





Article

Turpentine as an Additive for Diesel Engines: Experimental Study on Pollutant Emissions and Engine Performance

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Abstract: The need for reducing fossil fuel consumption and greenhouse gas (GHG) emissions in internal combustion engines has raised the opportunity for the use of renewable energy sources. For the progressive replacement of fossil fuels like diesel, those derived from the sustainable management of forest resources may be a good option. In Portugal, pine trees (*pinus pinaster*) are among the most widely cultivated tree species. Turpentine can be extracted from their sap without harming the tree. Turpentine is known to be a good fuel with a lower viscosity than regular diesel but with a comparable calorific value, boiling point and ignition characteristics, although it is not widely used as a compression ignition fuel. Moreover, recent research has highlighted the possibility of substantially increasing the turpentine yield through biotechnology, bringing it closer to economic viability. The present study investigates the performance, pollutant emissions and fuel consumption of a 1.6 L four-cylinder direct-injection diesel engine operating with several blends of commercial diesel fuel and turpentine obtained from pine trees. The aim of this study was to assess whether it would be possible to maintain or even improve the performance, fuel consumption and GHG and pollutant emissions (HC, NO_x, CO and PM) of the engine with the partial incorporation of this biofuel. Turpentine blends of up to 30% in substitution of regular diesel fuel were tested. The main novelties of the present work are related to (i) the careful testing of a still-insufficiently studied fuel that could gain economical attractiveness with the recent developments in yield improvement through biotechnology and (ii) the tests conducted under fixed engine load positions typical of road and highway conditions. The addition of this biofuel only slightly impacted the engine performance parameters. However, a slightly positive effect was observed in terms of torque, with an increase of up to 7.9% at low load for the 15T85D mixture and 6.8% at high load being observed. Power registered an increase of 9% for the 15T85D mixture at low speed and an increase of 5% for the 30T70D mixture at high speed when compared to the reference fuel (commercial diesel fuel). While the efficiency and fossil GHG emissions were improved with the incorporation of turpentine, it had a mixed effect on polluting emissions such as unburned hydrocarbons (HC) and smoke (PM) and a negative effect on nitrogen oxides (NO_x). NO_x emissions increased by 30% for high loads and 20% for low loads, mainly as an indirect effect of the improvement in the engine performance and not so much as a consequence of the marginally higher oxygen content of turpentine relative to commercial diesel fuel.

Keywords: turpentine fuel; diesel substitution; engine testing; terpene biofuels



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1. Introduction

In the last 30 years, the main energy source for the field of transport has been represented by fossil fuels. They are still needed today for internal combustion engines (ICEs). Fossil fuels are not a renewable source of energy, and that is why alternative energy sources such as biofuels have been produced from various sources [1] and blended with fossil fuels. Biofuels are an important alternative to fossil fuels as they produce fewer greenhouse gases (GHG) on a life-cycle basis and can be produced from renewable sources such as agricultural crops, forest products and food waste. They also aim to improve the quality of life by significantly reducing harmful gases. Biofuels can be used in a variety of ways, from powering vehicles to producing electricity. Because the standards of the European Union are becoming increasingly challenging in terms of the pollutant emissions of internal combustion engines [2], emissions harmful to humans and the environment must be drastically reduced. The transesterification of plant/animal fats with methanol is the basis for producing biodiesel, an environmentally beneficial and renewable fuel that is primarily made up of high-fatty-acid methyl esters. In addition to being non-toxic, flammable, non-explosive and biodegradable, biodiesel also boasts a large supply of raw materials and supply security [3–5].

Biodiesel production in Europe is a rapidly emerging industry, as the European Union has set ambitious targets for biofuel production in the continent. To meet these targets, Europe has invested heavily in research and development (R&D) for biodiesel production, which has resulted in the development of numerous biodiesel plants across the continent. Biodiesel is produced by combining vegetable oils and animal fats with methanol and a catalyst to produce a fuel that is substantially similar to diesel fuel. It is then blended with diesel fuel to create biodiesel blends, which can be used in any diesel engine. In addition to being a renewable source of energy, biodiesel also has several environmental benefits. It emits fewer pollutants than traditional diesel, except for nitrogen oxides. The European biodiesel industry is highly competitive, with many major players competing for market share. The largest biodiesel producers in the region are Germany, France and the Netherlands. These countries have invested heavily in R&D for biodiesel production, leading to the development of several plants across the continent. In addition, several smaller countries are beginning to enter the market, such as Austria, the Czech Republic and Denmark [6,7].

Despite its popularity as an alternative biofuel to diesel fuel, new alternatives to biodiesel are being developed. These alternatives do not rely on the intensive cultivation of energy crops but rather on sustainable forest management, in which the extraction of energy does not require cutting down trees. Turpentine is such an example. It is a volatile organic compound derived from the resin of certain coniferous trees such as *Pinus Pinaster*, the most abundant conifer species in Portugal, and it is obtained without the need to cut down the tree. It is a powerful solvent and cleaning agent that is derived from pine trees. It has been used for centuries as a medicine, disinfectant and paint thinner. Turpentine is a clear, colourless liquid with a slight pungent odour and flavour. It is composed mainly of a mixture of terpenes and terpenoids, and its main component is alpha-pinene. It is also used in making varnishes, adhesives and inks. It can also be used to make solvents, which can be used to dissolve oils and waxes. Turpentine has several medicinal uses. Turpentine can be irritating, and it is toxic if ingested or inhaled in large quantities [8].

In recent years, turpentine has been gaining attention as a potential biofuel. It is a renewable, sustainable, carbon-neutral fuel source. Turpentine can be produced from sustainably harvested pine trees or from the waste products of sawmills and paper mills. Turpentine can also be made from vegetable oils and other plant-based materials. Turpentine has an energy density that can surpass that of diesel fuel and can be used, to a certain degree, in diesel engines. It has a low sulphur content and generally does not produce as many pollutants as traditional fuels, except for NO_x. Turpentine can also be blended with other biofuels, such as ethanol and biodiesel, to increase the global incorporation of

renewable fuels into engine fuel blends and thus reduce fossil fuel consumption and GHG emissions. This is valid for both diesel and gasoline engine fuel blends [9–12].

Mixing turpentine with diesel provides many beneficial properties that can improve the performance of diesel engines. Turpentine also has a lower viscosity than diesel, which can improve the fuel's ability to flow through an engine's fuel system. In addition, it can also reduce the amount of sulphur dioxide produced by diesel engines, helping to reduce air pollution and extending the life of aftertreatment systems. Being a biofuel that emits CO₂ with its combustion, it can be considered as carbon-neutral or even carbon-negative because of the CO₂ absorption by the plant during its whole lifetime [13]. Finally, turpentine can be used to help improve the fuel economy of a diesel engine. This is related to factors such as its higher heating value, its improved combustion due to oxygen in the molecule and its lower viscosity, which facilitates injection and fuel atomisation [14].

Although turpentine has been used for a long time in a lot of applications, its research and use as a biofuel is still not widespread. There are some notable studies on this fuel being incorporated into diesel engines [9,12,15–17].

Some of the studies involving turpentine or pine oil reported a lower efficiency and higher fuel consumption. This was the case with [12], which assessed blends of turpentine and diesel, and [18], which assessed blends of jatropa oil and turpentine. However, there were some cases where a lower consumption was recorded during the driving cycle [12], reporting a lower fuel consumption for pine oil blends than diesel or jatropa blends [19]. Thus, it seems that further exploration of the impact of turpentine blends on consumption is still needed.

The authors of [20] reported that pollutant emissions such as HC, CO and smoke decreased by 65%, 30% and 70%, respectively, compared to diesel at a high engine load. However, at maximum load, pine oil had up to 25% higher NO_x production than the reference fuel.

Torque and power are parameters that are important in assessing vehicle performance. Often, authors either report results on turpentine blends for a full engine load [21] or as a function of several engine loads. However, not only is a full engine load an engine setting that is rarely used in regular driving but also many studies do not even highlight the torque/power corresponding to a given engine load. This makes it difficult to assess the usefulness of the results for real driving scenarios.

From the abovementioned literature review, it is apparent that this fuel is still insufficiently explored. The recent advances in biotechnologies for increasing turpentine yields have raised the potential economic interest of this fuel, especially in a country such as Portugal, in which the pine industry has such a strong economical role. Additionally, the existing studies on turpentine fuel do not present the results in a way that is practical for assessing vehicle performance under engine loads that are typical of road driving and highway driving. Under these circumstances, it seems important to carefully test this fuel that is still insufficiently studied now that its economical relevance might increase.

The present study performs a series of tests using mixtures of turpentine with diesel in different proportions in a light-duty four-cylinder 1.6 L direct-injection engine.

The mixtures tested were 5T95D (turpentine 5% and diesel 95%), 10T90D, 15T85D, 20T80D and 30T70D. The performance of these mixtures was compared under four combinations of speed and load that are typical of different driving scenarios: 1700 RPM and 2250 RPM, roughly corresponding to a speed of around 90 km/h and 120 km/h for a light duty car, respectively, and two different loads. The variation in the degree of turbocharging was avoided by fixing it at 0.5 bar. The performance characteristics (torque power, consumption and efficiency) and pollutant emissions were analysed and compared.

2. Data and Methodology

In this study, commercially available turpentine was combined with diesel in order to evaluate the influence of the additive on the combustion behaviour, engine performance and

exhaust emissions. Details about the fuel preparation process that is typically performed to obtain this fuel, as well its main characteristics, are presented in the following section.

2.1. Fuel Preparation

Biofuel extraction involves the steam distillation of pine resin, as shown in Figure 1.

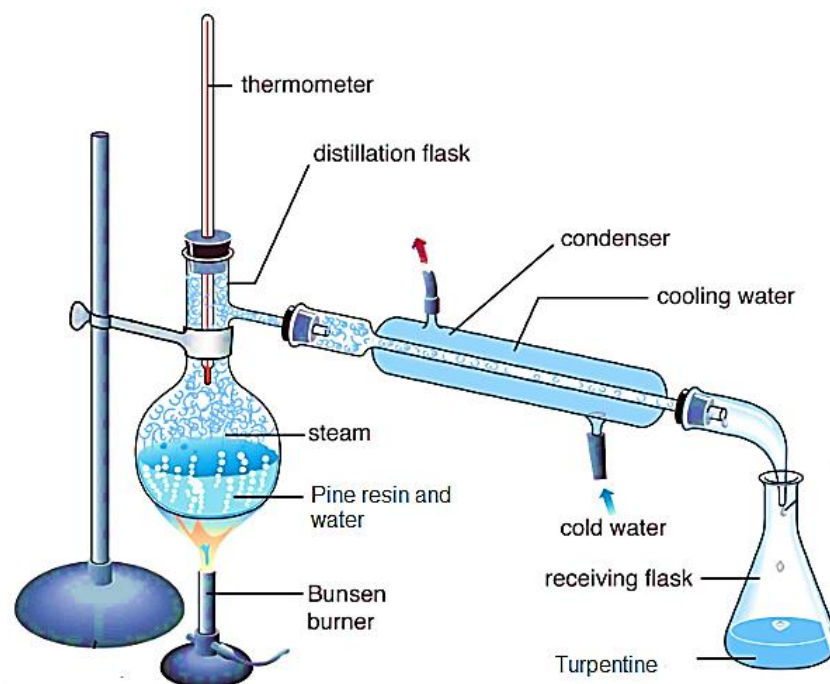


Figure 1. Schematic representation of the distillation process for the extraction of turpentine, adapted from [22].

The typical methodology of pine sap extraction can be found in [23,24]. Pine sap is usually added to a distillation flask together with a quantity of distilled water; considering that the high viscosity of this sap depends on its temperature, it is necessary to add a part of water. After the mixture is exposed to a heat source, the mixture homogenises, and the sap from the trees changes its viscosity and colour, becoming a liquid. Depending on the intensity of the heat source and the amount added to the flask, the duration until the mixture reaches its boiling point is approximately 15 min. As the mixture boils, the content in the flask decreases. This is due to the decrease in the level of water content in the mixture; therefore, a quantity of water is gradually added to extract as much of the substance as possible. Water vapour and turpentine vapour are condensed to reach a liquid state, and they drain into a container. The newly formed mixture is left to settle for 24 h; due to the different density of turpentine compared to water, it separates from the water and can be collected. In general, it is commonly observed that the majority of fuels that are derived through the process of steam distillation and have not undergone transesterification are regarded as fuels characterised by their low viscosity and a lower cetane number [25,26]. In the present study, the authors only performed the blending and some tests to check the solubility of turpentine in diesel and in water. Figure 2 illustrates the decantation process of water that was purposefully added by the authors to turpentine in a test tube to confirm the full phase separation of the fuel and water.

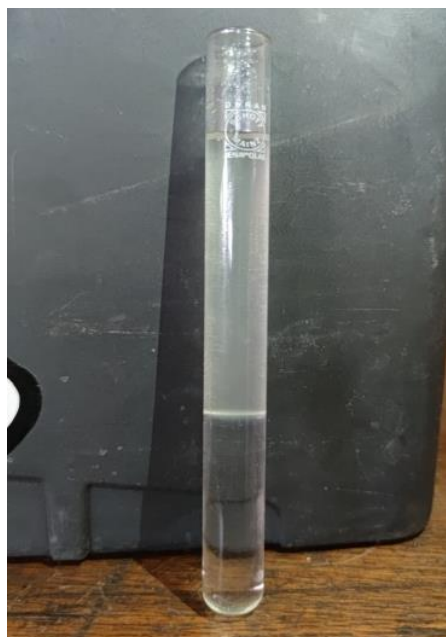


Figure 2. Separation of turpentine from water by decantation.

2.2. Fuel Properties

In the paper [24], Merghini et al. conducted a study regarding the main chemical compounds of turpentine. Twenty-four chemical compounds were identified in this substance, and the dominant compounds were monoterpene hydrocarbons with 81.4% α -pinene and 6.47% β -pinene; the amounts of the chemical compounds in turpentine differ depending on the area where the raw material comes from.

Table 1 shows the properties of turpentine and diesel. It is noticeable that the values for turpentine are somewhat different from those of diesel fuel. Namely, the cetane number is slightly lower. However, the calorific value is higher. Despite this, turpentine has the potential to be well mixed with diesel to create a new fuel blend. Table 2 shows the typical chemical composition of this substance.

Table 1. Typical properties of diesel and turpentine, adapted from [23,27–30].

| Properties | Turpentine Oil | Diesel |
|--|----------------|----------------|
| Formula | $C_{10}H_{16}$ | $C_{12}H_{23}$ |
| Molecular weight (g/mol) | 136 | 167 |
| Boiling point ($^{\circ}C$) | 150–180 | 180–340 |
| Specific gravity | 0.86–0.9 | 0.83 |
| Kinematic viscosity @ 40 $^{\circ}C$ (cSt) | 1.3 | 2.5 |
| Latent heat of vaporisation (kJ/kg) | 305 | 230 |
| Flash Point ($^{\circ}C$) | 38 | 74 |
| Auto-ignition temperature ($^{\circ}C$) | 220–255 | 254–285 |
| Calorific value (kJ/kg) | 44,400 | 42,500 |
| Cetane index | 20–25 | 40–55 |
| Density (kg/m^3) | 860–900 | 830 |

Table 2. Chemical composition of turpentine [24].

| N° | Component | RI | % |
|------------------------|-----------------------------------|------|--------------|
| 1 | Tricyclene | 930 | 0.13 |
| 2 | α -Thujene | 935 | 0.33 |
| 3 | α -Pinene | 940 | 81.41 |
| 4 | α -Fenchene | 949 | 0.01 |
| 5 | Camphene | 952 | 3.1 |
| 6 | β -Pinene | 979 | 6.47 |
| 7 | β -Myrcene | 991 | 0.04 |
| 8 | α -Terpinene | 1019 | 0.11 |
| 9 | Limonene | 1032 | 1.9 |
| 10 | Υ -Terpinene | 1063 | 0.06 |
| 11 | α -Terpinolene | 1089 | 0.03 |
| 12 | <i>Cis</i> - β -Terpinene | 1144 | 0.09 |
| 13 | <i>Trans</i> - β -Terpinene | 1163 | 0.1 |
| 14 | α -Terpineol | 1190 | 0.06 |
| 15 | α -Terpinen-7-al | 1282 | 0.38 |
| 16 | α -Terpinyle acetate | 1350 | 0.13 |
| 17 | α -Longipinene | 1351 | 0.01 |
| 18 | Longicyclene | 1372 | 0.11 |
| 19 | β -longipinene | 1398 | 0.09 |
| 20 | Longifolene | 1403 | 2.4 |
| 21 | β -Caryophyllene | 1427 | 2.37 |
| 22 | α -Humulene | 1461 | 0.03 |
| 23 | Germacrene-b | 1555 | 0.33 |
| 24 | β -Caryophyllene oxyde | 1588 | 0.28 |
| Retention Index | | | 99.99 |

2.3. Experimental Setup

The engine (Figure 3) in which the fuels were tested was a 1.6 L PSA HDI four-cylinder, four-stroke, water-cooled, turbocharged diesel engine with an intercooler in the intake manifold. The only changes made to the engine were related to the turbocharger pressure and the EGR, which was deactivated. These changes were carried out to avoid an excessive number of parameters being varied at the same time, which would have made it impossible to suitably analyse the effect of fuel blends on the behaviour of the engine. Namely, the turbocharger pressure was set at a fixed value throughout the speed range in order to have the same boost pressure (0.5 bar) for all tests independently of the speeds and loads tested. A similar statement may be made regarding the EGR levels. Although these alterations somewhat limited the scope of the results obtained, they allowed a more objective assessment of the impact of turpentine blending for the different test conditions. The original ECU was used, but it was reprogrammed to eliminate errors associated with using the engine outside of the vehicle and also to deal with the changes made to the engine, as mentioned above. A rotary encoder measuring both 1 and 2500 pulses per revolution was used on the electromechanical brake shaft to monitor its speed. The brake controller varied the braking torque so that it kept the engine speed within ± 5 rpm of the setpoint. The engine was equipped with a high-pressure fuel pump and a common rail fuel system. The injection command was carried out electronically through the electronic control unit (ECU). A high-pressure sensor inserted into the common rail was responsible for monitoring the fuel pressure. To facilitate the analysis of the engine behaviour, the EGR was not active.

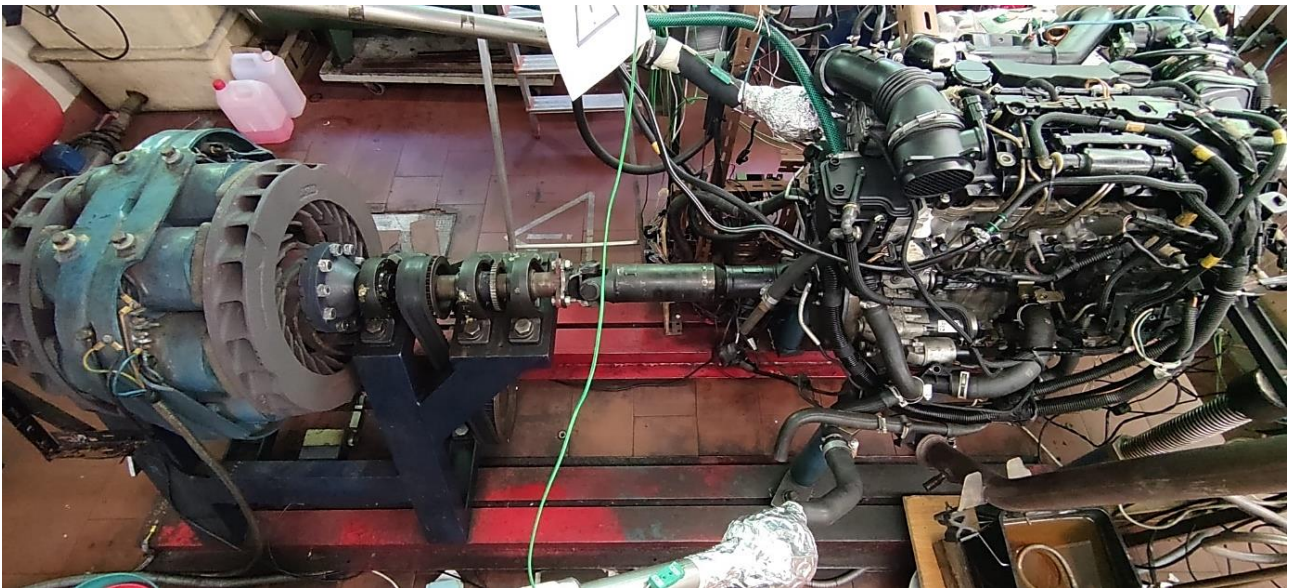


Figure 3. Experimental engine test stand.

There was no particle filter, which allowed a direct assessment of the particle emissions through opacity measurements. The technical information of the engine is highlighted in Table 3. The monitoring of the temperatures of the coolant, intake manifold, lubricant and exhaust flow was performed using type-K thermocouples connected to a National Instruments (NI 9214,) data acquisition system connected to a graphical interface. The engine load setting was monitored in the same interface with the help of the data acquisition board from National Instruments (NI 9201). The data collection had the same time reference because all the programs were in the same interface.

Table 3. Test engine specifications.

| |
|-------------------------------------|
| Engine: in-line 4 |
| Fuel: diesel |
| Fuel injection: common rail |
| Displacement: 1560 cm ³ |
| Bore/Stroke: 75/88.3 mm |
| Valves: 16 valves |
| Turbo-charging: turbo + intercooler |
| Compression ratio: 18:1 |
| Power: 75 HP/56 kW @ 4000 RPM |
| Torque: 170 Nm @ 1700 RPM |

The engine was connected to a Telma AD6-55 electromagnetic brake with eddy currents to dissipate the power produced [31]. The torque was measured with an S-type 500 kgf Zemic B3G load cell with a combined full-scale error of $\pm 0.02\%$. This translated into a maximum error of ± 0.1 Nm in the engine torque for considering the load cell installation and the 3.86:1 transmission relation. Regarding power, it was obtained from multiplying the torque by the angular speed. The error in power calculation for the worst combination of speed and torque values was 0.93%. The calibration curve of the cell can be seen in Figure 4.

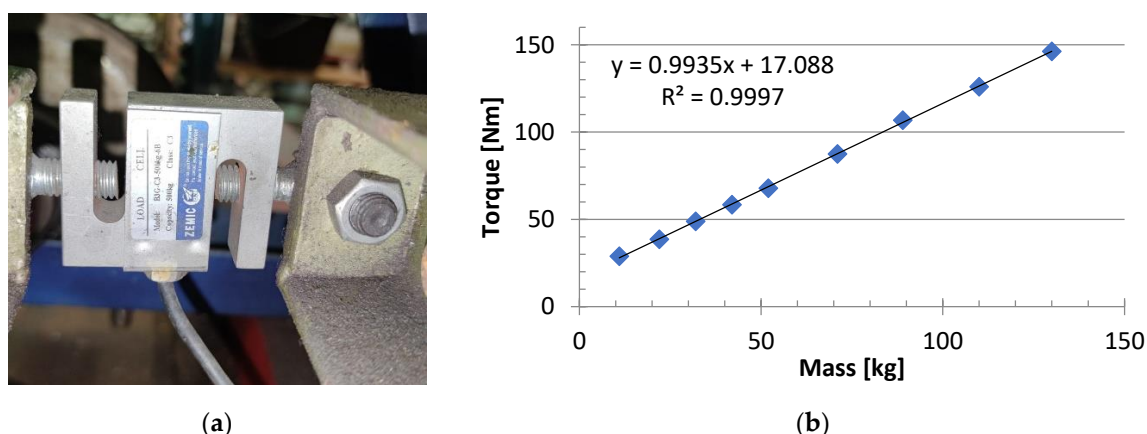


Figure 4. (a) S-type torque cell and (b) calibration curve, with calibration points in blue.

A model AVL DIGAZ 4000 Light analyser from the company AVL for measuring HC, CO₂, CO and NO_x emissions was used to determine the concentrations of pollutant emissions from the exhaust gas. The smoke was measured with an AVL DISMOKE 4000 device. The details of the measuring devices and the measurement precision are presented in Tables 4 and 5.

Table 4. Technical specifications of the AVL gas analyser.

| Measurement Data | Measurement Range | Resolution |
|-------------------|-------------------|------------|
| CO: | 0–10% Vol. | 0.01% Vol. |
| CO ₂ : | 0–20% Vol | 0.1% Vol. |
| HC: | 0–20,000 ppm Vol | 1 ppm |
| NO _x : | 0–5000 ppm Vol. | 1 ppm |
| O ₂ : | 0–25% Vol. | 0.01% Vol. |
| Engine speed: | 250–9990 rpm | 10 rpm |
| Oil temperature: | 0–150 °C | 1 °C |

Table 5. Technical specifications of the AVL smoke analyser.

| AVL DiSmoke 4000 | Measurement Range | Resolution |
|-----------------------------|-------------------------|----------------------|
| Opacity | 0–100% | 0.10% |
| Absorption (K-value): | 0–99.99 m ⁻¹ | 0.01 m ⁻¹ |
| Acceleration time: | 0–5 s | 0.05 s |
| Engine speed: | 250–9990 rpm | 10 rpm |
| Oil temperature: | 0–150 °C | 1 °C |
| Ignition angle TDC sensor: | –60–100 °c.a. | 0.1 °c.a. |
| Ignition angle stroboscope: | 0–60 °c.a. | 0.1 °c.a. |

Fuel consumption was measured using a Kern PCB3500-2 (Figure 5) precision weighing scale with a ±0.01 g precision [32]. The scale was connected to the data acquisition system for the continuous and real-time recording of the experimental data. The consumption was calculated by extracting the slope of the mass vs time curve through least-squares analysis fit to the stabilised portion of the curve. Average sample rates higher than 3 Hz were acquired. Measurements spanning several minutes were performed so that the number of samples used to extract the consumption value (slope of the curve) were close to or even surpassed a thousand samples. The oscillation of the consumption was exceptionally low, as seen in Figure 6. The R² fit was mostly higher than 0.999, as seen in the example displayed in Figure 6. Thus, the random error related to the fit was negligible. The external

temperature, air humidity and atmospheric pressure at which the tests were conducted were also recorded and saved with a thermo-hygro-barometer [33].



Figure 5. Fuel consumption measurement and data acquisition board.

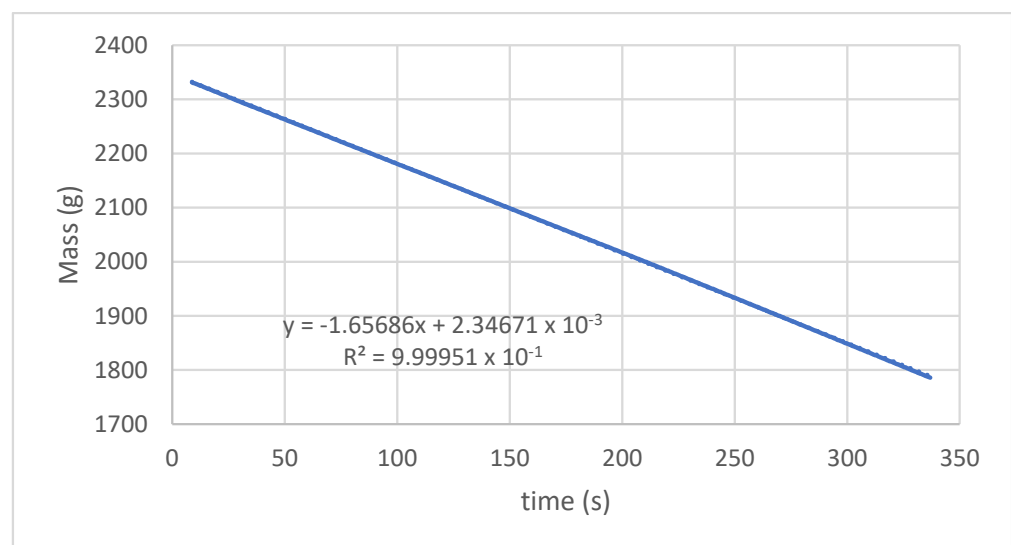


Figure 6. Example of the evolution of fuel mass in the tank over time to enable calculation of consumption including linear regression fit, in which the slope is the resulting mass flow rate of fuel.

Each test was performed at least three times. The results were recorded only once the engine operation was stabilised. This occurred once the coolant and lubricant temperatures, as well as the pollutant levels, were stabilised. Measurement of the average fuel consumption was conducted for at least 2 min, but it was often conducted a lot more. The results represent the average values of several repetitions of each test. Differences between repetitions were generally quite low. For instance, deviations in the fuel consumption errors from the average were in the range of 1%, while those of pollutants were generally below 4%, except for opacity, which sometimes reached slightly above 10% from the average.

2.4. Performance Parameter Calculation

A measure of the overall efficiency of an engine is given by the brake thermal efficiency. The brake thermal efficiency is the ratio of the energy produced by the engine to the fuel energy. The brake thermal efficiency was calculated using Equation (1). For a variation in the calorific value of 1% the maximum combined error in efficiency would be lower than 3%.

$$BTE = \frac{BrakePower \text{ (kW)} \cdot 3600}{FuelFlow \left(\frac{\text{kg}}{\text{h}}\right) \cdot CalorificValue \left(\frac{\text{kJ}}{\text{kg}}\right)} \cdot 100 [\%] \quad (1)$$

2.5. Test Parameters

Table 6 displays the parameters tested. In particular, two different speeds and engine loads were tested for all the fuel blends. Two baseline torques of 58 Nm and 87 Nm were imposed for the baseline fuel. These torques corresponded to the engine loads represented in the table for each torque/speed combination. The engine loads were chosen to simulate a vehicle in motion in the highest gear, at 90 km/h and 120 km/h along flat and mildly sloped roads. These speeds are typical of the national roads and highway roads of the European Union.

Table 6. Test parameters.

| Engine Speed [RPM] | 1700 | | 2250 | |
|---|------------------------|------------|------------------|------------|
| Equivalent driving conditions | National road 90 km/h | | Highway 120 km/h | |
| | horizontal | mild slope | horizontal | mild slope |
| Engine torque (baseline fuel—diesel) [N·m] | 58 | 87 | 58 | 87 |
| Power (baseline fuel—diesel) [kW] | 10.4 | 15.3 | 13.6 | 20.6 |
| Engine load (all fuels) [%] | 27.1 | 34.0 | 31.6 | 37.3 |
| Turpentine incorporations tested [%] Example: 5T95D = 5% turpentine + 95% diesel | 5%, 10%, 15%, 20%, 30% | | | |

Then, these same engine loads were imposed for all the fuel blends, resulting in slightly different torques depending on the fuel performance.

3. Results and Discussions

The present section describes the results of the experimental tests, such as the performance characteristics and the pollutant emissions of the engine that used diesel as a reference fuel and mixtures of diesel with turpentine at the same engine load with the same operating parameters.

3.1. Performance Characteristics

The performance parameters described in this section are the brake thermal efficiency BTE (in %), torque (N·m) and power (kW).

3.1.1. Brake Thermal Efficiency

The BTE (in %) of the engine for the different concentrations of mixtures of biofuel with diesel is presented in Figure 7. As can be seen, the turpentine addition always had a positive effect relative to diesel except for at the high-speed, low-load setting, at which the improvement was only visible for the highest level of turpentine incorporation.

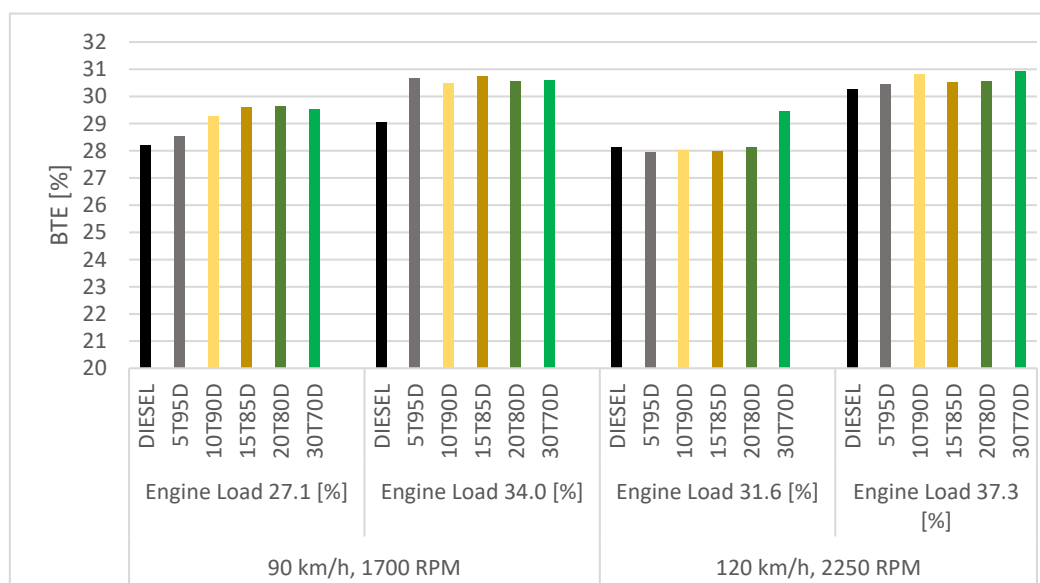


Figure 7. Brake thermal efficiency (%) of the engine for different fuel blends.

Regarding the general trend, the differences in efficiency were fairly small, with a maximum difference of 1.5 percentage points in terms of efficiency being obtained, meaning that there was a relative difference of 5.2% between the pure diesel and any of the turpentine blends. Strictly speaking, there was no set of loads/speeds in which the efficiency always increased with increasing the turpentine incorporation. However, when accounting for oscillations, the trend can be considered to have roughly increased when the turpentine incorporation increased in two of the four conditions.

Despite the small differences between the blends, the oscillations around the mean value obtained between the tests carried out with the same conditions were also small, generally between 0.1% and 3%. Therefore, although the specific differences between the different blends were too close to be assessed, the general trends seemed to be sufficiently visible to allow a qualitative comparison and to evaluate the addition of turpentine as mostly positive. This was similar to what some authors have found and might be attributed to a better atomisation of the fuel, better vaporisation and a reduction in the viscosity of the mixture. In addition, the presence of oxygen in the fuel helped it to burn more efficiently, increasing the BTE of the engine [34,35]. Some other authors have found the efficiency to decrease, attributing this to the negative effect of the lower cetane number of turpentine [36]. However, this tended not to be the case for the present study. In fact, for a high load and at low speed (corresponding to a vehicle speed of around 90 km/h), the mixture with the highest turpentine incorporation registered a 1.5% increased efficiency. The highest efficiency was recorded by the mixture 30T70D for a high speed and at both loads, with values of 1.3% and 0.7%, respectively, being obtained. These results seem interesting regarding the potential of turpentine. The fact that the negative effect of a lower cetane number was not observed might be related to the fact that low boost pressures were used. Under these conditions, the improvement in combustion due to the higher oxygen content seems to have played a larger net positive effect than the challenges to combustion due to the higher ignition delay of lower-cetane-number fuels.

3.1.2. Fuel Consumption

The variations in the fuel consumption can be seen in Figure 8. It should be noted that a higher fuel consumption does not necessarily mean a lower efficiency because of the different calorific values of the two components and the different powers produced. Also, a higher speed also tends to induce a higher consumption because of the higher number of cycles per unit time. Curiously, the high-load/low-speed tests recorded a higher

absolute consumption than the low-load/high-speed tests. The lowest fuel consumption values were recorded for the 20T70D mixture. A slight trend seemed to be that the lowest consumption tended to occur for the extremes of pure diesel and the highest turpentine incorporation. Nevertheless, these results did not allow the extraction of a lot of conclusions given that too many parameters affected them.

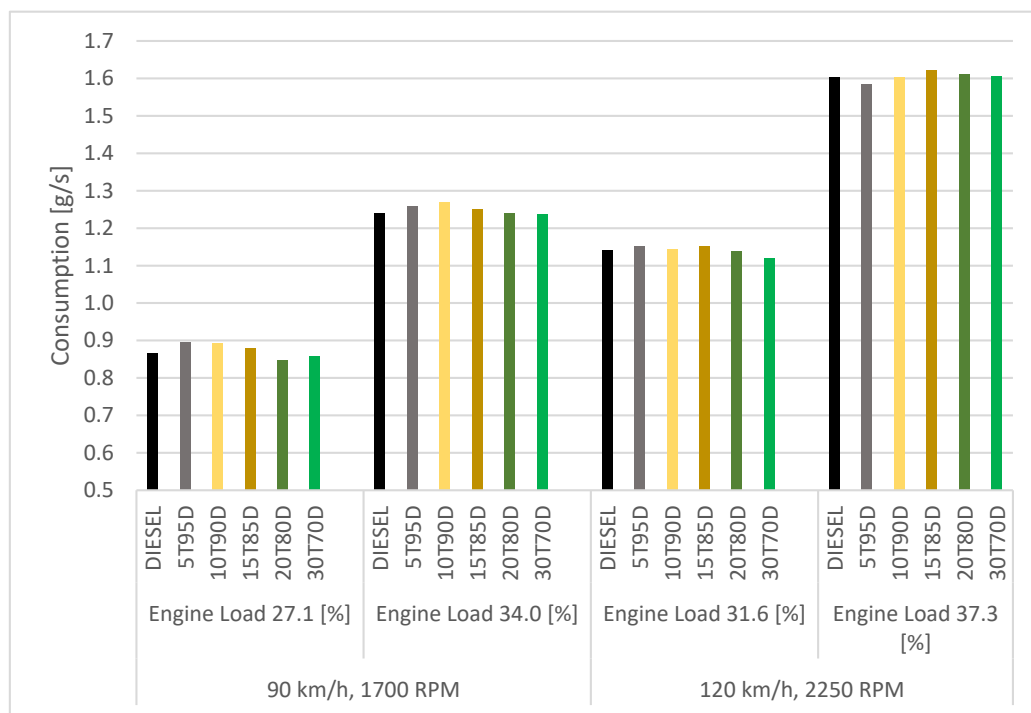


Figure 8. Fuel consumption (g/s) of the engine for different fuel blends.

3.1.3. Torque and Power

In Figure 9, the variation in the torque with turpentine incorporation can be seen for the four different conditions tested.

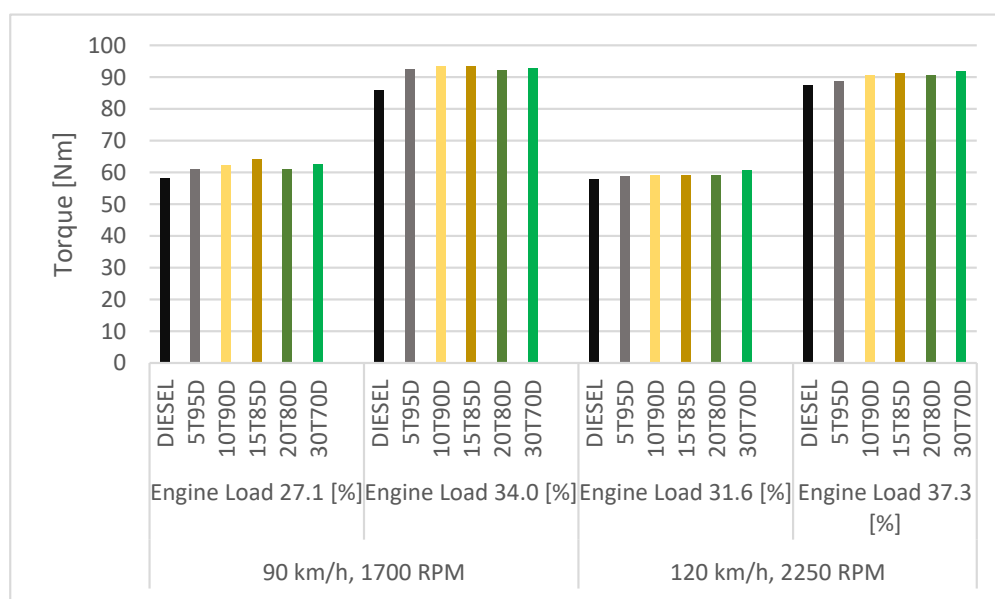


Figure 9. Torque (N-m) of the engine with different blends.

For the low load and with an engine speed of 1700 RPM, the 15T85D mixture registered the highest increase in torque, which was 7.9% higher than that of diesel. For the engine speed of 2250 RPM at low load, the 30T70D mixture recorded the highest performance, with a torque that was 5.2% higher than that of diesel. For the high engine load at an engine speed of 1700 RPM, the 15T85D mixture registered the highest increase in torque relative to the baseline fuel, specifically with an increase of 6.8%. The 30T70D mixture had an increase of 4.7% at a high load and high speed of the engine.

Figure 10 displays the brake power of the engine obtained with several fuel blends. At low speed, the increases were around 9% for the fuel with a 15% incorporation of turpentine for both the low-speed and low-engine-load settings. For the high-speed setting, the fuel with a 30% incorporation of turpentine displayed the highest increase in power, which was close to 5% for both engine load settings. These improvements were related to the improvement in torque, as already discussed above. These improvements seem interesting for the potential of turpentine mixtures in engines.

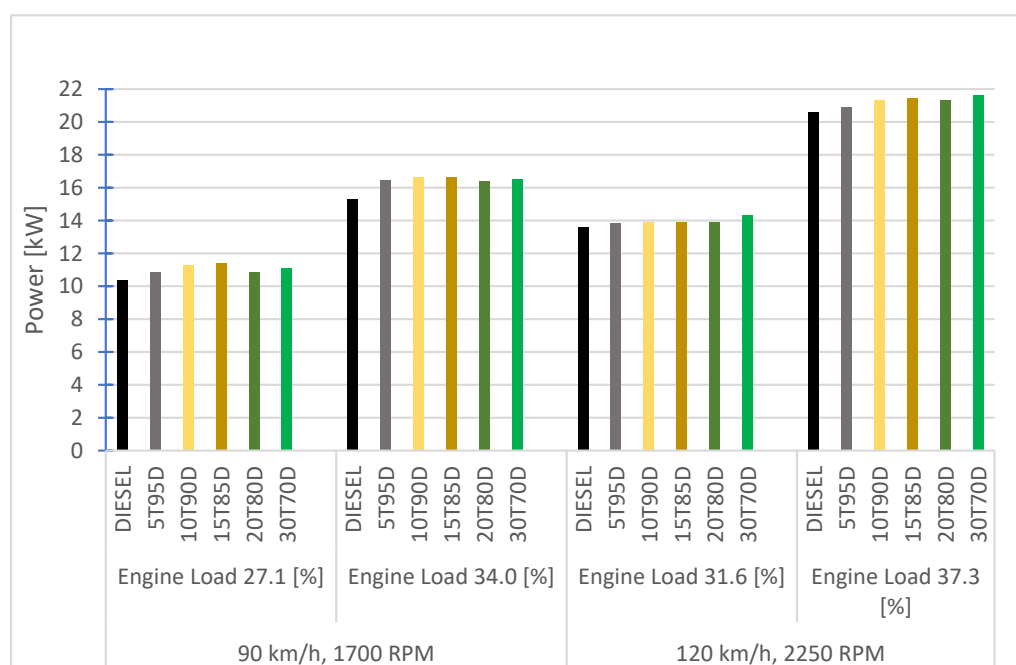


Figure 10. Brake power (kW) of the engine with different blends.

3.2. Emission Characteristics

The emissions of unburned hydrocarbons (HC) can be seen in Figure 11. The highest HC emissions for all engine loads were recorded for the mixture with the highest percentage of turpentine in diesel (30T70D). The HC emissions for this mixture at 1700 RPM were 24.6% and 37.1% higher than those of the reference fuel for the two different engine loads. For 2250 RPM, the HC emissions for 30T70D were 17.3% and 25.3% higher than those of diesel. However, it should be noted that the incorporation of turpentine also improved the torque. For this reason, the specific emissions did not increase as much.

Figure 12 displays the emission of smoke for the several fuel blends. The most apparent fact was that the test conditions with high load and low speed provided much higher levels of smoke than all the other test conditions, and this happened to all the fuel blends. This signalled a sub-optimal combustion, which was probably due to the fact the turbocharger did not deliver a large amount of air at 1700 RPM and high load. However, for these operating conditions, the incorporation of turpentine provided a very substantial reduction in smoke emissions for all the blends, with a maximum reduction of 24.8% relative to diesel. The formation of smoke is intimately associated with the air–fuel ratio and the combustion effectiveness [16]. The oxygen that was present in the composition of the bio-additive

tended to cause the smoke emissions to decrease considerably because a more complete combustion could take place. Similar conclusions were found in works such as that of [37], where the authors mixed oxygenated fuel and reported a decrease in smoke emissions. The trends were difficult to assess, although the highest incorporation of turpentine provided good results for all but one of the test conditions, i.e., the one with a lot of smoke.

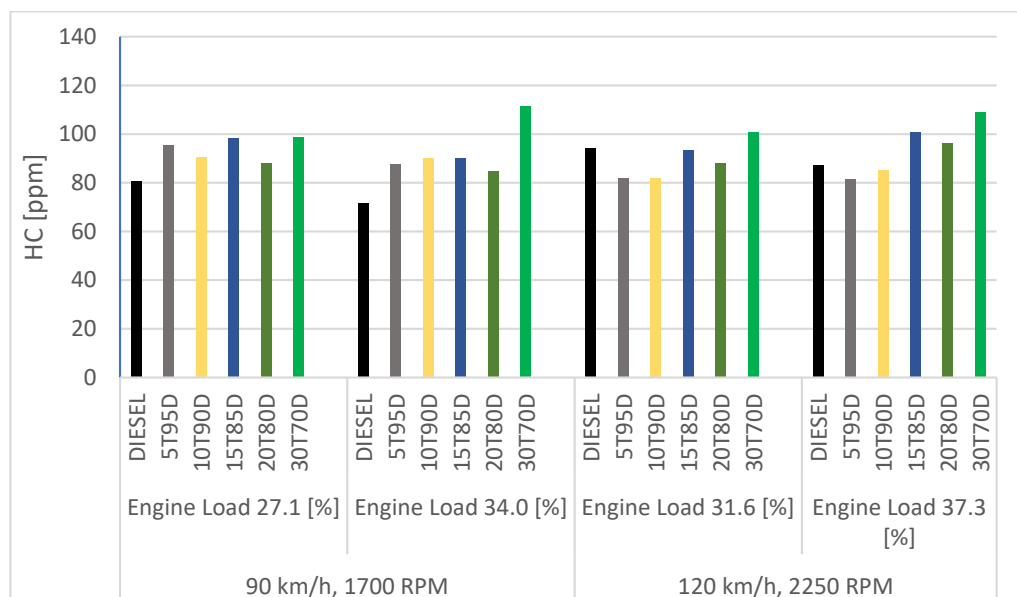


Figure 11. HC (ppm) emission of various blends.

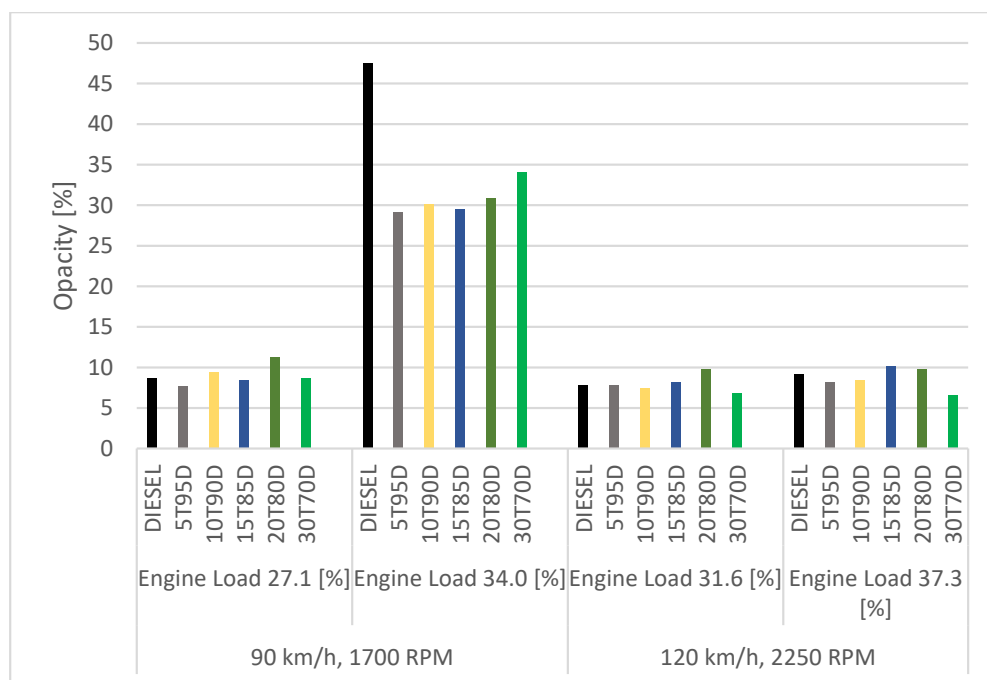


Figure 12. Smoke emission (opacity %) of various blends.

For the engine rotation of 2250 RPM, the 30T70D mixture obtained the lowest value compared to the reference fuel.

Figure 13 shows the level of NO_x emissions. It was observed that as the concentration of turpentine increased, the NO_x emissions tended to be higher. This was likely due to the presence of oxygen in the additive, which promoted NO_x production. Also, it is known that an increase in the combustion performance tends to increase the temperature and indirectly

increase the emission of NO_x due to the favourable environment for the appearance of nitrogen oxides. The highest recorded values were for the 30T70D mixture. Again, the increase in specific emissions was not as high because the incorporation of turpentine had a positive effect on the torque.

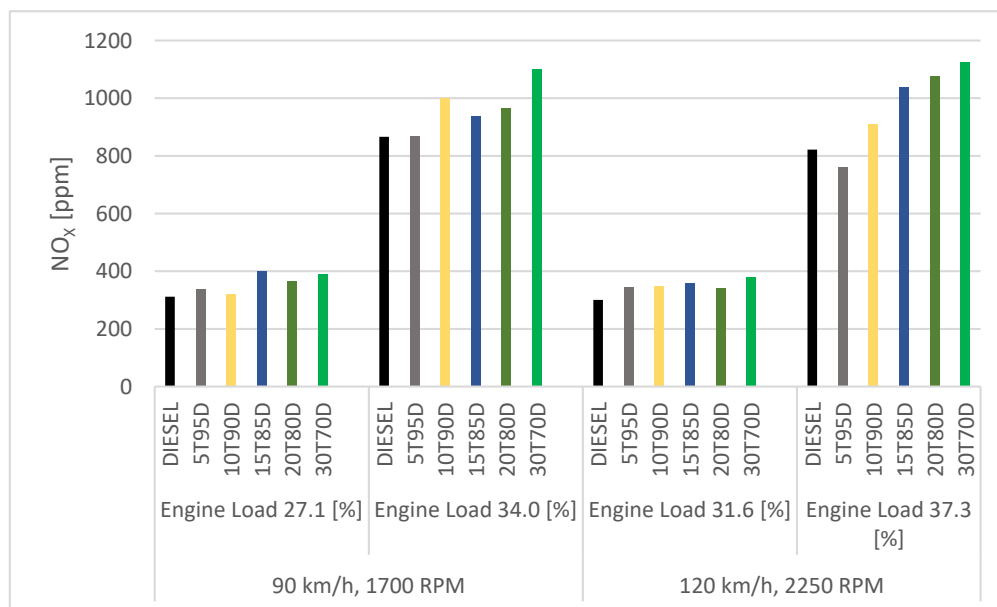


Figure 13. NO_x (ppm) emissions of the various blends.

4. Conclusions

In the present work, incorporations of turpentine into regular diesel of between 5 and 30% were assessed in a direct-injection diesel engine used in light-duty vehicles. The objective was to assess whether it would be possible to maintain or even improve the performance and emissions parameters of the engine. One of the main advantages of this incorporation being feasible would be a direct cut in fossil greenhouse gas emissions.

The comparisons were made in a slightly different way compared to the existing literature. Namely, comparisons for conditions typical of road vehicle driving were made, with the comparison of the different fuel blends being carried out for fixed values of the engine load.

For the conditions tested, the following conclusions may be drawn:

- The differences obtained in the performance parameters such as torque, power and efficiency were not big, so the discussion of these results is necessarily limited. Nevertheless, a qualitative assessment may be conducted.
- The incorporation of turpentine into regular diesel fuel was beneficial for the brake thermal efficiency for most of the turpentine incorporations tested. Namely, improvements of up to 5.5% were recorded at high loads and low speeds for the fuel with highest turpentine incorporation (30%). The brake torque always increased when incorporating turpentine into diesel fuel. Increases of nearly 8% and 7% were obtained for the fuels with 15% and 30% incorporations of turpentine. The improvement in the brake power was even better, with 9% being obtained with a 15% turpentine incorporation at the low-speed setting, while a 5% improvement was achieved for the high-speed setting with a 30% incorporation of turpentine.
- Regarding pollutant emissions, the results were mixed. On the one hand, the level of unburned hydrocarbons (HC) was almost always higher with the turpentine–diesel mixtures than with pure diesel, although the specific emissions (per unit torque or power produced) were not as high because the torque was also higher. On the other hand, this study found that the particulate-matter-induced opacity, commonly referred

to as smoke, displayed either higher or lower values with the turpentine incorporation when compared to diesel. However, a sharp drop in the opacity occurred in the case of low speeds and high loads for all the turpentine blends. This might be related to the positive effect of the slight oxygen content of turpentine on the combustion. Also, the highest incorporation of turpentine (30%) had a positive effect on the smoke reduction in almost all cases.

- Unfortunately, the level of nitrogen oxides (NO_x) produced registered a considerable increase in relation to the concentration of turpentine, which was probably due to not only the extra oxygen in the composition but also due to the improved performance of the engine. In fact, it is known that an increase in combustion performance is generally accompanied by a rise in NO_x emissions.

As an overall evaluation of the results obtained, it seems reasonable to assume that incorporations of turpentine of up to 30% could represent a good opportunity for a proportional reduction in fossil fuel consumption and the associated CO₂ emissions due to the neutral or even negative contribution of turpentine coming from sustainable pine forest management (pines are not cut down for turpentine extraction). This substitution could be achieved with minimal modifications to engines, and even a slight increase in torque, power and efficiency can be obtained in most driving conditions, with potentially lower smoke emissions at high engine loads and low speeds.

The higher emissions of HC and NO_x seem to be an objective disadvantage of turpentine incorporation. However, these results were obtained without implementing advanced aftertreatment. A full analysis of the impact on the viability of turpentine due to these emissions would need further assessment, which was out of the scope of the present study.

Turpentine as a fuel might come closer to becoming economically competitive with the advent of the latest-generation biotechnology-enhanced pines. And in the case of Portugal, *Pinus Pinaster* is among the most-explored tree species, and it could be explored for turpentine production without losing its economic value for the wood and paper paste markets in which it is currently explored commercially [38].

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