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 NOx 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.

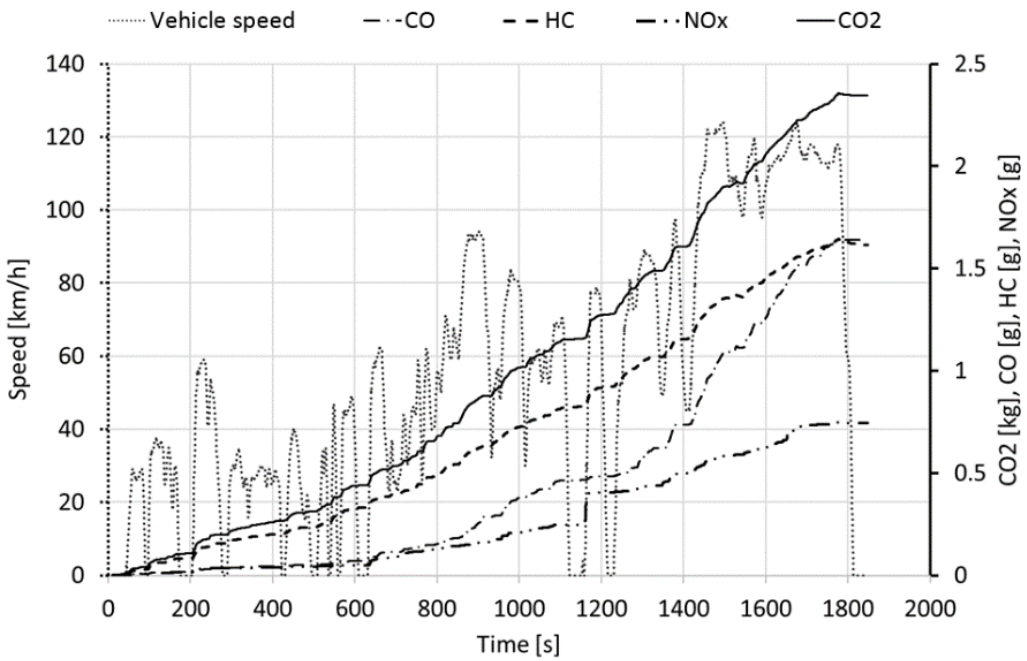

Fig. 2. Cumulative curves of pollutant during a WLTC driving cycle.

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].

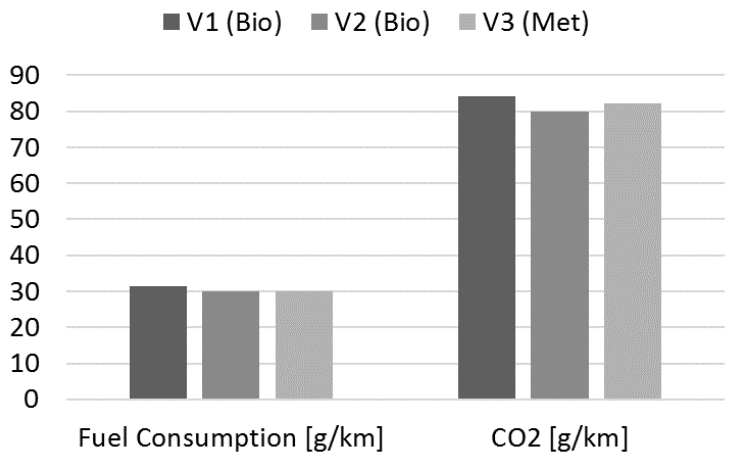

Fig. 3. Comparison of fuel consumption and CO2 emissions during a WLTC driving cycle.

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.

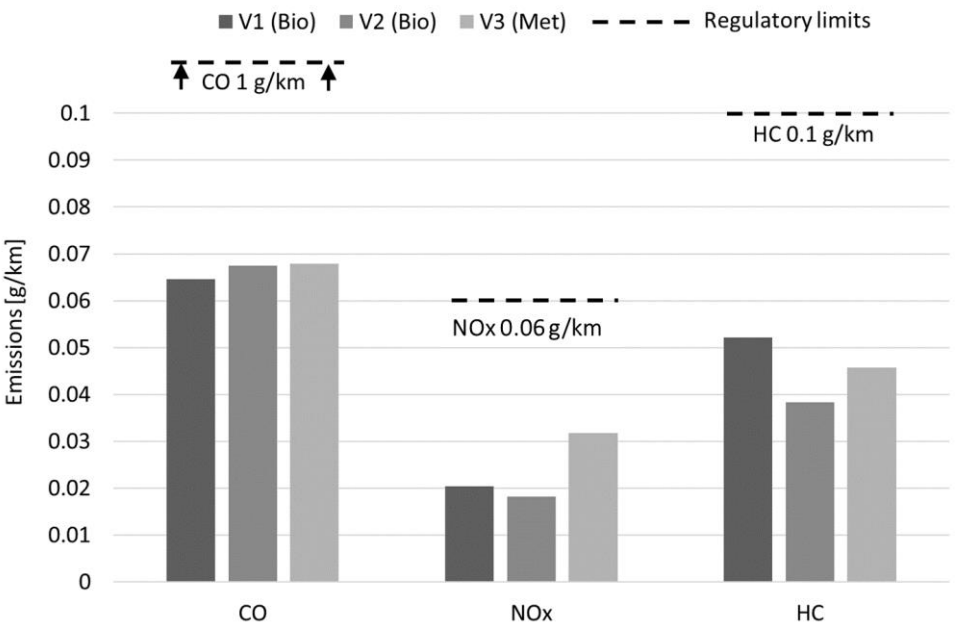

Fig. 4. Pollutants measurements during a WLTC driving cycle.

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**	**CO2**	**CO**	**NOx**	**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.

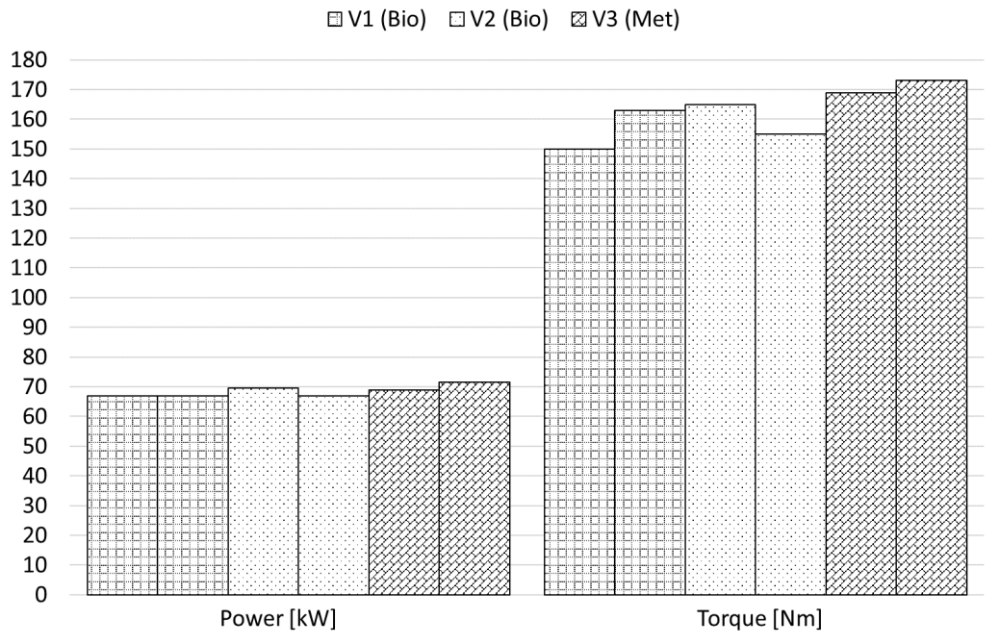

Fig. 5. Power and Torque comparison.

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.

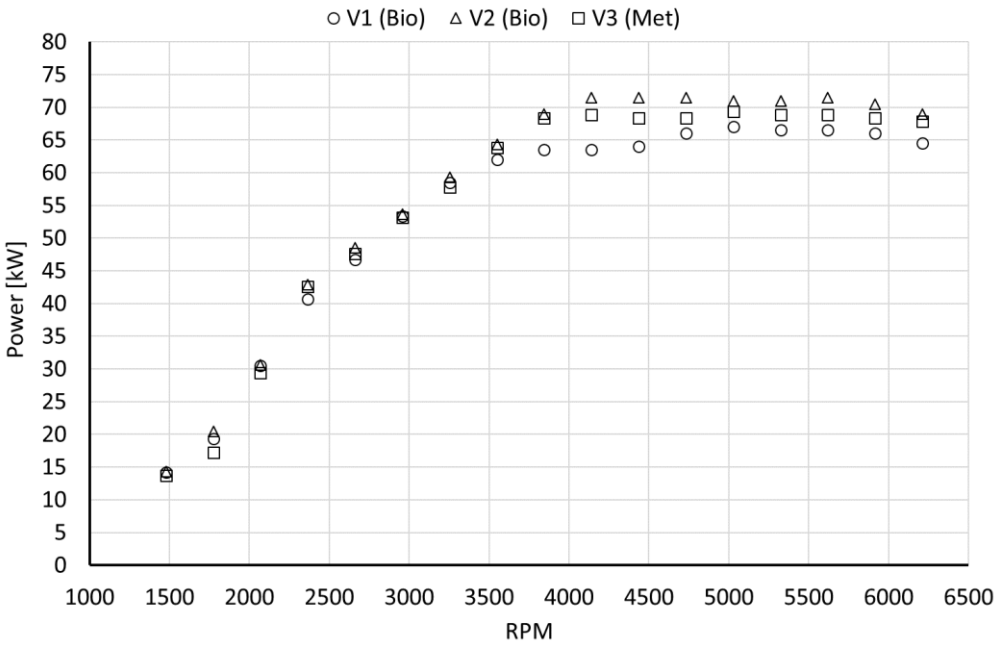

Fig. 6. Power versus RPM trend.

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 NOx 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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References

1. Official Journal of the European Union, «directive 2009/28/EC of the European Parliament and the council,» (23 April 2009). [Online]. Available: http://www.nezeh.eu/assets/media/fckuploads/file/Legislation/RED_23April2009.pdf. [Accessed on 20 January 2020].
2. Official Journal of the European Union, «directive 2009/30/EC of the European Parliament and the council,» (23 April 2009). [Online]. Available: https://eur-lex.europa.eu/lexuriserv/lexuriserv.do?Uri=OJ:L:2009:140:0088:0113:EN:PDF. [Accessed on 20 January 2020].
3. Eurostat, «Energy from renewable sources,» [Online]. Available: https://ec.europa.eu/eurostat/web/energy/data/shares. [Accessed on 20 January 2020].
4. Eurostat, «Energy, transport and environment indicators,» (2018).
5. European Commission, «A policy framework for climate and energy in the period from 2020 to 2030,» 22 January 2014. [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2014%3A15%3AFIN. [Accessed on 21 January 2020].
6. European Commission, «A Roadmap for moving to a competitive low carbon economy in 2050,» (8 March 2011). [Online]. Available: http://www.europarl.europa.eu/meetdocs/2009_2014/documents/com/com_com(2011)0112_/com_com(2011)0112_en.pdf. [Accessed on 22 January 2020].
7. E. Ryckeboscha, M. Drouillon, and H. Vervaeren, «Techniques for transformation of biogas to biomethane,» Biomass and bioenergy, vol. 35, pp. 1633-1645 (2011).
8. BiomethER project, «Chi siamo,» (2012). [Online]. Available: http://www.biomether.it/p/chi-siamo.html. [Accessed on 22 January 2020].
9. Biosurf project, «About Biosurf,» (2016). [Online]. Available: http://www.biosurf.eu/en_GB/about-biosurf/. [Accessed on 21 January 2020].
10. IEAGHG, «WHO ARE IEAGHG,» [Online]. Available: https://ieaghg.org/about-us/what-do-we-do. [Accessed on 22 January 2020].

11. European Biogas Association, «EBA Annual Report 2019,» (2019). [Online]. Available: https://www.europeanbiogas.eu/wp-content/uploads/2020/01/EBA-AR-2019-digital-version.pdf. [Accessed on 23 February 2020].
12. L. Beibei, W. Qi, Z. Bing, and B. Jun, «Life cycle GHG emissions of sewage sludge treatment and disposal options in Tai Lake Watershed, China,» Science of The Total Environment, vol. 447, pp. 361-369, (2013).
13. Y. Xiyue, M. Hailin, Z. Heran, X. Zhaoquan and L. Nan, «Environmental impact and economic benefit evaluation of sewage sludge treatment technologies,» (IOP Conference Series: Earth and Environmental Science, 2020).
14. Joint Research Centre of the European Commission, «Well-to-wheels analysis of future automotive fuels and powertrains in the European context,» Publications Office of the European Union, Luxembourg, (2014).
15. SNAM rete gas, «Gas tipici immessi in rete anno termico 2017-2018,» (14 November 2019). [Online]. Available: http://misura.snam.it/portmis/coortecDocumentoController.do?menuSelected=4300. [Accessed on 10 February 2020].