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## Comparative study of regulated and unregulated gaseous emissions during NEDC in a light-duty diesel engine fuelled with Fischer Tropsch and biodiesel fuels

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Title: COMPARATIVE STUDY OF REGULATED AND UNREGULATED GASEOUS EMISSIONS DURING NEDC IN A LIGHT-DUTY DIESEL ENGINE FUELLED WITH FISCHER TROPSCH AND BIODIESEL FUELS

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Abstract: In this study, regulated and unregulated gaseous emissions and fuel consumption with five different fuels were tested in a 4-cylinder, light-duty diesel EURO IV typically used for the automotive vehicles in Europe. Three different biodiesel fuels obtained from soybean oil, rapeseed oil and palm oil, a Fischer Tropsch fuel and an ultra low sulphur diesel were studied. The test used was the New European Driving Cycle (NEDC), this allowed tests to be carried out on an engine warmed up beforehand to avoid the effect of cold starts and several tests a day. Regulated emissions of NOX, CO, HC and CO<sub>2</sub> were measured for each fuel. Unburned Hydrocarbon Speciation and formaldehyde were also measured in order to determine the maximum incremental reactivity (MIR) of the gaseous emissions. Pollutants were measured without the diesel oxidation catalyst (DOC) to gather data about raw emissions. When biodiesel was used, increases in regulated and unregulated emissions were observed and also significant increases in engine fuel consumption. The use of Fischer Tropsch fuel, however, caused lower regulated and unregulated emissions and fuel consumption than diesel.

Response to Reviewers:

In this article is tried to evaluate the regulated and unregulated emissions during the NEDC cycle, using different fuel formulation. In order to determine the potential of the exhaust gases in produce tropospheric ozone was consider compounds from the C<sub>2</sub> to the C<sub>7</sub>, formaldehydes and formic acid emissions.

*Manuscript Title*

COMPARATIVE STUDY OF REGULATED AND UNREGULATED GASEOUS EMISSIONS DURING NEDC IN A LIGHT-DUTY DIESEL ENGINE FUELLED WITH FISCHER TROPSCH AND BIODIESEL FUELS

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Valencia, 26<sup>nd</sup> October 2010

Dear Editor,

Please find enclosed the modified manuscript of our article entitled “Comparative study of regulated and unregulated gaseous emissions during NEDC in a light-duty diesel engine fuelled with Fischer Tropsch and biodiesel fuels”, by Vicente Bermúdez, José M. Lujan, Benjamín Pla, Waldemar G. Linares to be accepted for publication with minor’s revision in the Journal of Biomass and Bioenergy.

In the following pages we have included all the comments made by the reviewers together with our detailed answers to their points.

We hope that the modified version of the paper will be publishing in your Journal.

Yours sincerely,

Dr. Vicente Bermúdez Tamarit

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First of all, we would like to thank you for your comments. They helped us to address some weak points in the manuscript first revision.

In the following paragraphs we try to answer more specifically your comments:

- 1. P7 lines 32 - 34 has an example of a non unit or multiplier in the chain - make it clear that the ozone is the substance and the rate is 0.983 g km<sup>-1</sup>*

The units has been modified

- 2. In the references there is still too much punctuation e.g [2] needs to have no commas in the surname, no spaces in the multiple initials, the journal should be the official abbreviations, and note the year is separated from the volume number by a semicolon.*
- 3. References that need some work are [8,9]. It seems that they are chapters in a special report of Health Institute.*
- 4. Reference [9] would follow the same model.*
- 5. [11] has a problem in that there are more than 6 authors as well as an incorrect journal abbreviation it should read:*
- 6. Reference [17] is a conference proceedings and should be formatted appropriately so that readers can find the papers.*
- 7. [19] is a chapter in an edited book in the Springer Verlag series in Chemical Physics #75 - your reference needs to identify the actual article in the edited book that you are citing and to follow the Vancouver system. Likewise [20] is a book and Vancouver does not need the ISBN, but it does need the place of publication - see the format requirements.*

All the references have been modified in to the format expected for JBB

Thanks again for your positive comments. We hope that the manuscript will be worth publishing after the modifications we have performed.

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# 1 Comparative study of regulated and unregulated gaseous 2 emissions during NEDC in a light-duty diesel engine 3 fuelled with Fischer Tropsch and biodiesel fuels

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## 9 **ABSTRACT**

10 In this study, regulated and unregulated gaseous emissions and fuel consumption with five  
11 different fuels were tested in a 4-cylinder, light-duty diesel EURO IV typically used for the automotive  
12 vehicles in Europe. Three different biodiesel fuels obtained from soybean oil, rapeseed oil and palm oil,  
13 a Fischer Tropsch fuel and an ultra low sulphur diesel were studied. The test used was the New  
14 European Driving Cycle (NEDC), this allowed tests to be carried out on an engine warmed up  
15 beforehand to avoid the effect of cold starts and several tests a day. Regulated emissions of NO<sub>x</sub>, CO,  
16 HC and CO<sub>2</sub> were measured for each fuel. Unburned Hydrocarbon Speciation and formaldehyde were  
17 also measured in order to determine the maximum incremental reactivity (MIR) of the gaseous  
18 emissions. Pollutants were measured without the diesel oxidation catalyst (DOC) to gather data about  
19 raw emissions. When biodiesel was used, increases in regulated and unregulated emissions were  
20 observed and also significant increases in engine fuel consumption. The use of Fischer Tropsch fuel,  
21 however, caused lower regulated and unregulated emissions and fuel consumption than diesel.

## 22 **1. INTRODUCTION**

23 Air pollution is a serious problem worldwide, much of which is caused by the use of fossil fuels  
24 for transport. One option to help reduce this problem is to design engines able to run effectively on  
25 alternative fuels. Oxygenated fuels are known to reduce exhaust emissions from motor vehicles. This  
26 type of fuel is of particular interest because it is a potential renewable source of energy. [1] Investigated  
27 the effects on emissions of several oxygenated compounds used as diesel fuel additives. [2] Studied the  
28 performance and regulated emissions during the European MVEG-A cycle. [3] Examined regulated and  
29 unregulated emissions in a diesel engine fuelled with biodiesel of different blends obtained from waste  
30 cooking oil under steady state conditions.

31 On the other hand, the many studies of exhaust gases speciation is an indication of the increasing  
32 interest in this topic by the scientific community [3-6] as a result of recent epidemiological and  
33 toxicological research suggesting a relationship between exposure to exhaust emission gases and  
34 adverse health effects [7-10].

1 It is well known that diesel gaseous emissions have been progressively reduced over the last  
2 twenty years in response to tough emission legislation and due to the application of new technologies.  
3 In-cylinder emission control strategies, such as modifications of injection pressure and injection timing  
4 and the application of exhaust gas recirculation, have been used by researchers in order to reduce  
5 exhaust emissions and comply with legislation. This study evaluates the use of different fuels as an  
6 emission control strategy to reduce gaseous emissions and thereby comply with further, new  
7 regulations.  
8

9 Many studies have been conducted into the effects of biodiesel on NO<sub>x</sub> emissions [2], [11-13].  
10 Taking into account the differences in the origin of biodiesel fuels the results are obtained by different  
11 authors may be expected to vary greatly. Most of them agree that in general, biodiesel increases NO<sub>x</sub>  
12 emissions: the most commonly accepted reason being that the fuel's higher cetane number reduces  
13 ignition delay. Reducing ignition delay increases NO<sub>x</sub> emission because the burning mixture remains in  
14 the cylinder longer [14]. Another reason for the increase in NO<sub>x</sub> emissions in an engine running on  
15 biodiesel is the improved combustion producing higher temperatures. In addition, the higher levels of  
16 oxygen in the combustion chamber lead to an increase in NO<sub>x</sub> [4]. Finally, other theories that emphasise  
17 the importance of soot radiation in the combustion chamber uphold that this phenomenon helps reduce  
18 NO<sub>x</sub> emissions and since biodiesel produces less soot this leads to an unwanted increase in NO<sub>x</sub> [14].  
19

20 In this study three biodiesel fuels of different origins and a fuel obtained by the Fischer Tropsch  
21 process were investigated in a light-duty diesel engine under the New European Driving Cycle (NEDC).  
22 The aims of this study were to test the NEDC in an engine test cell by simulation. In addition, regulated  
23 and unregulated emissions were measured by the Fourier transform infrared spectroscopy (FTIR)  
24 method.

## 25 **2. STRUCTURE OF THE EXPERIMENT**

### 26 **2.1. Engine and fuel properties**

27 The engine specifications are shown in **Table 1**. It is a 2.0-litre HSDI, turbo-diesel engine for  
28 passenger vehicles that complies with EURO IV. The engine is fitted with high pressure fuel injection  
29 using the common-rail injection system, an intercooler, variable geometry turbocharger (VGT) and  
30 exhaust gas recirculation (EGR).

#### 31 **Table 1.**

32 Ultra low sulphur diesel fuel (D) was used in this study as the reference fuel. The second fuel  
33 used was a Fischer Tropsch fuel (FT) produced by a gas-to-liquid process. The different types of  
34 biodiesel used in each instance were obtained by the transesterification of soybean oil (BS), rapeseed oil  
35 (BR) and palm oil (BP). Transesterification consists in the process of a reaction between a triglyceride  
36 (vegetable oil) and alcohol in the presence of a catalyst in order to produce glycerol and ester. The  
37 biodiesel produced from the transesterification should respect the EN-14214. So a complete  
38 characterization of the fuels involucrate in the tests according to the EN-590 for diesel fuel and to the  
39 EN-14214 for biodiesel fuel has been obtained. The characterization had been realized by an external  
40 certified laboratory and results of the fuel characterization are presented in Table 2 shows the main fuel  
41 information.

#### 42 **Table 2.**

## 2.2. General instrumentation

In order to perform transient cycles, the test cell was equipped with an asynchronous dynamometer manufactured by HORIBA ATS<sup>®</sup> controlling online torque and speed. The STARS<sup>®</sup> software used is able to program the driving conditions of the vehicle. With this software, the NEDC cycle is programmed as a time sequence for gears and vehicle speed taking into account the vehicle features and current driver skills. To enable possible modifications of engine parameters, the Engine Control Unit (ECU) is completely open and the engine settings map can be recalibrated by the ETAS INCA<sup>®</sup> software. The engine was fully equipped with type K thermocouples and mean pressure sensors suitably located in the intake, exhaust and cooling system zones.

Fuel consumption was determined by two systems. The first consists of a fuel gravimetric system with an AVL<sup>®</sup> 733S Dynamic Fuel Meter. The measurement device consists of a measuring vessel filled with the fuel and suspended on a balance system. Fuel consumption values are obtained by calculating the vessel's weight loss over time to an accuracy of 0.12% at 75g in accordance with DIN 1319. Since the response time of this system might possibly be too long for this study, the fuel consumption signal provided by the ECU was calibrated in steady state. After calibration, the ECU was used as a second fuel consumption measuring system.

The Sensyflow P Sensycon hot-plate anemometer system was used to measure the flow rate of the intake air mass. The measurement range of the anemometer is 0-720 kg·h<sup>-1</sup>, accurate to within 2% of the measured value.

Engine gaseous emissions were analyzed without exhaust after-treatment system (Diesel Oxidation Catalyst). Emissions (CO, CO<sub>2</sub>, NO<sub>x</sub>, HCHO, CH<sub>3</sub>OH, C<sub>4</sub>H<sub>6</sub>, C<sub>6</sub>H<sub>6</sub>, C<sub>7</sub>H<sub>8</sub> and other compounds) were directly measured in the exhaust pipe by a HORIBA<sup>®</sup> MEXA-6000FT engine exhaust gas analyser. The exhaust line was connected directly to the equipment by a pipe whose wall temperature was maintained at 113° C in order to avoid hydrocarbon condensation. Firstly, the system obtains an interferogram using the Michelson interferometer and the interferogram is then converted to the infrared absorption spectrum by Fast Fourier Transform (FFT) whilst a multivariable analysis enables the concentration analyses of different components to be combined in a single analysis. Since the unique spectrum of many compounds is in the infrared range, this method is used for quantitative and qualitative analysis [15]. The measurement range and accuracy depends on the component being measured and ranges from 0-100 ppm to 0-10%, with accuracy of 1% to 3% of the value measured.

## 2.3. Driving cycle and measurement protocol

Measurement strategies are necessary in a realm like engine emission experimental research due to the many dispersion factors able to introduce variability. The European directive 91/441/EEC defining NEDC contains no explicit procedure for preconditioning the engine before running a transient test. The only specification in current European emission legislation as regards the performance of transient tests is that ambient temperatures must be above 20° C. Although legislation stipulates an engine coolant temperature of between 20 and 30 °C when NEDC starts, it must be remembered that these tests were performed for the purpose of research, not regulations.

Nevertheless, a preconditioning procedure to limit the influence of external factors is vitally necessary to ensure that tests can be repeated well. Thermophoresis is a process that can affect HC measurements in cold start conditions. This phenomenon is due to the existence of a temperature gradient between the exhaust system walls and the exhaust gas in cold start conditions. As a result, HC condenses on the walls. This occurs until a thermal equilibrium between the gas and the walls is reached in the exhaust system. For a detailed description of the test schedule, see the study [16].



1 Despite the on-going development of enhanced exhaust gas analysers, there are considerable  
2 difficulties with emission measurement that must be taken into account when conducting transient tests.  
3 The main problem is that exhaust gas analysers usually have longer response times than other engine  
4 transducers. Pollutant emission signals are, therefore, slightly delayed in comparison with the other  
5 engine parameters. Since exhaust gas analysers measure pollutant concentration, exhaust mass flow  
6 must be determined in order to calculate the instantaneous mass of pollutants emitted.  
7

8 The synchronization of exhaust mass flow and pollutant emission measurement devices is,  
9 therefore, critical. The synchronizing method adopted in this study is described in-depth in the [17].  
10

### 11 **3. RESULTS AND DISCUSSIONS**

#### 12 **3.1. Fuel Consumption and CO<sub>2</sub> emissions**

13  
14  
15 The first effect of the use of biodiesel is the different fuel consumption recorded in each test.  
16 **Figure 1** shows how fuel consumption changes during NEDC. It can be seen that most of the fuel is  
17 consumed in the last phase of the cycle, in highway driving conditions. The increase in fuel  
18 consumption is related mainly to the lower heat value of biodiesel in comparison with diesel fuel.  
19 However, the Fischer Tropsch fuel has lower consumption which can be linked to the high heat value of  
20 this fuel (43.7 MJ·kg<sup>-1</sup>) in comparison with diesel (42.9 MJ·kg<sup>-1</sup>).  
21

22 The difference in fuel consumption between diesel and the different fuels are: +2.7% for  
23 rapeseed oil, +4.85% for soybean oil, +6.23% for palm oil and -7.2% for Fischer Tropsch fuel.  
24

#### 25 **Figure 1**

26  
27 In addition to the economical and environmental effects, higher fuel consumption affects engine  
28 behaviour. Injected fuel mass becomes an essential variable in the engine control system. Most engine  
29 control actuators are controlled by engine speed and fuel mass flow signals. As a result, major engine  
30 elements such as the fuel injection system, EGR (Exhaust Gas Recirculation) valve or VGT (Variable  
31 Geometry Turbine) are heavily dependent on the fuel mass flow.  
32

33 Notice in **Table 2** the differences in the stoichiometric air-fuel ratio. Thus, biodiesel fuels need  
34 less air mass to achieve complete combustion, while Fischer Tropsch fuel needs more air mass.  
35 However air mass flow calibration does not take fuel consumption into account. In short, if the fuel  
36 properties vary from standard diesel fuel properties, the engine must be recalibrated to optimize its  
37 performance with each fuel. However, engine map calibration lies beyond the scope of this study.  
38

39 Tailpipe CO<sub>2</sub> emissions are given in **Figure 2**. CO<sub>2</sub> emissions showed similar fuel consumption  
40 trends, with increases of +4.85%, +5.40% and +11.42% for rapeseed oil, soybean oil and palm oil  
41 respectively in comparison with diesel fuel, and a decrease of 2.40% for Fischer Tropsch fuel compared  
42 with diesel fuel. Overall NEDC emissions were higher as result of declining engine performance and  
43 differences in fuel composition [18].  
44

#### 45 **Figure 2**

#### 46 **3.2. Regulated emissions**

47  
48  
49 In order to a better compression of the figures the results have been expressed in grams of specific  
50 emissions per unit of carbon dioxide, due to the carbon dioxide was coupled to the fuel consumption,

1 with the use of these units we ensure to achieve the results in terms of specific emissions normalized  
2 with the principal compound responsible of the greenhouse effect (CO<sub>2</sub>).

### 3 4 3.2.1. NO<sub>x</sub> emissions

5  
6 **Figure 3** shows the evolution of NO<sub>x</sub> emissions, clearly demonstrates that most NO<sub>x</sub> is emitted  
7 during the extra-urban driving cycle (EUDC) phase. As expected, NO<sub>x</sub> emissions increased with the use  
8 of biodiesel and Fischer Tropsch fuel. Finally, total NO<sub>x</sub> emissions are shown in **Figure 4**.

### 9 10 **Figure 3**

### 11 12 13 **Figure 4**

### 14 15 3.2.2. CO emissions

16  
17 CO exhaust emissions are shown in **Figure 5**. The use of biodiesel increased CO levels,  
18 beginning 1.3 times higher for palm and rapeseed oil, and 2.8 times higher for soybean oil compared to  
19 diesel fuel, but Fischer Tropsch fuel showed a decrease of 0.7 in CO emissions compared with diesel  
20 fuel. CO emissions from diesel and Fischer Tropsch fuel remained below EURO 3 limits (0.64 g·km<sup>-1</sup>),  
21 Again it should be noted that the after treatment device (Diesel Oxidation Catalyst) was removed. Since  
22 oxidizing catalysts drastically reduce CO emissions, this caused the large differences in emissions to  
23 disappear [19], [20].

### 24 25 **Figure 5**

### 26 27 3.2.3. THC emissions

28  
29 HC emissions are the result of incomplete combustion in which some hydrocarbons are not fully  
30 oxidized. In this respect, HC emissions are closely linked to CO emissions since they are both caused by  
31 low quality combustion. The effect of biodiesel on HC emissions is, therefore, similar to its effect on  
32 CO emissions. As a result, increases of +6%, +133% and +280% were observed for palm oil, rapeseed  
33 oil and soybean oil in comparison with diesel fuel, and a reduction of 84% was seen when Fischer  
34 Tropsch fuel was used.

35  
36 It is common knowledge that the reaction between nitrogen oxides (NO<sub>x</sub>) and some total  
37 hydrocarbons (THC) in sunlight produces photochemical smog. Since not all THCs react with NO<sub>x</sub> in  
38 the same way, THC speciation is needed in order to determine the potential of these gases to produce  
39 ozone precursors. One way of detecting photochemical smog is to determine the reactivity of each THC  
40 with NO<sub>x</sub> according to different scales such as the Maximum Incremental Reactivity (MIR) scale  
41 developed by Carter (used by the California Air Resources Board and the USEPA) and the  
42 Photochemical Ozone Creation Potential (POCP) scale [22]. These scales are used to determine the  
43 quantity of tropospheric ozone: the parameter that determines the level of harmful exhaust gases  
44 produced by different fuels.

45  
46 With the traditional HC measurement system it is not possible to detect the levels of the different  
47 compounds in hydrocarbon emissions. In order to understand the nature of these compounds better,  
48 exhaust hydrocarbons from each fuel were speciated.

### 49 50 **Figure 6**

### 3.3. Unregulated emissions

#### 3.3.1. Hydrocarbon speciation

**Figure 7** shows the THC composition of all the fuels used. This is the composition of the total hydrocarbon emissions in **Figure 6**. Hydrocarbon levels from C<sub>1</sub> to C<sub>7</sub> (Methane (CH<sub>4</sub>) to Toluene (C<sub>7</sub>H<sub>8</sub>)) are shown. The changes in hydrocarbon structures can be explained by three phenomena that occur in different pressure and temperature conditions [4], [19] i.e.:

- ✓ Cracking: the division of a long-chain carbon molecule into two small molecules (paraffin and olefin) or two paraffin molecules
- ✓ Polymerization: a combination of two olefin molecules to form one larger olefin molecule.
- ✓ Reformed: the catalytic conversion of paraffinic or naphthenic molecules into aromatic molecules by pyrolysis.

#### **Figure 7**

#### **Figure 8**

Thermal cracking affects all long-chain paraffin's when the ratio of saturated fatty acids to saturated hydrocarbons is close to 1. This process involves a mechanism in which bonds are broken and form radicals, leading subsequently to pairs of paraffin's and olefins as the chains are shortened [4]. Olefins have a greater tendency to split than paraffin's, hence the high ethylene (C<sub>2</sub>H<sub>4</sub>) levels in exhaust gases in comparison with light paraffin's such as ethane (C<sub>2</sub>H<sub>6</sub>) and propene (C<sub>3</sub>H<sub>6</sub>). Ethylene is an interesting compound to analyse due to its high maximum incremental reactivity (MIR: 9.08). So is butene (C<sub>4</sub>H<sub>8</sub>), which has the highest incremental reactivity of all the compounds, considered in this study (MIR: 10.29). The ethylene and butene variations in different NEDC phases shown in **Figures 8** and **9**, demonstrate that the highest levels of hydrocarbons occur during the ECE phase where operating conditions are low load and low speed. In such operating conditions, the combustion process is less efficient due to the low fuel/air ratio ( $\phi$ ), resulting in higher levels of said hydrocarbons. In the EUDC phase, emissions of these hydrocarbons are virtually zero in comparison with the ECE phase.

#### **Figure 9**

1,3 butadiene (C<sub>4</sub>H<sub>6</sub>), although emitted in lower quantities, is an interesting compound because of its high incremental reactivity (MIR: 7.7). This compound is not found in the fuel, which means that it is formed by the thermal cracking processes. Butadiene is usually produced by olefin cracking, although it can also be produced by double or multiple paraffin cracking. Its appearance in exhaust gases is explained by the high stability conferred upon it by its two double conjugated bonds.

Benzene (C<sub>6</sub>H<sub>6</sub>) and Toluene (C<sub>7</sub>H<sub>8</sub>) (the compounds of most concern due to their supposedly carcinogenic effects), have lower atmospheric reactivity (MIR: 0.81 and MIR: 3.97 respectively). They are emitted only when diesel and Fischer Tropsch fuels are used. Aromatic hydrocarbons in general (toluene, xylenes, ethyl benzene and particularly benzene) can be also be generated from paraffinic hydrocarbons C<sub>6</sub> and C<sub>7</sub> by isomerisation or the reforming process. The main way to produce aromatic hydrocarbons is by pyrolysis. This process occurs in high-temperature, high-pressure environments and removes some hydrogen atoms from the hydrocarbon molecule. To make up for this imbalance the hydrocarbon molecules form an aromatic ring structure. However, gas pressure and temperature are not the only factors affecting aromatic hydrocarbon production: the aromatic hydrocarbon of the fuel affects it too.

1  
2 Aromatic hydrocarbons are difficult to remove by oxidation catalysis [23] so biodiesel is at an  
3 advantage in this respect in comparison with Fischer Tropsch fuel and diesel.  
4

5 Finally, methane can be generated by the thermal cracking of both paraffinic and olefin  
6 hydrocarbons. The atmospheric reactivity of methane is lower than the other compounds analysed  
7 (MIR: 0.01). The use of soybean oil produced CH<sub>4</sub> emissions twice as high as diesel fuel, whilst  
8 rapeseed oil caused an increase of 10%. Palm oil and Fischer Tropsch fuel, however, caused reductions  
9 of 3% and 55% respectively.  
10

### 11 3.3.2. *Formic acid and formaldehyde emissions*

12

13 Formaldehyde and formic acid are the main aldehydes formed in the combustion of both diesel  
14 and biodiesel [24]. Formaldehyde is an intermediate product of diesel fuel combustion [25]. Total  
15 formaldehyde emissions are shown in **Figure 10**. Formaldehyde emissions follow a trend similar to  
16 THC emissions, but in this case there is a certain relationship between the H/C fuel ratio and  
17 formaldehyde emissions which resembles [26]. However [27] also pointed out that exhaust  
18 formaldehyde has multiple sources not always linked to the original fuel. This study recorded  
19 formaldehyde emissions 6 to 10 times higher when biodiesel was used and a reduction of 54% in  
20 formaldehyde emissions when Fischer Tropsch fuel was used as opposed to diesel fuel.  
21

22 No clear correlation was found between the fuel and formic acid emission. A reduction in  
23 complete formic acid emissions was observed in **Figure 11** when Fischer Tropsch fuel was used. There  
24 seem to be several sources that affect formic acid emission. In fact, the emissions resulting from the use  
25 of different fuels were affected by the fuel origin, engine type, engine condition and modes of operation,  
26 [24], [28], [29].  
27

### 28 3.3.3. *Maximum Incremental Reactivity*

29

30 The MIR (Maximum Incremental Reactivity) of each gas in the exhaust gases was measured.  
31 This indicates the ozone (O<sub>3</sub>) arising from the production of photochemical smog in the atmosphere.  
32 **Figure 12** shows how MIR increases from 0.983 g.km<sup>-1</sup> for diesel fuel to 1.174 g.km<sup>-1</sup> for soybean oil.  
33 The exhaust gases of palm oil produce 0.968 g.km<sup>-1</sup> and of rapeseed oil, 1.078 g.km<sup>-1</sup>. The MIR of  
34 Fischer Tropsch emissions was 0.788 gO<sub>3</sub>.km<sup>-1</sup> the lowest of all the fuels used.  
35

## 36 4. *CONCLUSIONS*

37 This paper sets forth the findings of our study of regulated and unregulated gaseous emissions in  
38 a light-duty diesel engine during NEDC fuelled with biodiesel and Fischer Tropsch fuel. The main  
39 conclusions of the study are as follows:  
40

- 41 - Fischer Tropsch and biodiesel fuels can be used in a diesel engine without modifying the  
42 engine's configuration.
- 43 - Fuel consumption increases with the use of biodiesel and decreases with the use of Fischer  
44 Tropsch fuel due to their different calorific values. A similar pattern was observed in CO<sub>2</sub>  
45 emissions with an 11% increase when palm oil was used and a 2% decrease when Fischer  
46 Tropsch fuel was used, in comparison with diesel fuel

- 1 - Our study found that the NO<sub>x</sub> emissions of all the fuels studied were higher than those of  
2 standard diesel fuel. This may be due to the high cetane number of the fuels tested, leading to  
3 a very short ignition delay phase.
- 4 - CO and THC emissions increase when biodiesel is used but reduced when Fischer Tropsch  
5 fuel is used.
- 6 - The similar trends in short-chain hydrocarbon emissions (<C<sub>4</sub>) and THC emissions suggest  
7 that these molecules are produced mainly by cracking.
- 8 - Important link established between biodiesel and aromatic hydrocarbon emissions: the use of  
9 biodiesel reduces these emissions to negligible levels.
- 10 - Formaldehyde emissions increase as the H/C fuel ratio falls but there is no clear correlation  
11 between the origin of the fuel and formic acid emissions.
- 12 - Maximum Incremental Reactivity was used to analyse the potential of exhaust gases to  
13 create tropospheric ozone. Lower potential ozone production was observed when Fischer  
14 Tropsch fuel was used.

## 15 **5. ACKNOWLEDGEMENTS**

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17 Valencia (Spain), for granting financial support for the linguistic revision of this paper.  
18

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### **Table Captions**

Table 1. Engine characteristics

Table 2. Fuel properties



Table 1.

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<i>Type</i>	4-stroke Multiple Cylinder Engine
<i>Displacement [Litres]</i>	1998
<i>Bore [mm]</i>	85
<i>Stroke [mm]</i>	88
<i>Valves [-]</i>	4 per cylinder
<i>Compression Ratio [-]</i>	18:1
<i>Injection System</i>	Common Rail 160 MPa
<i>Turbocharger [-]</i>	Garret VGT GT 1749V
<i>Max Power / Speed</i>	100 kW – 66.6 Hz
<i>Max Torque / Speed</i>	320 Nm – 29.17 Hz

---

Table 2.

<i>Property</i>	<i>Unit</i>	<i>Diesel</i>	<i>B100 Soybean</i>	<i>B100 Rapeseed</i>	<i>B100 Palm</i>	<i>Fischer Tropsch</i>
Summarized Formula	[-]	C <sub>14.3</sub> H <sub>26.6</sub>	C <sub>18.2</sub> H <sub>33.4</sub> O <sub>2</sub>	C <sub>18.3</sub> H <sub>34</sub> O <sub>2</sub>	C <sub>17.8</sub> H <sub>34.5</sub> O <sub>2</sub>	C <sub>14.1</sub> H <sub>30</sub>
Cetane Number	[-]	50.6	50.6	56.6	69.5 <sup>(*)</sup>	81.2 <sup>(*)</sup>
Viscosity at 40° C	mm <sup>2</sup> ·s <sup>-1</sup>	2.68	4.24	4.48	4.44	2.79
Density at 15° C	kg·l <sup>-1</sup>	0.84	0.88	0.88	0.87	0.77
Lower heating value	MJ·kg <sup>-1</sup>	42.9	36.8	37.1	36.6	43.7
Sulphur content	mg·kg <sup>-1</sup>	7.4	2.8	1.7	1.9	0.4
Oxygen content	%(m/m)	0	11.2	11.3	11.4	0
Stoichiometric Air- Fuel Ratio	[-]	14.66	12.49	12.54	12.60	15.04
Distillation 10% vol	°C	195	316	323	314	212
Distillation 50% vol	°C	262	328	332	323	271
Distillation 90% vol	°C	339	334	342	330	344
Oxidation stability at 100° C	Hours	>72	9.6	6.2	9.2	55.2

(\*) Above the calibrated measurement range (maximum 60.8)

## Figure Captions

Figure 1. Fuel consumption during NEDC

Figure 2. Carbon dioxide emissions

Figure 3. Evolution of nitrogen oxides emissions during NEDC

Figure 4. Specific nitrogen oxides emissions

Figure 5. Specific carbon monoxide emissions

Figure 6. Specific hydrocarbon emissions

Figure 7. Hydrocarbon speciation for each fuel used

Figure 8. Evolution of ethylene emissions during the NEDC

Figure 9. Evolution of butene emissions during the NEDC

Figure 10. Specific Total formaldehyde emissions

Figure 11. Specific Total formic acid emissions

Figure 12. Maximum Incremental Reactivity of exhaust emissions

Figure 1

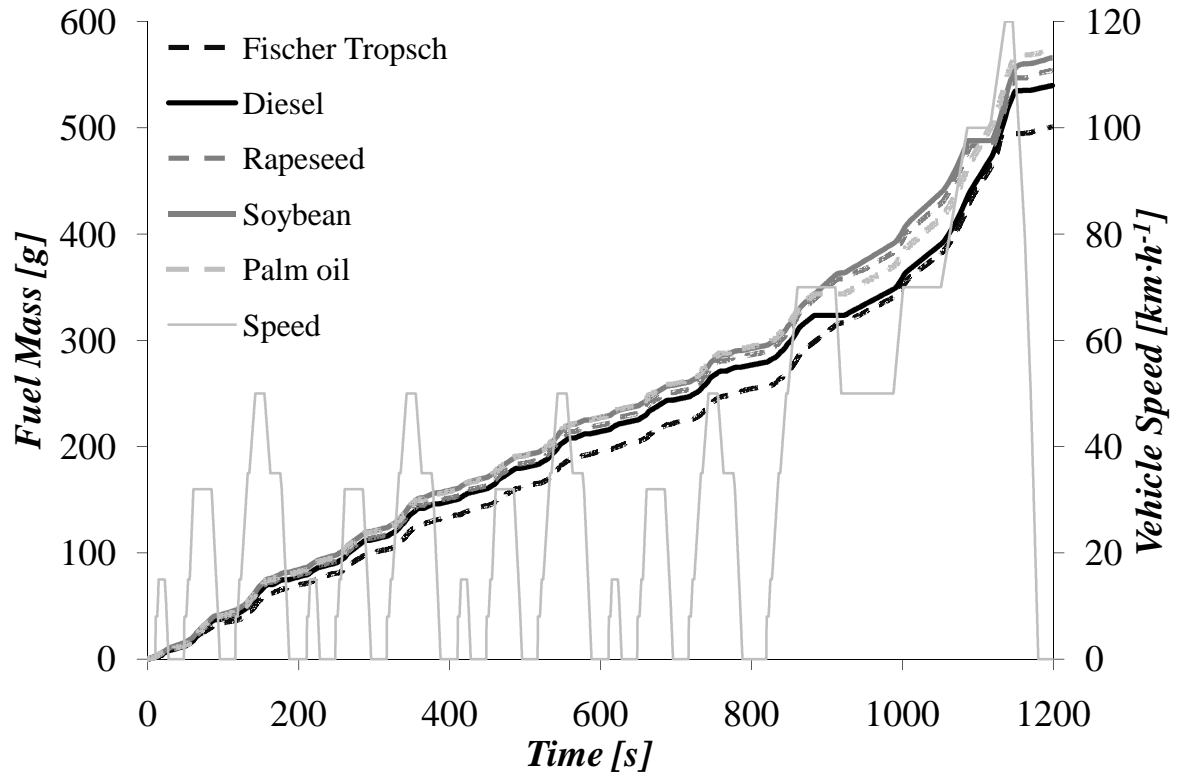


Figure 2

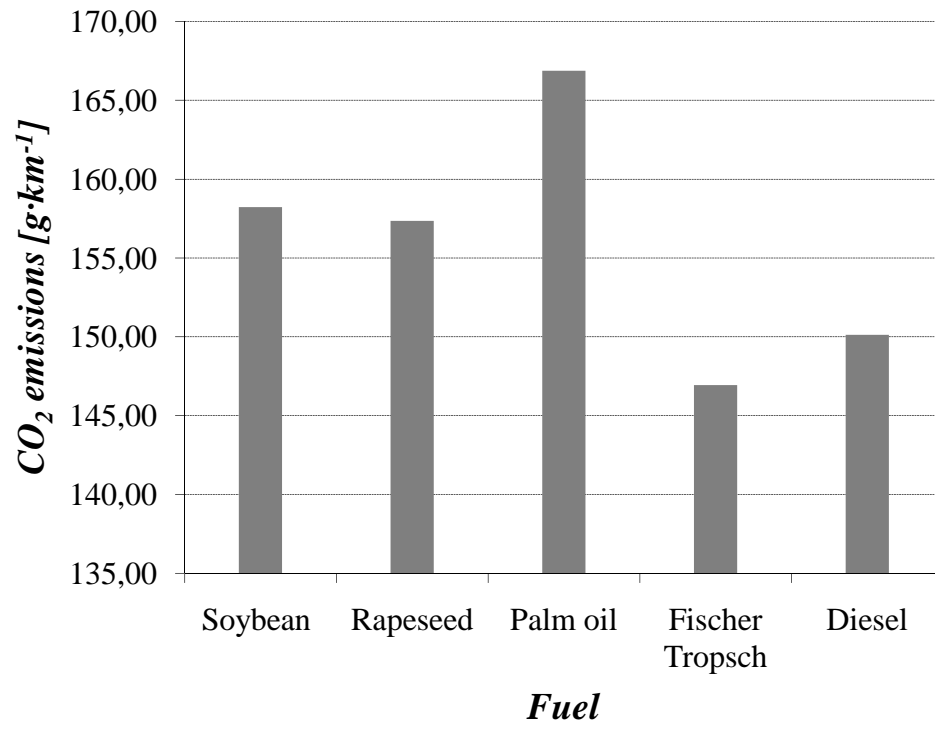


Figure 3

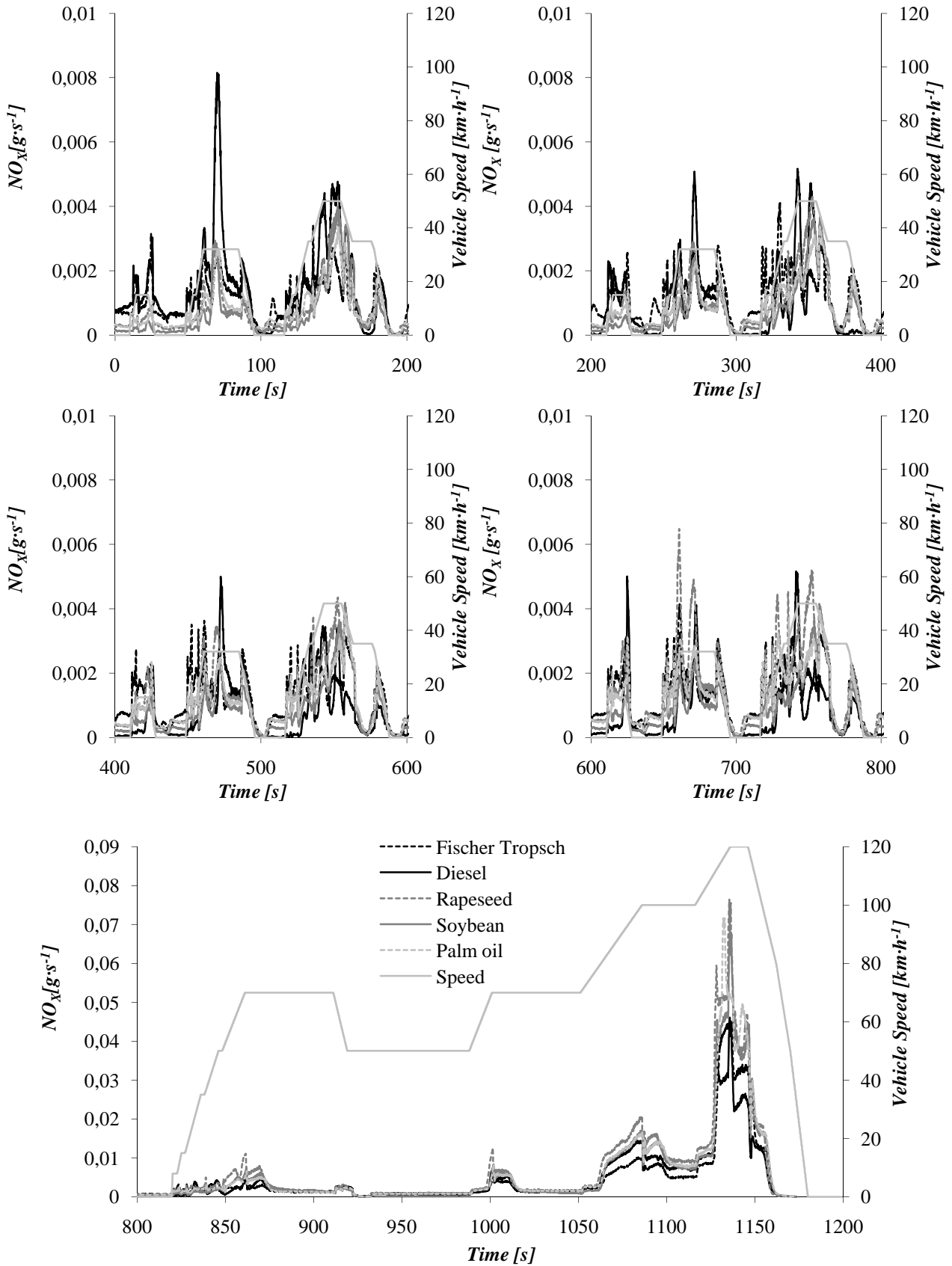


Figure 4

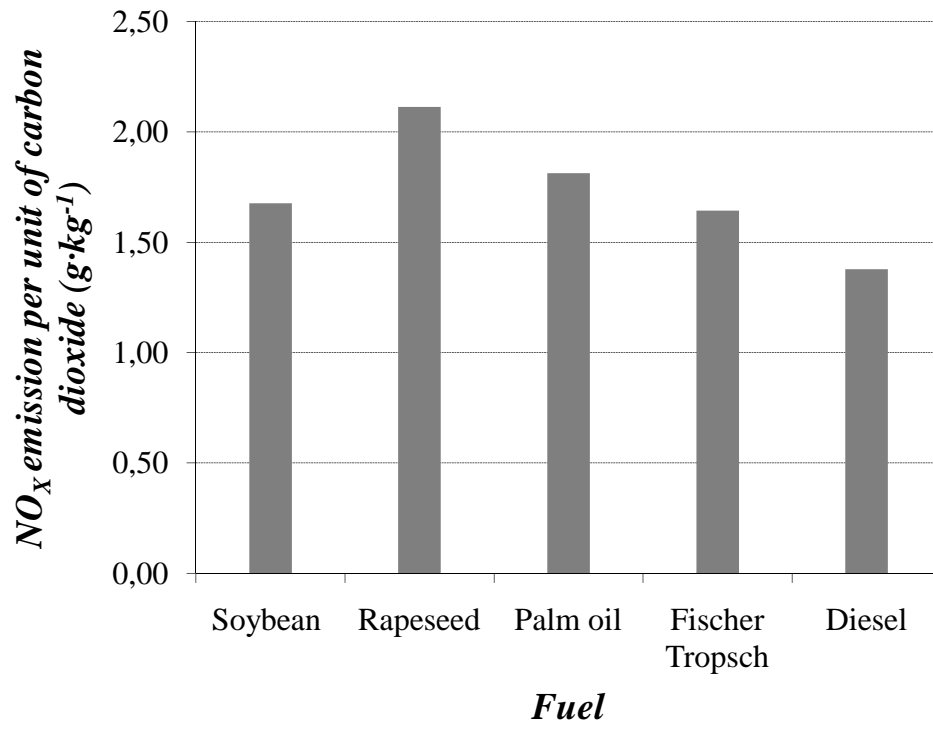


Figure 5

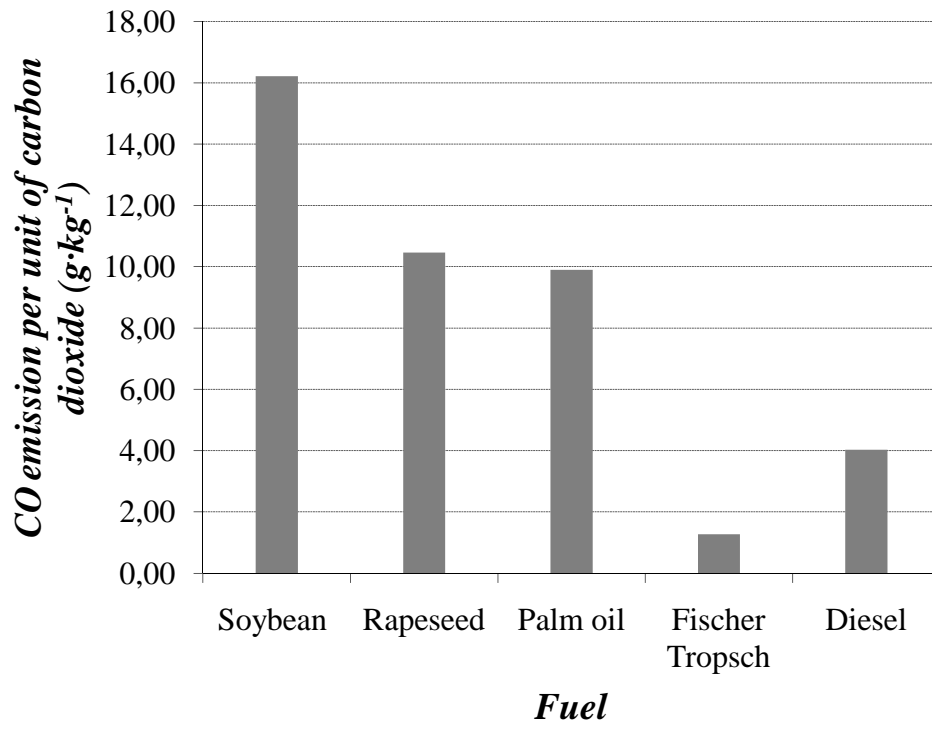




Figure 6

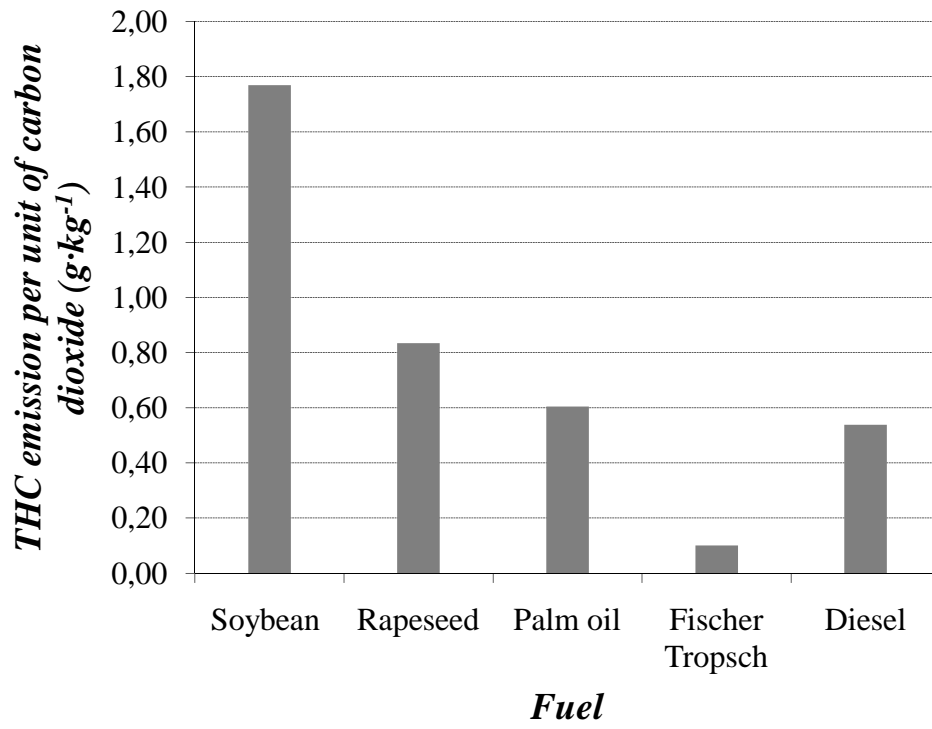


Figure 7

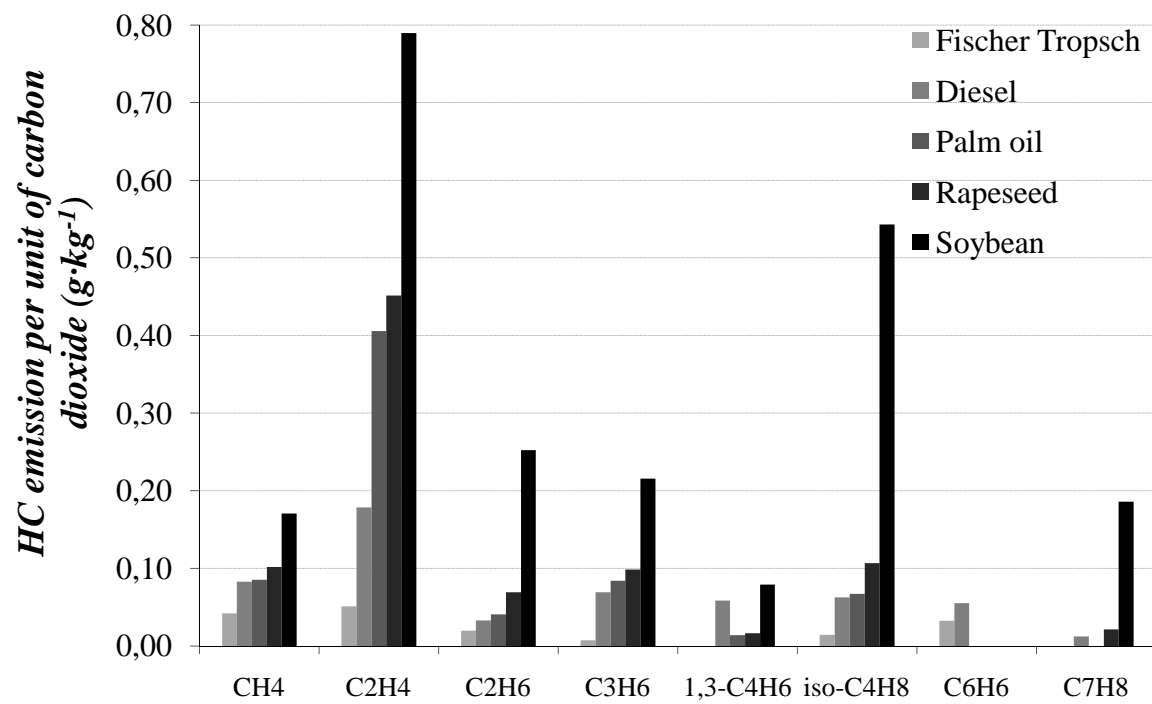


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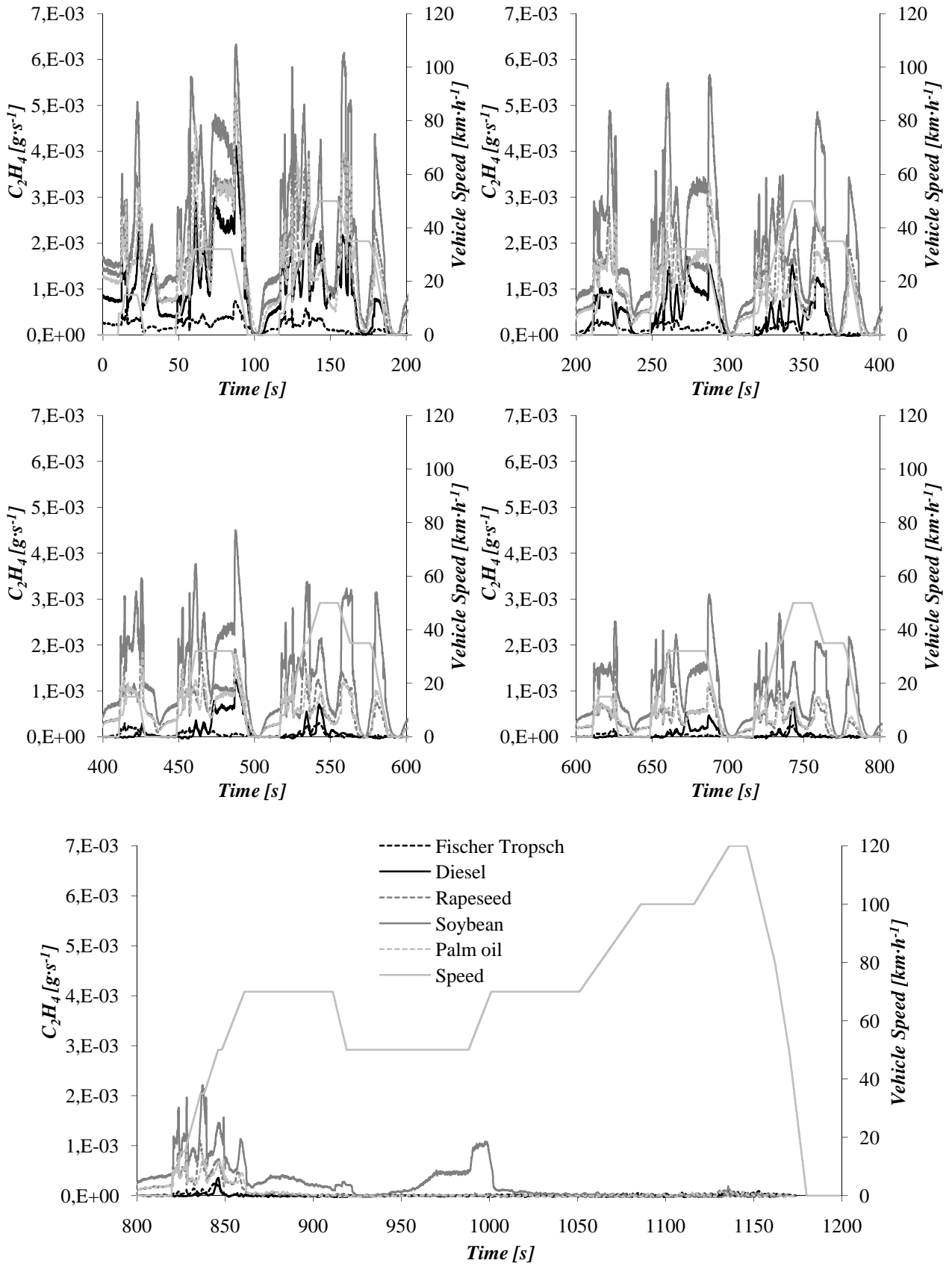


Figure 9.

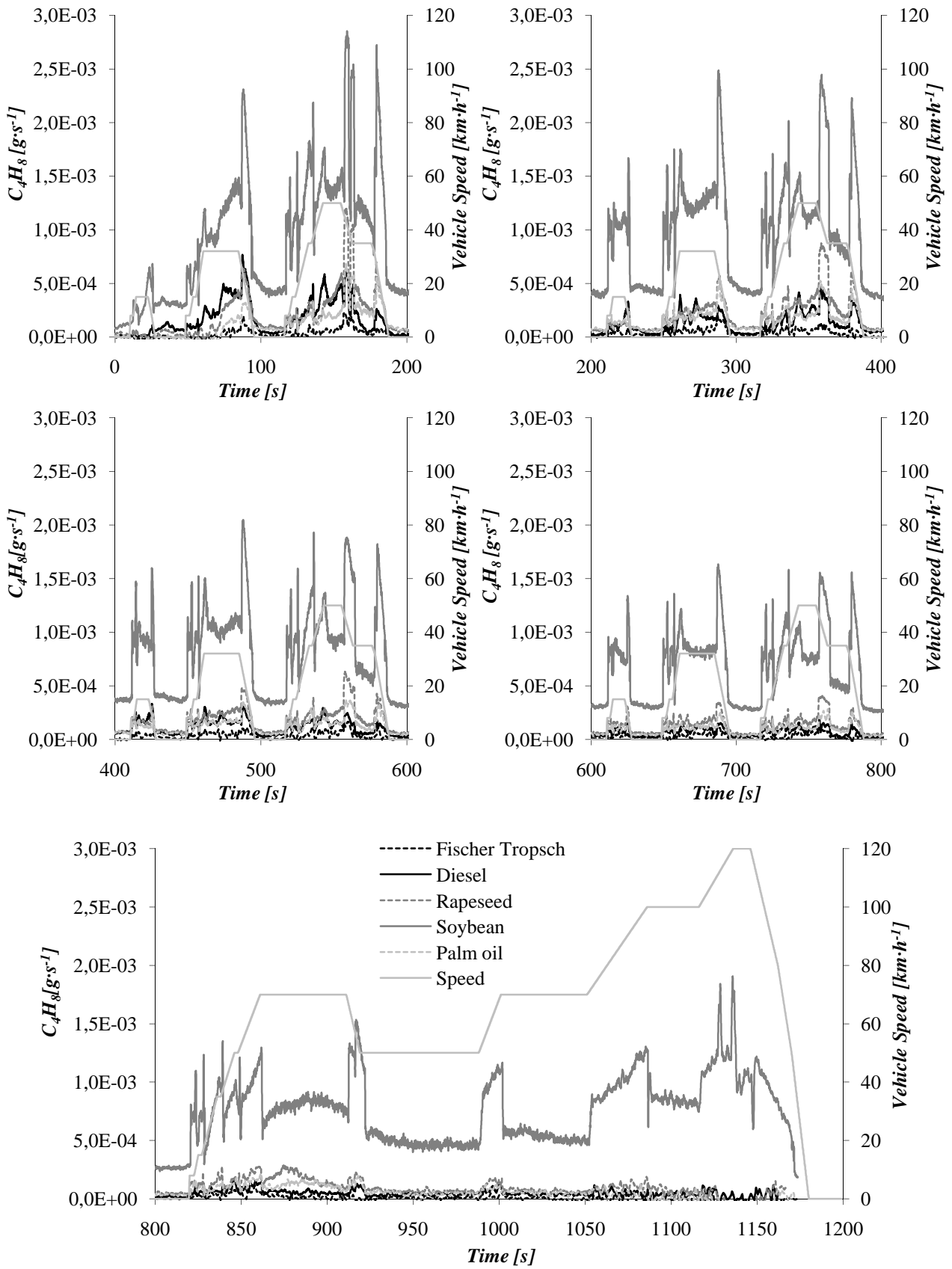


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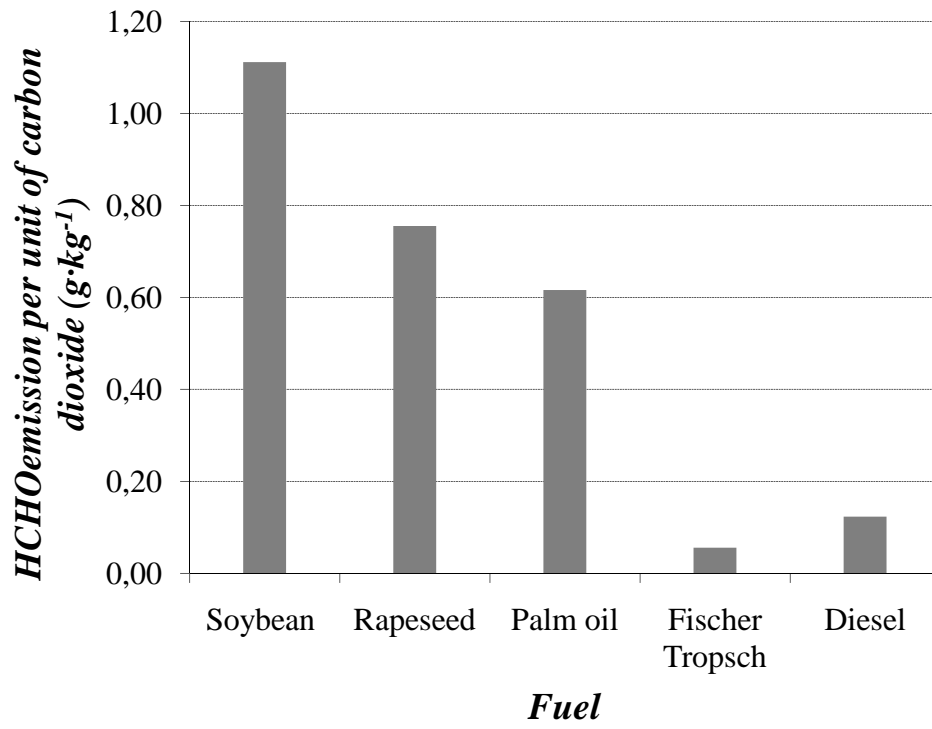


Figure 11.

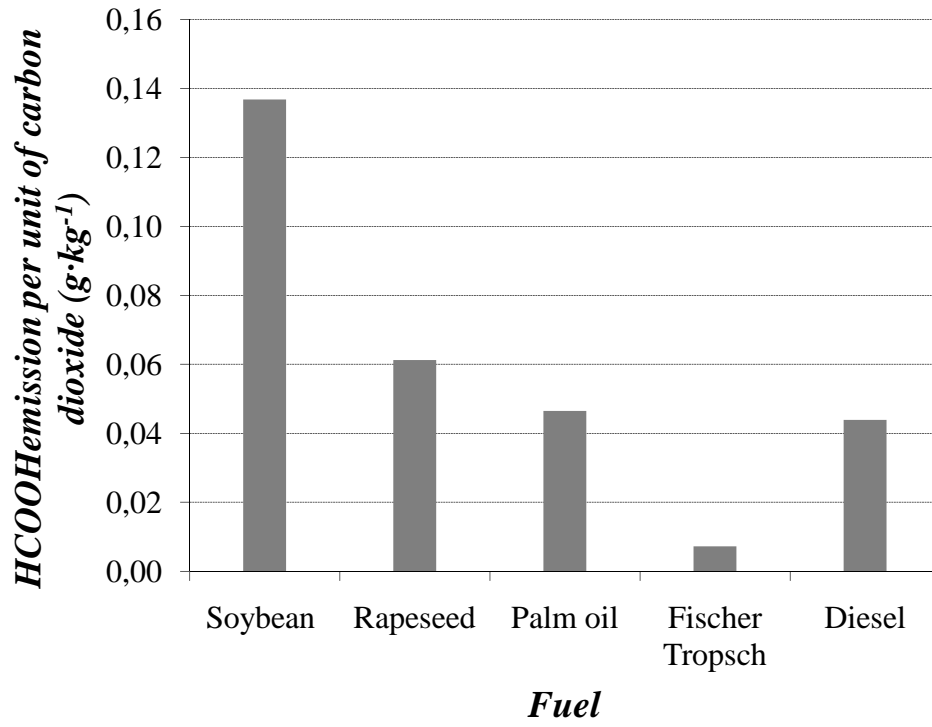


Figure 12.

