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Full Length Article

Pollutant emissions from Euro 6 light duty vehicle tested under steady state and transient operation on a roller test bench with hydrogenated paraffinic and biodiesel fuels

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ABSTRACT

The effort to implement more environmental-friendly fuels has been enhanced not only by the desire to reduce the greenhouse effects but also for public health issues. This paper studies the effects on pollutant emissions from a light-duty Euro 6 vehicle with four types of fuel: diesel (fossil origin, used as reference), biodiesel (renewable origin), Gas-to-Liquid (fossil origin) and farnesane (renewable origin). Both stationary engine and real-world driving cycles are studied. First, each fuel was tested in stationary modes in a vehicle test-bench and then tested in a realistic driving cycle with the same vehicle. This allows the separation the transient effects of the driving cycle from stationary results. Stationary tests lead to engine emission maps and driving cycle tests allow weighting the importance of each stationary condition during a realistic route. Instantaneous and cumulative CO, THC (total hydrocarbon), NO_x and PN (particle number) emissions on route were obtained. The fuel that presented a highest level of emissions at stationary conditions was, for CO, diesel, for THC, diesel, for NOx, biodiesel and for PN, diesel. The behaviour of fuels during the driving cycles, from less pollutant to more pollutant, was: for CO, diesel, farnesane, GTL and biodiesel; for THC, GTL, farnesane, biodiesel, diesel. For NOx, farnesane and diesel (very similar values), GTL and biodiesel; for PN, GTL, biodiesel, farnesane and diesel.

1. Introduction

Passenger and commercial vehicles on the road represent a large fraction of the global energy consumption. The current tendency in new developments of internal combustion engines is to make engines more adiabatic [1], increasing the indicated work and the exhaust flow enthalpy, which can be later recovered via thermoelectric generators [1–4] or Organic Rankine Cycles [5,6]. Another trend is the hybridization of vehicles [7,8].

Other paths to mitigate pollutant emissions are after-treatment devices. In diesel vehicles, must use aftertreatment devices are Diesel Oxidation Catalysts (DOC) for THC and CO oxidation [9], Diesel Particle Filters (DPFs) for retention of particulate matter (PM). Lastly, with the Euro 6 standard, Selective Catalytic Reduction (SCR) [10,11,12] and Lean NO_x Traps (LNTs) have been introduced for reducing NO_x emissions [13].

To reach the independence from fuels with fossil origin and to comply with environmental regulations, the use of renewable or alternative has been promoted. Alternative fuels for use in Diesel engines, can be classified, according to their molecular structure, in three groups: fatty acid methyl or ethyl esters (known as biodiesel) [14,15,16], blends of alkanes with olefins [17,18,19,20,21], and different types of isoprenoids [22].

The most important characteristics of biodiesel are the presence of molecular oxygen and the absence of aromatic compounds. Both favor a combustion process with less smoke. As discussed in [14], many published works have reported increases of NO_x emissions during biodiesel fuel combustion compared to diesel fuel combustion. Involved phenomena that increase biodiesel NOx emissions relative to conventional diesel are: advances in engine combustion phasing leading to a longer

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residence time, higher in-cylinder temperatures, and lower radiative heat loss due to less in-cylinder soot production, leading to higher actual flame temperatures [23]. Other disadvantages of biodiesel fuel are: the difficulty of flowing under cold conditions, a lower volumetric heating value and the tendency to oxidize.

Hydrotreated vegetables oils (HVO) are blends of alkanes and olefins. However, their properties are like those of diesel fuels. Most of the published works on HVO have reported less THC and PM emissions [17,18,19]. In most of cases, authors have attributed these results to its paraffinic molecular structure without aromatic compounds in its composition.

A different way to obtain fuel blends composed by alkanes and olefins is called the Fischer – Tropsch process. With this process is typical to obtain three different types of synthetic fuels, in many cases denoted as XTL, where X means C - coal, G - gas, or B- biomass [22].

Another non-negligible group of compounds used as fuels is that obtained from isoprene. In this case, farnesane is the most used and reported as a fuel. This fuel is obtained from sugar cane subproducts by means of a biotechnology process. The most important characteristics of this fuel are its high heating value and high cetane number. The high cetane number together with their low freezing point makes this type of fuel a potential candidate not only for using as diesel fuel, but also as an aviation fuel. [22].

To assess the effect of different fuels on pollutant emissions and fuel consumption in real conditions, driving cycles are employed. Most studies focus on transient measurements of pollutant emissions during these cycles.

Ramos et al. [22] presented results related to performance, combustion timing and emissions for a light duty vehicle at three different altitudes were assessed. Comparisons between animal fat biodiesel, GTL and diesel fuels were presented. It was found that altitude particularly increases the combustion duration of paraffinic fuels and NOx emissions.

Using Real Driving Emissions (RDE) procedures, Gallus et al. [24] tested and compared results of two types of vehicles (Euro 5 and 6). Tests were done using different driving styles. Results from these tests showed a great effect on both CO_2 and NO_x emissions.

In Triantafyllopoulos et al.[25], the authors assessed the potential of a SCR device for reducing NO_x emissions compared to the limits established for RDE tests. In another work [26], the authors tested a medium size Hatchback, a large size Station-wagon and a light duty Sedan, following two routes. Authors observed that vehicles fulfilled the RDE limits established.

Following the Worldwide Harmonized Light Vehicle Test Procedure (WLTP), Luján et al. [27] worked on the optimization of systems for controlling pollutant emissions. The work was done using a hybrid vehicle, equipped with diesel engine. The objective of the work was to reduce the fuel consumption without increase of NO_x emissions beyond the restrictions established by legislation.

On-board pollutant emissions determination is a not an easy task. For this reason, the development of experimental and calculation methodologies for determining or predicting pollutant emissions has been a recurrent objective of different works. For example, Oliveira et al. [28] developed and published a model for estimating NO_x emissions using different types of vehicles, depending on both the propulsive system configuration and the driving conditions. In [29], the authors developed a calculation procedure for optimizing efficiency, remaining constant CO_2 and other pollutant emissions. In [30], authors proposed a method to assess the effect of the acceleration and vehicle power on CO_2 and NO_x emissions. These authors found different measured variables correlated with vehicle power. Obtained results indicate that these measured variables constitute a good tool to predict CO_2 emission rates. However, these variables do not predict NO_x emissions with good accuracy.

García-Contreras et al. [31] carried out RDE tests using two different Euro 6d-Temp Diesel light-duty vehicles (Peugeot 308 and BMW X1) in Madrid City (Spain). The authors reported that these vehicles produced similar values of emissions in comparison with spark ignition vehicles. Nitrogen oxides and number of particles emitted were around 70 and 90% lower than the normative limits, respectively.

Gomez et al. [32] performed a comparison of real driving emissions from Euro VI buses with diesel and compressed natural gas (CNG) fuels, respectively. Both buses were tested following the Euro VI In Service Conformity (ISC) requirements. Tests were carried out in Madrid, Spain. Compared to Euro VI C stablished limits, with both types of buses very low emissions were registered. In this work, authors observed that THC emissions from CNG bus were approximately twice than those registered with Diesel bus. For the Diesel bus, equipped with a SCR device, slightly higher NOx emissions were registered mainly along the urban part of the circuit. The authors explained this result arguing that the exhaust gas temperature and the SCR temperature were below the light-off temperature. The authors also observed a significant emission of particles produced by the CNG bus. This observation was important along the rural part of the test circuit. Authors also observed that NO_x and particle emissions were mainly influenced by the urban traffic.

Puricelli [33] studied the effects of innovative blends of petrol with renewable fuels on the exhaust emissions of a GDI Euro 6d-TEMP car. The tested renewable components were bioethanol, bionaphtha, bio-ETBE, and methanol. Exhaust emissions were compliant with Euro 6 (WLTC tests) and Not-To-Exceed (RDE tests) limits. It showed that blending petrol, ethanol, and bionaphtha reduces CO_2 emissions and fuel consumption.

Some experiments and models rely on stationary or pseudo-stationery tests to assess or predict pollutant emissions. But real results are transient, as some above-mentioned studies. The target of this work is to analyze the effects on pollutant emissions (CO, THC, NO_x and PM) on a real route with four different fuels: diesel, GTL, biodiesel and farnesane. Two phases of the study were carried out: engine mapping via pseudo-stationary tests and driving cycles. The main novelty of this study is that particularities of emission engine maps with each fuel are highlighted and their influence in driving tests is assessed. This allowed a comparative study of stationary and real driving methods to assess pollutant emissions.

2. Materials and methods

The methods described in this section were applied to driving strategies of a diesel Nissan X-Trail. First, an engine mapping on a test-bench was done to obtain data of representative parameters for any engine requested output. Later, a characterization of a selected route in terms in altitude above sea level and maximum permitted speed in each segment was done.

2.1. Fuels tested

In this work four fuels were tested, a fossil diesel fuel without biodiesel content was used reference fuel, a natural gas GTL alternative synthetic fuel, a renewable fatty acid methyl ester (FAME) fuel (denoted as Biodiesel), obtained from 72% of soybean and 28% palm oils, an *iso*-paraffinic renewable fuel, called Farnesane. In Table 1, the main fuel properties used in this work are presented. In all cases sulphur content was 0 or below 10 ppm by weight.Fig. 1.

2.2. Vehicle

The vehicle used in this study was a Nissan X-Trail with a 1.6 L, turbocharged, diesel engine equipped with high-pressure and low-pressure EGR (Exhaust Gas Recirculation). The parameters provided by the ECU (Electronic Control Unit) of the vehicle were used for the analyses carried out. Table 2 summarizes vehicle and engine characteristics.

Table 1
Characteristics of fuels used in this work.

Characteristics	DIESEL	GTL	BIODIESEL	FARNESANE
Chemical formulation	$C_{15.18}H_{29.13}$ [a]	$C_{16.89}H_{35.77}$ [a]	$C_{18.52}H_{34.52}O_2$ [b]	$C_{15}H_{32}$
Molecular mass (g/mol)	211.4[c]	238.6[c]	289.25	212.41
H/C relation	1.92	2.12	1.86	2.13
Stoichiometric fuel/air ratio	1/14.64	1/14.95	1/12.46	1/14.92
Carbon (% w/w)	86.13	84.82	76.91	84.91
Hydrogen (% w/w)	13.87	15.18	12.03	15.09
Oxygen (% w/w)	0	0	11.06	0
Density @ 15 °C (kg/m^3)	843	771	883	770
Viscosity @ 40 °C (cSt)	2.97	2.57	4.2	2.32
Lower Heating Value (MJ/kg)	42.43	43.86	37.14	43.39
Cetane number	54.2	>73	53.3	56.7
Cold filter plugging point (°C)	−17	−7	0	−40
Distillation curve (vol.)				
10%	207.6	213.9	279.5	
50%	278.2	269.3	282.7	
90%	345.0	340.7	302.2	

[a] *Determined by the molecular mass and the % of different hydrocarbon families, in GTL case, a paraffinic structure was considered.*
[b] *Determined by means of the composition of basic esters.* [c] *Determined by means of the AspenTech HYSYS software, using CHNS analysis and density.*

2.3. Experimental facilities for measuring pollutant emissions

A HORIBA OBS-ONE portable emissions measurement system (PEMS) was used to measure CO, CO_2, NO, NO_2, NO_x, and THC and Particle Number with different. A detailed description of this PEMS can be found in [31].

2.4. Test route

The vehicle was initially tested in Valencia province (Spain). The main objective of these tests was to register the vehicle velocity profile which was affected by actual traffic conditions. Then reproduce this profile with the same vehicle on a chassis dynamometer. A route from Valencia (approximately 0 m above sea level) to Olocau (approximately 300 m ASL) was chosen (see Fig. 2).

This route comprises an urban driving zone in a populated city and extra-urban driving before reaching the destination. The maximum speed during the route was 120 km/h. The total distance travelled was 33 km. An initial driving test along the route to gather altitude and speed limit information was carried out. This data is shown in Fig. 3.

2.5. Engine mapping

Bench tests were done to characterize the engine map. The tests were carried out maintaining a constant engine speed and the torque was increased to sweep the engine map (see Fig. 4). The full load conditions were not reached, since they were not necessary to simulate the route.

3. Results

Following the methods described in the previous section, the engine maps with the pseudo-stationary operating modes for each fuel were obtained and are presented in subsection 3.1. Later, results of the driving cycles are shown in subsection 3.2.

3.1. Engine maps

3.1.1. CO emissions

Fig. 5 shows the exhaust gas CO concentration for the tested part of the engine map. A general increase in the high load, low engine speed part of the tested map can be appreciated. This increase is more pronounced for diesel fuel, followed by farnesane and GTL fuels. The biodiesel shows very low levels throughout all the tested conditions, but there is a slight increase in in the low load, low regime part of the engine map. In addition, the diesel fuel emits more throughout the whole tested area, being that the base value is higher than for the other fuels (slightly lighter blue color in Fig. 5).

Table 2
Vehicle specifications.

Mass (kg)	1575 kg
Engine	CI, turbocharged
Displacement (cm^3)	1598
Max torque @ 1750 min^{-1} (Nm)	320
Max power @ 4000 min^{-1} (kW)	96

Fig. 1. View of the vehicle used during the tests (Nissan make X-Trail model).

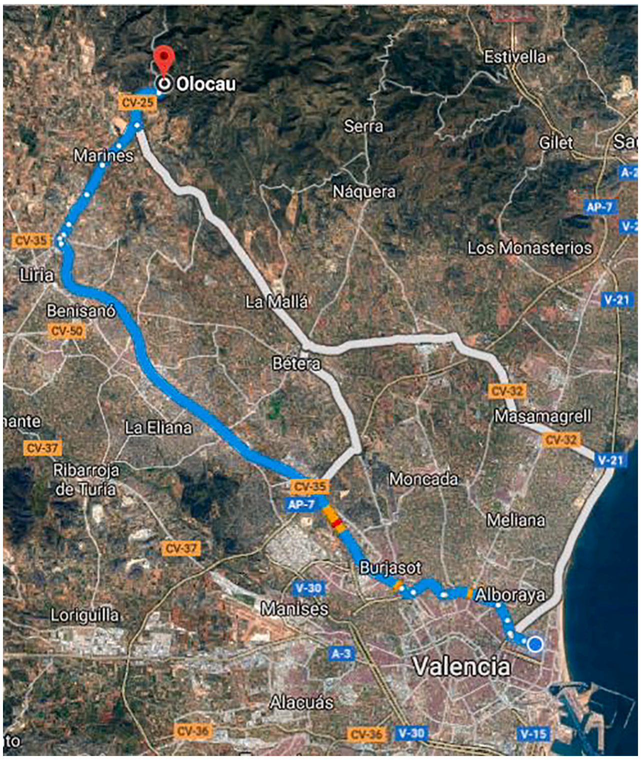

Fig. 2. Route followed during the driving cycle.

3.1.2. THC emissions

Fig. 6 shows the exhaust gas THC (total hydrocarbon) concentrations within the tested part of the engine map. The THC follows a trend similar to that seen for CO emissions. There is again a general increase in the high load, low engine speed part of the tested map that can be seen. This increase is more pronounced for diesel fuel, followed by farnesane and GTL fuels. There is also an increase in the low load, low regime part of the engine, being more pronounced for biodiesel fuel that for diesel and GTL. This second zone of THC production could not be appreciated for farnesane.

Lower THC emissions were registered when biodiesel, GTL and farnesane fuels were consumed. This result could be justified by the high cetane number and a better vaporization of both paraffinic fuels (GTL and farnesane) while, in case of biodiesel fuel, by its oxygen content which leads to a better combustion process.

3.1.3. No_x emissions

In this section, results for NO and NO_x are presented separately. Fig. 7 shows the exhaust gas NO concentration within the tested part of the engine map. NO emissions show an increase in the high load, middle-to-high engine speed part of the tested area. Higher values are obtained for the conventional diesel fuel, whereas for biodiesel a wider high-emission zone, compared with the other three fuels, appears.

In the case of NO_x concentrations (Fig. 8), the same tendencies appear. As for differences with respect to NO concentration, not only does biodiesel have a the wider high-emission area corresponds to the biodiesel fuel, but biodiesel also has higher concentration values.

Higher NO_x concentrations were registered with the biodiesel fuel. These results could be also explained, by the oxygen content and the lower H/C ratio. For a more complete combustion process (with more oxygen) and lower H/C ratio (which lead to a higher adiabatic flame temperature) higher NO_x emissions are obtained. The slightly lower NO_x emissions measured with the paraffinic fuels, is explained by the higher H/C relation and higher cetane number of both paraffinic fuels. Higher H/C ratios lead to a lower adiabatic flame temperature, while higher cetane number leads to reduced premixed combustion processes [34,35].

It is notorious that this area of higher NO_x production matches with the part of the engine map where there is enough thermal energy in the exhaust gas to be harvested with recovery systems such as thermoelectric generators [36].

3.1.4. Particulate matter emissions

Regarding particulate matter (PM), as shown in Fig. 9, a high Particle Number (PN) concentration zone appears in the high-mid low load, high engine speed part on the tested conditions. This zone is more pronounced for diesel and farnesane fuels, followed by the GTL fuel. In the case of biodiesel fuel, this high PN concentration pole is less pronounced, but this fuel presents a more diffuse emission zone, across most of the higher load area and in the middle values of engine speed within the tested range.

3.2. Driving cycles

The same driving cycles were followed with each of the four fuels. It can be observed that at the start of the cycle (Fig. 10 – blue dots) the engine is working at low torque and low engine speed and increases in load and engine speed as the cycle continuous. Towards the end of the cycle, low to middle loads and middle to high engine speeds prevail. At the end of the cycle, the engine works again at low loads (Fig. 10 – dark red dots). Fig. 11 shows the vehicle speed profiles during the cycles and Fig. 12 the accumulated fuel mass consumed. The big difference in biodiesel fuel mass consumption from other fuels is due to a lower LHV (see Table 1).

An overall performance of the fuels regarding emissions and average engine efficiency is shown in Table 3. The instantaneous behaviour of the fuels for the studied pollutant species is shown in the following subsections.

3.2.1. CO emissions

In Fig. 13, diesel fuel shows higher CO emissions during the route, which is consistent with the overall CO production found during the stationary tests. Diesel, GTL and Farnesane fuels show pronounced peaks at certain parts of the route (Fig. 14), which is consistent with the high CO emission areas in the stationary maps, not present for biodiesel. In the case of GTL and farnesane, the peaks are more pronounced since

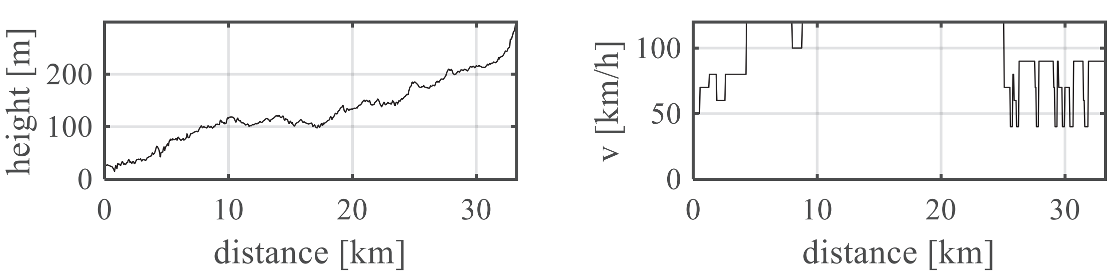

Fig. 3. Characteristics of the route. Left: Altitude above sea level (height) and right: vehicle speed limits (v) along the route.

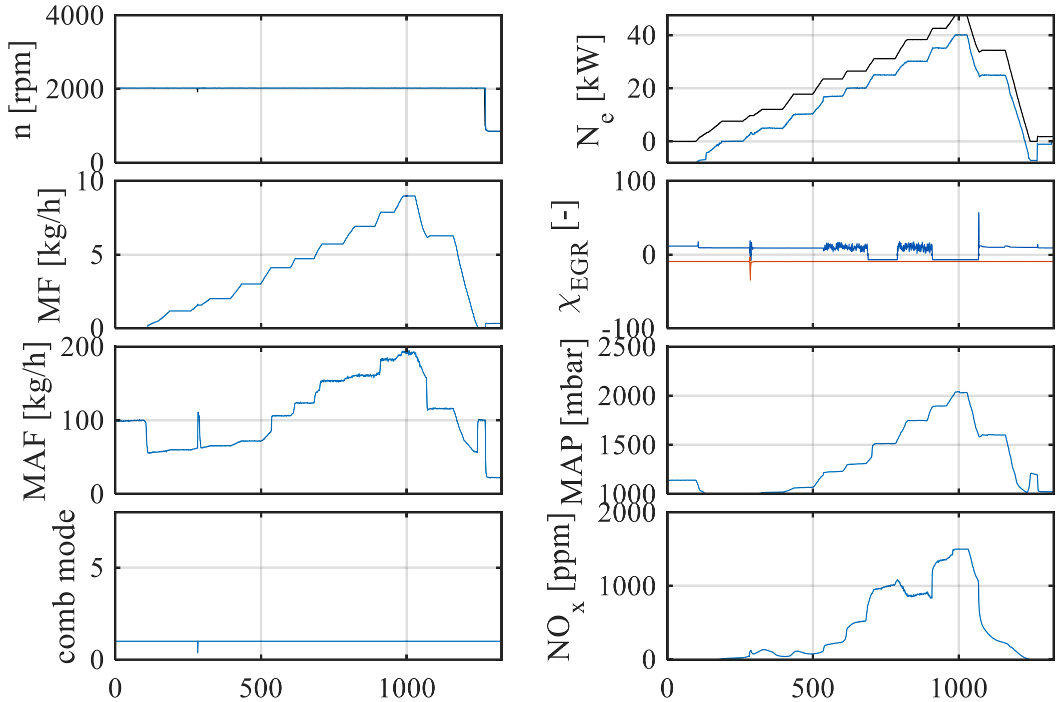

Fig. 4. Tests characteristics under 2000 rpm. Magnitudes showed are: engine rotation speed (n), brake power (Ne), fuel mass flow rate (MF), Exhaust Gas Recirculation (EGR) mode, air mass flow rate (MAF), air pressure (MAP), combustion mode (comb mode) and NO_x concentration (NO_x).

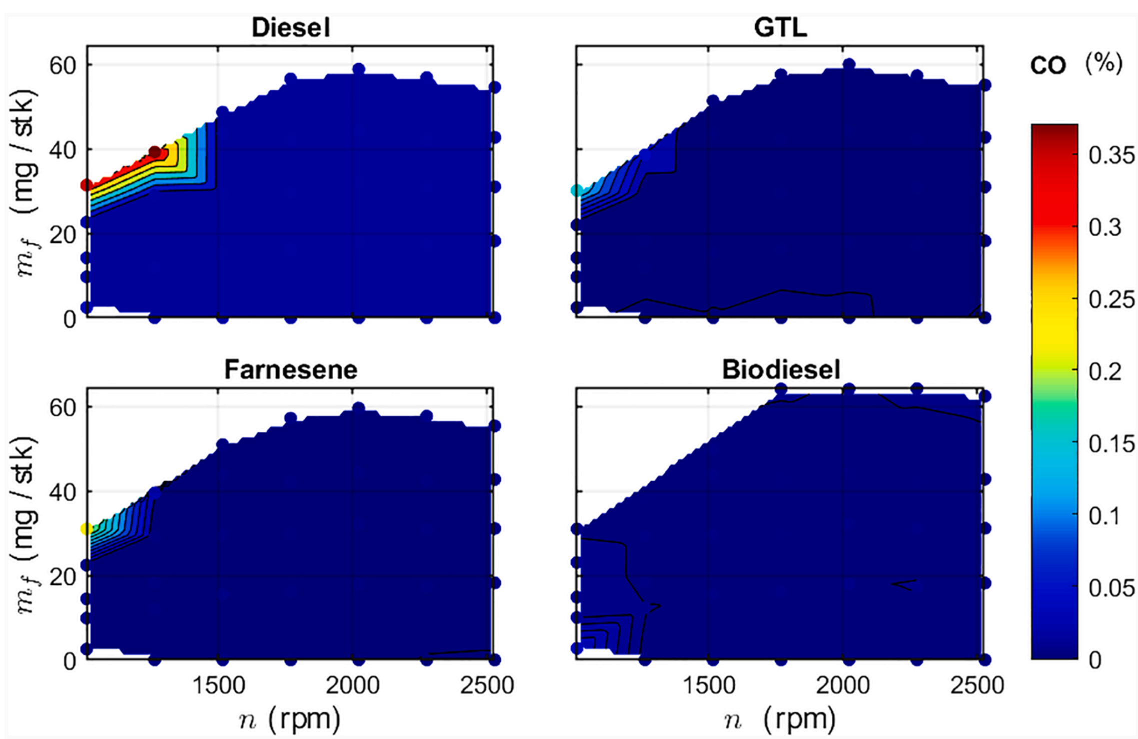

Fig. 5. CO emission maps (%vol) for different fuels at low-to-middle engine loads.

during the cycle the engine tended to spend more time near high-emission conditions. Notice that during the first part of the cycle diesel and biodiesel fuels show very similar values. This could be due to a not so different behaviour at low loads and low engine speeds (see Fig. 5). In addition, cold-start effects are not taken into account in stationary tests. In the stationary tests the DOC is at higher temperature that just after the start of a transient cycle.

3.2.1.1. THC emissions. As seen in Fig. 15 and Fig. 16. Most of the THC emissions are produced in the first part of the route, i.e. the urban part. Peaks does not appear as in CO, as THC high emission conditions are

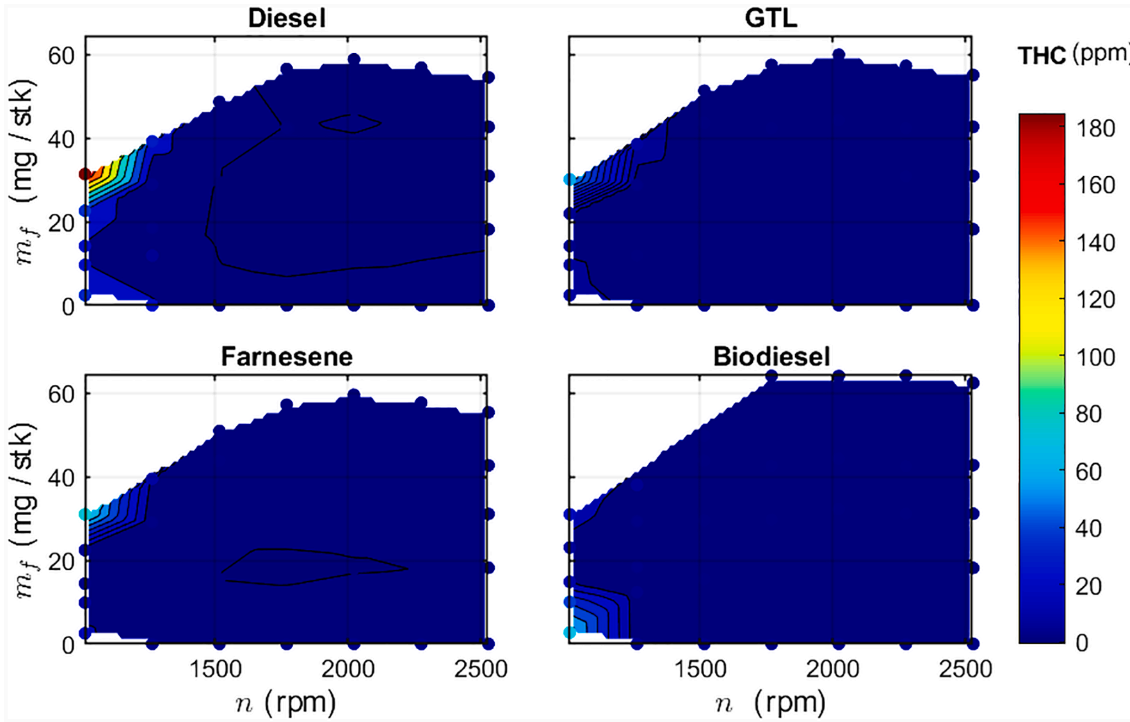

Fig. 6. THC emission maps for different fuels at low-to-middle engine loads.

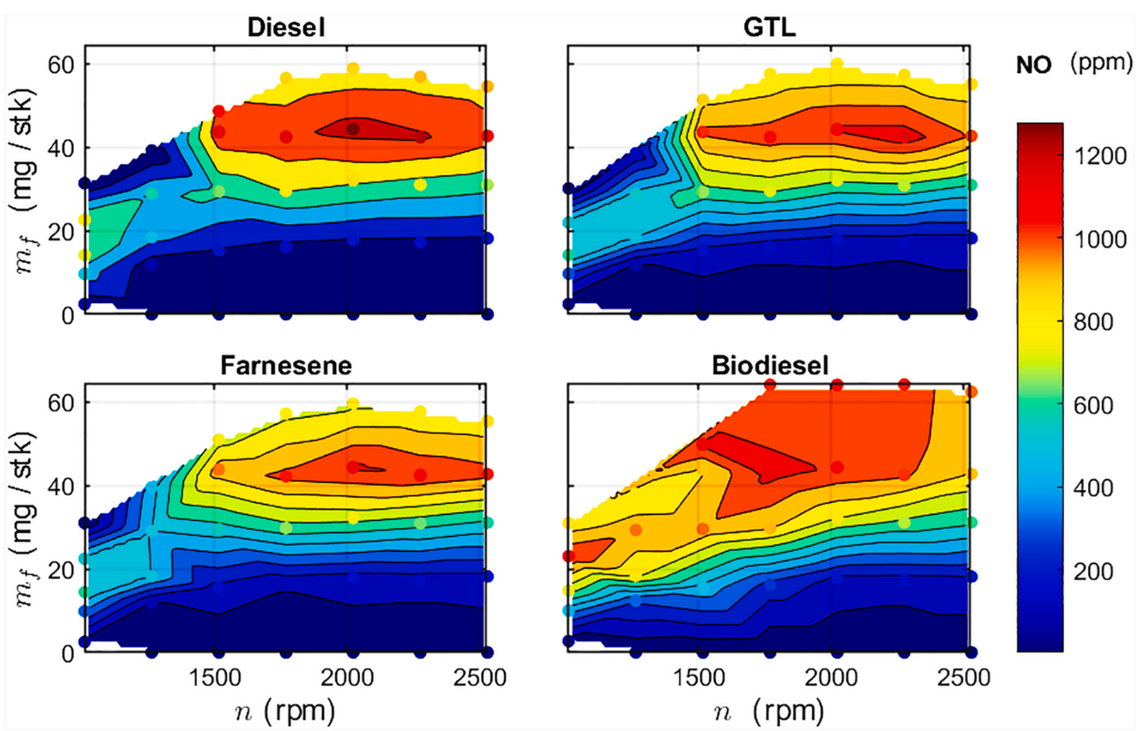

Fig. 7. NO emission maps for different fuels at low-to-middle engine loads.

narrower and not as pronounced (see Fig. 6). Diesel and biodiesel show higher accumulated emissions because they present more high THC emission conditions than the other two fuels.

Biodiesel emissions grow faster during the start of the test, since during this period the engine is at low loads and engine speeds, and biodiesel presents high emissions in this part of the engine map (Fig. 6). The same happens with diesel fuel, although on a lower level. In addition, at the start of the cycle, the DOC (Diesel Oxidation Catalyst) has not reached the light-off temperature [9] and its efficiency is reduced.

Comparing CO emissions in Fig. 13 with THC emissions in Fig. 15, it can been seen that apart from the diesel fuel, having higher emissions in both cases, the order of the alternative fuels pollutant level reverses, with emissions increasing, for CO, from biodiesel, farnesane and GTL,

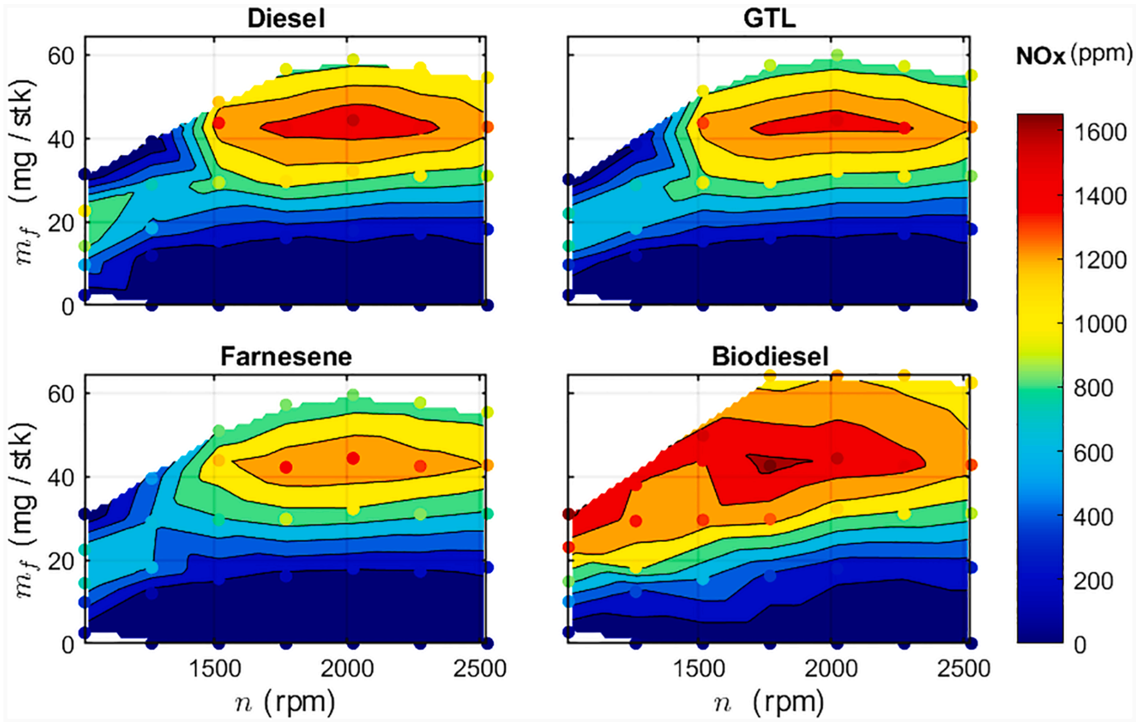

Fig. 8. NO_x emission maps for different fuels at low-to-middle engine loads.

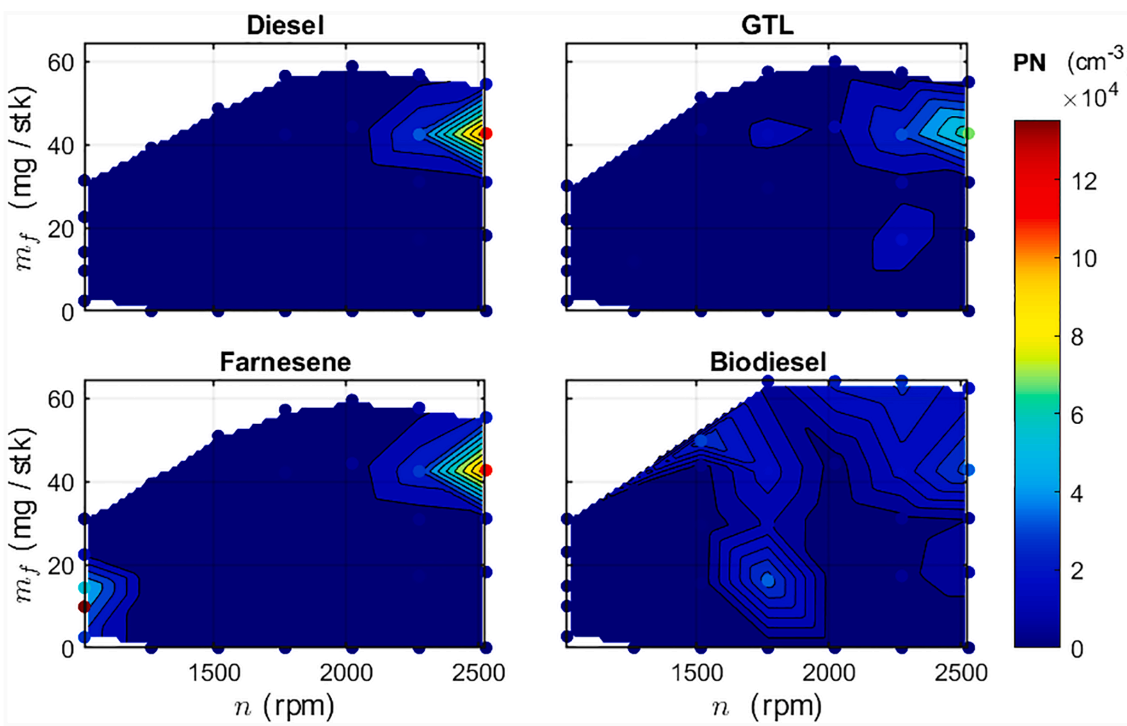

Fig. 9. Particle number emission maps for different fuels at low-to-middle engine loads.

and, for THC, emissions increasing from GTL, farnesane and biodiesel. This shows how the fuel composition affects the competing formation of CO and HC, and also its competing reduction in the DOC.

3.2.1.2. No_x emissions. Regarding NO_x emissions, its production is more gradual than the production of CO and THC emissionsdue to the wider production area in the engine map. NO_x emissions do not present higher levels and accumulation in the first part of the route, since it is at higher loads and engine speeds where the NO_x production is more prevalent. Cumulative NO_x emissions rises exponentially up to the first 2000 s of the route and then show a logarithmic trend (Fig. 17), due to lower engine loads and speeds on the final part of the route. Fig. 18 shows that the maximum instantaneous production of NO_x is during the high velocity part of the cycle.

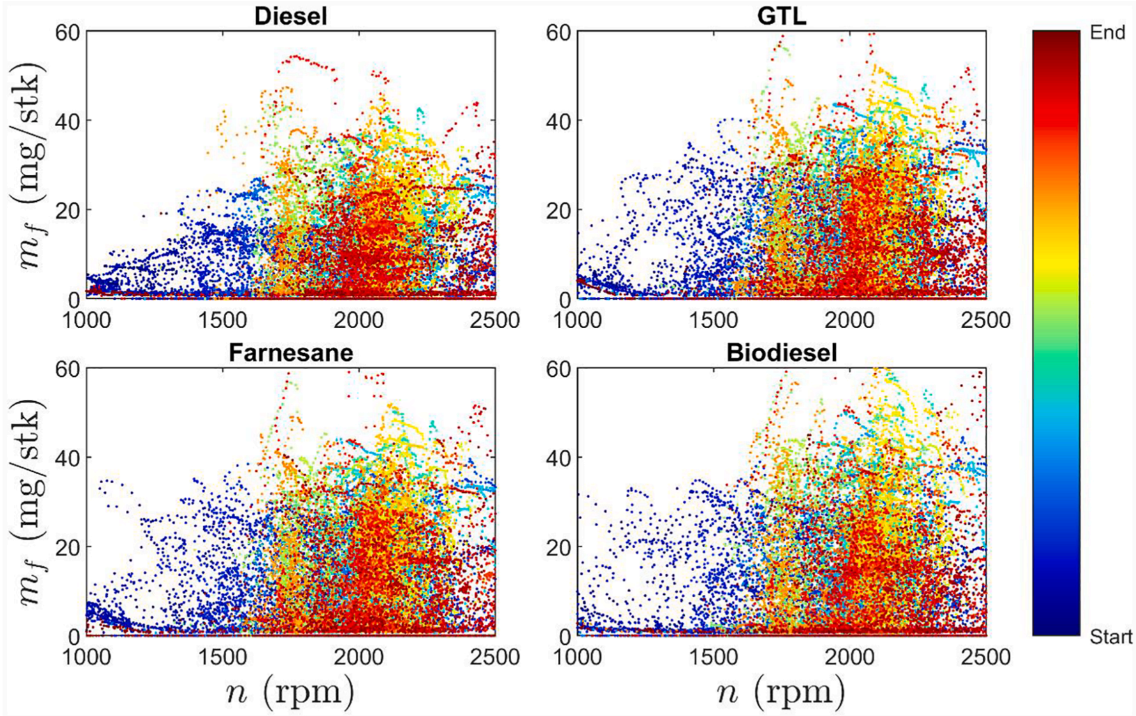

Fig. 10. Working conditions of the engine of the vehicle during the driving cycle with four different fuels from the start of the test (blue) to the end of the test (red).

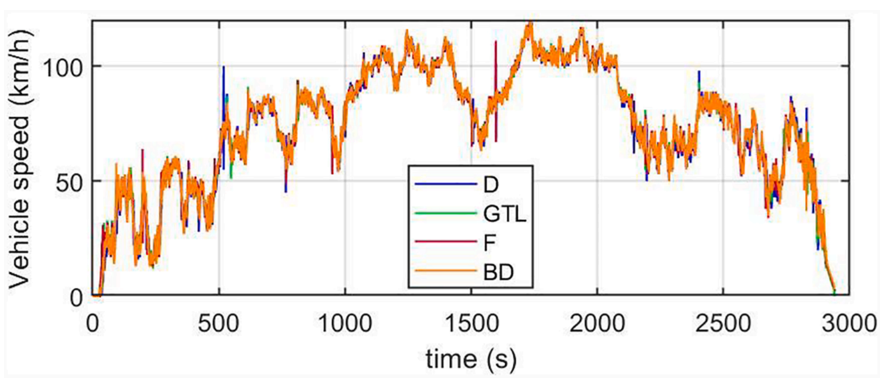

Fig. 11. Vehicle speed profile of the driving cycle repeated for the different fuels. Minor variations correspond to driver response.

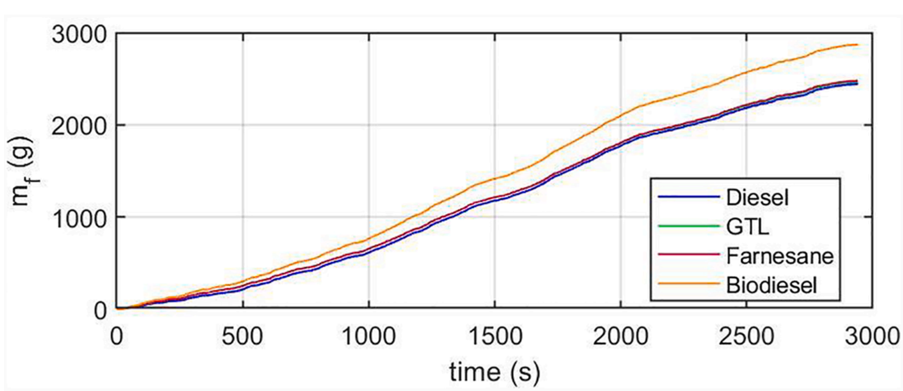

Fig. 12. Cumulative fuel mass consumed during the driving cycles for the different fuels.

The biodiesel produces the highest level of NOx, followed by GTL. Results from GTL stationary tests show more NOx emissions from diesel fuel than for GTL. This highlights the importance of stationary tests, since it is not only important to work at a certain engine speed and load but also the operating conditions from before. Diesel and farnesane produced a similar cumulative value of total NOx.

Table 3
Overall results of the driving cycles.

		Diesel	GTL	Farnesane	Biodiesel
CO	g/km	6,9E-01	5,3E-01	3,0E-01	2,0E-01
	g/kWh	3,21	2,43	1,37	9,07E-01
THC	g/km	1,8E-02	6,4E-03	8,0E-03	1,2E-02
	g/kWh	8,24E-02	2,96E-02	3,69E-02	5,52E-02
NOx	g/km	1,7	1,9	1,7	2,3
	g/kWh	7,89	8,94	7,89	1,04E + 01
PN	#/km	3,9E + 02	6,2E + 01	2,6E + 02	2,1E + 02
	#/kWh	1,83E + 03	2,87E + 02	1,19E + 03	9,57E + 02
Average engine efficiency	–	0,247	0,237	0,238	0,242

3.2.1.3. Particulate matter emissions. The number of particles emitted rises in the first part of the route and then lowers significantly (Fig. 19), with the total number of particles dropping significantly after approximately the first 500 s of the cycle (Fig. 20). This is due to the cold-engine conditions, where more HC is unburned as particle nucleation sources and there is worse fuel atomization. The diesel fuel aromatic content increases the particle emissions. As seen in Fig. 19 and Fig. 20, all alternative fuels tested decrease the particle number. The biodiesel shows higher particle number production than GTL due to the more extended area of emissions in the engine map (Fig. 9). However, its emissions are lower than for farnesane and diesel. These two fuels show a very high peak of particle production (Fig. 9), which occurs at the start of the tests (blue colour, Fig. 10).

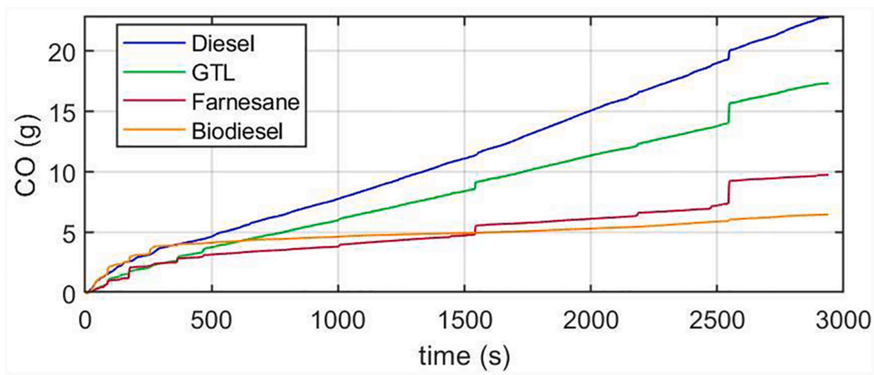

Fig. 13. Cumulative mass of CO emissions for the four fuels tested.

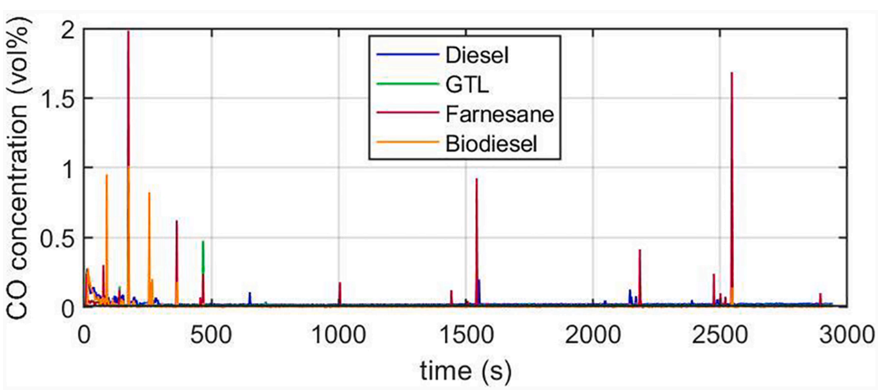

Fig. 14. Instantaneous CO concentration for the four fuels tested.

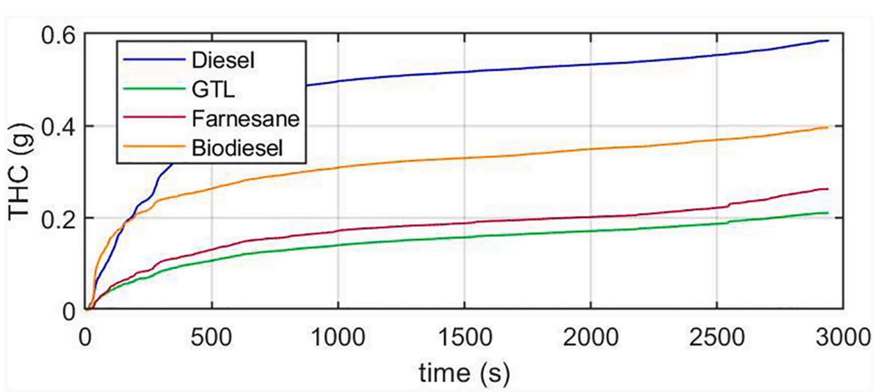

Fig. 15. Cumulative mass of THC emissions for the four fuels tested.

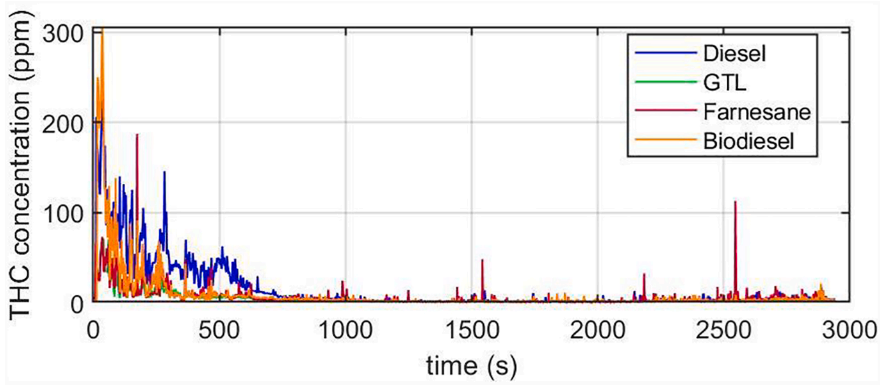

Fig. 16. Instantaneous THC concentration for the four fuels tested.

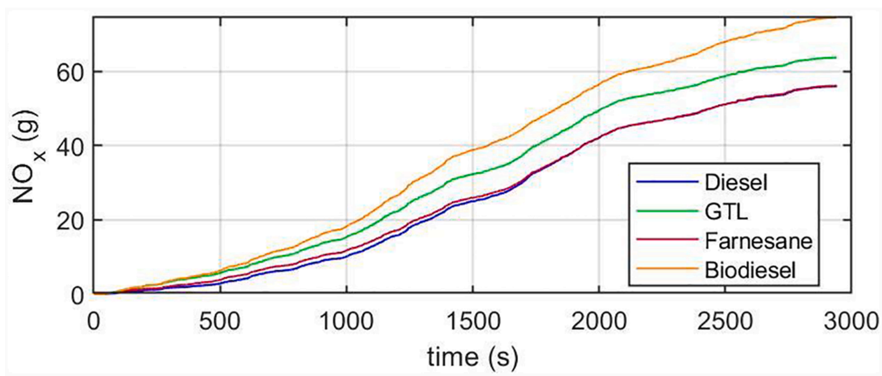

Fig. 17. Cumulative mass of NO_x emissions for the four fuels tested.

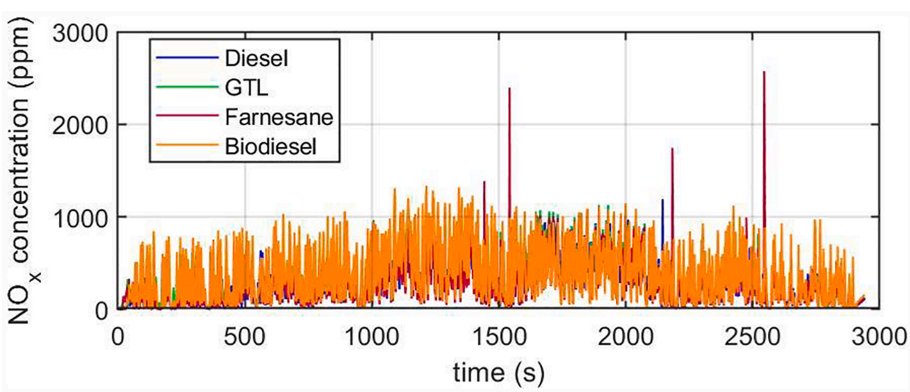

Fig. 18. Instantaneous NO_x concentration for the four fuels tested.

4. Conclusions

Stationary tests allow the assessment the emissions with fuels at different parts of the engine map and a comparison of their effects in combustion and after-treatment systems. The following conclusions can be drawn from the use of biodiesel, GTL and farnesane fuels as alternative fuels during stationary tests:

- The fuel that presented a highest level of emissions (at any engine conditions) was, for CO, diesel, for THC, diesel, for NOx, biodiesel and for PN, diesel. Notice that this not necessarily means that these fuels would be the more pollutant in each category during real driving, as the transient tests show.

- For all fuels, CO and THC show high levels of production localized in a very narrow zone of the tested engine conditions. PN emissions are more spread within the tested area of the engine map. NO_x shows a wider production area.

-In terms of particulate matter emissions, biodiesel shows lower levels of emissions throughout a wider area in the engine map than the other three fuels.

- All alternative fuels show an improvement in terms of pollutant emissions, except for NO_x levels, with only farnesane showing a slight improvement with respect to diesel.

The effect seen in stationary tests do not imply that a certain fuel produces more or less pollutants on road, as engine conditions observed time during driving may hinder some but enhance other differences in emissions among fuels and enhances others. In addition, the engine conditions instants before during a transient test could alter emission results, and not only the engine conditions (load and engine speed) in

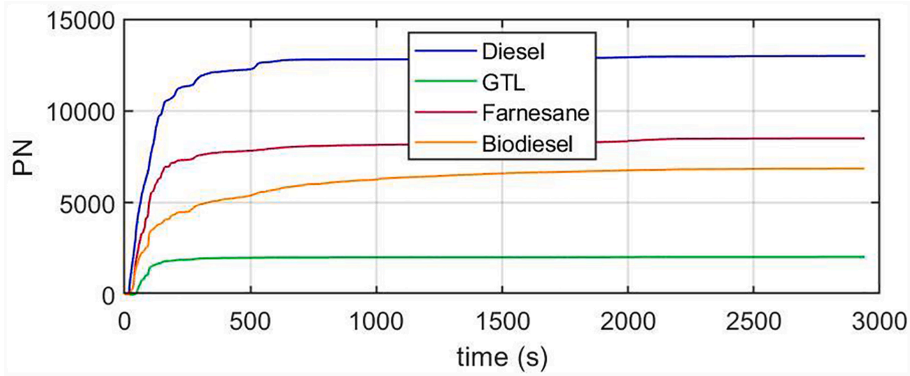

Fig. 19. Cumulative number of particles during the driving cycle.

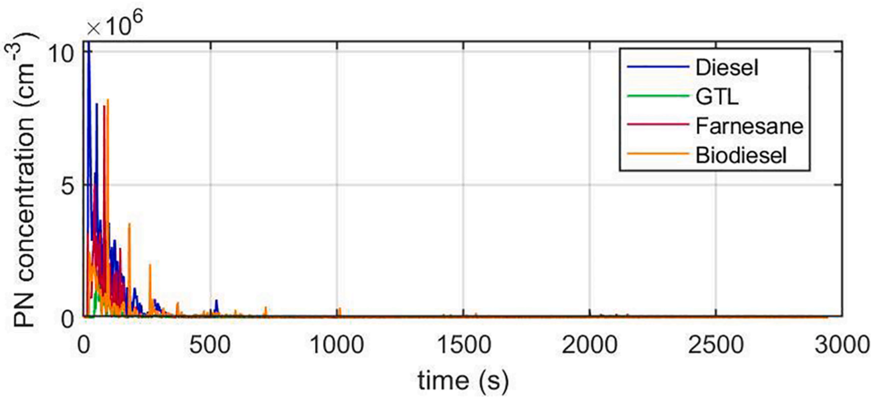

Fig. 21. Instantaneous PN concentration for the four fuels tested.

that instant. The following conclusions can be drawn from the use of biodiesel, GTL and farnesane fuels as alternative fuels during driving cycle tests:

- The results of emissions, from less pollutant to more pollutant were: for CO, diesel, farnesane, GTL and biodiesel; for THC, GTL, farnesane, biodiesel, diesel. For NOx, farnesane and diesel (very similar values), GTL and biodiesel; for PN, GTL, biodiesel, farnesane and diesel.

-THC and particulate matter are emitted mainly during the first 600 s of the driving cycle. The THC high emission zone of the biodiesel engine map, at low load, low engine speeds, makes THC more prevalent for biodiesel than diesel during the first seconds of the route. Biodiesel, despite not showing a very high particulate number emission zone during stationary tests, emits more along the route than GTL.

-NO_x and CO emissions are more distributed across the route, although CO emissions are more significantly produced during the first 600 s of the route.

- Despite showing globally lower CO emission values in the stationary tests, biodiesel emits the same quantity during the first part of the cycle, but then emissions radically decay showing a lower CO accumulated mass. Under low speed, low load, cold-start driving conditions, the biodiesel did not provide any advantage with respect to conventional diesel for the driving tests.

-The slight improvement in NOx seen in the farnesane stationary tests is not seen in lower total accumulated NO_x mass with respect to diesel.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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