

# Fuel Effects on Emissions from Heavy-Duty Diesel Engines – Results of Recent Research Programs

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## Abstract

The main goal of the work presented here was to compile a review of the available literature on the effects of diesel fuel properties on emissions from heavy-duty diesel engines (HDDEs). Because of the large number of various studies that have been performed in this area, the present review is mainly based on the most comprehensive recent research programs: the European Programme on Emissions, Fuels and Engine Technologies (EPEFE), and the USA Programs EPA Heavy-Duty Engine Working Group (EPA-HDEWG) and Diesel Emission Control – Sulfur Effect (DECSE). Fuel properties that have been identified over the years as influencing emissions from HDDEs, and were considered in this work, are cetane number, density, aromatics (total and poly-), sulfur and oxygen contents and back-end distillation.

The impact of fuel sulfur content on emission control systems was reviewed, based mainly on the findings of the latest DECSE Program, which was concluded in 2000. These systems include diesel oxidation catalysts, lean-NO<sub>x</sub> catalysts, NO<sub>x</sub> adsorbers and diesel particulate filters (traps).

A comparison is presented between the regression models, developed in the framework of the EPEFE and EPA-HDEWG programs. Only limited data are available addressing oxygen effects on HDDE emissions. It is noted that there is still lack of data regarding the fuel effects on emissions of engines tested over the new European Transient Cycle.

## 1. Introduction

Diesel engines have wide applications in present-day automotive industry. They dominate in the market of heavy-duty vehicles, and increasingly penetrate and compete in the market of light-duty vehicles of passenger cars. The reasons for this are well known: higher efficiency than gasoline engines (by up to 20%), better reliability and durability, lower risk of fire, and less expensive diesel fuel. Due to their higher efficiency, they emit much less carbon dioxide (greenhouse gas) per unit of power delivered. The fuel

combustion under rich-oxygen conditions yields substantially lower emissions of unburned fuel fragments (compared with petrol engines): hydrocarbons (HC) and also carbon monoxide (CO). However, the operating processes in a diesel engine of fuel-air mixture formation and combustion lead to increased noise and emissions of nitrogen oxides (NO<sub>x</sub>) and particulate matter (PM). The latter is sometimes accompanied by transparency decrease of the exhaust gases (smoke).

For many countries around the world, the last decade has been marked by increased attention to the control of harmful emissions from motor vehicles. For example, the European standards stipulate by 2005 reduction of NO<sub>x</sub>, CO and HC emissions by 30%, smoke by 38% and PM emissions by 80% in comparison with present-day Euro-3 standards; US Federal standards stipulate by 2004 reduction of the sum NO<sub>x</sub> + HC by 53%[1,2]. The current rigid emission standards, and the outlook of further legislation severity in the near future, prompt the industry to continuously improve the design and operating processes of the engines. As a result, new generations of diesel engines are introduced, for example, with increased injection pressure (over 150 MPa), electronic control of injection, high-rate turbulence and swirl of combustion chamber air charge, cooled exhaust gas recirculation (EGR), etc. [3].

After-treatment systems are also developed, which affect the exhaust gases before their release to the atmosphere. At present, the most promising and advanced of these technologies are diesel oxidation catalysts (DOC), lean-NO<sub>x</sub> catalysts (L-NO<sub>x</sub> Cat), diesel particulate filters or traps (DPF) and NO<sub>x</sub> adsorbers (NO<sub>x</sub>-Ad). As noted in [3], Euro-3 standards may still be achieved by improving engine operating cycles and components, but for engines of next generations, the use of these devices becomes quite inevitable [3,4,5].

At low emission levels of modern HDDEs, the effect of diesel fuel properties becomes very important. Therefore, much attention has been placed by the researchers on evaluating these effects. This paper presents a review of major research programs devoted

to this subject worldwide, and a comparison of their. Indeed, in the last decade many researchers, e.g. [2,6] were concerned with the impact of individual fuel properties on HDDE emissions. It has been concluded, based on their work, that the basic set of properties having the most significant effects on emissions consists of density, cetane number, back-end distillation temperature (T95), total and poly-aromatics, sulfur and oxygen content. Unfortunately, only limited data on effects of oxygenates are available.

## 2. Main objectives

The main goal of this work was to compile a review of the recent available literature for assessment and understanding of the impact of diesel fuel properties on emissions from HDDEs of current and future technologies, and identifying contradictions and gaps in the gained knowledge. The analysis of these effects includes their influence on engine-out emissions and on conversion efficiencies of advanced after-treatment technologies, under different test cycles conditions.

The most comprehensive investigations of the effects of fuel properties on HDDE emissions have been carried out within the scope of the following programs:

- European programme on emissions, fuels and engine technology, 1995 (EPEFE);
- EPA heavy-duty engine working group program, USA, 2000 (EPA-HDEWG);
- Diesel emission control – sulfur effects program, USA, 2000 (DECSE);
- Japan clean air program, planned to be completed in 2001; no results are yet available.
- EPA project on modeling effects of diesel fuel properties on HDDE emissions; no results are yet available.

## 3. Comparison of EPEFE and EPA-HDEWG programs

The goals of the European EPEFE and the USA EPA-HDEWG programs were identical, but the fuels and the engines were of different manufacturers, generations and technologies, and the tests were performed over different test cycles. Therefore, a comparison of the results is very interesting and important. Obviously, it is impossible to make such a comparison with respect to absolute values of the results. However, general trends and tendencies, as well as magnitude impacts of the various parameters may be compared. Table 1 includes the ranges of property values of the fuels tested in these two programs, a brief description of the engines, types of test cycles and a list of measured emissions. As can be seen, the cetane numbers of the US fuels were significantly lower than those of the European fuels. This represents the actual historical development of the diesel fuel market in the USA [2].

results.

THE EPEFE PROGRAM [7,8] included tests on HDDEs, which were selected to represent wide range of dimensions and technologies of European engines, up to Euro-2 emissions standards. All the engines were equipped with pump+line+injector fuel injection systems. The engines tested in this program were not equipped with any after-treatment devices.

The fuel density effect was studied for a reference engine setting as well as for three other settings: reference power, reference fuel mass delivery and reference dynamic timing. The conclusion derived from the results is that the fuel density influence on diesel emissions is only an outcome of the changes in the physical properties of the working fluid inside the hydraulic injection system (such as the velocity of sound, flow speed through constrictions, specific heat etc.). The fuel density does not directly affect the combustion process in the engine.

It is noted that all the fuels tested in the program had almost the same level of sulfur content (402-469 ppm). Nevertheless, the researchers succeeded, based on data processing from available literature, to assess quantitatively the impact of sulfur content on engine-out emissions by the addition of complementary blocks to the regression equations, derived as a result of their own data processing (Table 2). As a result, it was established that fuel sulfur content has an impact only on PM emissions (fig. 1). It is noted by HDDEs manufacturers [9], that fuel sulfur impact on PM emissions from HDDEs may be more substantial than the EPEFE predictions: decrease of sulfur content from 500ppm down to 30ppm may lead to decrease of PM emissions by 9%.

An important finding was that the spread of emissions values with change of fuels on the same engine was substantially less than that with different engines operating on the same fuel. The only exception was NO<sub>x</sub> emissions, where the spread was the same and rather small (Table 3).

THE EPA-HDEWG PROGRAM objective was to assess the role that diesel fuel could play in meeting of 2004+ emission standards for HDDEs. It consisted of three phases [10,11].

In the course of phase I, three fuels were tested. One of them had cetane number, aromatic and sulfur contents close to the USA commodity diesel fuel. The tests were carried out on seven engines, with six tested by engines manufacturers over both AVL 8-mode steady-state and FTP transient cycles, and one (Caterpillar 3176 truck engine) was tested on the Southwest Research Institute (SWRI) test bench only on the former cycle. On the basis of phase I results, the researches came to the conclusion that this engine is representative, and that the results obtained in the AVL 8-mode steady-state cycle can represent the results

received in the FTP transient cycle with sufficient accuracy, except for PM emissions.

In the course of phase II, the impact of 18 different fuels on gaseous emissions from the Caterpillar 3176 engine was investigated. The engine tests were performed on the SWRI test bench over the AVL 8-mode steady-state cycle. The engine was equipped with a unit electronic injector (UEI), capable of up to 207 MPa injection pressure, and a water-cooled exhaust gas recirculation system (EGR) satisfying the 2004 NO<sub>x</sub> standard. The effect of fuel sulfur content was not investigated in this phase, because of the following reasons: it has negligible impact on NO<sub>x</sub>, CO and HC emissions; the engine had no sulfur-sensitive after-treatment device; no PM measurements were planned since the results of the steady-state cycle PM emissions do not correlate with the FTP transient cycle results. By statistical processing the experimental results, the regression equations (included in Table 2) were employed to correlate the AVL 8-mode weighted emissions with diesel fuel properties. One of the significant results that were found is that the relative effects of EGR are the same, independent of the fuel properties. This result is similar to earlier findings by European researchers [6].

The goals of phase III of the EPA-HDEWG program were verification of the phase II results on the most modern engines, as well as investigations of fuel properties impact on PM emissions in the FTP transient cycle (these results are not available yet).

**COMPARISON OF EPEFE & EPA-HDEWG MODELS.** Fig. 2-4 present relative changes of gaseous emissions versus changes of fuel properties (as calculated by equations in Table 2), which were investigated in both the EPEFE and EPA-HDEWG programs.

The effects of poly-aromatic content (PA) in the fuel on gaseous emissions were found to be practically the same in both programs (fig. 2). The results of PA increase from 1% to 8% mass were:

- Negligible increase of CO emission (by 0.08%) in the EPEFE program, while no change in the EPA-HDEWG;
- Increase of HC emission by 4% ± 0.2% in both programs;
- Increase of NO<sub>x</sub> emission by 1.9% ± 0.2% in both programs;

The cetane number (CN) effects (fig. 3) were as follows (it is noted that in the EPEFE program the CN range was 50-58, and in the EPA-HDEWG 42-52):

- Identical for CO emissions: decrease, per CN unit increase, by 1.28% in EPEFE and by 1.25% in EPA-HDEWG);
- Very close for HC emissions: decrease, per CN unit increase, by 0.781% in EPEFE and by 0.597% in EPA-HDEWG;

- Negligible, but opposite trends for NO<sub>x</sub> emissions: Decrease, per CN unit increase, by 0.075% in EPEFE and increase by 0.13% in EPA-HDEWG.

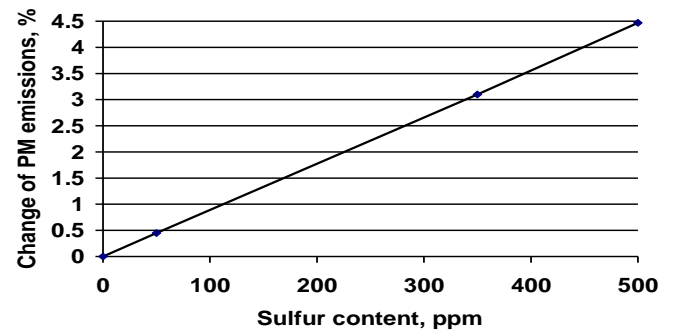


Figure 1. Relative change of PM emissions from heavy-duty engines versus fuel sulfur content, as calculated by equations of Table 2.

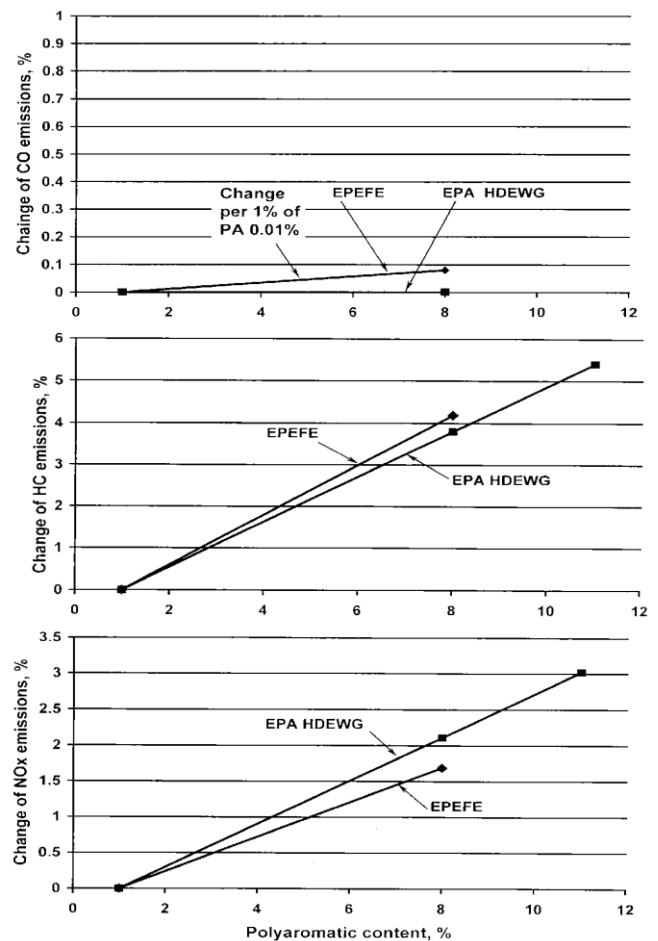


Fig. 2. Relative change of emissions from heavy-duty diesel engines versus fuel aromatic content, as calculated by equations in Table 2.

Table 1. EPEFE (Europe) and EPA-HDEWG (USA.) programs - range of investigations.

	EPEFE	EPA-HDEWG
Fuels tested	11 diesel fuels	Phase II: 18 diesel fuels
density, kg/m <sup>3</sup>	855-828	860-830
cetane number	50-58	42-52
back-end distillation (T95), °C	370-325	311-327
total aromatic content, % m	no data	10-25
poly-aromatic content, % m	1-8	1-11
sulfur content, ppm	402-469	53-473
Engines tested	5 HDDE turbocharged and intercooled, all met at least Euro-2 standards	Phase II: Caterpillar 3176, turbocharged and intercooled, met 2004 NO <sub>x</sub> standard
swept volume, liter	2.8-11	10.3
rated power, kW	84.5-250	260
rated speed, rpm	1900-3600	1800
max torque, Nm	1600-253	1515
fuel injection system	pump+line+injector	electronic injector unit
Test cycle	13-mode 88/77 ECE	Phase II: 8-mode AVL
Emissions measured	NO <sub>x</sub> , CO, THC, PM	NO <sub>x</sub> , CO, THC, CO <sub>2</sub>

Table 2. EPEFE and EPA-HDEWG programs regression equations [8,11].

emission	EPEFE, g/kWh	phase II of EPA-HDEWG, g/hp h
CO=	2.24407-0.00111D+0.00007P-0.00768C- -0.00087T	1.28-0.0105C
HC=	1.61466-0.00123D+0.00133P-0.00181C- -0.00068T	0.2027-0.00186C+0.00677M+0.00160P
NO <sub>x</sub> =	-1.75444+0.00906D+0.0163P-0.00493C+ +0.00266T	-1.334+0.00413D+0.00337C+0.00646M+ +0.00763P
PM=	(0.06959+0.00006D+0.00065P-0.00001C)* *[1-0.000086(450-S)]	Particulate matter was not investigated in this phase.

D – density, g/m<sup>3</sup>; P – poly-aromatics content, % m; M – mono-aromatics content, % m; C – cetane number; T – back-end distillation temperature T95, °C; S – sulfur content, ppm.

The result of the EPA-HDEWG program is inconsistent with well-established knowledge that increase of CN leads to decrease of ignition delay and the portion of the fuel involved in the premixed phase of combustion. This portion is burnt by explosive combustion, which is the main mechanism of NO<sub>x</sub> generation. Therefore, the NO<sub>x</sub> emissions decrease when the CN is increased. It is noted that the authors of [10] had been, indeed, surprised by their result, and suggested that it was caused by design of the engine tested and of the fuel test matrix.

The injection pressure maintained by the unit electronic injector was extremely high (up to 200 MPa), and the dimensions of the combustion chamber were relatively small (125 mm cylinder diameter). Therefore, it can be assumed that part of the fuel injected during ignition delay is applied as a film on the combustion chamber walls, and does not burn by explosive combustion, which suppresses NO<sub>x</sub> formation. As a result of raising

Table 3. Spread of emission values by variations of fuels and engines (EPEFE results) [7].

Emissions	Variation of fuels, %	Variation of engines, %
NO <sub>x</sub>	8	8
PM	7	67
HC	19	75
CO	17	33

the cetane number, the injection delay decreases and also this part of the fuel (forming a film on the walls). Hence the part of the fuel burning in the bulk of the combustion chamber increases, the temperatures of engine operating cycle rise and NO<sub>x</sub> formation increases.

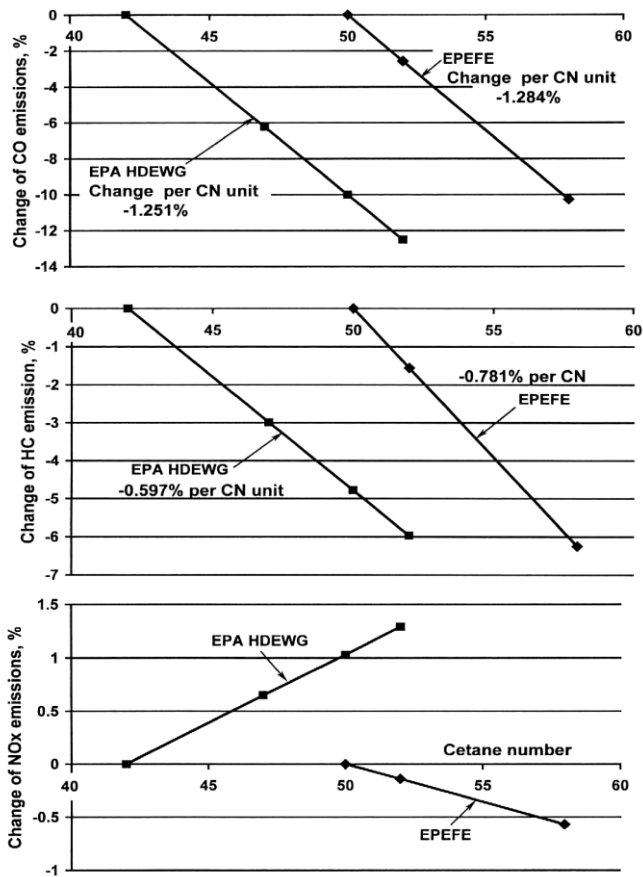


Fig. 3. Relative change of emissions from heavy-duty diesel engines versus cetane number of fuel, as calculated by equations from Table 2.

The impact of the fuel density on gaseous emissions (fig. 4) was compared for the reference setting of engines tested. Under such conditions, increase of the fuel density causes the following changes in the injection system:

- Increase of the dynamic timing, as a consequence of the increase of the sound velocity in the fuel, i.e. decrease of the time of pressure pulse movement from the injection pump to the injector (only for injection systems of the pump+line+injector type);
- Increase of the fuel mass injected (in each operating cycle) resulting in increase of engine power;
- Decrease of fuel volume injected (in each operating cycle) according to the equation:

$$q = 1.41 \cdot \mu f \cdot g^{0.5} \cdot \rho^{-0.5} \cdot \Delta p^{0.5}$$

where:  $\mu f$  – effective cross section of nozzle orifice,  $g$  – acceleration of gravity,  $\rho$  – fuel density,  $\Delta p$  – pressure difference on the nozzle.

This effect partly compensates the increase of the engine power due to increase of the fuel mass.

The phenomena listed above furnish an explanation for the changes of emissions with the fuel density, as well

as for the conflicting results received in the EPEFE and EPA-HDEWG programs.

As can be seen from fig. 4, increase of the fuel density from 828 kg/m<sup>3</sup> to 855 kg/m<sup>3</sup> causes decrease of the average CO and HC emissions from EPEFE engines (with the pump+line+injector fuel systems) by about to 5% and 13%, respectively. This is the typical response of diesel engines to the increase of timing. The CO and HC emissions from the Caterpillar 3176 with unit electronic injector (EPA-HDEWG program) were independent of fuel density. This results from the absence of an injection line and of keeping the timing unchanged. In both programs, the increase of fuel density caused practically the same increase of NO<sub>x</sub> emissions. This is a combined result of the dynamic timing increase (only in the EPEFE program), increase of the fuel mass injected during the ignition delay, and some increase of power due to the increase of fuel mass delivery.

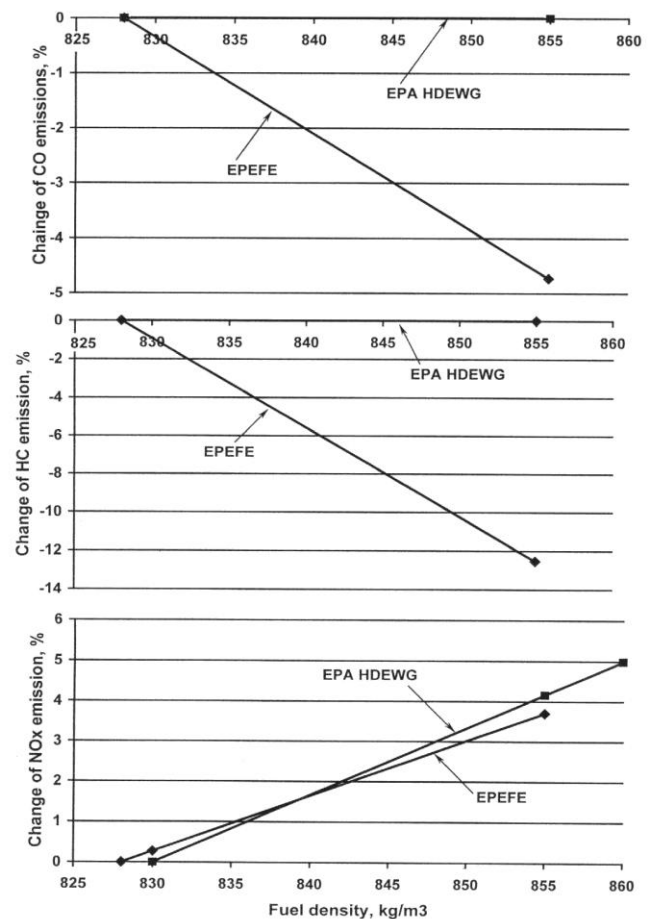


Fig. 4. Relative change of emissions from heavy-duty diesel engines versus fuel density, as calculated by equations from Table 2.

#### 4. DECSE program results

As stated above, HDDEs of generations after Euro-3 may satisfy the emission standards only by application of after-treatment systems. Hence it is important and quite urgent to assess the impact of fuel properties on

the efficiency and durability of these devices. The experience gained to date shows that the main property that affects the efficiency of after-treatment devices is the fuel sulfur content, e.g. [12-16]. During the recent years, a comprehensive assessment has been undertaken, by co-operation of USA government organizations, manufacturers of engines and after-treatment devices and research laboratories, in an attempt to determine the effects of fuel sulfur content on the efficiency of some devices. The technologies studied were: diesel oxidation catalysts (DOC); lean-NO<sub>x</sub> catalysts (L-NO<sub>x</sub> Cat); diesel particulate filters or traps (DPFs); NO<sub>x</sub> adsorbers (NO<sub>x</sub>-Ad).

Fuels with 3, 16, 30, 150 and 350 ppm sulfur content were studied on the engines which were considered as representative by emissions and exhaust temperatures values. The main results of the studies are presented below.

**DIESEL OXIDATION CATALYST.** The investigations performed on the Cummins ISM 370 diesel engine confirmed the results of some earlier studies [12,15,17]. They demonstrated a dramatic decline of DOC efficiency (as a result of sulfates formation), when the upstream exhaust temperature exceeds 350°C – 400°C, and this trend is strengthened by increase of the sulfur content in the fuel.

From fig. 5, one can see that in the maximum torque mode (518°C upstream exhaust temperature) the PM emissions after the DOC exceed the engine-out values already at 30 ppm sulfur content. At 350 ppm, they are more than double, and, moreover, sulfates account for nearly half of the total PM emissions. It is important to note that over the FTP transient cycle with average exhaust temperature about 240°C, PM emissions were practically independent of fuel sulfur level.

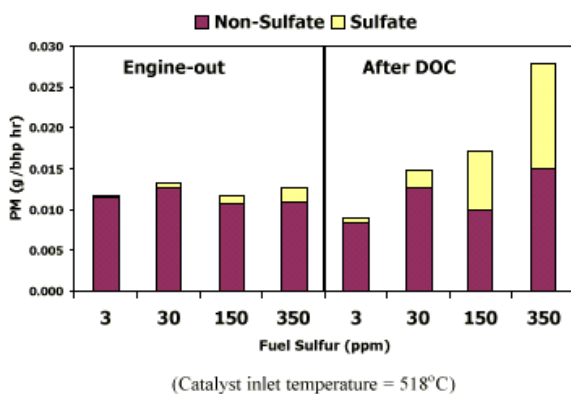


Figure 5. The impact of sulfur content on PM emissions, Cummins ISM 37D + DOC, maximum torque [16].

The impact of fuel sulfur content on CO, HC and NO<sub>x</sub> emissions was not reported in [16]. However, the results in [18] demonstrate that decrease of the sulfur content from 368 ppm down to 54 ppm on an HDDE DDC series 60, equipped by DOCs with different

activities, caused a decrease of HC conversion efficiency by 6-15% and increase of CO efficiency by 10-11%.

LEAN-NO<sub>x</sub> CATALYST (L-NO<sub>x</sub>) decreases NO<sub>x</sub> emissions by adding hydrocarbon matter, e.g. diesel fuel, to rich-oxygen upstream exhaust gases, according to the reaction:

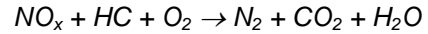


Figure 6 shows that increasing the fuel sulfur content from 3 ppm to 150 – 350 ppm causes dramatic increase, by a factor of 10 – 20, of sulfates emissions after the L-NO<sub>x</sub>, while the increase of engine-out sulfates emissions was only by a factor of 2 – 5. After the L-NO<sub>x</sub>, total PM emissions increase by nearly a factor of 1.5.

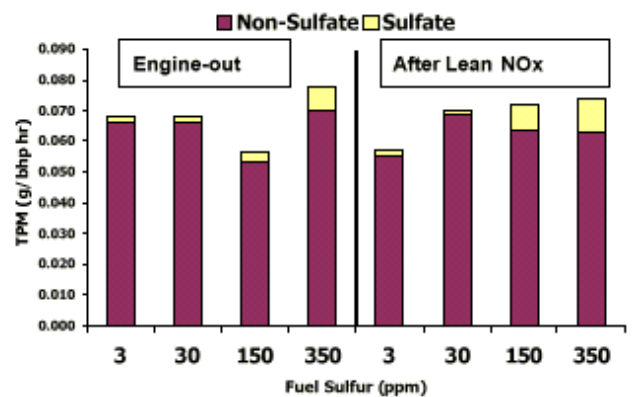


Figure 6. PM emissions at engine-out and after Lean-NO<sub>x</sub> catalyst versus sulfur content in the fuel [16].

CONTINUOUSLY REGENERATING DIESEL PARTICULATE FILTER (CR-DPF) and CATALYZED DIESEL PARTICULATE FILTER (C-DPF) have been directly designed to remove particulate matter from the engine exhaust. In the CR-DPF, the continued regeneration is achieved by oxidizing soot particles, caught on trap sites, by nitrogen dioxide, which is continuously generated in the exhaust by the reactions:

$$2NO + O_2 \rightarrow 2NO_2; \quad 2NO_2 + C \rightarrow 2NO + CO_2$$

In the C-DPF, the regeneration is achieved by catalytic oxidation with oxygen, of particulate matter trapped on the filter. For both types of DPFs, oxidation of sulfur causes increase of PM emissions as a result of sulfates increase. Moreover, in the CR-DPF, the reaction of sulfate formation may suppress those of NO and NO<sub>2</sub>.

The results presented in fig. 7 show that the conversion efficiency of the two DPFs was 95% when the sulfur content was 3 ppm, and about 73% with 30 ppm sulfur content. Increasing the sulfur content to 150 ppm leads to zero efficiency, and further increase, to 350 ppm, causes PM emissions to rise by a factor of 2.2 for C-DPF and by 2.5 for CR-DPF. As noted in [19], the

exhaust temperature required for the DPF regeneration process grows with the increase of fuel sulfur content. The right part of fig. 7 represents the efficiencies of the two DPFs with 30 ppm sulfur content, after about 400 hours operation with 150 ppm and 350 ppm. One can see that this causes recovery of the DPFs efficiencies. Although Ref. [19] did not comment on the statistical significant impact of sulfur content on the CO, HC and NO<sub>x</sub> conversion efficiencies, very high values have been observed: for HC about 70% with C-DFC and about 83% with CR-DPF; for CO 90-99% with both DPFs.

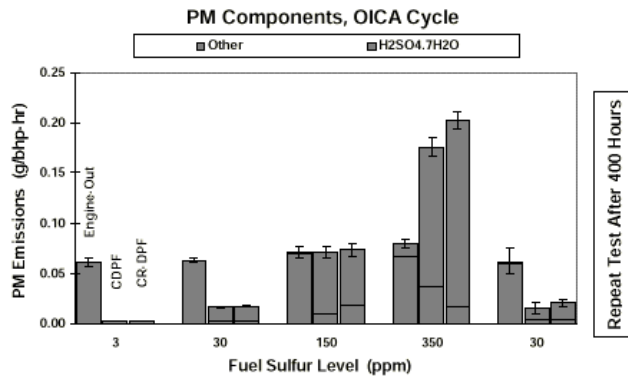


Figure 7. PM emissions at engine-out and after C-DPF and CR-DPF versus sulfur content in the fuel [19].

THE NO<sub>x</sub> ADSORBER CATALYST (NO<sub>x</sub>-Ad-C) is an after-treatment device capturing NO<sub>x</sub> from the exhaust gases and cleaned periodically from NO<sub>x</sub> by short-term switch of the engine to operation under fuel-rich exhaust conditions, and NO<sub>x</sub> to N<sub>2</sub> transformation over precious-metal catalyst sites in the adsorber. The impact of the fuel sulfur content on the efficiency of NO<sub>x</sub>-Ad-C manifests itself in the fact that SO<sub>2</sub>, present in the exhaust, undergoes chemical reactions that produce adsorbent much more reactive than NO<sub>2</sub>, thus suppresses the NO<sub>x</sub> reduction. The investigations reported in [20] were carried out for developing a process of NO<sub>x</sub>-Ad-C de-sulfurization and to study the impact of sulfur on the long-term performance of the device. Fig. 8 illustrates the effect of fuel sulfur content on the NO<sub>x</sub>-Ad-C performance. One can see that even a slight increase of the sulfur content (from 3 to 30 ppm) causes drastic decrease of the NO<sub>x</sub>-Ad-C efficiency. As noted in [16], there is no impact of fuel sulfur content on NO<sub>x</sub>-Ad-C efficiency for total PM, SOF or non-SOF emissions over the temperature range studied (250 - 500°C) or during adsorber aging of up to 250 hours.

## 5. Conclusions

The main conclusions drawn from the results of the EPEFE, EPA-HDEWG, DECSE programs and other recent studies, and their analysis in the present work, are summarized henceforth.

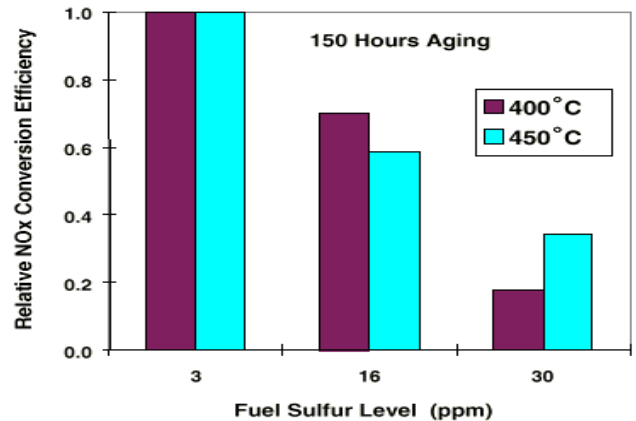


Figure 8. Effect of increasing fuel sulfur level on relative NO<sub>x</sub> conversion efficiency of an NO<sub>x</sub> adsorber catalyst, at 150 hour aging, evaluated at 400 and 450°C [21].

1. The main fuel properties that affect HDDEs emissions and efficiencies of after-treatment devices are cetane number, total and polyaromatics content, back-end distillation, density, sulfur content and oxygenates. Only limited data are available of oxygenates effect on emissions.
2. For HDDEs without after-treatment devices, the fuel sulfur content has no significant impact on gaseous emissions. PM emissions increase by about 4.5% with sulfur content increase from zero to 500 ppm.
3. The results of the EPEFE research program showed that the spread of emission values with change of fuels on the same engine was substantially less than that with different engines operating on the same fuel.
4. The results of the EPA-HDEWG program showed that the relative effects of EGR are the same, independent of the fuel properties. This is confirmed by earlier European investigations.
5. The cetane number effects on NO<sub>x</sub> emissions turned out to be negligible and of opposite trend: decrease in the EPEFE program and increase in the EPA-HDEWG program. The result of the latter is inconsistent with well-established knowledge, and it is probably a consequence of non-optimal process of the fuel-air mixture formation during ignition delay. To clear up this point, additional studies are necessary.
6. The EPEFE results showed that the fuel density itself does not have any practical influence on the fuel combustion process, and its impact on emissions is a result of changes inside the hydraulic system of the fuel injection equipment: timing, mass fuel delivery, etc. Fuel density increase from 828 to 855 kg/m<sup>3</sup> causes decrease of CO emissions by about 5%, HC emissions by about 13%, and increase of NO<sub>x</sub> emissions by 3.7% from HDDEs with fuel injection system of the type "pump+line+injector" (EPEFE). The same change of fuel density in the EPA-HDEWG program (engine

with unit electronic injectors) caused practically the same change of NO<sub>x</sub> emissions, but CO and HC emissions were invariable.

7. The conversion efficiency of diesel oxidation catalysts (DOC) decreases when the upstream exhaust temperature increase above 400°C, and varies with fuel sulfur content as a result of the increase of sulfates emissions. Under FTP test conditions, the fuel sulfur content does not influence, practically, PM emissions.
8. Increasing the sulfur content from 3 to 350 ppm causes increase of sulfates emissions from high temperature lean-NO<sub>x</sub> catalyst by a factor of 10-20. As a result, PM emissions increase by a factor of about 1.5.
9. Increase of the fuel sulfur content from 3 to 150 ppm causes decrease down to zero of the conversion efficiencies of diesel particulates filters; further increase of the sulfur content (up to 350 ppm) causes increase of PM emissions by a factor of 2.2 (C-DPF) and of 2.5 (CR-DPF).
10. The conversion efficiency of NO<sub>x</sub> adsorber catalysts decreases dramatically by increase of the fuel sulfur content, and already at fuel with 30 ppm it falls down to 0.2-0.3 in comparison with 3 ppm.
11. The comparison of the EPEFE and EPA-HDEWG results allows to conclude that the impact of fuel poly-aromatic content (1% - 8%) on CO, HC and NO<sub>x</sub> emissions, of cetane number (42-58) on CO and HC emissions, and of fuel density (828-855 kg/m<sup>3</sup>) on NO<sub>x</sub> emissions from HDDEs is universal and practically independent of engine technology and type of test cycle; the impact of cetane number on NO<sub>x</sub> emissions and fuel density on CO and HC emissions have special features, which depend on engine technology.
12. It has to be noted that there is still lack of data regarding the fuel effects on emissions of engines tested over the new European Transient Cycle.

This review includes only partial analysis and evaluation of the available results regarding fuel effects on emissions from heavy-duty diesel engines. A more comprehensive report is prepared within the EC ARTEMIS Project, and the main results will also be published in a journal paper.

## Acknowledgement

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