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Impact of Fischer-Tropsch and biodiesel fuels on trade-offs between pollutant emissions and combustion noise in Diesel engines

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Abstract

Over recent decades, direct injection diesel engines have become the propulsion systems most commonly used in automotive vehicles in Europe. Their leading position in the European market is due to improvements in performance, driveability and their capacity for facing the increasingly restrictive standards to which are subject. Nevertheless, their main drawbacks are related to the emission levels, the use of fossil fuels and the engine noise. To mitigate the first two problems, alternative fuels are being used in these engines with encouraging results. The impact of these fuels on engine noise might therefore be analyzed in order to evaluate the feasibility of such a solution. In this work the effect of diverse alternative fuels on emissions, performance and engine noise quality was analyzed. Compared with standard diesel fuel, results show a scarce variation of combustion noise quality whereas soot level decreases, NO_x emissions increase and specific consumption deteriorates.

Keywords: Alternative fuels, Exhaust emissions, Diesel engine, Performance, Combustion noise.

Nomenclature

Latin:

C_i	coefficients of the combustion noise assessment equation	(–)
E	signal energy	(J)
I_1, I_2	combustion indicators	(–)
n	engine speed	(rpm)
p	pressure	(Pa)
t	time	(s)

Greek:

λ	excess of air	(–)

Abbreviations:

BSFC	brake specific fuel consumption
CO	carbon monoxide
CO_2	carbon dioxide
DI	direct injection
EGR	exhaust gas recirculation
FSN	filter smoke number
FT	fisher tropsch
ID	ignition delay
NO_x	nitrogen oxides
O_2	oxygen
PCCI	premixed charge compression ignition
RB	rapeseed blends
SB	soybean blends
SO_2	sulphur dioxide
TDC	top dead center
UHC	unburned hydrocarbons

Subscripts and Superscripts:

comb	Combustion sub-signal
comp	Compression-expansion sub-signal
idle	Idle condition
max	Maximum value
res	Resonance sub-signal

1. Introduction

In recent years, diesel engines have become the most widely used power plant in passenger vehicles in Europe. This fact is mainly due to improvements in driveability, comfort, and to their low fuel consumption. However, in spite of the important advances experienced, these propulsion systems are not free from drawbacks. High levels of pollutants caused by a poorly controlled combustion, the use of fossil fuels, and high levels of radiated noise, are the main problems of this type of engine. To face up these problems, the use of either biodiesel or synthetic fuels (such as Fischer Tropsch) seems to be a feasible alternative

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to the use of fossil fuels.

Fuels obtained from vegetable oil sources appear to be an excellent substitute for petroleum fuel, because of their easy production, utilization, storage, and the significant reduction achievable in pollutant emissions, mainly carbon dioxide (CO_2). Some studies [1] have shown that biodiesel can reduce net CO_2 emissions by 78% when compared to petroleum diesel. This is due to the closed carbon cycle of biodiesel, in which the CO_2 released into the atmosphere when biodiesel is burned is recycled by growing plants, which are later processed into fuel. The sulphur and aromatics content of biodiesel fuels are negligible while their oxygen (O_2) concentration is substantially high (in the order of 10% on weight basis) [2]. These characteristics allow significant reductions of sulphur dioxide (SO_2), soot, carbon monoxide (CO) and unburned hydrocarbons (UHC) [3, 4]. However, due to their influence on the ignition delay (ID), the production of nitrogen oxides (NO_x) during combustion is usually increased [5]. In addition, biodiesel fuel is biodegradable, nontoxic, recyclable, locally available, benzene-free and cleaner than fossil fuels [6, 7, 8]. It can be used pure or in different blends because of its miscibility with diesel [9]; it has an excellent lubricity and its use does not require considerable modifications on the engine hardware. Biodiesel can be produced from several oils of different types of oilseed crops, such as those of sunflower, palm, soybean, rapeseed, cottonseed and peanut.

Despite their many advantages, biodiesel have some negative effects on engine operation since its use can have an impact on the injection system (injector coking, fuel lines clogging, etc.), on combustion (poor atomization, carbon deposits, etc.) and on the hardware (piston ring sticking) [10, 11]. Moreover, due to its higher surface tension and viscosity the cold startability of diesel engines with biodiesel is deteriorated [12]. Some of these effects affect negatively the vaporization process, so that incomplete combustion is induced during the engine start and also an increase of NO_x emissions can be noticed [13]. Additionally, since the heat value of biodiesel is about 13% lower than that of standard diesel fuel, the brake specific fuel consumption (BSFC) increases while the thermal efficiency is scarcely affected [14, 15].

Synthetic fuels like Fischer Tropsch are produced from synthesis gas (CO and H_2), using either natural gas or coal as feedstock. This alternative fuel is characterized by its high cetane number, which leads to short ignition delays [16, 17]. As in the case of biodiesel, the sulphur and aromatic content of Fisher Tropsh fuel are negligible, so that reductions of SO_2, CO, UHC and soot emissions are also expected [18, 19]. Due to its higher heat value compared with that of a standard diesel fuel, Fischer Tropsch fuel allows also to reduce fuel consumption. Some studies have shown that both the heating value and the fluid-dynamic characteristics of fuel during the injection are the parameters which mostly govern the combustion process and have thus the highest impact on engine performance [20].

Regarding radiated noise, the engine is considered as the main noise source in diesel-powered vehicles due to the characteristic impulsive noise of diesel combustion. For that reason, many efforts have been devoted by car manufactures to mitigate diesel engine noise alongside with the previously commented improvements in performance and driveability. Despite these efforts, current designs are still too noisy, specially during transient operation [21] and new combustion concepts such as the PCCI [22]. While the control of the overall noise is imperative to fulfill the current legislation, sound quality and comfort are essential for the customer purchasing decision [23, 24].

The external sound field of diesel engines comprises the contribution of both combustion and mechanical noise. In these engines, the self-ignition of premixed fuel causes a rapid pressure rise, producing the well known "knock", which excites the gas in the combustion chamber and consequently induces its oscillation [25, 26]. The source of the combustion noise is related to pressure and mechanical forces, which are characterized by in-cylinder pressure, the system response is associated with the vibration of the block wall, and the radiated noise is the final effect of such a vibration [27, 28].

In this investigation the repercussions of alternative fuels (from synthetic and vegetable oils) on engine performance, pollutant emissions (NO_x and soot) and combustion noise were analyzed. With this purpose, different biodiesel blends and a synthetic fuel were tested in a light-duty direct injection (DI) diesel engine at different operating conditions. A procedure based on the decomposition of the in-cylinder pressure signal was used in order to evaluate the subjective aspect of combustion noise [23].

2. Experimental set up

The experiments of this study were performed on a light-duty 4-cylinder Euro IV turbocharged DI diesel engine, with a total displacement of 1.6 l and common rail injection. The engine was directly coupled to an asynchronous electric brake, which allows controlling the engine speed and load. Engine and injection system specifications are shown in Table 1.

Table 1: Main characteristics of the engine and injector.

Engine Type	Direct-injection Diesel engine
Cylinders	4 in line
Bore (mm)	75
Stroke (mm)	88.3
Compression ratio	18:1
Injector nozzle holes	6
Nozzle holes diameter (mm)	0.124
Spray angle (deg)	150

In order to precisely control engine operation, the temperature of all fluids in the engine was measured with K type thermocouples; pressure sensors and fuel and air mass flow meters were also used. A Horiba MEXA-720 exhaust gas analyzer was used to measure NO_x emissions, O_2 concentration in the exhaust, equivalence ratio and excess of air (λ). The O_2 concentration in the intake air was measured with a lambda probe located at the intake manifold. Soot emissions were indirectly determined with the correlation proposed by Christian et al. [29] that relates soot and the filter smoke number (FSN). The FSN was measured with an AVL 451S smoke meter.

The pressure trace was measured in all the cylinders with glow-plug piezoelectric transducers. These sensors were calibrated by applying the usual method [30], based on a quasi-steady calibration by means of a deadweight tester with NPL and NIST traceability. Table 2 summarizes the accuracy of the instrumentation used in this work. In-cylinder pressure was recorded with a sampling frequency of 50 kHz, so that a bandwidth similar to the human domain of hearing (20 Hz-20 kHz) was available. 50 consecutive cycles were recorded for each test.

Table 2: Accuracy of the instrumentation used in this work.

Sensor	Variable	Accuracy (%)
Piezoelectric	In-cylinder pressure	0.4
Thermocouples	Temperature of all fluids	0.35
Encoder	Engine speed	0.006
Exhaust gas analyser	NO_x emissions and O_2 concentration in the exhaust	2
Lambda probe	O_2 concentration in the intake	1.81
Smoke meter	FSN	3
Piezoresistive	Intake and exhaust pressure	0.65
Torque meter	Torque	0.1
Fuel mass flow meter	Fuel mass	0.2
Air mass flow meter	Air mass	0.12

3. Methodology

In order to dispose a sufficiently wide range of engine running conditions, 15 operation points (7 conditions at low load, between 5% to 24% of full load, and 8 of mid load, between 35% and 74% full load) were chosen. These precise conditions were selected because they are representative of those engine operating points during the European MVEG cycle in which combustion noise is critical.

Test were performed with different fuels keeping constant torque. With this purpouse, the quantity of fuel mass injected during the pilot was kept as in the baseline settings whereas the quantity injected in the main injection was varied until the target torque was met. The exhaust gas recirculation (EGR) cooling system of the engine was modified so that a constant intake temperature of 45°C was ensured in all the tests. In addition, the intake air mass was also controlled –by setting the EGR valve opening– so that the flow was the same as in the baseline condition (with standard diesel fuel) independently of the alternative fuel used. In this way, one can be sure that any variation of the EGR rate was caused by the fuel itself and not by differences in the air mass flow. Table 3 summarizes the main operating parameters considered in each running point.

With the purpose to define suitable reference conditions, preliminary tests with standard diesel fuel and with the baseline engine settings were performed. From these tests, the reference values of BSFC, NO_x levels, soot emissions and sound quality of combustion noise were obtained for each of the 15 operation points referred to above. These reference values were compared with those measured with the biodiesel and Fischer Tropsch fuels. The biodiesel fuels used in the tests were six blends of soybean and rapeseed oil with standard diesel fuel in volume concentrations of 30%, 50% and 80%. The synthetic fuel considered in this study was an ester obtained from a Fischer-Tropsch process whose mass composition, determined according to the ASTM D-5291 standard, is 84,7% carbon, 15% hydrogen and 0.3% oxygen. Table 4 shows a summary of the main properties of the different fuels used in the tests. In order to avoid any effect from the fuel used in previous tests, after each test the fuel line was emptied, the main tank was refilled with a different fuel, and then the engine was run at high load for 1 hour before any new measurements were taken.

3.1. Combustion noise characterization

The assessment of combustion noise is based on the methodology proposed by Payri et al. [27], in which in-cylinder pressure is decomposed into three sub-signals each one characterizing the relevant phenomena taking place during the operation of diesel engines: compression-expansion (pseudo-motored signal), combustion, and combustion chamber resonance. The compression-expansion signal does not represent any tendency related to combustion and is used to provide a convenient reference. The combustion signal is influenced by the rate of heat release, which is governed by the injection strategy and engine operating conditions. The resonance signal is associated with the gas oscillation produced by the abrupt pressure rise occurring in the combustion chamber [26]. This decomposition technique was previously applied to the analysis of

Table 3: Running conditions tested.

Point		Speed (rpm)	Torque (Nm)	Pilot timing (°BTDC)	Main timing (°BTDC)	Pilot mass (mg/str)	Injection pressure (bar)	Air mass flow (kg/h)
	1	1500	38	25.28	-3.00	1.62	859	45.1
	2	1900	20	25.05	-0.65	1.54	666	45.4
Low	3	1900	50	27.50	-0.66	1.62	850	60.0
load	4	2250	13	27.89	1.50	1.58	687	86.8
	5	2400	50	30.21	3.00	1.65	900	117.7
	6	2850	20	32.80	5.50	1.29	516	158.2
	7	2850	50	33.00	6.80	1.60	795	170.8
	8	1500	76	27.80	-1.17	1.76	1035	62.3
	9	1500	152	31.78	3.60	1.77	1050	104.8
	10	1900	127	33.35	4.33	1.90	1212	104.1
Mid	11	1900	152	34.28	5.55	1.90	1215	127.3
load	12	2280	104	33.98	5.00	1.92	1250	120.1
	13	2400	152	37.66	9.51	1.94	1288	198.6
	14	2850	89	35.20	8.41	1.87	1119	188.8
	15	2850	152	38.60	11.15	1.98	1238	221.0

cause-effect relations between the source (caused by combustion) and both the objective and subjective aspects of noise [23, 24]. In this investigation, the procedure proposed by Payri et al., was used to predict the sound quality of the combustion noise, which is quantified by a mark as would be given by a jury during a listening test as is described in [23]. According to this procedure, the mark is highly correlated with two combustion indicators. The first one, I_1, is related to the sudden in-cylinder pressure rise and is expressed mathematically by:

$$I_1 = \frac{n}{n_{idle}} \left[\frac{(dp_{max1}/dt)_{comb} + (dp_{max2}/dt)_{comb}}{(dp_{max}/dt)_{comp}} \right] \quad (1)$$

where n and n_{idle} are the actual speed and idle speed, respectively; $(dp_{max1}/dt)_{comb}$ and $(dp_{max2}/dt)_{comb}$ represent the two maximum values corresponding to the two higher peaks of the pressure derivative curve during combustion, and $(dp_{max}/dt)_{comp}$ is the peak value of the pressure derivative corresponding to the compression-expansion component.

The second indicator, I_2, quantifies the contribution of the resonance in the combustion chamber through the energy of the high frequency content of the in-cylinder pressure trace [26, 31]. It is expressed by:

$$I_2 = \log \left[E_0 \frac{E^{res}}{E^{comp}} \right] \quad (2)$$

where E_0 is a convenient scaling factor, E^{res} is the signal energy of the resonance and E^{comp} is the signal energy of the compression-expansion.

With these indicators, the sound quality of the combustion noise can be assessed by a mark ranging from 0 to 10 –which represents the satisfaction degree of an average customer– through the following correlation:

$$Mark = 10 - C_1 I_1 - C_2 I_2 \quad (3)$$

where C_i are coefficients dependent on the engine family and size.

4. Results and discussion

The results of EGR rate, fuel consumption, emission levels and combustion noise quality measured during the engine tests defined in the methodology are presented and analyzed in this section. Contour plots were drawn in order to determine the relationship among each one of these variables and the engine torque and speed for the tested fuels: standard diesel, biodiesel blends and Fischer Tropsch.

The EGR rate is one of the most important parameters affecting engine efficiency, emissions and noise. Fig. 1 shows the EGR maps as function of engine speed and torque for the fuels tested. For all the fuels, the highest EGR rates were used in the low speed-torque range since it covers a wide part of the operating area during the homologation cycle (i.e. MVEG). As either torque or engine speed increases the EGR rate diminishes progressively. Comparing the results obtained with different fuels, some differences in the EGR rate are observed. Despite the tests were performed keeping constant air mass flow rate, some differences in intake pressure were observed. Variations in the intake pressure at similar speeds and loads are due to different turbocharging conditions, which are induced by the different exhaust temperature obtained with diesel, biodiesel and Fischer Tropsch fuels. Since the mass

Table 4: Properties of fuels used.

Fuel (in volumetric concentrations)	Density 15°C (kg/m^3)	Cetane index	Viscosity 40°C (cSt/seg)	Calorific value (MJ kg^{-1})
D: 100% Diesel	839.3	51.2	2.676	45.200
SB30: 30% Soybean/70% D	855.4	51.7	3.419	43.619
SB50: 50% Soybean/50% D	866.9	52.1	3.571	42.547
SB80: 80% Soybean/20% D	874.1	59.4	3.958	40.705
RB30: 30% Rapeseed/70% D	854.2	52.1	3.496	43.658
RB50: 50% Rapeseed/50% D	865.0	52.7	3.636	42.412
RB80: 80% Rapeseed/20% D	873.9	60.0	4.094	40.698
FT: 100% Fischer Tropsch	772.0	78.1	2.785	47.010

induced depends on the intake pressure, for given engine operating conditions, the EGR rate must be different due to the effect of the fuel on the exhaust temperature. The highest EGR rates were measured at low load and speed with standard diesel fuel. Conversely the lowest EGR rates were measured with Fischer Tropsch fuel at almost the whole operating range of the engine. Finally, these differences in the EGR rate have a relevant impact on the performance parameters that will be analyzed in the following sections.

4.1. Effect on BSFC

Fig. 2 shows that the BSFC increases when the engine runs with biodiesel fuels. In agreement with the literature [19], the differences in BSFC are due to the lower heating value of biodiesels, while engine thermal efficiency is almost unaffected by the use of this kind of fuels. According to Table 3, the heating value of the biodiesel blend decreases in proportion to the biodiesel content and hence the BSFC increases. Since the heating value of both soybean and rapeseed biodiesels was quite similar (see Table 3) the BSFC of the engine is scarcely sensitive to the type of biodiesel fuel used. In addition, since their density, viscosity and cetane number are also similar, any difference in the injection rate and combustion behaviour which could cause variations of engine efficiency is not expected.

Regarding the Fischer Tropsch fuel, its higher heating value leads to a noticeable fuel saving despite thermal efficiency is not increased. The results shown in Fig. 2 indicate that the BSFC of the engine at mid loads and low speeds can be reduced by almost 20 g/kWh when using this synthetic fuel.

It must be remarked that the combustion settings considered were optimized in order to run the engine with standard diesel fuel. Therefore, parameters such as injection pressure, injection timing and EGR rate amongst others were set to maximize the engine efficiency and minimize emissions and noise when standard diesel fuel was used. Since both biodiesel and Fischer Tropsch properties differ from those of standard diesel, the engine should be recalibrated in order to obtain the optimum trade-off between performance, pollutant emissions and noise for each

fuel, so that results better than those previously discussed should be expected. Nevertheless, engine recalibration is out of the scope of this study.

4.2. Effect on soot emissions

Soot emission levels are presented in Fig. 3. These results show that independently of the fuel used, the maximum soot levels are obtained at the zones of high torque and speed, where power demands cause a reduction in the air to fuel ratio. Soot emissions also become important when maximum EGR rates are used due to the substantial reduction of the O_2 concentration in the combustion chamber in such conditions.

Regarding the impact of the biodiesel on soot emissions, results in Fig. 3 also show an important reduction in comparison with the standard diesel fuel. Moreover, the reduction is more apparent as the biodiesel content of the fuel blend increases. According to Lapuerta et al. [32], the oxygen contents in biodiesel fuels is the factor with a higher impact on this reduction, since it allows a more complete combustion in zones of the combustion chamber with low air to fuel ratios and hence soot oxidation is enhanced. The fact that biodiesel is sulphur- and aromatics-free –both compounds are soot precursors– is another reason why soot emissions can be reduced with these fuels. Comparing the two types of biodiesel fuel tested, similar emission levels were measured in both cases. Nevertheless, when comparing both types of biodiesel fuels, the results shown that soy achieved a higher reduction in soot emissions.

With the Fischer Tropsch fuel, lower soot emission levels than those obtained with standard diesel were also measured. However, these levels are higher than those obtained with any of the biodiesel fuels. Since the oxygen content of Fischer Tropsch fuel is zero, the reduction in soot emissions should be attributed to other effects than those promoted by the excess of oxygen during combustion. Despite the higher heating value of Fischer Tropsch causes a lower fuel-to-air ratio in tests as the air mass flow was kept constant, it should be noticed that since the Fischer Tropsch has a lower stoichiometric fuel-to-air ratio than diesel fuel (1/14.92 and 1/14.54, respectively), the
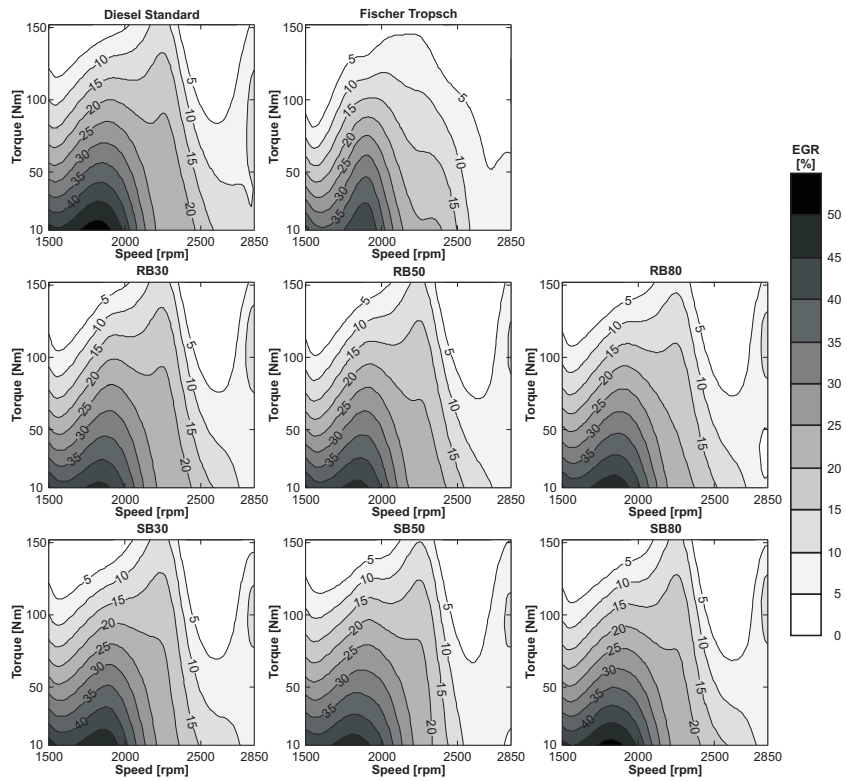
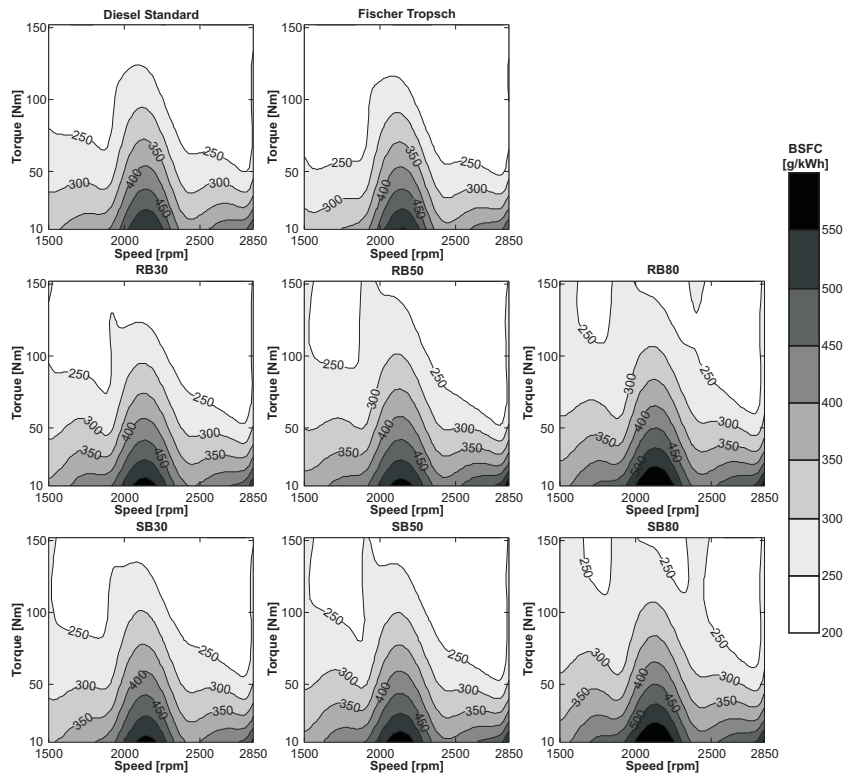Figure 1: Contours of measured EGR rate for different fuels.

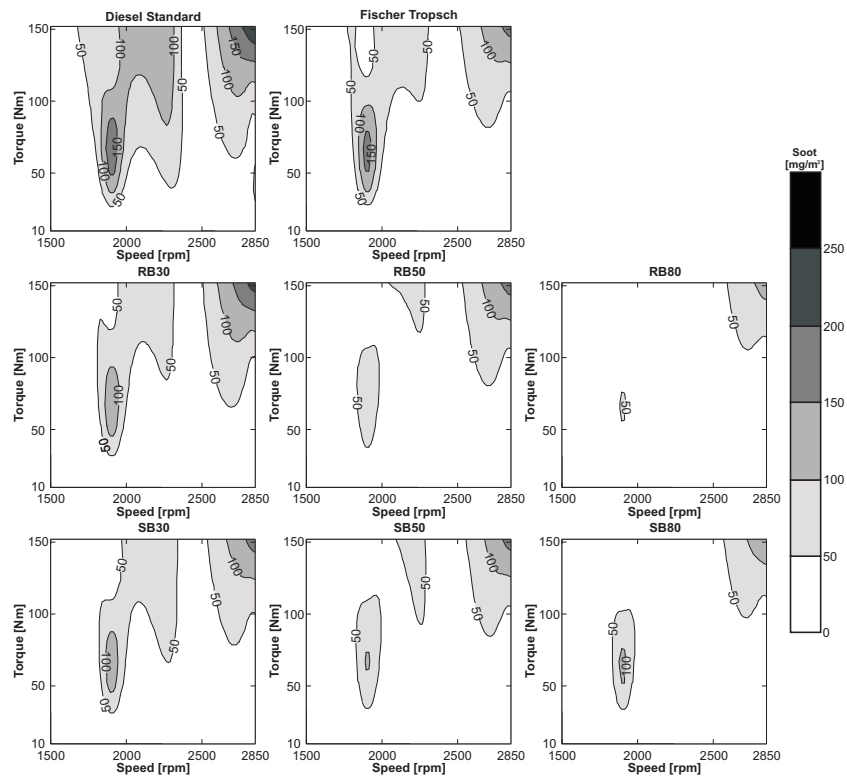Figure 2: Contours of BSFC for different fuels.

Figure 3: Contours of soot emissions for different fuels.

soot reduction cannot be attributed to a higher excess of air. Indeed, this reduction must be related to the fact that Fischer Tropsch is a sulphur-free fuel and has less aromatics than standard diesel.

4.3. Effect on NO_x emissions

The measured NO_x emissions for the fuels tested are shown in the plots in Fig. 4. The emission pattern measured with the standard diesel fuel shows that NO_x increases as the load rises due to the higher combustion pressure and temperature. Particularly, points with lower torque than 100 Nm and engine speeds up to 2250 rpm have lower NO_x emissions due to the high EGR rates considered at these conditions (see Fig. 1). For the rest of fuels tested similar NO_x emission patterns were also measured.

Unlike the clear trends obtained for BSFC and soot, the impact of biodiesel fuel on NO_x emissions is more difficult to analyze. At low load, tests with biodiesel fuels show NO_x emissions similar to those with standard diesel despite the slightly lower EGR rate shown in Fig. 1. However, as load increases NO_x emissions with biodiesel fuel increase faster and hence, biodiesel blends produce higher NO_x emissions than standard diesel fuel at high load. The NO_x emissions obtained with both types of biodiesel are almost equal due to their similar properties. Moreover, the results show that increasing the biodiesel content of the blend, NO_x emissions are scarcely affected.

In spite that most of the results available in the literature show that NO_x emissions are deteriorated with biodiesel fuel, there is not a single explanation for such behaviour. The reason for this lack of agreement is that the NO_x increase experimented with biodiesel fuel is not related to a single physical property, but rather is the result of a set of properties whose effects may counteract or promote each other depending on the operating conditions.

The increase in NO_x emissions is frequently attributed to the advanced injection timing caused by the higher bulk modulus of compressibility of biodiesel that modifies the propagation speed of the fuel pressure wave in the injection system [32]. This phenomenon affects to fuel injector pumps but its impact on common-rail systems such as that used in this study should be minimum. Differences in fuel density also affect the fuel injection rate since for a given injection duration, the mass fuel rate of a heavier fuel is higher [33]. Additionally, the effect of the radiative heat transfer from soot in the combustion chamber on NO_x formation must also be considered. It is known that soot radiation may reduce the combustion temperature and consequently NO_x emissions should be reduced [32]. However, due to the lower soot formation during the combustion of biodiesel fuels, the opposite effect should be expected so that in-cylinder temperature during combustion is increased and consequently the NO_x formation increases. NO_x emissions are also sensitive to the cetane number of the fuel. The higher cetane number
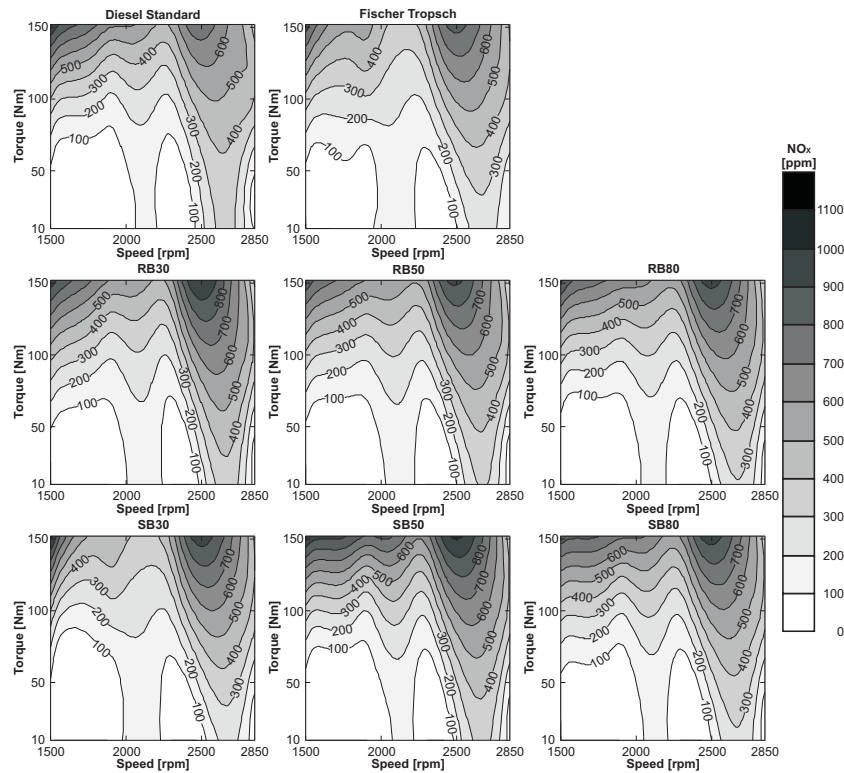
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Figure 4: Contours of NO$_x$ emissions for different fuels.

of biodiesels, compared to standard diesel fuel, affects the combustion process reducing the amount of fuel burned in the premixed phase, thus contributing to lower temperatures and hence lower NO$_x$ emissions. This positive effect of biodiesel on NO$_x$ emissions can be observed at low loads; however, as reported by other authors [32, 33], at medium to high loads NO$_x$ emissions are not affected by cetane number.

The effect of Fischer Tropsch on NO$_x$ emissions is similar to that obtained with biodiesel fuels, since Fischer Tropsch presents an earlier combustion and its soot emissions are also lower.

Finally, it should be remarked that NO$_x$ emissions are quite sensitive to the EGR rate and, therefore, slight differences in the EGR rate and composition between tests may also cause noticeable differences in the NO$_x$ emission levels [34].

4.4. Effect on the combustion noise quality

Fig. 5 shows the characteristic mark of the sound quality of combustion noise calculated with the procedure described in section 3.1 for all the fuels tested. Taking into account that a mark of 7 specifies the comfort limit for combustion noise, these results evidence that the engine noise at the considered operating conditions is a critical issue and therefore should be improved. Independently of the fuel used, this limit was surpassed only at low loads. As the load increased, the mark decreased to unacceptable

values due to the faster pressure rise during the combustion process.

The results in Fig.5 show that the combustion noise quality is deteriorated –lower mark– as the biodiesel content in the fuel blend increases. In addition, the sound quality of combustion noise with soybean is somewhat better than with rapeseed oil. Differences in combustion phasing and injection shape explain the higher pressure rise as the biodiesel content increases, and therefore the deterioration of the sound quality of combustion noise. Fig. 6a and b evidence that in-cylinder pressure and the rate of the fuel burning –represented by the pressure derivative of the combustion signal for 2400 rpm and 152 Nm– advance when any any biodiesel or Fischer Tropsch fuels are used. These differences contribute to the noise deterioration.

The mark is reduced by almost a 13% when the Fischer Tropsch fuel is used. Despite its lower density, its higher heating power forced to use shorter injection timings, so that the injected mass of fuel was kept constant. Therefore more fuel burned in premixed combustion phase is expected and thus higher rates of in-cylinder pressure rise during combustion are produced.

Apart from the above reasons, the lower EGR rates measured during tests with biodiesel and Fischer Tropsch fuel also contribute to reduce the ID, thus increasing the impact on the engine noise.
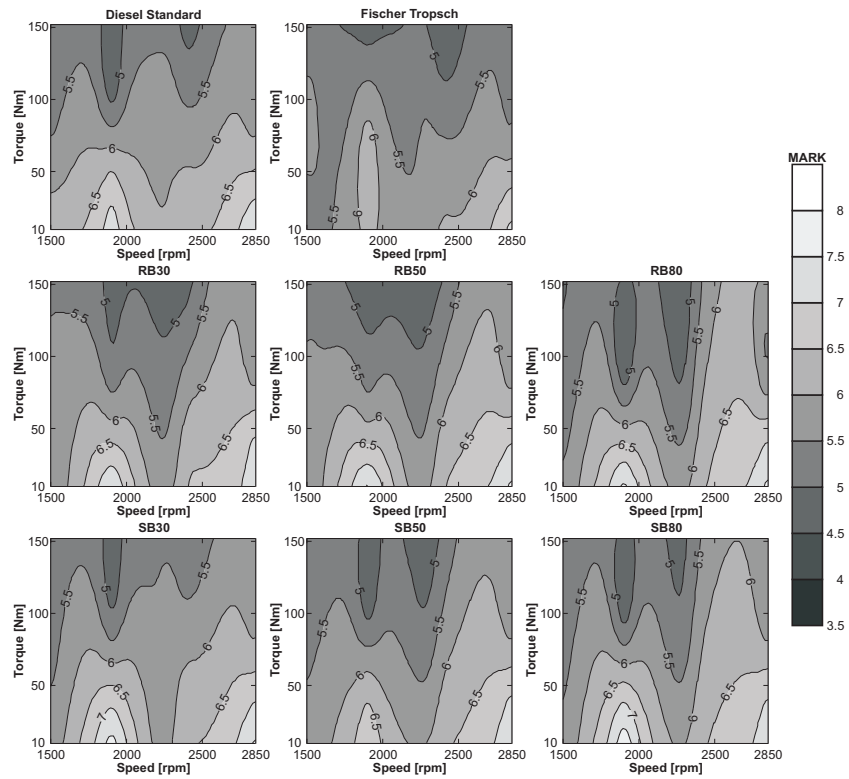
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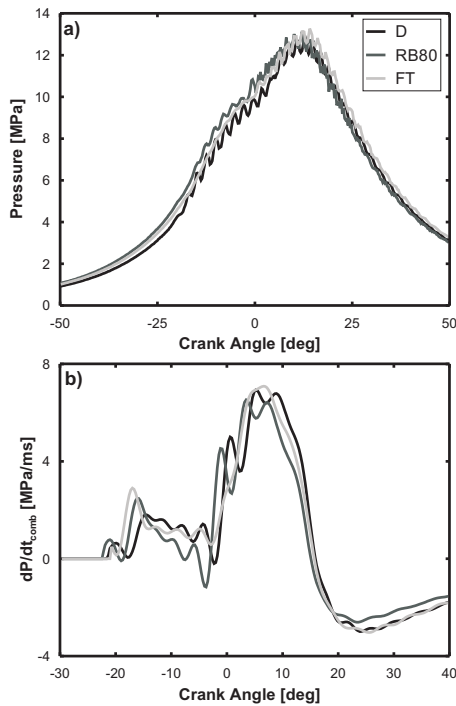Figure 5: Contours of sound quality mark of combustion noise for different fuels.

Figure 6: Effect of fuel on: in-cylinder pressure (a) and in-cylinder pressure derivative (b).

4.5. Effect of EGR rate

The analysis presented in the previous sections has shown that BSFC, soot, NO_x and combustion noise quality are very sensitive to the EGR rate. The purpose of this section is to perform a deeper analysis of the impact of EGR rate on these parameters in order to evaluate the feasibility of defining optimal EGR settings for the improvement of those parameters when biodiesel fuel is used. With this purpose, the EGR rate was varied actuating on the EGR valve while the rest of the engine parameters –which were optimized for standard diesel fuel– were kept equal to the baseline settings. The tests were performed at 1500 rpm and 38 Nm torque with the three rapeseed based biodiesel blends considered.

The sensitivity of emissions and noise to both EGR rate variation and biodiesel content is represented in Fig. 7. These results evidence that the reduction of the O_2 concentration of the charge due to the EGR rate shifts the whole combustion process further towards the expansion stroke. Due to this fact both the combustion temperature and the rate of pressure rise in the cylinder can be reduced, which allows a decrease in the NO_x formation and an improvement in combustion noise, respectively. Nevertheless, since the EGR causes low local oxygen to fuel ratios, soot emissions are increased. Moreover, the reduction of the oxygen availability in the cylinder produces also an increase in BSFC.

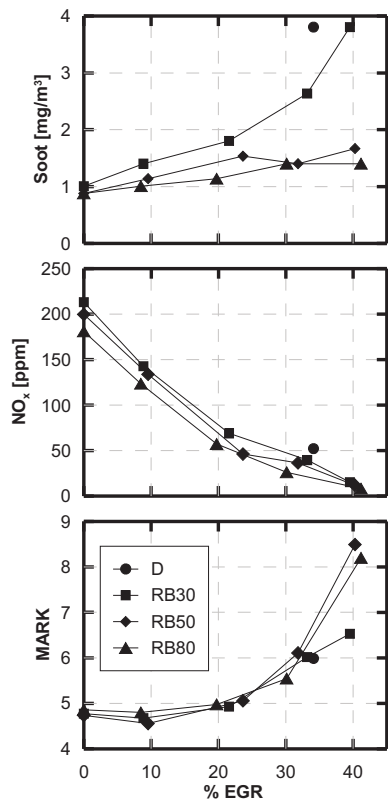Fig. 7 also shows that for a given EGR rate, soot emis-

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Figure 7: Effect of EGR rate on emissions and noise for different rapeseed blends.

sions decrease as the biodiesel content increases. The soot reduction is more apparent for blends containing more than 50% of biodiesel. Regarding NO_x and noise quality the effect of the fuel blend composition is not as evident as for the case of soot emissions. For the low range of EGR rates a noticeable reduction of NO_x emissions can be appreciated. These differences seem to be smaller as the EGR rate increases because very low levels were measured at these conditions. The opposite trend is observed for the combustion noise, which notably improves for higher EGR rates.

Finally, results in Fig. 7 indicate that by increasing the EGR rate from the baseline (32%) to 35% acceptable levels (7) of the noise quality can be achieved, and soot and NO_x emissions are reduced when either rapeseed blends RB50 or RB80 are used. In order to reach the acceptable limit of combustion noise with the RB30 blend, an EGR rate higher than 40% must be used, but then soot would exceed the level emitted with standard diesel fuel and an increase of BSFC of more than 27% should be expected.

5. Conclusions

This investigation confirmed that biodiesel fuels are very appropriate substitute for oil fuels and suitable for reducing pollutant emissions in diesel engines. However,

their potential in base-line diesel engines for environmental preservation could be missed due to their low values of sound quality, which is an aspect most oftenly considered by the customers during their purchasing decision of vehicles powered by diesel engines. This fact puts in evidence that further work is still required to adapt the engine settings to the alternative fuels and the importance of incorporating combustion noise issues together with performance and emissions requirements during the definition of such settings.

Since biodiesel fuels have heating values lower than that of standard diesel, the brake specific fuel consumption is deteriorated with these fuels, but the engine efficiency is just slightly affected. In addition, consumption increases in proportion to the biodiesel content in the blend. Conversely, the synthetic Fischer Tropsch fuel permits a noticeable reduction in the fuel consumption of the engine.

Regarding pollutant emissions, the results showed a great potential of biodiesel and Fischer Tropsch fuels for reducing soot emissions in comparison to the standard diesel fuel. Soot emission reduction is increased as the proportion of biodiesel in the blend is larger. On the contrary, NO_x emissions increase mainly due to the higher combustion pressure and temperature induced by changes in injection rate and combustion phasing.

From the acoustic point of view, combustion noise is sensitive to both biodiesel and synthetic fuels. The results showed that combustion noise was deteriorated as the biodiesel percentage in the blend increases. Moreover, a more apparent deterioration of the sound quality of combustion noise was observed with the Fischer Tropsch fuel. In both cases, differences in combustion phasing and injection rate are the cause of noise deterioration.

Finally, in order to reduce NO_x emission and improve the sound quality of engine noise with biodiesel fuels, high EGR rates are imperatively required. The experiments showed that good trade-offs between pollutant emissions and noise can be reached with EGR rates of 35% and with RB50 and RB80 blends. Despite the increase of soot emissions that may be expected with these strategies, the levels were still lower than those obtained with standard diesel fuel.

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