricity, hydrogen, advanced biofuels, and spreading of low emissions vehicles. Directive 2014/94 (DAFI) established a set of measures for the deployment of alternative fuels infrastructure to promote the development of a large refuelling network including compressed and liquefied natural gas (CNG and LNG), hydrogen and electric energy.

The Renewable Energy Directive (RED) 2009/28 [1] settled national targets for the share of energy from renewable sources in transport in 2020 and established sustainability criteria for biofuels. Each member State shall ensure a share of renewable energy at least 10% from transport in 2020. Directive 2009/30 on Fuel Quality Directive (FQD) [2] sets a target for life cycles GHGs emissions reduction and defines the criteria of sustainability for biofuels inherent the GHG reduction, raw material, land use, and biodiversity protection. Finally, Directive 2018/2001 on the promotion of the use of energy from renewable sources (well-known as RED II) imposed a share of 14% of renewable energy for the transport sector with a sub-target for advanced biofuels of 3.5% in 2030.

The 2030 Climate & Energy framework includes important targets in the period 2021-2030 in terms of GHG emissions reduction, renewable energy increasing, and improvement in energy efficiency. Member States are invited to adopt national energy and climate plans for the period 2021-2030 to achieve these targets.

Accordingly to Eurostat statistics (updated up to 2018 [3] and [4]), all 2020 targets have been widely achieved and let hope the green revolution could happen. So, the EU raised the bar with 40% of GHG reduction and 27% of renewable energy by 2030 [5], with a potential reduction of 80-95% of GHG and 55-75% of gross final energy consumption from renewable sources by 2050 [6]. A role in these big challenges can be taken from bio-methane [7]. Biomethane is produced from biogas after a cleaning and upgrading process. There are two primary production pathways for biogas: landfill and anaerobic digestion of biodegradable material. Later, biogas is cleaned from impurities (i.e. ammonia, sulphur, and hydrogen components) and upgraded to biomethane removing CO₂. The current state of the art offers several promising processes to produce biogas through anaerobic digestion of organic compounds, from waste and agriculture scraps (as waste treatments, livestock, agricultural process and so on). Several research projects as BiomethER [8], Biosurf [9] and IEAGHG's studies (IEA Greenhouse Gas R&D) suggest biofuels could save GHG emissions up to 10-13% of the world's current emissions by 2050 [10].

BiomethER Project, co-founded by EU as part of LIFE programme, aimed to design and build two innovative bio-methane production plants in Emilia Romagna region (Italy), based on sewage sludge fermentation and landfill waste treatment (by separating the organic part of urban garbage) respectively. Specifically, the biogas derived from the sewage sludge plant is filtered and upgraded up to biomethane available for transportation. To replace the fossil methane with bio-methane in a natural gas vehicle (NGV), a comparison was performed to evaluate the energy and environmental performances of three identical vehicles powered by those two fuels.

Tests concern pollutant emissions and fuel consumption at dynamic roller bench on standard driving cycles and, accelerations and maximum power measuring on the chassis dynamometer, conducted mainly at ENEA Casaccia research centre (Fig. 1) in June and July 2019.



Fig. 1. One of the NGVs tested in the chassis dynamometer of ENEA facility

Being interesting to evaluate a trend in emissions, fuel consumption and dynamic performances at a various grade of engine wear the testing campaign will be repeated when vehicles will have reach 15000 and 30 000 km.

This paper reports the results of the first testing campaign, it is organized into four paragraphs: 2 Testing Campaign Description, 3 Well To Wheel GHG Emissions, 4 Results of Testing Campaign and 5 Conclusions.

2 Testing campaign description

The target of this experimental campaign is to make a comparison of the environmental and energy performance of NGV passenger cars powered with natural gas and biomethane. Cars under testing were three passenger cars equipped with a CNG engine complying with EURO 6 standard and belonging to the B segment. When tests starting all cars had 1000 kilometres covered (just the minimum required for a break-in).

A car was fuelled with natural gas available at refuelling station near the ENEA Casaccia test facility (Rome) while the other two were powered with biomethane coming from Roncoresi (RE) biomethane production plant.

The measurement concerns fuel consumption, emissions, and dynamic performances. All of them have been collected during the following tests on the dynamometer chassis: Driving cycle, Maximum acceleration, Maximum power. These procedures measure if there are any changes of performances during a common dynamic usage of vehicle, which stresses all parts (intake air pipes, valves, exhaust pipes, etc...) and all their mechanical and electrical settings. In this case, if there were an unwanted behaviour due to fuel characteristics or combustion process it would be also an evident power loss (in comparison with fuel approved).

The comparison of maximum power curves between two fuels highlights any differences in performance, such comparison becomes more important with the increase of engine wear. Main exhaust gas emissions, carbon dioxide (CO₂), carbon monoxide (CO), nitrogen oxide (NO_x) and hydrocarbons (HC), were collected by a Portable Emissions Measurement System (PEMS). Such system measured also the exhaust airflow (through a Pitot pipe and a Lambda probe), allowing an evaluation of the air/fuel rate and fuel consumption. In order to validate results obtained, it was compared the fuel consumption measure by PEMS with the one obtained from engine data, and provided by the manufacturer through On-Board Diagnostic (OBD) connection. Main data of vehicles are listed in Table 1.

Table 1. Nominal specification of test vehicle (OEM data).

Parameter	Description or value
Vehicle Type / Category / Year	Passenger car / M1 / 2018 (registration date)
Odometer reading	1000 km
Inertia Class	1185 kg
Fuel	Petrol and Methane
Emission standard	Euro 6C + Euro 6D TEMP
CO2 emissions (NEDC cycle)	89 g/km
Range	360 km (methane) + 800 km (petrol)
Tank capacity	12.5 kg of methane (about 75 l) + 40 l of petrol
Injection System / Aspiration	MPI / Turbocharged
Combustion Type	Homogeneous stoichiometric
After-treatment device	Three-Way Catalyst
Displacement / Number cylinder	999 cm ³ / 3
Max. Power / Max. Torque	66 KW (between 4500-5800 RPM) / 160 Nm (1900 RPM)

The vehicle year of approval is 2017, the registration date is 2018, so, they must comply with emissions tests with the NEDC driving cycle. In the present study, the authors choose to test also the newest WLTC driving cycle. In fact, from the 1st of September 2019, all the light-duty vehicles that are to be registered in the EU must comply with the WLTP standards.

The WLTP replaces the NEDC as European homologation test bench procedure. Perform a driving cycle on a dynamometer chassis allows a comparison avoiding all the variables of real driving: traffic jams, lights, weather conditions, driving style, and so on. In this research both NEDC and WLTC driving cycles have been tested, each one repeated at least three times. To perform a test at dynamometer test bench we need to know some vehicle powertrain specification as gear ratios, maximum power, weight, RPM working range of the engine; values of those parameters are described in Table 2.

The WLTC cycle lasts about 1800 seconds and the vehicle travel for 28.9 km with an average speed of 58 km/h. The acceleration test simulates the overtaking manoeuvres of vehicles in a real situation, starting at different speeds. In this case, the vehicle starts from 0 to 100 km/h and from 40 to 100 km/h.

Table 2. Nominal specification of vehicle powertrain.

Max power	Kerb mass	Max Rpm	Idling speed	Engine RPM - Vehicle speed (NV) ratio				
				1st	2nd	3rd	4th	5th
(kW)	(kg)	(rpm)	(rpm)					
67	1348	5500	950	126.53	65.63	43	29.58	22.59

The first part of acceleration test measures how long it takes to reach 100 km/h with a standing start, increasing the gear one by one. The second part concerns to engage the highest gear and decelerate vehicle speed under 40 km/h by using the cut off (both accelerator and brake pedals are in the full up position), immediately under 40 km/h the accelerator pedal goes in kick down, requiring maximum power to the engine.

The test ends when speed reaches 100 km/h. Test at maximum power aims to measure power up to the wheels, by using the dynamometer chassis with a standing start up to maximum speed, with proper gear shifting. It is analogue to maximum acceleration but the test ends when the vehicle reaches its maximum speed.

3 Well To Wheel GHG Emissions

Present analysis takes care of equivalent GHG emissions from the production/extraction of fuel up to its consumption in the NGV. Each fuel production chain is characterized by its GHG emissions [1] produced in three separated phases: raw material extraction (cultivation in case of biomass) and upgrading to become an energy carrier; transport and distribution up to the final customer; conversion from chemical energy to mechanical energy.

These three phases identify respectively three nodes of fuel chain that can be used to separate the emissions evaluation: well, tank and wheel. So, total GHG emissions can be analysed between those three nodes with the two steps of well to tank (WTT) and tank to wheel (TTW). The sum of the two contributions is the total GHG from well to wheel.

In the following are described those two steps for both fuels (biomethane and methane), then, a comparison of both WTW GHG emissions.

3.1 Natural gas

The study proposed by JR-EUCAR-CONCAWE [11] shows the natural gas plants all whole Europe and their CO₂ emissions due to extraction plants and transport through pipelines and Liquid Natural Gas (LNG) ships, also called methane tankers. These measurements include liquefying, filtering, and pressurizing treatments required to serve local storage and gas stations. The Italian Natural Gas (NG) extraction plants are in the Adriatic Sea and Italian southern regions, but they are not enough for Italian needs, so, Italy imports natural gas through pipelines from other countries: northern Europe (Russia, Netherland, Norway), Africa (Algeria, Libya and so on); at the same time it imports also Liquefied Natural Gas (LNG) regasified from Niger, Mozambique, Indonesia, Malaysia, and Algeria.

Such variety of gases implies differences of chemical composition, methane number, calorific value and Wobbe index (IW); see [12] for more details.

The present study adopts the Italian average of net calorific value (NCV), referred to 2017 data, it values 35.27 MJ/Nm³, while the European average values 35.7 MJ/Nm³. Emission factor value of CO₂ equivalent for NG EU mix is equal to 13 gCO₂eq/MJf. So, equation 1 allows calculating the total greenhouse gas emissions expressed as equivalent carbon dioxide per kilometre GHG_{WTT}km.

$$GHG_{WTT}^{km} \left[\frac{gCO_2eq}{km} \right] = \frac{C_f}{M_v} \cdot PCI \cdot GHG_{WTT} \quad (1)$$

The average consumption c_f equal to 30 g/km has been measured during the driving cycle on chassis dynamometer (see chapter “5 Results of testing campaign” in the following), fuel density M_v values 0.736 kg/Nm³, net calorific value (PCI) is 35.27 MJ/Nm³, GHG_{WTT} is 13.00 gCO₂eq/MJf, so, the results of equation 1 is 18.69 gCO₂/km.

The second part of the evaluation concerns emissions from TTW, it includes direct carbon dioxide due to combustion and to indirect emissions of unburned gases (i.e. hydrocarbons). The emission factors (IPCC) of equivalent carbon dioxide are shown in Table 3.

Table 3. Equivalent emission factors of green-house gases (IPCC).

Gas	IPCC [tCO ₂ eq/t]
CO ₂	1
CH ₄ (and HC)	25
N ₂ O	298

Equation 2 allows to calculate the GHG emissions, they are expressed as equivalent carbon dioxide per kilometre GHGTTWkm from TTW. The emissions of carbon dioxide (ECO2) is 82.24 gCO2/km, hydrocarbons (EHC) is 0.046 g/km, those two pollutants are measured within the WLTC driving cycle [13] on the chassis dynamometer. While, the nitrous oxide emission (EN2O) is not measured directly from exhaust gas but calculated adopting the EMEP/EEA emission factor equal to 0.001 g/km (tier 2 method, [14]). So, the result of equation 2 is 83.7 gCO2eq/km.

$$GHG_{TTW}^{km} \left[\frac{gCO2eq}{km} \right] = IPCC_{CO2} \cdot E_{CO2} + IPCC_{HC} \cdot E_{HC} + IPCC_{N2O} \cdot E_{N2O} \quad (2)$$

3.2 Biomethane

Italian regulations for biomethane fuel comply with a chemical composition of 97.3% of pure methane (CH4) and maximum residue in nitrogen, carbon dioxide and hydrogen of 2.2%, 0.02% and 0.025% respectively.

Table 4 shows the physical and chemical parameters of biomethane used by the BiomethER project, it has a gross calorific value (GCV) and an IW lower than Italian average values, respectively of 3 MJ/m3 and 2 MJ/m3. The methane number (MN) of BiomethER is close to pure methane (NM=100) while methane of Italian pipeline has an MN that ranges from 75 to 98 depending on sampling location. So, this new methane is suitable to replace natural gas in an internal combustion engine.

For biomethane produced from sewage sludge, the related tailpipe CO2 emissions are treated as biogenic and not considered to contribute as GHG. So, WTT CO2 emissions are equal to zero. The GHG emissions per unit of fuel values 14.8 gCO2eq/MJf [12], the carbon dioxide per unit of kilometre values 20.53 gCO2eq/km. This value does not include the additional HC and N2O produced during combustion within the engine, that can be evaluated as 1.38 gCO2eq/km, so, the GHG from TTW for biomethane values 21.53 gCO2eq/km.

Table 4. Physical and chemical parameters of biomethane used by BiomethER.

Parameter	Unit	Biomethane (BiomethER project)	Methane (Average of Italian pipeline)
Gross calorific value (GCV)	MJ/m3	36.76	39.11
Net calorific value (NCV)	MJ/m3	33.09	35.31
Wobbe index (IW)	MJ/m3	48.80	50.65
Density	kg/m3	0.729	0.733
Relative density		0.567	0.598
Molecular weight	mg/mol	16.34	16.86
Methane number (MN)		99.09	From 75 to 98

3.3 Well To Wheel GHG Comparison

Total greenhouse gases from well to wheel GHGWTWkm can be obtained by the sum of previous two evaluations: from well to tank GHGWTTkm and from tank to wheel GHGTTWkm.

Table 5 summarizes the comparison of results, it highlights that biomethane cycle life outputs 79% less GHG than traditional methane. The testing campaign was conducted in ENEA research centre of Casaccia, the acquisition instrumentation included: the chassis dynamometer (made by Assing), the Horiba OBS1300 (PEMS), and an OBD diagnostic

software made by ENEA researcher to collect engine data through Original Equipment Manufacturer (OEM) sensors.

Table 5. Comparison of greenhouse gas emission from well to wheel for both fuels analysed, values are in gCO₂eq/km.

Parameter	Biomethane	Methane
Well to tank (WTT)	0.00	18.69
Tank to wheel (TTW)	21.45	83.70
Total GHG emission	21.45	102.40

4 Results of testing campaign

Fig. 2 shows the cumulative trends of main pollutants during a WLTC driving cycle. They rise greater when there is a deep acceleration with high loads requested to the engine, e.g. the NO_x between 1100 and 1200 seconds has a rapid growth. The carbon monoxide has the highest growth between 1400 and 1800 seconds; when the speed rises over 100 km/h and the power is closest to the maximum available.

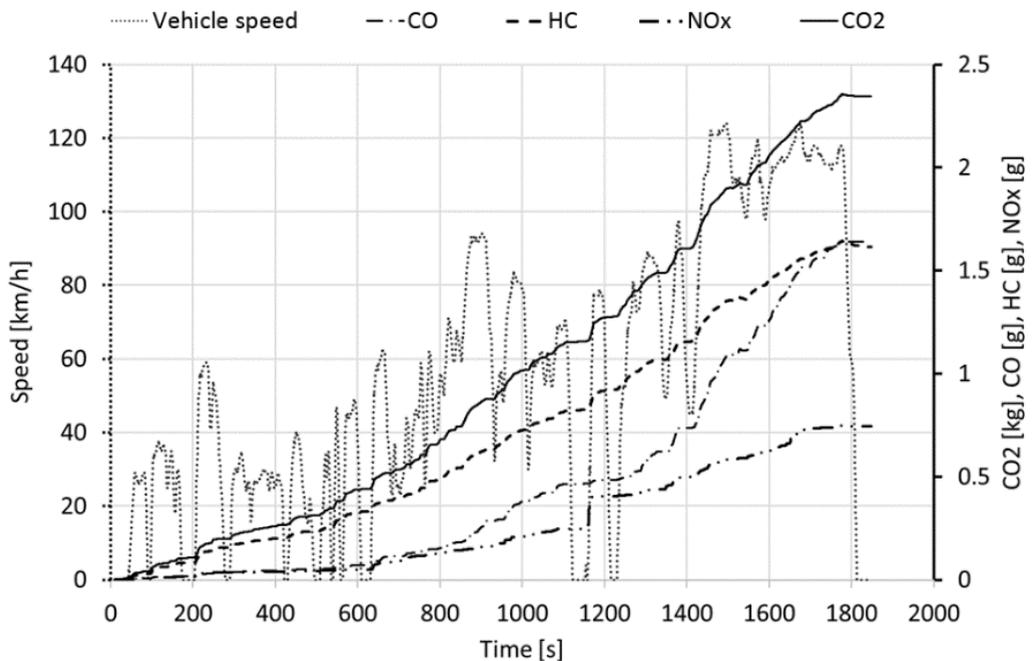


Fig. 2. Cumulative curves of pollutant during a WLTC driving cycle.

Fig. 3 shows the fuel consumption and the carbon dioxide emissions for the three vehicles tested, where vehicle number 3 is the one powered by traditional methane. The three vehicles consume between 30 and 31 g/km of fuel. The carbon dioxide emissions are between 79 and 87 g/km, they comply with the next EU regulations that prescribe 95 g/km as limit by January the 1st of 2020, then postponed to January 1st of 2021 [1].

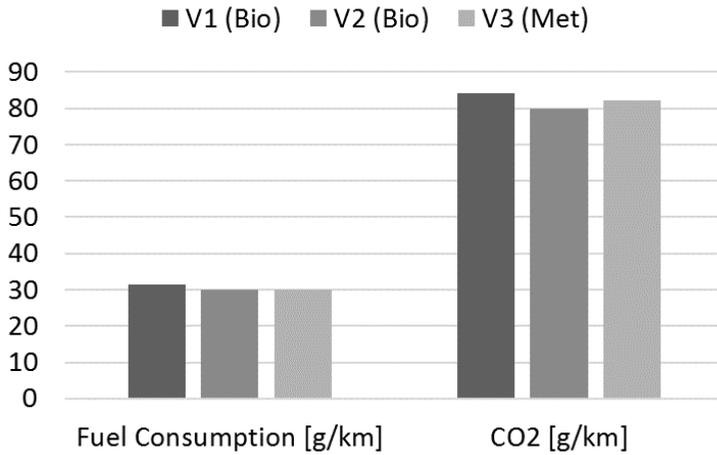


Fig. 3. Comparison of fuel consumption and CO2 emissions during a WLTC driving cycle.

Fig. 4 confirms that vehicle tested have all emissions under the regulatory limits independently by fuel, they are indicated in the same figure with dotted lines (1 g/km of CO, 0.06 g/km of NOx, and 0.1 g/km of HC). Hence, both biomethane powered vehicles (V1 and V2) emits 33% NOx lesser than the traditional methane, while HC and CO have not enough differences.

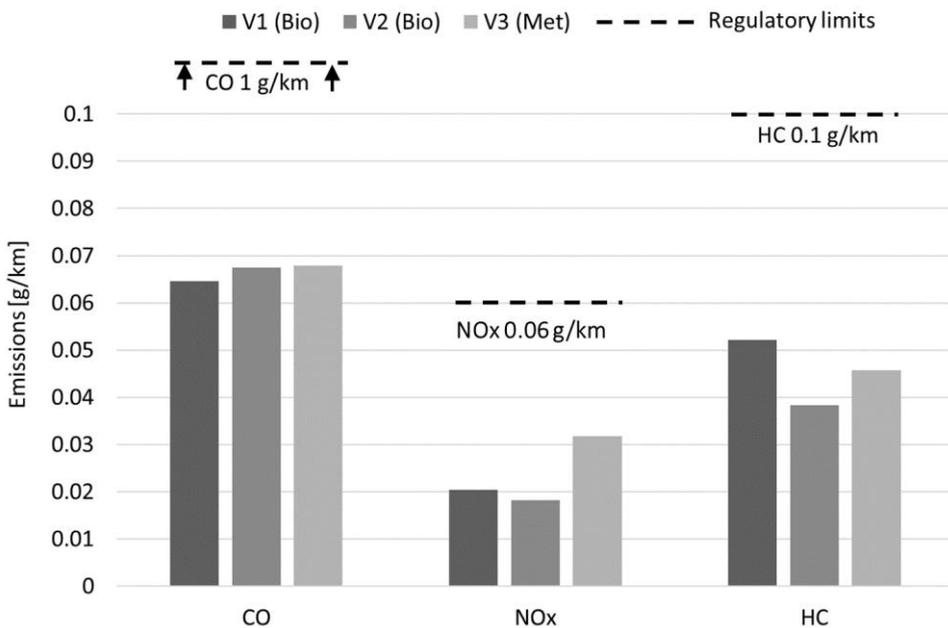


Fig. 4. Pollutants measurements during a WLTC driving cycle.

Table 6 summarizes results achieved during the WLTC and NEDC driving cycles seen in Fig. 3 and Fig. 4. The NEDC test on V2 is not available due to technical reasons.

Table 6. Results of measurements during NEDC and WLTC driving cycles.

		Distance	Fuel consumption	CO ₂	CO	NO _x	HC
Vehicle	Driving cycle	km	g/km	g/km	g/km	g/km	g/km
V1 (Biomethane)	NEDC	11.0	32.462	87.649	0.040	0.033	0.062
	WLTC	28.9	31.302	84.265	0.065	0.020	0.052
V2 (Biomethane)	WLTC	28.9	29.954	79.868	0.067	0.018	0.038
V3 (Methane)	NEDC	11.0	32.227	88.423	0.049	0.059	0.063
	WLTC	28.9	30.059	82.243	0.068	0.032	0.046

Table 7 summarizes results of acceleration tests. Each test has been repeated several times to improve driver skills (shifting timing and vehicle behaviour). So, Table 7 shows the better results achieved, represented by the lowest time for each test.

Table 7. Results of acceleration tests in seconds.

Vehicle	40-110 km/h	0-100 km/h
V1 (Biomethane)	23.7	12.4
V2 (Biomethane)	23.8	13.7
V3 (Methane)	23.4	13.0

Fig. 5 shows the results of maximum power tests, each vehicle repeats two times the test. The maximum power is greater than or equal to the vehicle manufacturer's declaration (67 kW), for V1 and V2 (the biomethane vehicles) is between 67 and 69.5 kW, and the torque is between 150 and 165 Nm. Thus, the power of V3 is between 69 and 71 kW and the torque is between 169 and 173 Nm. The results show power and torque losses, respectively of 2.9% and 7.5% by biomethane vehicles in comparison with traditional methane. Such differences belong to sensors tolerance fields and not directly connected to the fuels.

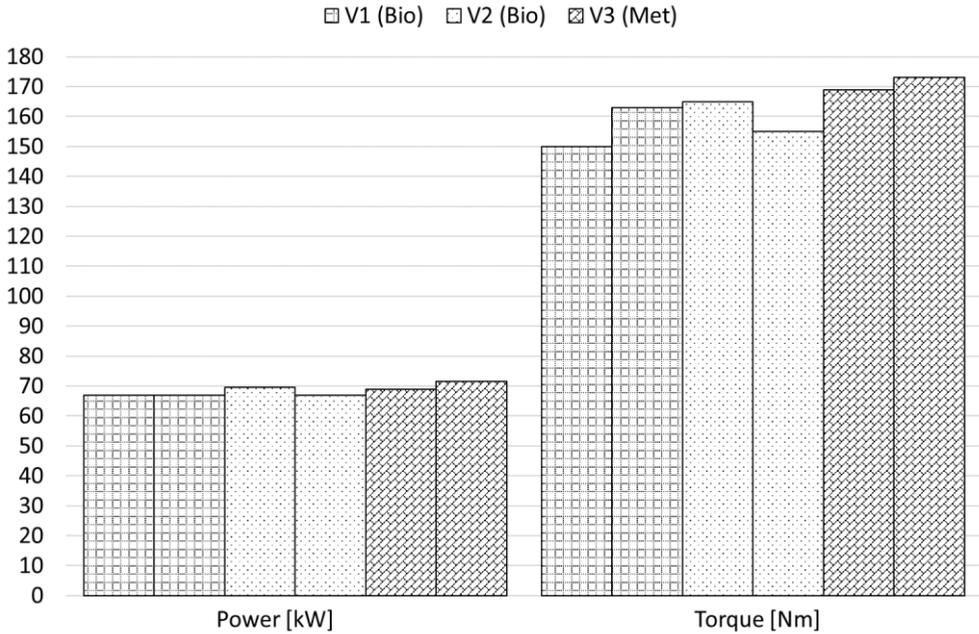


Fig. 5. Power and Torque comparison.

Fig. 6 shows the power trends related to the engine revolution (RPM), only one measurement for each vehicle has been shown. There is a little power loss for V1 when the engine RPM is between 3500 and 5000. The tests of V1 show a power loss between 4000 and 5000 RPM, it has also a large gap in comparison with V2. The V2 is close to V3. The large gap between the two curves V2 and V3 is attributable to a driver error during a gear shift. The maximum power test is done manually at roller bench, the driver should release the accelerator pedal and press clutch pedal in the right time with same engine RPM for all the tests, maybe V3 curve has a non-perfect timing during a shift (e.g. between third and fourth gear) so the engine can't express maximum power as the other tests.

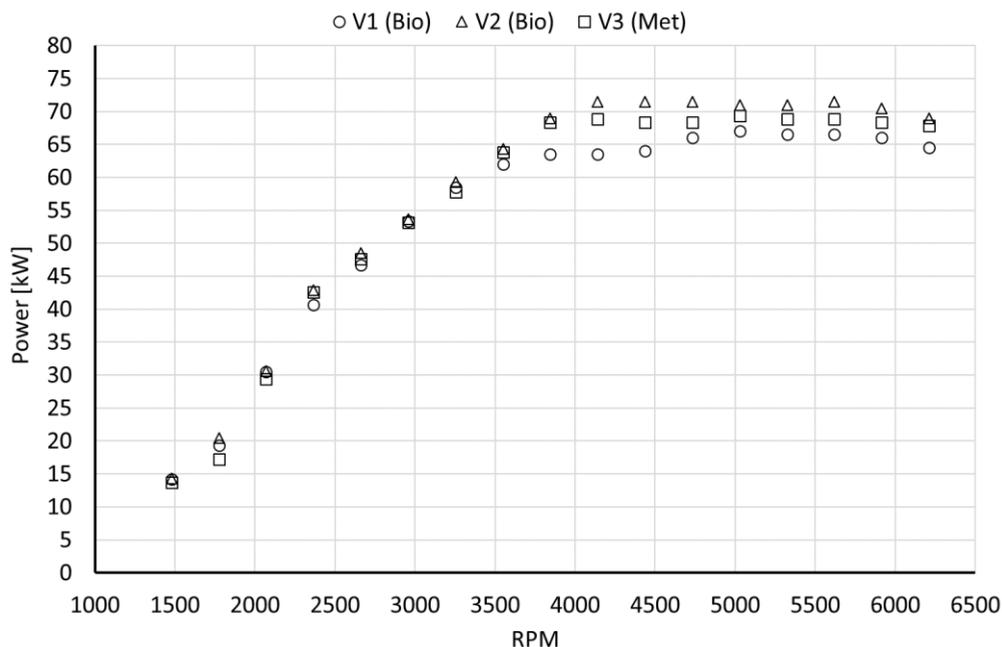


Fig. 6. Power versus RPM trend.

5 Conclusions

The present paper describes an experimental campaign of project BiomethER, where a biomethane fuel replaces the traditional (non-renewable) methane in a natural gas vehicle (NGV). This is the first of three campaigns within the project, vehicles tested have less than 15000 km each. The other two campaigns are foreseen when the vehicle odometers will reach 15 000 km and 30 000 km.

Three vehicles have been tested by measuring fuel consumption, emissions, and dynamic performances. Two vehicles are powered by biomethane and the other one by traditional methane. Moreover, it has been evaluated the equivalent carbon dioxide emission per kilometre from well to tank and from tank to wheel. The comparison highlights that biomethane cycle life from well to wheel outputs 79% less GHG than traditional methane (21 gCO₂eq/km of biomethane against 102 gCO₂eq/km of methane). Such difference is due to less emission in the well to tank path.

The tests have been conducted to research centre ENEA by using a chassis dynamometer, a PEMS and an OBD diagnostic measurement system.

Results of emissions measurements are:

- Fuel consumption and Carbon dioxide are equal for all vehicles, they need an equal amount of gas to fulfil the WLTC or NEDC driving cycles.
- The amount of CO₂ is just under 95 g/km, so, it complies with the future EU limits by January 2021.
- The CO and HC pollutant emissions are not affected by fuel.
- The biomethane vehicles emit 33% less NO_x than the other powered by methane.
- All vehicles emit pollutants under regulatory limits as manufacturer's declaration.

Dynamic performance comparison shows:

- Time of acceleration from 0 to 100 km/h and from 40 to 100 km/h are not affected by fuel.
- All vehicles have a maximum power greater than or equal to 67 kW (as declared by manufacturer).
- The torque varies between three vehicles with a maximum value of 14% from the smallest to the largest, equal to 25 Nm in comparison with 175 Nm of maximum torque for V3).
- All vehicles have a comparable power curve within the engine working range (RPM)

The small differences just explained can be attributed to external variables that are not be evaluated, e.g. sensors tolerances or environmental temperature (some tests were done in the morning and some others in the afternoon).

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