

Influence of Innovative Diesel-Ethanol Blend on Combustion, Emission and Fuel-Carrying Components

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ABSTRACT

The strong demand for diesel fuel is producing a surplus of gasoline fractions in Europe. Despite new vehicles using less energy, the rising volume of traffic will lead to more diesel being consumed. European legislation demands that renewable fuels cover 10% of energy consumed in the transport sector. The present strategy of dividing biofuels in equal shares between diesel and gasoline does not help to improve this situation. It seems reasonable not only to add FAME but also ethanol to diesel.

Unfortunately, fuel blends containing ethanol cannot be used in existing cars without hardware modifications. This is because of ethanol's characteristics and well-known from the experience gathered with gasoline cars. As such, the first part of this study investigates material compatibility, focusing on corrosion and changes to the mechanical properties of the materials used in diesel engines. Alongside tests for material compatibility with ethanol-RME blends, it also includes a comparison of RME and SME fuels. This first part concludes by explaining the modifications necessary to fuel lines and fuel-tank systems to make them safe for use with diesel-FAME-ethanol blends.

In a second part, investigation characterizes the properties of the selected RME-ethanol-diesel blend, showing its potential in a single-cylinder research engine. It evaluates five operating points representative of the engine map. The aim is to assess changes in engine operation in a EU5 combustion system and define the recalibration measures needed to meet base-line performance. One aspect of investigating recalibration is to find out whether the better soot levels gained with oxygenated fuels can be translated into attaining lower NO_x emission in line with the EU6 emission target.

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INTRODUCTION

Global warming, the finite nature of fossil fuels and reliance on imports from oil-producing countries demand action on the policy-making front. For this reason, the EU aims in Directive 2009/28/EC to replace 10% of energy consumed in the transport sector with renewable resources by 2020. In 2009, 4.2% was covered by the biofuels of FAME and ethanol. [1]

Today, Europe is already using more diesel than gasoline. The fraction of crude oil is unable to cover this demand. Part of the diesel deficit is covered by crude oil conversion processes with the drawback of increasing greenhouse-gas emission and part of it by diesel imports from countries such as the USA. With the volume of transport expected to rise by 2030, this will see a shift in the ratio between diesel fuel and gasoline from 1.3 (2008) to ~3 (2030) in Europe, despite less energy being needed by new vehicles. [2, 3]

Instead of spreading the renewable fuels over both fractions, this situation can be countered by reducing the demand for diesel on the basis of the targeted 10% biofuel component. Until 2020 and beyond only first-generation biofuels will be available in appreciable quantities. This underpins the recommendation to blend all available renewable components of FAME and ethanol with diesel at a level of 20%.

A first part of this study examines the potential of a RME-ethanol-diesel blend in a single-cylinder research engine. The aim is to assess changes in engine operation in a EU5 combustion system and define the recalibration measures needed to meet base-line performance of Diesel. A recalibration will check whether the better soot levels gained with oxygenated fuels can be translated into attaining lower NO_x emission and a lower fuel consumption with

maintenance of the advantage in soot and a constant Noise level.

The second part investigates material compatibility with focus on corrosion and changes to the mechanical properties of the materials used in diesel engines. Also included is a comparison of RME and SME fuels. Furthermore necessary modifications to fuel lines and fuel-tank systems due to safety requirements will be shown.

Extensive European and American studies on ethanol-diesel blends were conducted between 2005 and 2010. Blends were analyzed with an ethanol content of 7 to 20% and an additive content of up to 5%. The properties of the fuel as well as the resultant effects and measures are summarized in [Table 1](#). The studies describe the influence of fuel properties on regulated emissions. Soot emission falls sharply (20 to 70%), NO_x emission varies by +/- 20% and consumption goes up by a maximum of 8%. Statements on HC and CO emissions depend on the blend, engine or vehicle and operating state, and vary from one quote in literature to another. Long-term studies under real-world operating conditions were unable to reveal any adverse effects from ethanol-diesel blends on the durability of vehicle components, oil condition and exhaust gas aftertreatment components of DOC and DPF. Going on the study by the Irish Environmental Protection Agency, the cost of avoiding CO₂ only runs to € 284/t for bioethanol compared with € 531/t for biodiesel. For cost reasons, a clear preference must be given to bioethanol over biodiesel. The truck segment is seen as the dominant area of use for the ethanol blends which, from the aspect of safety, are only suitable for fueling at fleet level. A market analysis in Ireland shows that around 20% of the companies with truck fleets surveyed are thinking about using ethanol-diesel blends. Although the studies list a number of suppliers of ethanol-diesel blends and of the additives needed, most of them have disappeared from today's market. [4, 5, 6, 7]

Table 1. Properties influenced by ethanol, their effects and potential measures

Property	Effect / Measures
Miscibility of ethanol and diesel	Blending with additives or FAME
Cetane number	Extended ignition delay / addition of Cetane improver
Flashpoint	Fuel system modification (FAME arrestor, vapor separator, special tank etc.), stuff training
Lubricity	Blending with additives or FAME
Solvent	Removal of deposits / cleaning fuel systems before using ethanol blends
Material compatibility	Test elastomers
Corrosion	Substitute, blending with additives
Vapor pressure	Vapor lock / adjustment of injection system
Caloric value	Lower power / higher fuel flow rate
Conductivity	Electric grounding
No standard	Loss of guarantee / Use ethanol blends after guarantee

Reinforcing studies on the effects of fuel properties examined ethanol blends for combustion behavior, emissions and consumption. They looked at ethanol contents of up to 50%. Studies on fuel injected in a single event reveal a longer ignition delay as ethanol content increases, this also being accompanied by a higher premixed combustion component. Although this increases NO_x emission in the high load range, it can be reduced by raising the EGR rate. Soot emission is extremely low, unburned hydrocarbon emissions, however, are far higher. Depending on operating state, CO emission tends to remain constant or rise. Analysis of non-limited emissions with 20% ethanol content shows formaldehyde emissions to be up only slightly over diesel fuel. Acetaldehyde emission doubles in blends with 20% ethanol. With ethanol, the content of formic acid is as much as 7 times higher, and is greater for an ethanol content of 10% than it is for 20%. [8, 9]

Rail pressure, EGR, COHR as well as interval, duration and number of pilot injections (PI) are identified as measures for optimizing combustion with changed fuel properties. Adjusting PI is a good way of shortening ignition delays. At lower part load, this reduces the HC and CO emissions for the ethanol blend. At upper part load, this provides a way of lowering NO_x emission and noise. However, it also leaves soot less favorable. Increasing rail pressure ensures combustion stability. [10, 11]

The far lower level of soot formation with an ethanol-GTL-diesel blend makes it possible to improve the NO_x/PM/CO₂ trade-off with the aim of saving any need for DPF. After optimizing the EGR rate, rail pressure, COHR and defining the best injection strategy, it was possible to cut soot and NO_x emission while reducing CO₂ emission and noise. However, this was also at the expense of higher HC and CO emission. At lower part load, only a double PI strategy produces the desired result. Optimization at lower part load provides significantly cutting soot emission, NO_x emission and noise as well as achieving a slight reduction in CO₂ emissions but sharply increasing CO emission. In the higher engine-speed and load range, it was possible to achieve major improvements for soot and minor ones for CO₂ and CO, other emissions remaining constant. In combination with recalibration for the ethanol-GTL-diesel blend, the EU4 vehicle managed to remain below the EU5 limit values. [12]

Aiming to meet EU6 NO_x limits, recalibration was carried out for diesel blended with an E85 content of up to 40%. As more E85 is added to the blend, particulate emission falls and ignition lag increases, exacerbating noise emission. HC emission increases too. The emission of CO shows no clear trend. HC and CO emissions are shown to be a problem at lower part load. At higher part load, the sum of HC and CO is balanced, although noise increases. Using a continuously operated spark plug, it was possible to keep ignition stable during cold starting. [13]

METHODOLOGY

Test Fuel

Ethanol diverges from diesel in virtually all relevant properties - compared here on the basis of the EN 590 standard effective in Europe (Table 2). The aim is to select a blend in such a way that satisfies as many requirements of the standard as possible while permitting use of a high portion of regenerative fuel. The miscibility of ethanol and diesel is governed by temperature, water content and ethanol content. Unfavorable blending ratios can result in segregation even at room temperature. Stable blends demand ethanol with a high level of purity, i.e. low water component. The ethanol content in the blended fuel should not be greater than 15% either. Stable blends can be produced by mixing in an additive or an emulsifier. FAME is an amphiphile, it has a polar and nonpolar side, making it a highly suitable emulsifier which is why it is used for the investigations. [5, 14, 15]

Table 2. Fuel properties

Property	Unit	Diesel EN590*	RME	Bio-Ethanol	B7E13
Density	kg/m ³	820 – 845*	882	794	828
Flashpoint	°C	>55*	164	13.5	< 20
Kinetic viscosity	mm ² /s	2 – 4.5*	4.46	1.08	2.29
Water content	mg/kg	<200*	165	535	365
Cetane number		>51*	55.5	-	45
Caloric value Hu	MJ/kg	43.0	37.9	26.8	40.7
HFRR	mm	<460*	177	478	193
Ignition temperature	C	200	240	410	260
C content	wt.-%	86.5	77.1	52.2	81.8
H content	wt.-%	13.4	12.1	13.1	13.5
O content	wt.-%	0.1	10.8	34.7	4.7
Boiling vol. at 350°C	vol.-%	85*	96	100	94.5

In Europe; 7% FAME is permissible in diesel. This provided the basis for examining its properties by mixing diesel, 7% FAME and ethanol in various ratios. 7% FAME, in this case RME, and 13% bioethanol were selected as the optimum mixing ratio and blended with a diesel fuel available at German filling stations. This blend is referred to below as B7E13. The properties of density, kinetic viscosity, lubricity and boiling volume of B7E13 comply with EN 590 despite divergent flashpoint, Cetane number and water content. The blend's caloric value is 5.5 % below that of diesel.

Test Engine

The measurements were conducted on an automobile single-cylinder engine based on the Daimler 2.2l CR DI four-cylinder in-line engine of type OM646 (EU4). The piston

bowl was widened to a geometric compression ratio of $\epsilon = 16$ and a state of the art fuel injection system was adapted to reproduce the combustion characteristics of modern EU5 engines. The engine's key data are shown in Table 3. The OM646's cylinder head has a tangential and a spiral port on the intake side. IAV's MPEC® development environment was used for controlling (open and closed loop) the engine periphery on the single-cylinder test bench. Constant indicated mean effective pressures from the high-pressure loop (IMEP_{HP}) and discrete setpoint values for the center of heat release (COHR) were set as the reference input variable for the measurements. Two Kistler 6041A-type water-cooled laboratory sensors were used for the purpose of cylinder pressure indication.

Table 3. Specifications for the test engine

Displaced volume	537 cc
Stroke	88.3 mm
Bore	88.0 mm
Compression ratio	16:1
Number of valves	4
Injector	Servo magnetic, 7-hole, 153°
Max. rail pressure	2000 bar
Nozzle flow	410 cc / 30s at 100 bar
Max. cylinder pressure	220 bar

Test Conditions

Representative of the entire engine map, five operating points were selected for the studies. These include idling and the rated output point as well as three part-load operating points. The calibration values for operating points were taken from the calibration of the power unit for EU5 certification (Table 4).

Table 4. Engine operating points

Operating Point	Speed	IMEP _{HP}	P _{rail}	P _{2abs}	T ₂	T _C	Injection strategy
-	rpm	bar	bar	bar	°C	°C	mg/stroke
OP1	600	2.3	320	1.0	35	90	2 PI + MI
OP2	1400	4.0	600	1.09	35	90	2 PI + MI
OP3	1900	4.5	710	1.17	35	90	2 PI + MI
OP4	1900	8.0	1020	1.37	35	90	2 PI + MI
OP5	4000	20.5	2200	1.64	50	90	MI

Investigations aim to identify the influence of changed fuel properties on ignition delay, combustion characteristics, emissions and fuel consumption and estimate their potential impact on engine management and exhaust-gas aftertreatment (EGA).

IAV's MPEC® permits selection of any injection parameters. Following basic measurement with diesel fuel,



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the first step involves analyzing the fuel blend with the injector control data used for diesel. This can be used for determining the influence fuel properties have on combustion characteristics. In a second step, the blend's lower caloric value is compensated for by adjusting the actuation duration of MI. The third step entails readjusting the center of heat release. This is done by shifting injection in parallel fashion and adjusting load through the duration of MI.

Soot emissions are expected to fall in line with the fuel blend's higher oxygen component. Ethanol's evaporation and ignition characteristics demand a lower Cetane number, giving reason to expect higher HC and CO emissions.

Subsequent recalibration sets out to achieve two objectives. This first one is to approximate combustion with diesel without drawbacks in consumption, noise and emissions by making up for the changed ignition delay through varying the start and duration of pilot injection. The second objective is to lower energy consumption with soot and NO_x emissions equivalent to those for diesel, unchanged noise and minimum impacts on HC and CO emissions. Variation parameters here are the EGR rate, center of heat release as well as the start and duration of pilot injection.

ENGINE TEST RESULTS

Upper Part Load

Emission characteristics, fuel consumption and noise

Representing the five operating points under study, the following explains the results obtained for operating point 4 (OP4). Figure 1 compares the combustion characteristic for B7E13 with that of the diesel reference. Adjusting IMEP and COHR only involves a minor change to injector control. The blend's lower CN retards the start of pilot-quantity combustion and halves the conversion rate for the second pilot quantity (PI2). This unburned fuel mass is then converted in combustion of the main injection mass (MI) and leads to higher noise emissions (see Figure 3).

The premixed component of combustion can be reduced by optimizing pilot injection. Although the result still shows a later start of PI2 combustion, it was possible to reduce the MI combustion rate for B7E13 to a level similar to that for diesel. PI1 is hardly realized for B7E13 and diesel fuel. However, it does support realization of PI2 through preliminary chemical reactions and the formation of radicals.

The control parameters for both pilot injections were extensively varied to optimize approximation of B7E13 combustion with that of diesel. For an example center of heat release and EGR rate, Figure 2 shows the result of varying PI2 duration while varying PI1 and PI2 as well as varying the start of injection. The aim of reducing noise while leaving emissions and consumption constant can be attained by increasing the fuel mass for PI2 for the same start of injection.

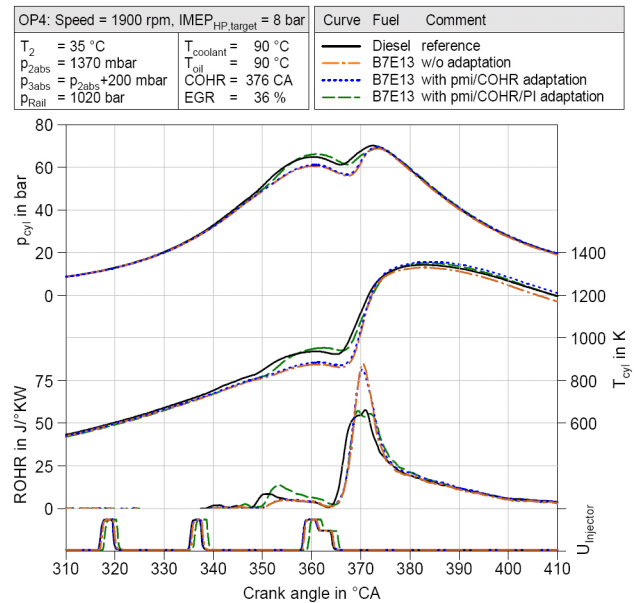


Figure 1. Thermodynamic Analysis, OP4

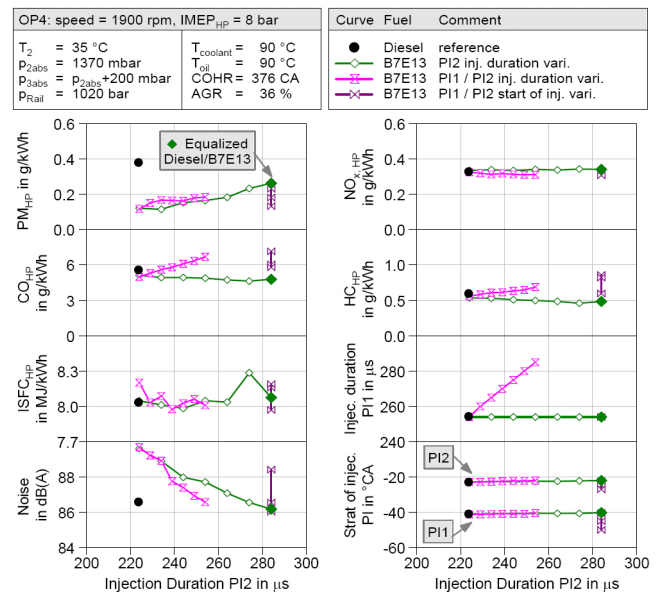


Figure 2. Variation of pilot injection duration and start of pilot injection, OP4

No measurable conversion of PI1 could be achieved by significantly lengthening the duration of injection either. Ultimately, the measures only result in a sharp increase in unburned fuel and thus to higher HC and CO emissions. Pilot-injection combustion could not be advanced for PI1 or for PI2.

It was possible to eliminate the influence of the fuel properties of B7E13 in relation to emissions, consumption and noise by extending the duration of PI2 by 60µs.