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# Dual fuel diesel combustion with an E85 ethanol/gasoline blend

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## HIGHLIGHTS

- E85 blend is suitable for dual-fuel combustion on heavy duty engines.
- Very high diesel fuel substitution rates were achieved on medium load conditions.
- THC and CO emissions increase significantly and $NO_x$ emission decrease with E85.

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## ABSTRACT

In this experimental study, the ethanol/gasoline blend E85 was used as the primary fuel in a dual-fuel combustion concept. The E85 blend was injected at low pressure into the intake manifold and the mixture was ignited via a diesel fuel injection near top dead centre. The research engine was based on a heavy-duty diesel engine equipped with a common-rail injection system. Only the duration of the diesel injection was modified in the diesel injection system during the tests – the other diesel injection parameters were not changed. The goal was to study the possibilities of using the waste material-based E85 ethanol blend on dual-fuel concept as a promising future bio-fuel option. The results were promising, though the engine was not optimised for the combustion concept being studied and minimum modifications were done to the engine. High E85 rates (up to 89%) by energy content were achieved, especially under medium load conditions. On the high and low load portions were lower, but the E85 rates were higher than 30% even in these cases. For most of the cases, the limiting issue was the pressure rise rate, but in cases with the highest portions of E85 the limiting factor was the minimum quantity of the diesel fuel enabling two phase diesel fuel injection. In all cases the E85 increased carbon-monoxide and un-burned hydrocarbon emission, but the nitrogen oxide emission decreased simultaneously in most of the cases. Smoke emissions were low in all cases, but at highest E85 rate smoke emissions further decreased to near zero value.



## 1. Introduction

The outlook of world energy markets has changed radically during the last few years. The main concerns and motivations for moving towards alternative fuels have been limited crude oil reserves and climate change. Currently the development of shale gas pumping technology has changed the outlook radically – from technological, market and political points of view [1–4].

To this day, compression ignition (CI) engines using diesel fuel have been the main power sources of both on-road and off-road heavy duty vehicles. Their conditions of use set high demands for engine efficiency, fuel price and fuel energy density and storage properties. However, CI engines that use traditional crude oil-based diesel fuel are facing new challenges in the form of uncertainties regarding diesel fuel prices and meeting strict emission legislation for particulates and nitrogen oxides. Since transportation consumes a significant portion of total world energy consumption [3], it is both environmentally and economically important to develop alternatives for crude oil-based diesel fuel in this market area.

The exploitation of shale gas has increased interest in natural gas (NG) as a transport fuel. However, gaseous fuel has a drawback compared to traditional liquid fuels. The biggest challenges to using more NG are its low energy content on gaseous phase and the limited distribution infrastructure currently in place. The challenge with respect to energy density can be partly avoided by liquefying the gas, but the process consumes energy and liquefied natural gas (LNG) also requires a specific distribution infrastructure because it is liquefied using cryogenic technology [5,6].

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**Nomenclature**

| | | | |
|---|---|---|---|
| ATDC | after top-dead-centre | NDIR | Non-Dispersive Infra-Red |
| BMEP | brake mean effective pressure | NG | natural gas |
| BTE | brake thermal efficiency | $NO_x$ | nitrogen-oxides |
| BTDC | before top-dead-centre | $p$ | pressure (Bar) |
| CA | crank angle (degrees) | PFI | port fuel injection |
| CI | compression ignition | PRR | maximum pressure rise rate (bar/CA) |
| CO | carbon-monoxide | $Q_n$ | net heat-release (J) |
| $CO_2$ | carbon-dioxide | RCCI | reactivity-controlled compression ignition |
| EGR | exhaust gas recirculation | rpm | revolutions per minute |
| EN590 | European diesel fuel grade | SECA | sulphur emission control area |
| E85 | ethanol gasoline blend, max 85% ethanol | SI | spark ignition |
| FAME | fatty acid methyl esther | SOI | start of injection |
| FSN | filter smoke number | $SO_x$ | sulphur oxides |
| HRR | heat release rate | $t$ | time (s) |
| IMEP | indicated mean effective pressure | TDC | top-dead-center |
| IMO | International Maritime Organization | THC | total unburned hydro-carbon |
| LNG | Liquefied natural gas | $V$ | volume ($m^3$) |
| LPG | Liquefied Petroleum Gas | wt. | weight |
| LTC | Low temperature combustion | $\gamma$ | specific heat capacities ratio |
| $n$ | Rotational speed (rpm) | | |

The dual fuel concept for NG was originally introduced several decades ago. With dual-fuel combustion, the primary fuel is injected into the intake manifold at low pressure, and it is ignited by injecting diesel fuel into the cylinder near the top-dead-centre (TDC) [7]. The concept is similar to the spark ignition (SI) process, but instead of an electric spark the combustion of gas is initiated with a small amount of diesel fuel injected at the TDC and ignited by the heat from the compression of the charge. A similar combustion concept as the one used with NG can also be used with liquid fuels that have their ignition properties close to the NG. These liquid fuels typically used as spark ignition engine fuels [5].

The NG dual fuel technology has mainly been used at power plants near natural gas sources or pipelines and pipeline compressor stations. The dual fuel engines were introduced for maritime markets at the same time that LNG tankers were developed in the early 1990s. More recently, the upcoming International Maritime Organization (IMO) Tier III regulations have been a driving force for dual fuel ship application development. Since NG does not contain any sulphur, the sulphur oxide ($SO_x$) emissions are zero, which is quite important in terms of specific Sulphur Emission Control Areas (SECA), where will enforce strict $SO_x$ limits in the few years [8]. The lean-burn dual fuel gas engines have very low nitrogen-oxides ($NO_x$) and soot emissions, and they can fulfil emission demands without the need for additional exhaust gas after-treatment systems in a ship use.

Natural gas has not become popular for both on-road and off-road applications because of the challenges related to distribution and energy density. Since NG prices have recently decreased due to the presence of shale gas in the US, NG dual-fuel has also been the subject of increasing interest in road transport. Though the dual fuel concept has traditionally been perceived as natural gas combustion, there are several liquid fuels that have been studied in dual fuel combustion: ethanol [9–17], methanol [18–22], butanol [23] Liquefied Petroleum Gas (LPG)/propane [24–26] and gasoline [27,28]. A common feature of these three fuels is that they are all well suited for SI engines and have similar combustion characteristics, e.g. a high octane number and low cetane number.

The objective of this study is to utilise the dual fuel concept to study the liquid blend of ethanol and gasoline most commonly called E85, which contains a maximum of 85% ethanol by volume. The motivation for using E85 is based on the fuel's higher energy content and the fact that it has a simpler distribution and storage infrastructure and lower carbon-dioxide ($CO_2$) emissions compared to NG. E85 is also an interesting fuel grade since it is already publicly available on some markets in Northern America and in Europe. The $CO_2$ emissions are lower since blended ethanol is typically manufactured from field crops or waste-based biomass. The E85 blend has been developed for SI engines, and the reason for mixing 15% light hydrocarbons with ethanol is to improve the cold start driveability of the engines [29].

As mentioned earlier, several fuels have been studied as alternatives for the dual fuel combustion. There are also many studies [29–31] focusing on how E85 performs in SI engines, but the writers are not aware of any earlier studies on E85 as a dual fuel combustion fuel. There are several studies on the effects of E85 on a reactivity controlled compression ignition (RCCI) combustion strategy [32,33], but since RCCI differs from the dual fuel concept employed in this study, it is not discussed further here.

In this study, we investigated the capability of E85 to affect the dual fuel combustion. The studies were performed using a heavy-duty diesel engine equipped with a port fuel injection system for E85. The engine was not optimised for the E85 dual fuel combustion and the diesel injection parameters were left as the engine manufacturer originally defined them.

## 2. Background

Ethanol, as also other alcohols like methanol and butanol, has a low cetane number, so it is not a suitable substitute for diesel fuel in CI engines without ignition-improving additives, which are required by as much as 16% by volume to ensure compression ignition [5]. The advantages of ethanol, e.g. its high oxygen content (34.8 wt.%), have been utilised in CI engines by blending it with diesel fuel and injecting it in the same way as in a normal diesel engine [5,9,34,35]. Abu-Qudais et al. [9] found that up to 25% ethanol displacement can be achieved by blending when using emulsifiers, although they reported that 15% was the optimum blend. In another study by Lei et al. [34], displacements of up to 30% were achieved. In practice, a diesel/ethanol blend always demands additives because of its poor solubility, and with higher than 10% ethanol content, ignition improvers are also needed to ensure proper ignition behaviour [5].