

# Emission Differences between Petroleum based Diesel and different Biodiesel Blend Ratios for Road Transport Vehicles

Morten WINTHER

National Environmental Research Institute, University of Aarhus, Frederiksborgvej 399, 4000 Roskilde, Denmark - Fax: +45 4630 1212 -e-mail: [mwi@dmu.dk](mailto:mwi@dmu.dk)

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## Abstract

The multidisciplinary integrated impact assessment project 'Renewable energy in the transport sector using biofuels as an energy carrier' (REBECA) is currently under implementation in Denmark (project period: 2007–2010), and an important project task has been to provide emission data for emission projections based on the available literature. This paper presents fuel consumption and NO<sub>x</sub>, CO, VOC and PM emission differences between petroleum-based diesel and diesel-biodiesel blends, established in REBECA as a function of biodiesel blend ratio. For heavy-duty vehicles, functions are prepared for Euro 3 and earlier and Euro 4/5 engine technologies, whereas cars and vans are treated as one single vehicle group. For the oldest heavy-duty vehicle segment, the fuel consumption/emission difference functions are well examined. For the two latter vehicle groups, however, further biodiesel emission measurements are needed in order to increase the accuracy of the difference functions. Most urgently, measurements are required for the modern Euro 4 passenger cars and vans, which are important from a traffic composition point of view. The data presented in this paper may serve as input for inventories or as general support for policy-makers, especially in light of the growing importance of the role of biodiesel in the future, as expressed by the EU 5.75 % biofuel limit in 2010 for road transportation fuels.

**Keys-words:** Biodiesel emissions, NO<sub>x</sub>, CO, VOC, PM, fuel consumption, Euro engine standards.

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## Introduction

Biodiesel is defined as Fatty Acid Methyl Esters (FAME) made from the conversion of triglycerides (vegetable oils or animal fat) with methanol in a transesterification process, and is completely miscible with petroleum-based diesel at any blend level. Biodiesel can be made from various types of oilseed crops as well as used frying oil, or can be made from animal fats (e.g. Lapuerta et al. 2008, Martini et al. 2007, Agarwal 2006). In order to comply with the current fuel quality legislation for Europe the fuel properties of biodiesel must meet the European standards given in EN-14214.

In recent years, many experimental studies have been undertaken in order to assess the influence on emissions of engines using biodiesel in various blends. In many cases the measurements have focused on the regulated emission components of NO<sub>x</sub>, PM, CO and VOC as well as fuel consumption and, most commonly, the emission differences between petroleum-derived diesel fuel, as reference fuel, and various diesel-biodiesel blend ratios. Apart from measuring the regulated pollutants, a few studies have also measured non-regulated emissions such as PAH (Correa et al. 2006) and nitro-PAH, as well as carbonyls (aldehydes and ketones) (Peng et al. 2008, Correa et al. 2008; Pang et al. (2008), Fontaras et al. 2008a). Also, recently, more and more attention has been focused on examination of particulate size and mass distribution relating to use of biodiesel.

In each case the studies specify the oil type used in the experiments as well as other relevant test conditions. In the larger review studies aiming to describe the emission differences between normal diesel and biodiesel as a function of blend ratio; however, no distinction is made between different types of biofuel. Apart from oil type, emissions are dependent on several other parameters such as fuel quality, engine operating conditions during test and measurement techniques (e.g. Lapuerta et al. 2008, Kousoulidou et al. 2008).

Funded by the Programme Commission on Energy and Environment under the Danish Strategic

Research Council, the multi-disciplinary integrated impact assessment project 'Renewable Energy in the transport sector using Biofuels as an Energy Carrier' (REBECA) is currently under implementation in Denmark. The aim of REBECA is to assess the impact on emissions, air quality and human health as well as resource and land-use change, and to consider economic and sociological aspects of the future use of biodiesel and bioethanol in Danish road transport. The project period is 2007–2010. An important task of work package II (emission inventories) in REBECA is to provide emission data for the emission projections.

With focus on biodiesel, the objective of the present paper is to present values for fuel consumption and emission differences between petroleum-based diesel and different blends of biodiesel (B%). The method is to consider the most relevant studies and experimental results published to date that assess these emission differences and, based on the available data, produce general functions of fuel consumption and emission differences for B0 to B100 blend ratios.

The functions will be presented for light duty vehicles and heavy duty vehicles, and in terms of emissions the components of NO<sub>x</sub>, CO, VOC and particulate matter (PM) will be considered.

## 1 – Fuel consumption and emission change functions

For older heavy-duty engine technologies the major review undertaken by EPA (2002) is the most thorough and most cited study made to date. Based on a very extensive literature review considering 80 studies, the authors selected 39 experimental studies meeting certain criteria in order to derive the relationship between biodiesel content and the emission of NO<sub>x</sub>, PM, CO and VOC. The vast majority of the engines considered in the study were sold no later than 1997.

In a more recent literature review made by Lapuerta et al. (2008), 158 different studies are examined in relation to biodiesel emissions. Although many new experiments have been carried out since publication of the EPA (2002) report, this review is recognized by Lapuerta et al. (2008) to be the most precise and comprehensive overview of the emission effects for older heavy duty engines using biodiesel.

In a complementary review study made for the European Environment Agency (EEA), Ntziachristos et al. (2007) suggest values for the emission differences for NO<sub>x</sub>, PM, CO and VOC when operating with normal diesel versus B10, B20 and B100 biodiesel blends, using the more recent Euro 3 engine technology regarding passenger cars, vans and heavy duty vehicles. This report considers results from seven different studies, and the proposed values are also printed in the EMEP/CORINAIR guidelines emission inventories reported to the UNECE LRTAP convention (EMEP/CORINAIR, 2007).

The aim of another report commissioned by the EEA (Kousoulidou et al. 2008) is to improve knowledge on emissions related to the use of biofuels by increasing the number of measurements over those considered by Ntziachristos et al. (2007) as well as by explaining the observed emission differences under different engine operation conditions and combustion behaviour. Part of the report discusses the emission differences for NO<sub>x</sub> and PM for different vehicle categories, engine technology levels and biodiesel content, based on a relatively large number of studies (28 for NO<sub>x</sub>, 24 for PM). Some consideration is also given to the NO<sub>x</sub> and PM emission behaviour with engine technologies beyond Euro 3. In Kousoulidou et al. (2008), the measurement results are not further assessed either to derive discrete values or general emission change functions for blend ratios between B0 and B100.

### Heavy duty vehicles

For heavy-duty vehicles with Euro 3 and earlier engines, the relationship between fuel consumption as well as NO<sub>x</sub>, PM, CO and VOC emission changes as a function of biodiesel content (vol.%) is based on the findings from EPA (2002). The fuel consumption and emission curves and their underlying mathematical expressions are shown in Figure 1.

The development in fuel consumption as a function of biodiesel content shown in Figure 1 is the result of two mechanisms. Thermal efficiency is found to increase as a function of the biodiesel blend ratio (e.g. Lapuerta et al. 2007 and 2008, Agarwal 2006), and there is a linear relationship between the brake specific fuel consumption (bsfc) and the loss in heating value for the biodiesel blend in question (e.g. Lapuerta et al., 2007 and 2008).

In terms of emissions, the higher content of oxygen in biodiesel compared to petroleum-based diesel plays an important role; as oxygen content increases the combustion becomes more complete. This means that the emissions of particulate matter, CO and VOC diminish. Conversely, the presence of more oxygen in biodiesel and higher combustion temperature increases the emission of NO<sub>x</sub> (e.g. Martini et al. 2007,

Agarwal 2006, EPA 2002).

Specifically for Euro 3 engines, data for emission changes have been compiled by Ntziachristos et al. (2007) from the use of biodiesel, see Table 1. The Ntziachristos et al. (2007) values, however, are based on a limited number of available studies, and the figures are given only as discrete values for B10, B20 and B100 blends. For NO<sub>x</sub> and PM the emission reduction figures from Ntziachristos et al. (2007) are somewhat similar to those proposed by EPA (2002). This is also true for CO and VOC, in the case of B10 and B20, whereas for neat biodiesel the emission reductions found by Ntziachristos et al. (2007) are much smaller compared with those in EPA (2002). Considering the data scarcity behind the Ntziachristos et al. (2007) study, and the general outcome of the comparison with EPA (2002) figures, the decision for Euro 3 engines is to use the EPA (2002) emission change functions, as is the case for prior engine technologies.

For Euro 4 and 5 engines, a significant part of the new vehicles sold (almost all engines from two of the large manufacturers) are equipped with EGR (Exhaust Gas Recirculation) in order to meet the emission standards for NO<sub>x</sub>. The Euro 4 and 5 engines from other large engine manufacturers sold in Denmark use SCR (Selective Catalytic Reduction) as a NO<sub>x</sub> reduction technology. EGR technology is rarely used in heavy-duty engines earlier than Euro 4 and SCR was not available before Euro 4 engines began entering the market.

The emission reduction functions for NO<sub>x</sub>, PM, CO and VOC used in the present project for Euro 4 and 5 engines are also shown in Figure 1. The basis for these is measurements made by McCormick et al. (2005). This study, which is considered to be one of the most thorough experimental works undertaken for modern engines to date, has measured the emission differences between 15 ppm sulphur diesel fuel as base fuel and B10, B20, B50 and B100 biodiesel blends for two relatively large engines (224 kW and 373 kW) equipped with EGR. It is also noted that the McCormick et al. (2005) results make up the consolidated view on NO<sub>x</sub> biodiesel emissions presented by Dieselnets ([www.dieselnets.com](http://www.dieselnets.com)) for modern engines. The curve applied by the latter is also emphasized by Kousoulidou et al. (2008) in their report discussing emission effects of biofuels.

Only three studies have been considered as relevant for comparison with the McCormick (2005) results. For NO<sub>x</sub>, measurements by Krahl et al. (2007) on a Euro 4 engine (5.9 l.) equipped with SCR (normal diesel vs. B100) predict similar emission increases to test results from Sze et al. (2007) on an engine (5.9 l.) from 2006 equipped with EGR (normal diesel vs. B20/B50). On the other hand, an average of the results obtained by Knothe et al. (2006), who tested base diesel and four different types of neat biodiesel on a modern engine (14 l.) equipped with EGR, are more in line with the emission change levels found by EPA (2002) for older engine technologies. No attempts are made by EPA (2002) to quantify NO<sub>x</sub> emission differences for modern engines. This source, however, expects the NO<sub>x</sub> emission effect to be more negative in the case of modern engines than in older engines, using biodiesel.

For PM, an emission difference of -80% for neat biodiesel is measured by McCormick et al. (2005). Knothe et al. (2006) find a similar value during test, while Krahl et al. (2007) measure a PM reduction between 60 % and 70 %. Sze et al. (2007) measure around 60% PM reduction for B50 blends. For CO and VOC Knothe et al. (2006) measure CO and VOC average emission differences of -36 % and -47 %, respectively, compared to the figures for CO (-40%) and VOC (-25%) presented by McCormick et al. (2005). Comparing results for B50 blends, Sze (2007) obtains emission reduction results for CO and VOC which are a little higher than the latter study results.

For diesel engines equipped with EGR, a few other studies have been published. The results from these, though, have not been taken into account in the present review. Some of the most recent studies (Tsolakis et al. 2007, Pradeep et al. 2007, Nabi et al. 2006, Agarwal et al. 2006) report measurements on small engines, for which test results may not be representative for engines in the size ranges which are normally used in road transport. Muncrief et al. (2008) measure the emissions at low engine loads for a refuse truck, which is not considered as representative for the actual engine loads during driving in real-world traffic conditions.

Kousoulidou et al. (2008) explain the reasons for the NO<sub>x</sub> emission increase and the PM emission decrease from modern EGR-equipped engines using biodiesel. To maintain a given load, a higher volume of biodiesel (compared to normal diesel) must be injected into the cylinder. In an engine equipped with electronic injection control, the increased injector opening time is interpreted as an increased load. As a consequence, the ignition timing is adjusted meaning a smaller ignition delay, combustion advance and higher combustion temperature. Also the rail pressure increases, and the EGR rate is lowered. These changes in combustion conditions lead to an increase in NO<sub>x</sub> emissions, and inversely the effect on PM is one of decreasing emission.

For engines equipped with SCR, according to Krahl (pers. comm., 2008) the urea dosing system is not optimized for the use of biodiesel, and hence compared to older engines without SCR, the NO<sub>x</sub> emission

differences between biodiesel and petroleum-based diesel are higher for engines with SCR installed. The normal trade off between  $\text{NO}_x$  and particulate emissions predicts even lower particulate emissions in the case of SCR-equipped engines for biodiesel due to the somewhat increased  $\text{NO}_x$  emissions. Apart from this, no in-depth explanation exists at the moment of the measured  $\text{NO}_x$  and particulate emission trends specifically related to the use of SCR. However, according to plans more tests will be conducted in the near future (pers. comm. Krahl, 2008), and hopefully a result of these experiments will be more knowledge in this specific area.

The cited literature values and the emission explanations provided above form the basis for the emission trends for Euro 4 and 5 engines shown in Figure 1. It must be highlighted that the number of measurements behind the curves are much more limited than for the earlier engine technologies, and that more measurements are needed in order to consolidate further the relations between emissions and biodiesel content. Also, special precautions must be taken before using the curve to select emission difference values for high biodiesel blend ratios. At higher blend ratios, engines running on biodiesel may face problems meeting the  $\text{NO}_x$  emission limits. Engine control and exhaust emission after-treatment systems will have to be optimized by the manufacturers, at least for the biodiesel blend ratios where emission problems occur.

Problems relating to elevated  $\text{NO}_x$  emissions from biodiesel usage are likely to have been solved by the time engines complying with the Euro 6 emission standard enter the market (pers. comm. K.F. Hansen, Dinex, 2008). Thus, the emission differences for Euro 6 engines are expected to be very similar to those in the pure engine-out case, i.e. without exhaust after-treatment. This assumption also applies for PM as well as for CO and VOC. For PM, particulate filters will be used in order to meet the Euro 6 emission standard. Since absolute PM emissions from engines equipped with filters are in any case very low, whether the PM emission prediction for Euro 6 fits closely with the emission differences measured in future when heavy-duty vehicles are sold with filters under the Euro 6 standard is less important. Consequently in the present study, the emission difference curves for Euro 0-3 in Figure 1 are assumed to apply to Euro 6 engines as well.

The following Table 2 lists the emission differences, in percent, used in the present study, with EPA (2002) and McCormick et al. (2005) as primary sources of information.

## Light duty vehicles

Emission data on the use of biodiesel in passenger cars and vans to date is scarce. During the literature survey in the present project, only four studies have been found with published measurement results of the emission differences between neat diesel and biodiesel for these vehicle types. In all cases emission differences are reported for  $\text{NO}_x$ , CO, VOC and PM.

Martini et al. (2007) measure the emissions during the New European Driving Cycle (NEDC) for two Euro 3 passenger cars, in each case using normal diesel, three types of B30 biodiesel, and two types of neat biodiesel. Fontaras et al. (2008a) conduct emission measurements on a single Euro 3 passenger car, using normal diesel and five different B10 biodiesel blends as test fuels. Driving patterns applied were the NEDC test cycle and the ARTEMIS urban, rural and highway driving cycles. Fontaras et al. (2007a) used the same test cycles to measure the emission differences between normal diesel and two different types of B10 biodiesel blends from a Euro 3 passenger car. In Durbin et al. (2007) measurements are reported for a large vehicle (Humvee).

Fontaras et al. (2008b) also present emission measurements for a Euro 3 passenger car using vegetable oil as a blend fuel. However, since vegetable oil as a fuel does not meet the European EN-14214 standards for biodiesel, the reported figures are disregarded in the present project.

Average emission differences for B10, B20, B30, B50, B70 and B100 are calculated based on the results from all four of the studies mentioned, and these averages are then applied in the case of passenger cars and vans. The emission differences expressed as linear functions are shown in Figure 2 for  $\text{NO}_x$ , CO, VOC and PM. Due to the scarcity of data behind the curves, any usage of these data must be made bearing in mind this uncertainty.

Along with the NEDC and ARTEMIS test cycle emission results, Fontaras et al. (2007a, 2008a), report measurements explicitly for cold starts. These emission data are, however, not included in the present survey, as it is regarded as too uncertain to formulate emission difference functions explicitly for cold starts on the basis of such a small number of measurements as available here.

For fuel consumption the relative changes were not derived explicitly for passenger cars and vans, due to lack of data. Instead, the general relations for heavy-duty vehicles are used also for passenger cars and vans, assuming a lower heating value for biodiesel which is partly compensated for by an increased thermal

efficiency. This assumption is confirmed by test results from a diesel car engine made by Lapuerta et al. (2008).

As part of an update of the emission information behind COPERT IV a literature survey was conducted by Ntziachristos et al. (2007). Emission measurements from three studies were considered, and relative emission changes for NO<sub>x</sub>, PM, CO and VOC for Euro 3 vehicles were proposed. The emission changes, however, are only given as discrete values for B10 and B20 blends. Another literature survey made by Kousoulidou et al. (2008) also deals with biodiesel emissions from passenger cars. The latter study, however, does not propose final figures for the emission changes for different biodiesel blend ratios.

Taking this into consideration, it is decided not to include the findings from the above two sources in the present study directly. However, for comparison purposes the figures from Ntziachristos et al. (2007) are shown in Table 3. It must be noted that the latter study predicts emission decreases for CO and VOC (Figure 2), in contrast to the findings from the present study.

In conclusion, for passenger cars and vans there is a distinct need for more measurements in order to obtain a better view of the emissions from today's vehicle fleet. In more specific terms, it is very important to obtain measurements for the modern Euro 4 passenger cars and vans, so that the majority of vehicle mileage driven can be covered from a traffic composition point of view.

The lack of emission data for old vehicle technologies is less serious. In today's traffic, the mileage share for older vehicles is minor, and this mileage share will decrease further in the future as new vehicle technologies enter the fleet, replacing the old.

## 2 – Conclusion

For heavy-duty vehicles with Euro 3 and earlier engines, the fuel consumption/emission differences between neat diesel and different diesel-biodiesel blend ratios are well examined, and the functions presented in this paper are based on the findings from EPA (2002).

In the case of Euro 4 and 5 heavy-duty engines, only a small number of measurement results have been published to date, and fuel consumption/emission difference functions have been prepared for these two engine technologies as averages only. Biodiesel emission data are even sparser for diesel passenger cars and vans. For these vehicle categories the available test results only allow for broad average functions to be produced from four experimental studies in which mainly Euro 3 cars were tested. Consequently, caution must be applied to use of the functions presented here, bearing in mind the scarcity of data behind the functions.

It is straightforward to conclude that further measurements are needed in order to gain a more precise view of the emission differences between neat diesel and diesel-biodiesel blends for Euro 4 and 5 heavy-duty engines as well as for diesel cars and vans in general. Most importantly, measurements are required from the modern Euro 4 passenger cars and vans, so that the majority of vehicle mileage can be covered from a traffic composition point of view.

The data presented in this paper may serve as input for inventories at national, regional or local scales, emission impact assessments or as general support for policy-makers in the field of road transport emissions. This is especially so in light of the increasing role of biodiesel in the future, as expressed by the EU biofuel limit value of 5.75 % in 2010 for fuels used by road transportation vehicles.

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**Figure 1: Fuel consumption and emission changes as a function of B% for heavy-duty engines.**

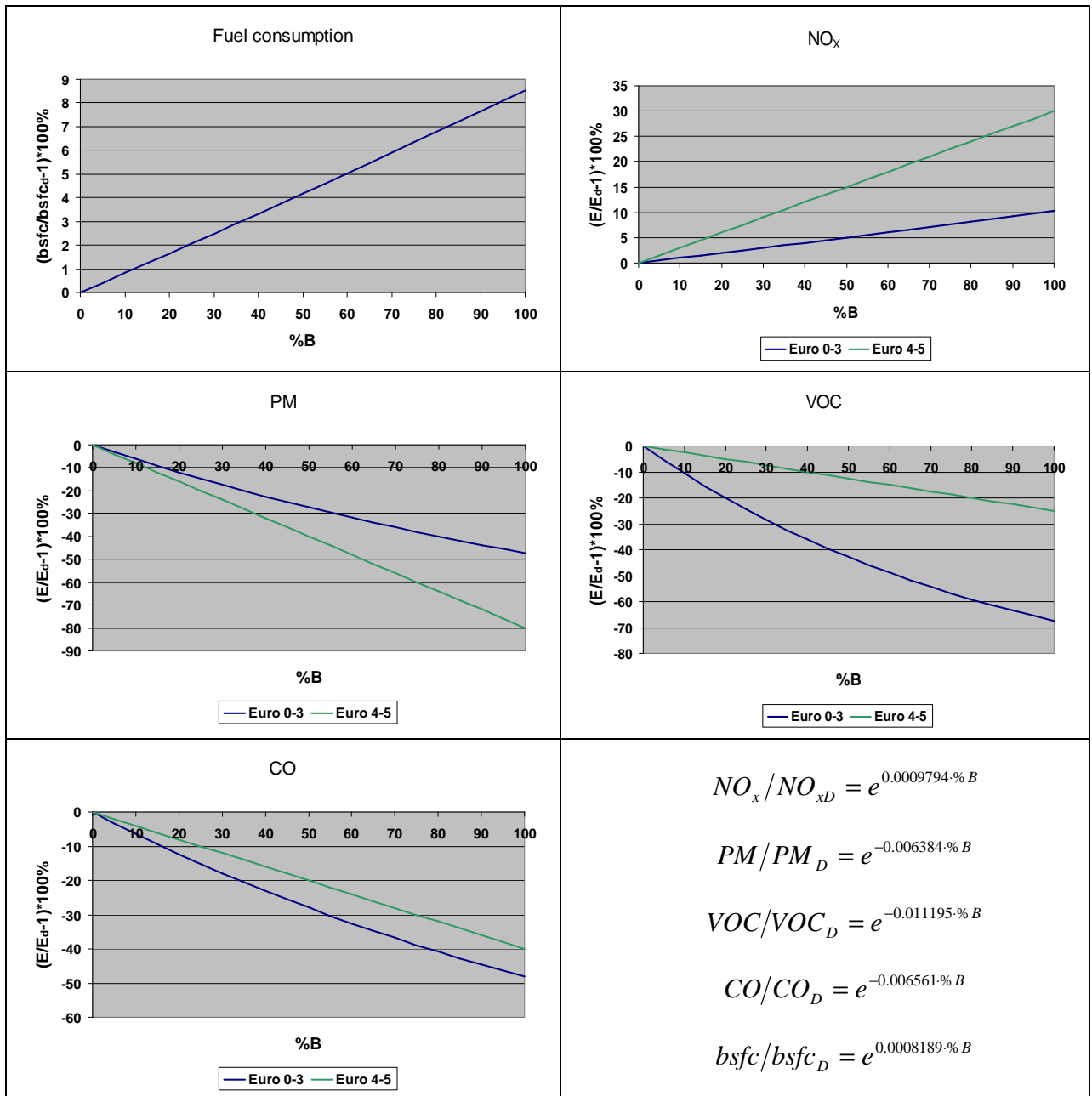
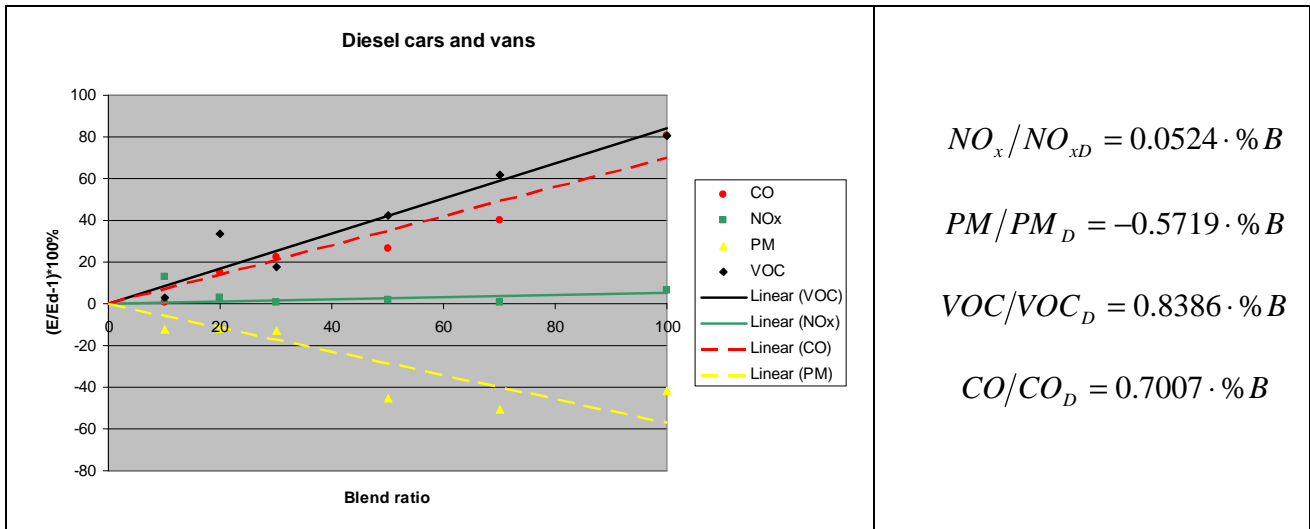


Figure 2: Fuel consumption and emission changes as a function of B% for diesel cars and vans.



**Table 1: Data for emission changes for Euro 3 heavy-duty engines from Ntziachristos et al. (2007).**

|                     | B10   | B20   | B100  |
|---------------------|-------|-------|-------|
| NO <sub>x</sub> (%) | 3.0   | 3.5   | 9.0   |
| PM (%)              | -10.0 | -15.0 | -47.0 |
| CO (%)              | -5.0  | -9.0  | -20.0 |
| HC (%)              | -10.0 | -15.0 | -17.0 |

**Table 2: Fuel consumption and emission changes as a function of B% used in the REBECA project.**

| Engine      | B%→                 | 0   | 5    | 10    | 15    | 20    | 25    | 30    | 35    | 40    | 45    | 50    | 75    | 100   |
|-------------|---------------------|-----|------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| Euro 0-3    | NO <sub>x</sub> (%) | 0.0 | 0.5  | 1.0   | 1.5   | 2.0   | 2.5   | 3.0   | 3.5   | 4.0   | 4.5   | 5.0   | 7.6   | 10.3  |
| Euro 4-5    |                     | 0.0 | 1.5  | 3.0   | 4.5   | 6.0   | 7.5   | 9.0   | 10.5  | 12.0  | 13.5  | 15.0  | 22.5  | 30.0  |
| Euro 6      |                     | 0.0 | 0.5  | 1.0   | 1.5   | 2.0   | 2.5   | 3.0   | 3.5   | 4.0   | 4.5   | 5.0   | 7.6   | 10.3  |
| Euro 0-3    | VOC (%)             | 0.0 | -5.4 | -10.6 | -15.5 | -20.1 | -24.4 | -28.5 | -32.4 | -36.1 | -39.6 | -42.9 | -56.8 | -67.4 |
| Euro 4-5    |                     | 0.0 | -1.3 | -2.5  | -3.8  | -5.0  | -6.3  | -7.5  | -8.8  | -10.0 | -11.3 | -12.5 | -18.8 | -25.0 |
| Euro 6      |                     | 0.0 | -5.4 | -10.6 | -15.5 | -20.1 | -24.4 | -28.5 | -32.4 | -36.1 | -39.6 | -42.9 | -56.8 | -67.4 |
| Euro 0-3    | CO (%)              | 0.0 | -3.2 | -6.4  | -9.4  | -12.3 | -15.1 | -17.9 | -20.5 | -23.1 | -25.6 | -28.0 | -38.9 | -48.1 |
| Euro 4-5    |                     | 0.0 | -2.0 | -4.0  | -6.0  | -8.0  | -10.0 | -12.0 | -14.0 | -16.0 | -18.0 | -20.0 | -30.0 | -40.0 |
| Euro 6      |                     | 0.0 | -3.2 | -6.4  | -9.4  | -12.3 | -15.1 | -17.9 | -20.5 | -23.1 | -25.6 | -28.0 | -38.9 | -48.1 |
| Euro 0-3    | PM (%)              | 0.0 | -3.1 | -6.2  | -9.1  | -12.0 | -14.8 | -17.4 | -20.0 | -22.5 | -25.0 | -27.3 | -38.0 | -47.2 |
| Euro 4-5    |                     | 0.0 | -4.0 | -8.0  | -12.0 | -16.0 | -20.0 | -24.0 | -28.0 | -32.0 | -36.0 | -40.0 | -60.0 | -80.0 |
| Euro 6      |                     | 0.0 | -3.1 | -6.2  | -9.1  | -12.0 | -14.8 | -17.4 | -20.0 | -22.5 | -25.0 | -27.3 | -38.0 | -47.2 |
| All engines | bsfc (%)            | 0.0 | 0.4  | 0.8   | 1.2   | 1.7   | 2.1   | 2.5   | 2.9   | 3.3   | 3.8   | 4.2   | 6.3   | 8.5   |

**Table 3: Data for emission changes (%) for Euro 3 cars and vans from Ntziachristos et al. (2007).**

|                     | Passenger cars |       | Vans  |       |
|---------------------|----------------|-------|-------|-------|
|                     | B10            | B20   | B10   | B20   |
| NO <sub>x</sub> (%) | 0.4            | 1.0   | 1.7   | 2.0   |
| PM (%)              | -13.0          | -20.0 | -15.0 | -20.0 |
| CO (%)              | 0.0            | -5.0  | 0.0   | -5.0  |
| HC (%)              | 0.0            | -10.0 | -10.0 | -15.0 |