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Review on the Effects of Dual-Fuel Operation, Using Diesel and Gaseous Fuels, on Emissions and Performance

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ABSTRACT

In recent years the automotive industry has been forced to reduce the harmful and pollutant emissions emitted by direct injected diesel engines. To accomplish this difficult task various solutions have been proposed. One of these proposed solutions is the usage of gaseous fuels in addition to the use of liquid diesel. These gaseous fuels have more gasoline-like properties, such as high octane numbers, and are thereby are resistant against auto-ignition. Diesel on the other hand, has a high cetane number which makes it prone to auto-ignition. In this case the gaseous fuel is injected in the inlet manifold, and the diesel is direct injected in the cylinder at the end of the compression stroke. Thereby the diesel fuel spontaneously ignites and acts as an ignition source. The main goals for the use of a dual-fuel operation with diesel and gaseous fuels are the reduction of particulate matter (PM) and nitrogen oxides (NO_x) emission. Furthermore, the application of such a dual-fuel operation can offer potential economic and efficiency advantages. Depending on the gaseous fuel used these goals can be achieved. In general, dual-fuel combustion of gaseous fuels and diesel decreases soot emissions compared with normal diesel combustion except for syngas. Furthermore, increasing load and/or gaseous fuel content leads to a further decrease in soot emissions. Both the application natural gas and liquefied petroleum gas as gaseous fuel offer the possibility to diminish nitrogen oxide emissions probably due to homogenous mixture compositions and/or decreased mixture temperatures. However, the using hydrogen or syngas in dual-fuel combustion tends to increase nitrogen oxide emissions; this might be due to the higher flame temperatures and combustion rates of these gasses. Furthermore, the emissions of unburned hydrocarbons and carbon monoxides tend to increase for all evaluated gaseous fuels with dual fuel combustion mainly due to incomplete combustion of mixture trapped in crevices. Efficiencies of the different gaseous fuels are in the same order of magnitude. Some seem to lead to slight efficiency improvements (hydrogen and LPG) while others result in a slight decrease (natural gas and syngas). However, the significant price difference of natural gas and LPG compared to diesel can offer a considerable economic advantage.

INTRODUCTION

In recent years the automotive industry has been forced to reduce harmful and pollutant emissions emitted by direct injected diesel engines. Currently for diesel fueled engines diesel particle filters (DPF), selective catalytic reduction catalysts (SCR-catalysts) and NO_x storage catalysts (NSC) are applied to reduce harmful emissions. The application of after treatment systems is a very effective method to reduce emissions; however, due to the usage of precious metals in these systems, this is a very expensive method to reduce harmful emissions. It would be preferable to develop strategies to reduce engine-out emissions, and thereby minimize the need for after treatment systems.

To accomplish this difficult task various solutions have been proposed. One of these proposed solutions is the use of gaseous fuels in addition to the use of liquid diesel. In this case the gaseous fuel is injected in the inlet manifold, and the diesel is injected directly in the cylinder. The dual-fuel concept will be further explained in chapter 2. The main goals for the use of a dual-fuel operation with diesel and gaseous fuels are the reduction of particulate matter (PM) and nitrogen oxides (NO_x) emission. Furthermore, the application of such a dual-fuel operation can offer potential economic and efficiency advantages.

Multiple gaseous fuels are suitable for the aforementioned dual-fuel operation. This study reviews the application of natural gas (NG), liquefied petroleum gas (LPG), synthesis gas (syngas), and hydrogen (H_2) together with conventional diesel. The gaseous fuels discussed are chosen because of their common availability, in the case of LPG and NG, and the possibility of acquiring these gasses by onboard reforming techniques. Depending on the gaseous fuel used, significant improvements are expected to be achieved. These improvements with respect to conventional diesel operation are discussed, and where possible, explained in chapter 3 and 4. In terms of engine-out emissions all the gaseous fuels are known to decrease the particulate matter emissions due to their higher degree of premixing. Furthermore, the influence of gaseous fuels on NOx emissions is discussed, and the effect of dual-fuel operation on the emissions of unburned hydrocarbons (HC) and carbon monoxide (CO) emissions will be discussed. Due to lower prices of for instance LPG and natural gas compared to diesel it is possible that economic advantages can be achieved.

"CONVENTIONAL" DUAL-FUEL CONCEPT

Currently two common internal combustion engines are available. That is compression ignition (CI) or diesel engines and spark ignition (SI) or gasoline engines. For the application of dual-fuel operations a combination of both combustion concepts is applied. To be precise the primary fuel (gaseous in this case) is injected in the intake manifold and the mixture of fuel and air is compressed during the compression stroke. Since the reviewed gaseous fuels are mainly gasoline-like fuels with a high octane number, they are resistant against auto-ignition, and therefore, not likely to ignite during the compressions stroke. At the end of the compression stroke, close to TDC, the pilot fuel (liquid diesel in this case) is injected which spontaneously ignites due to its high cetane number, which makes it prone to auto ignition. The ignited diesel fuel actually acts as an ignition source, and ignites the available mixture of gaseous fuel and air. Analysis of the dual-fuel combustion process divides the rate of heat release into three phases as is depicted in Fig. 1. First the premixed combustion of the direct injected diesel fuel and a minor part of the gaseous fuel entrained in the diesel spray. The second phase is characterized by the premixed combustion of the major part of the gaseous fuel and small amounts of the diesel. Finally, the third phase of the combustion represents the diffusion combustion of the rest of both fuels [1]. It seems trivial that the importance of phase one and two is characterized by the amount of diesel substitution by gaseous fuel. However, this is not the case. The peak of the ROHR during the first phase seems to be depended on the amount of pilot fuel that can be burned during this phase. Only when the amount of pilot fuel is decreased below this certain limit the importance of this phase decreases. The importance of the second phase on the other hand is determined by the amount of diesel substitution. The advantage of this concept is that it makes use of the difference in flammability of the used fuels. When leaving out the gaseous fuel the engine operates as a normal diesel engine. However, since the liquid diesel is necessary for ignition it is not possible to run exclusive on the gaseous fuel. All evaluated research on dual-fuel engines for this paper apply modified diesel engines as described above; except for the LPG-diesel operation. For this dual-fuel concept also direct injected blends of LPG and diesel are evaluated. When injecting a LPG-diesel blend directly into the combustion chamber the flash boiling of the LPG content in the fuel enhances the mixing of the fuel with the air. This can be beneficial for the emissions of soot and nitrogen oxides. Furthermore, there is the possibility of dual-fuel combustion in a PCCI (premixed charge compression ignition) combustion process. This is often called RCCI (reactivity controlled compression ignition) combustion since control of the combustion process is achieved by varying the reactivity of the mixture. That is, changing the ratio of fuels, where diesel is high reactive (prone to auto ignition) and the gaseous fuel is low reactive (resistant to auto ignition); e.g. natural gas and LPG. The RCCI concept is not discussed in this paper.

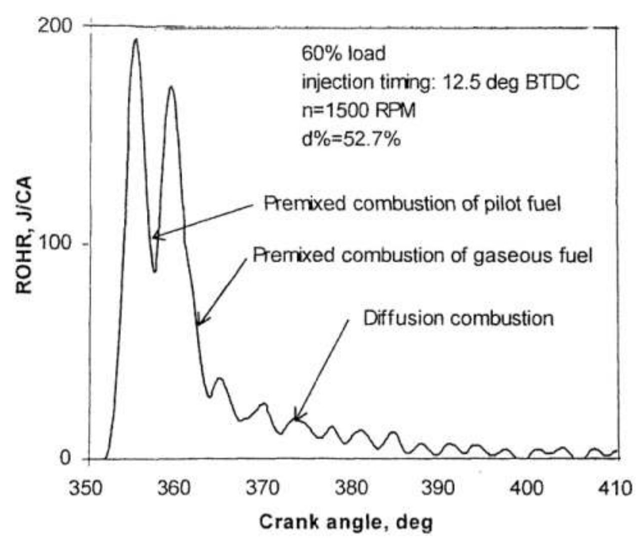

Figure 1. Rate of heat release for "conventional" dual-fuel combustion

EMISSIONS AND PERFORMANCE

The application of gaseous fuels, in combination with diesel, in a compression ignition engine is considered to be a good alternative for current automotive, maritime and stationary engines. It is said that such an application can provide environmental and economic advantages. Therefore, the effects of the application of diesel-gaseous fuel dual-fuel engines have been extensively investigated in numerous studies. These where conducted on different test engines with various types of gaseous fuels, and with various operating points. Therefore, the results of the different studies cannot be compared with each other due to the multiple different parameters and hardware differences. In these studies the influence on engine-out emissions, such as particulate matter, nitrogen oxides, carbon monoxide and unburned hydrocarbons, and performance are evaluated. The results are summarized and evaluated in this paper.

PARTICULATE MATTER

Particulate matter (PM), sometimes referred to as soot or smoke, emitted from compression ignition engines is mainly caused by an incomplete combustion of hydrocarbon fuels. The formation of PM is favored in the fuel-rich ($\phi \geq 2$) core of the diesel spray and by relatively low flame temperatures during diffusion combustion (between 1000 and 2800 K) [2].

Natural Gas

The research that has been done on the topic of dual-fuel diesel and natural gas operations shows a significant reduction in PM emissions. Since particle matter is mainly formed in the diesel rich areas the emitted particulate matter decreases when the natural gas ratio is increased [3,4]. Such an increased natural gas ratio results in a decreased proportion of diffusion combustion, and an increased homogeneous natural gas/air pre-mixture combustion [5]. Moreover, at high loads (60%-80%) and low natural gas additions, thus low air/natural gas ratio, slightly higher PM emissions occur as shown in Fig. 2. This might be due to an inferior charge temperature compared to conventional diesel operation, as stated by Papagianakkis [4]. Since advancing the amount of pilot diesel results in a better mixed diesel-air mixture due to the longer ignition delay (ID), lower PM emissions are realized with advanced diesel injection. This decrease is most significant with low natural gas/diesel ratios. At higher natural gas ratio's, advancing the diesel timing has a less significant influence on PM emissions [3]. The amount of injected diesel is a dominant parameter in de production of particulate matter. Hence, higher loads and an unchanged natural gas/diesel ratio results in higher PM emissions. This could be due to relatively big injected diesel droplets, of which the nucleus stays unburned. Moreover, the auto-ignition of diesel increases PM emissions, whereas the propagating flame front in a dual-fuel engine results in a more completes combustion, and therefore, a reduction of particulate matter [5]. Papagianakkis and Hountalas state that increasing the load of a conventional diesel operation results in increasing PM emissions, where in dual-fuel mode with natural gas and diesel the PM emissions do not follow the same trend as shown in Fig. 3 where soot emissions are near zero for NG-diesel dual-fuel combustion. It should be mentioned that in these tests when increasing the load, the amount of injected diesel is not significantly increased. This implies that an increasing load leads to an increased natural gas/diesel ratio. Hence increasing amounts and ratios of natural gas and increasing charge temperatures propagates the oxidation of soot. Furthermore, the main component of natural gas is methane (CH_4). Methane is a lower member in the paraffin family, and the therefore, has a small tendency to produce particulate matter [6].

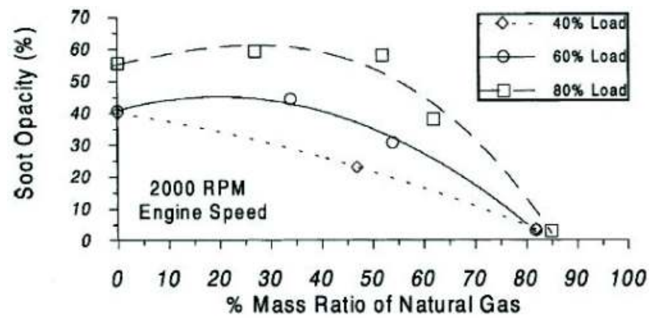

Figure 2. Soot opacity for different loads vs. different natural gas mass ratios (natural gas-diesel)[4]

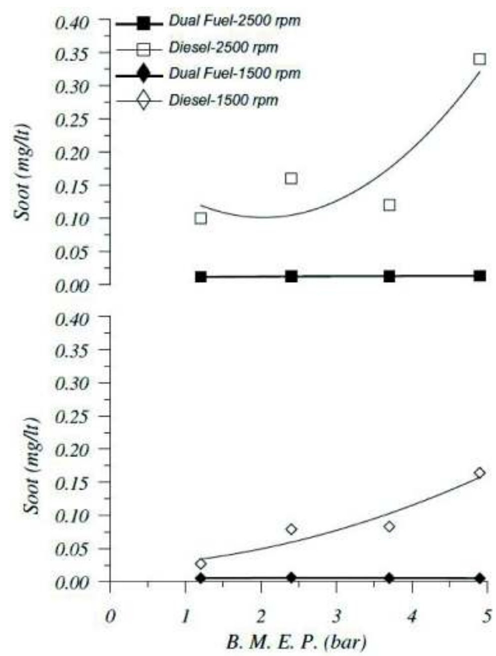

Figure 3. Soot emissions vs. different loads for two engine speeds (natural gas-diesel) [6]

Liquefied Petroleum Gas

The research done on the application of a dual fuel engine, fueled with a direct injected LPG-diesel blend, shows decreasing smoke emission with an increased LPG-fraction, as shown in Fig. 4 and 5. In Fig. 4 L10 and L30 represent 10% respectively 30% LPG content in the fuel blend, and in Fig. 5 “z” represents the LPG content of the fuel. The reduction of PM emissions, compared to conventional diesel operation, is most significant at high loads (≥ 70%). Due to the lower boiling temperature of LPG it evaporates more

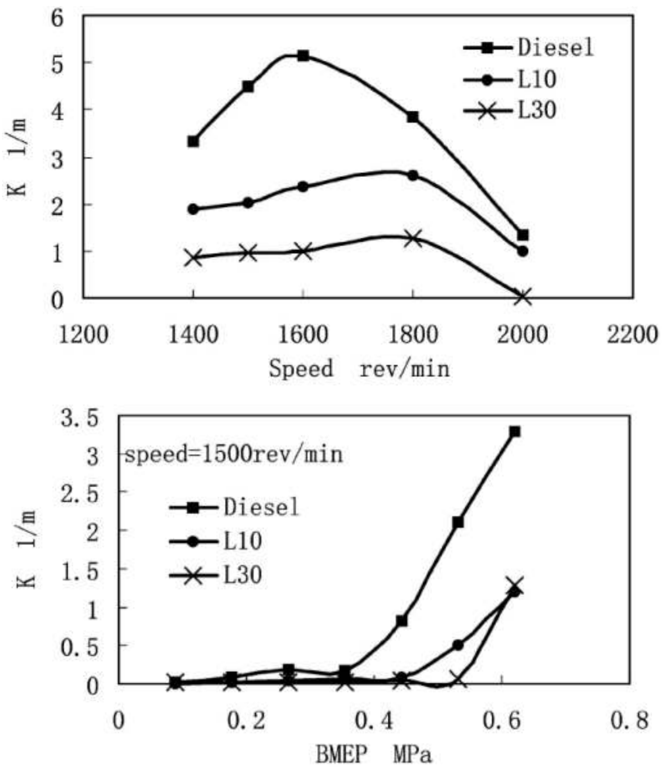

Figure 4. Smoke emissions (expressed in light absorption coefficient or K value) of diesel and 2 different LPG-diesel blends vs. BMEP and engine speed (DI LPG-diesel blend) [7]

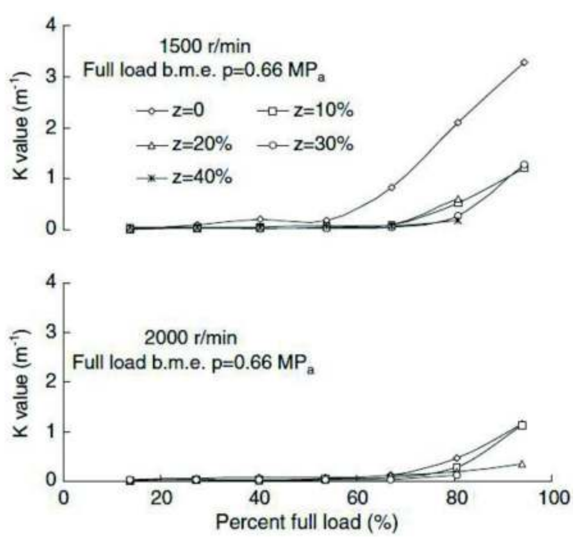

Figure 5. Smoke emissions (expressed in light absorption coefficient or K value) for different fuel blends and engine speed vs. load (DI LPG-diesel blend) [8]

easily. The LPG content in the injected blend of LPG and diesel will instantly vaporize as results of the pressure drop, and thereby, enhances the gas perturbation of the spray. This process is called flash boiling, and results in smaller droplets of blended fuel in the combustion chamber compared to a normal diesel injection. These smaller droplets result in better mixing and less fuel rich areas, thus lower PM emissions [7, 8, 9]. Research on butane, which is one of the components of LPG, blended with diesel shows similar results. With increasing butane percentage PM emissions also decrease [10].

Research done by Jian et al. [11] on LPG-diesel dual-fuel, with port fuel injected LPG, shows that such an operation is

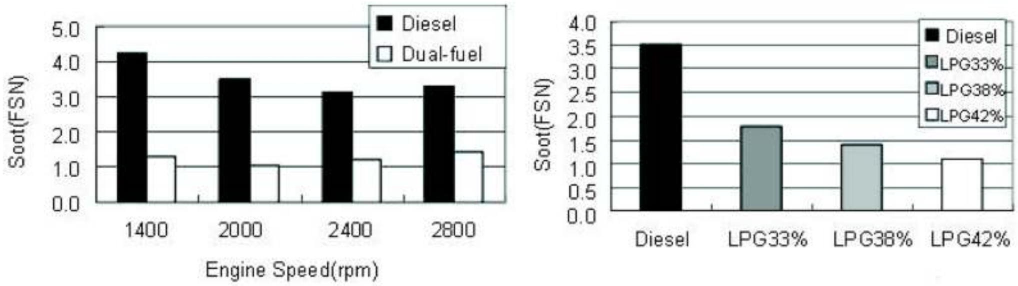

Figure 6. Soot emissions (filter smoke number) vs. different LPG mass ratios and engine speed at full load. Furthermore, in the left graph the LPG mass percentage is 42% and in the right graph the engine speed is 2000 RPM. (PFI LPG-diesel) [11]

an effective manner to reduce soot emissions. Experiments performed at full load and various engine speeds resulted in a reduction of soot emissions of 50% up to 70% in dual-fuel mode. These results are represented in fig. 6. When comparing the soot emissions of dual-fuel combustion with different LPG/diesel ratios and conventional diesel combustion decreasing soot emissions are observed when increasing the LPG content. In the particular case where 42% LPG is added a reduction of almost 70% is realized. Furthermore, it is mentioned that further increasing the LPG content does not significantly improve soot emissions.

Synthesis Gas

Unfortunately less research has been done on the effects of syngas-diesel dual-fuel operations on emissions compared to dual-fuel operations with other gaseous fuels. Even less research has investigated the influence of syngas on particulate matter emissions. Since syngas is a combination of hydrogen and carbon monoxide only the carbon monoxide can directly contribute to the formation of soot emissions. However, when the amount of added syngas transcends a certain it prevents sufficient amounts of oxygen to reach the cylinder. This is the case at high diesel substitute rates and at high loads. Insufficient amounts of oxygen result in an incomplete combustion with increased soot emissions as a consequence, as show in Fig. 7 [12]. However, it should be noted that the syngas used by Nipattummakul et al. consists of only 16.3% CO, 9% H_2 and 1.1% CH_4 complemented with 10.7% CO_2 and 61.9% N_2 and 0.9% O_2.

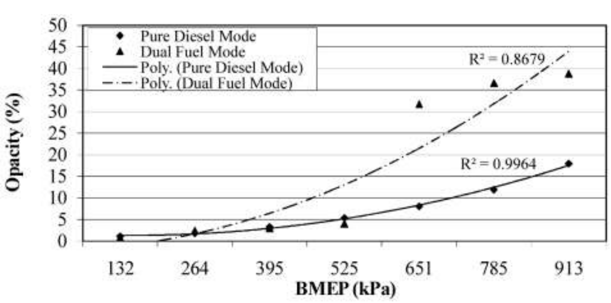

Figure 7. Smoke opacity vs. BMEP (syngas-diesel) [12]

Hydrogen

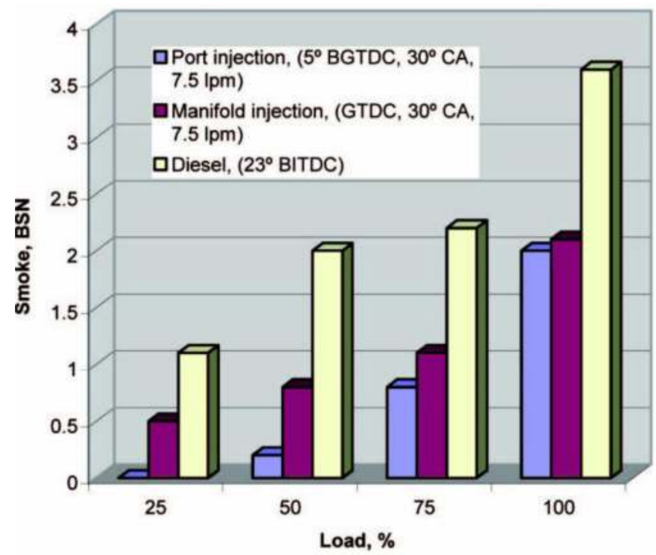

Figure 8. Smoke emissions (Bosch smoke number) vs. load for diesel only, port injection dual-fuel and manifold injection dual-fuel (hydrogen-diesel) [13]

Since there is no carbon present in hydrogen (H_2), hydrogen does not contribute to the formation of soot. Therefore, in dual-fuel mode operation on hydrogen and diesel the emission of soot particles can significantly be reduced. In general it would be logical to assume that when the hydrogen flow is increased, the soot emissions decrease. However, Saravan and Nagarajan [13] found with their experiments the maximum (optimum) mass flow of hydrogen injected is 7.5[l/min]. Above this flow rate the emitted soot increases due to an instable combustion. Furthermore, dual-fuel combustion of hydrogen and diesel reduces soot emission for all loads. More specifically, reductions of soot emissions from 45% up to 100% are realized for 100%, respectively 25% of the maximum rated power (3.7 kW) [13].These results are shown in Fig. 8. Other investigations show that, for all loads examined (40 Nm up to 120 Nm), particulate matter reductions of 10% up to 50% are observed with hydrogen energy input ratios up to 40%. These reductions can not only be explained by the reduction of carbon containing fuel.

Therefore, the addition of hydrogen clearly promotes the reduction of particulate emissions some other way [14]. The higher adiabatic flame temperature of hydrogen can be an explanation. This higher flame temperature is likely to promote the oxidation of particles in the cylinder.

NITROGEN OXIDES

The formation of nitrogen oxides (NO_X) is propagated by high charge temperatures and excess oxygen concentrations. Therefore, the nitrogen oxides emissions are highest in zones close to stoichiometric, slightly air-rich. Moreover, fuels with higher adiabatic flame temperatures compared to diesel tend to produce higher NO_X emissions.

Natural Gas

In general, for a natural gas/diesel dual-fuel engine, nitrogen oxide emissions should decrease with increasing natural gas ratios. With natural gas injected in the inlet manifold the charge temperature is lower due to the higher specific heat of the intake mixture compared to conventional diesel. As a result the combustion pressure is lower, and consequently, the combustion temperature is lower. Furthermore, the addition of natural gas in the intake manifold results in a less intense premixed combustion, lower combustion rates and a reduction of oxygen concentration in the intake mixture. This hypothesis is confirmed by Papagianakkis and Maij et al. who observed decreasing nitrogen oxides emissions with increasing natural gas/diesel ratios for various loads [4, 5, 6]. For high loads the emission of nitrogen oxides is significantly lower, where for low and part load conditions the reductions are less significant, as shown in Fig. 9 and 10.

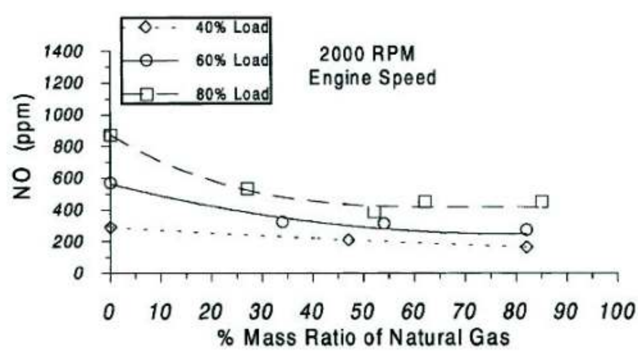

Figure 9. NO emissions (ppm) vs. different CNG mass ratios for different loads (natural gas-diesel) [4]

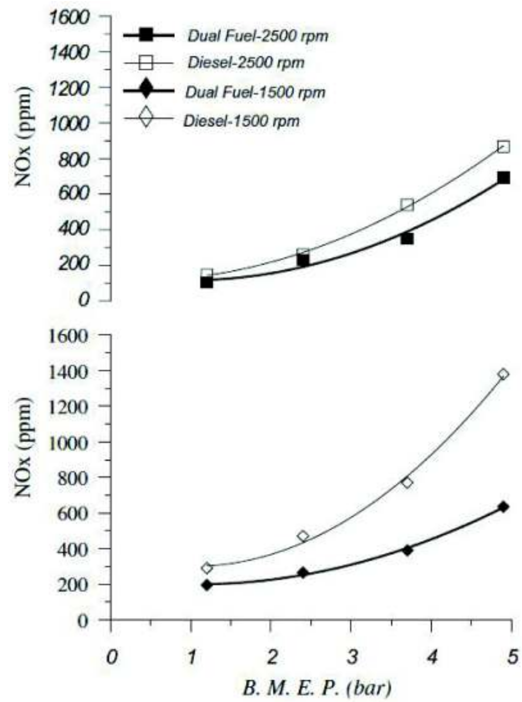

Figure 10. NO_X emissions (ppm) vs. different loads for 1500 and 2500 RPM (natural gas-diesel) [6]

Experiments performed on a turbo charged engine in low and medium engine speed mode show increasing nitrogen oxides emissions with increasing natural gas/diesel ratios. In these modes higher combustion pressures and temperatures are observed compared to normal diesel operation. However, in the rated power mode the combustion pressures and temperatures are lower, and the heat release rate is higher with dual-fuel combustion compared to conventional diesel combustion. These conditions make NO_X emissions decrease. Furthermore in Fig. 11 it can be noticed that advancing the pilot diesel has a negative effect on the NO_X emissions [3].

Liquefied Petroleum Gas

As with natural gas, running in dual-fuel mode on LPG and diesel tends to decrease nitrogen oxides emissions. Multiple reasons are considered to cause this phenomenon. Just like natural gas the injection of LPG in the intake manifold (or port fuel injection) increases the specific heat of the intake mixture, and thereby, decreases the cylinder temperature. In the case of a direct injected LPG/diesel blend the mixture has a significantly higher heat of evaporation, which also decreases the in-cylinder temperature. Furthermore, the ignition delay of a dual-fuel LPG/diesel is higher, which consequently leads to a retarded combustion and decreased charge temperature compared to conventional diesel operation when the injection timing is kept constant. As stated before the formation of nitrogen oxides is favored by high charge temperatures, accordingly less nitrogen oxide

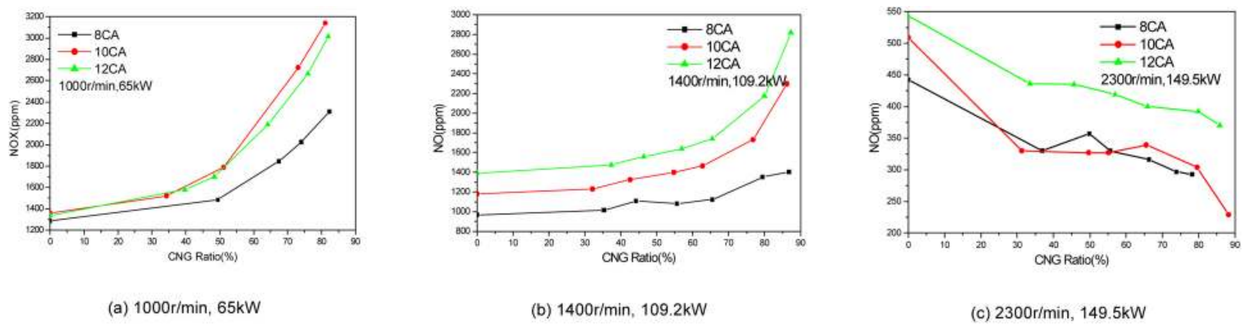

Figure 11. NO_x emissions (ppm) vs. varying CNG mass ratios for different injection timings (−8, −10 and −12 deg aTDC) and different operating points (65 kW @ 1000 RPM, 109.2 kW @ 1400 RPM and 149.5 kW @ 2300 RPM) (natural gas-diesel) [3]

emissions are formed at these lower temperatures since less oxygen reacts with nitrogen to nitrogen oxides [7, 8, 15].

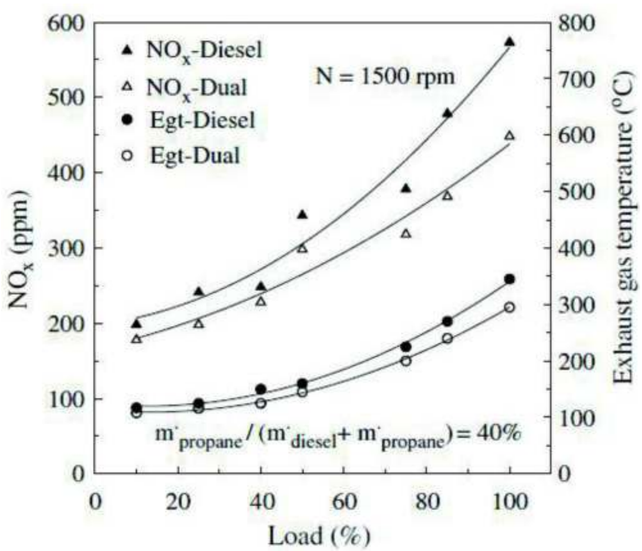

Figure 12. NO_x emissions (ppm) vs. loads (PFI LPG-diesel) [15]

As show in Fig. 12 the emission of nitrogen oxides can be reduced with approximately 20% over a load range of 25% up to 100% with the addition of 40% port fuel injected propane, which is a key component of LPG together with butane. Furthermore, in dual-fuel mode with 40% LPG, a butane and propane mixture, nitrogen oxides can further be decreased by increasing the butane percentage of the LPG as shown in Fig. 13. Compared to a 100% propane LPG blend the nitrogen oxide emissions can be decreased by 33% (high load) up to 65% (low load) for a LPG blend which consists of 30% propane and 70% butane. An increase in butane percentage results in an increased ignition delay, which consequently decreases the charge temperature [15].

Tested fuel	Propane	Butane
Fuel #1	100	–
Fuel #2	90	10
Fuel #3	70	30
Fuel #4	50	50
Fuel #5	30	70

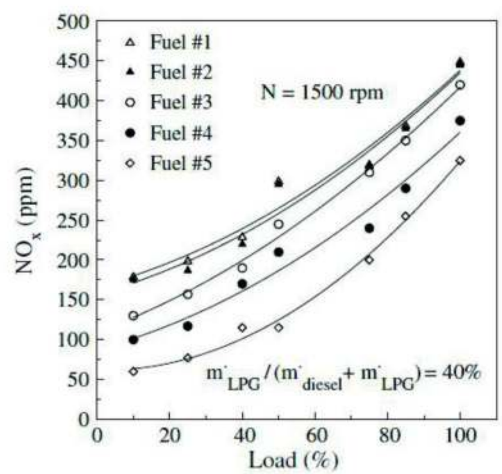

Figure 13. NO_x emissions (ppm) vs. loads for different LPG compositions (propane/butane ratios) (PFI LPG-diesel) [15]

The research of Qi et al. with LPG/diesel-blends, LPG/diesel ratios varying from 0% up to 40%, has shown similar results. For various loads and engine speeds nitrogen oxide reductions of 50% to 70% are reached. Moreover, with increasing LPG/diesel ratios the NO_x emissions decrease [8].

Synthesis Gas

Since synthesis gas is a gas mixture of hydrogen and carbon monoxide, it is different compared to other gaseous fuels which are commonly hydrocarbons (C_xH_y). A dual-fuel compression ignition engine fueled with carbon monoxide and hydrogen has a negative effect on the emissions of nitrogen oxides. Bika et al. [16] found that at low load (2 bar IMEP) the syngas composition, the H_2/CO ratio, has no significant influence on the emitted nitrogen oxides, as shown in Fig. 14. Increasing the synthesis gas/diesel ratio has a decrease of nitrogen oxide emissions as result. However, the reduction of nitrogen oxide emissions is not significant. Fig. 15 displays an increase of nitrogen oxide emissions with increasing diesel substitution of synthesis gas at 4 bar IMEP. A maximum increase of 27% NO_x emissions is observed with a 40% percentage of carbon monoxide added. Furthermore, the same trend is observed with the addition of 40% hydrogen, nitrogen oxide emissions increased with 16%.

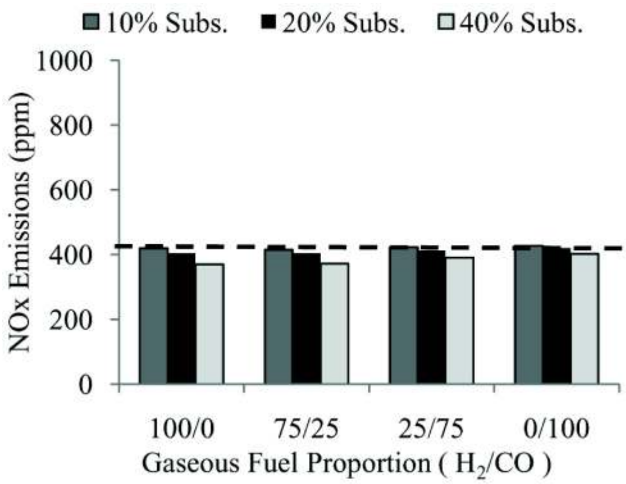

Figure 14. NO_x emissions (ppm) vs. syngas composition (hydrogen/CO ratios) and diesel substitution rates at 2 bar IMEP (syngas-diesel) [16]

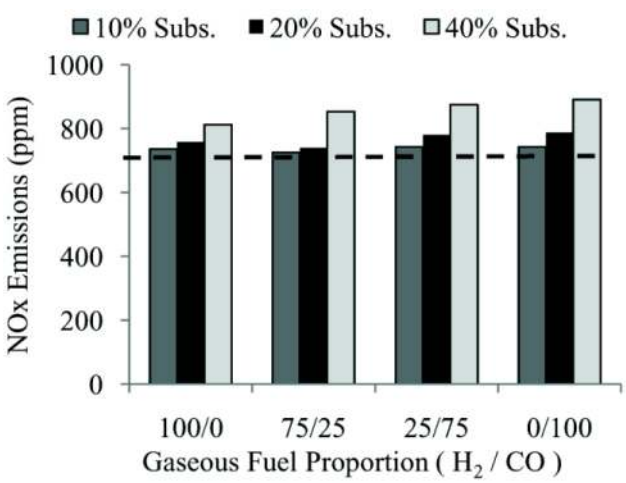

Figure 15. NO_x emissions (ppm) vs. syngas composition (hydrogen/CO ratios) and diesel substitution rates at 4 bar IMEP (syngas-diesel) [16]

This increase in nitrogen oxide emissions, with respect to the conventional diesel operation, could indicate an increased flame temperature caused by the higher adiabatic flame temperatures of carbon monoxide and hydrogen [17]. Dominant in the increase of nitrogen oxides (NO_x) is the increase in nitrogen dioxide (NO_2). Normally nitrogen dioxide plays only a minor secondary role in the NO_x distribution. Furthermore, the composition of the synthesis gas, the H_2/CO ratio, does not seem to influence the NO_2/NO_x ratio at the 4 bar IMEP. The main formation mechanisms of NO_2 in laminar flames are described by Hargreaves et al. [18]. These mechanisms suggest that an increase in HO_2 radicals promotes the conversion from nitrogen monoxide (NO) to nitrogen dioxide (NO_2). The main mechanism for production of the HO_2 radical from a H atom with oxygen occurs at lower temperatures. However, at higher temperatures oxygen and the H atom do not react to HO_2 radicals. Therefore, an increase in H atoms at lower temperatures increases the amount HO_2 radicals, and consequently promotes the conversion of NO to NO_2. Since there is no significant difference between the NO_2/NO_x ratio observed, whether hydrogen or carbon monoxide is used as gaseous fuel, the production of H atoms must also be independent of the used fuel. The fastest en predominant path for the formation of H atoms is the oxidation with OH radicals, which are present from the diesel reactions. Therefore, both carbon monoxide and hydrogen contribute equally to the conversion to NO_2.

Hydrogen

As stated in the synthesis gas section, nitrogen oxide emissions tend to increase when running in dual-fuel mode running on hydrogen and diesel [16]. The findings of Bika et al., as shown in Fig. 14 and 15, are supported by several other studies. The increase in nitrogen oxide emissions is probably due to the higher combustion temperatures compared to conventional diesel operation. The high combustion temperatures can physically be explained by the high flame temperature and combustion rates of hydrogen. These result in high cylinder pressures and consequently in increased temperatures. This is especially the case at high loads [19]. Furthermore, the combustion of hydrogen is possible at a broad range of air fuel ratios. Therefore, the combustion of an air-rich air-fuel mixture is possible; combined with the high temperatures this creates an ideal environment for the formation of NO_x.

CARBON MONOXIDE AND UNBURNED HYDROCARBONS

The emissions of carbon monoxides by internal combustion engines are first and foremost controlled by the air/fuel ratio of the mixture in the combustion chamber and mixture temperature, as stated by Heywood [2]. Carbon monoxide emissions are promoted by a fuel-rich mixture, and they tend to increase constantly with an increasing equivalence ratio. Diesel, or compression ignition, engines operate on fuel-lean mixtures, and therefore, carbon monoxide emissions are commonly low enough to be insignificant. Spark ignition engines, however, operate close to stoichiometric or fuel-rich depending on the operating point. Therefore, SI engines are more prone to carbon monoxide formation [2].

Unburned hydrocarbon emissions are a result of incomplete combustion of the hydrocarbon fuel. In diesel engines there are two major sources of hydrocarbon emissions: (1) During the combustion delay period the fuel-air mixture is too lean, and thereby, outside the flammability boundaries of the fuel. (2) Late in the combustion process fuel leaves the injector with a low velocity. This results in under mixing of the fuel, consequently resulting in unburned hydrocarbons. In spark ignition engines the origin of hydrocarbon emissions is primarily due to fuel-air mixture trapped in crevices during combustion (approximately 80% of the emitted unburned hydrocarbons). The largest crevices are mainly located between cylinder walls, piston and piston rings. During the compression stroke unburned mixture is forced into crevices, and cooled due to heat transfer from the cylinder walls. During combustion more mixture is forced into the crevices. Then the flame propagates into the crevices region, and partially burns the mixture, or the flame quenches at the crevice entry region. Furthermore, absorption of hydrocarbons by the oil layers, incomplete combustion and flame quenching at the cylinder walls play a secondary role in the emission of unburned hydrocarbons [2].

Natural Gas

The dual-fuel concept is actually a combination of the spark ignition (SI) and compression ignition (CI) combustion processes. In general the emissions of carbon monoxide and unburned hydrocarbons under dual-fuel operation with diesel and natural gas are significantly higher compared to conventional diesel (CI) operation. This is shown in Fig. 16 and 16 [4, 5, 6, 20, 21].

The emissions of carbon monoxide are a function of the air-fuel ratio and the charge temperature, which control the fuel's oxidation and decomposition [2]. At low speed (1500 RPM) carbon monoxide emissions tend to decrease with increasing load due to improved utilization of the gaseous fuel during the second phase of combustion. However, at higher engine speed (2500 RPM) there is no significant difference observed when increasing the load since there is less time available for combustion [6]. Furthermore, at part load an increase in natural gas amount results in an increase in CO emissions caused by the lower combustion rate. This has a lower charge temperature as result which leads to lower oxidation rates of CO. However, at high loads, increasing the amount of natural gas results in increasing CO emissions up to a certain equilibrium after which CO emissions start to decrease again [6]. Probably this equilibrium is due to the low temperatures during too low equivalence ratio operation, and a lack of oxygen during too high equivalence ratio operation [21].

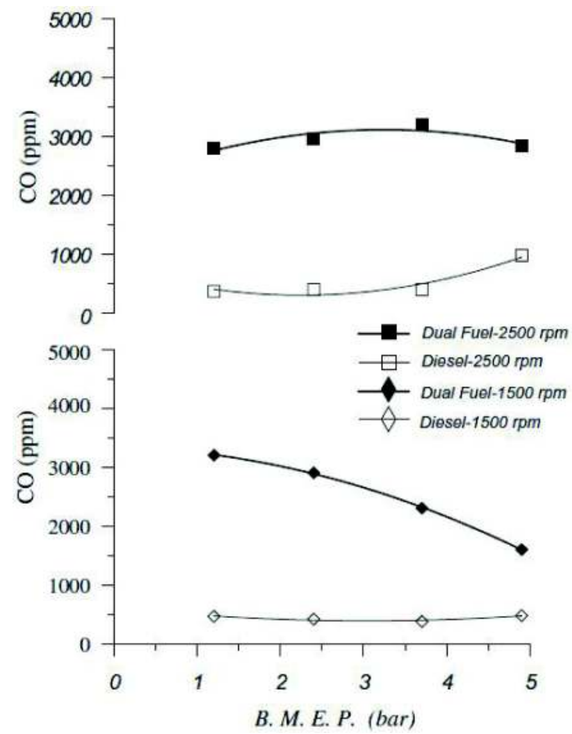

Figure 16. CO emissions (ppm) vs. load at 1500 and 2500 RPM (natural gas-diesel) [6]

The emissions of unburned hydrocarbons are significantly higher for natural gas-diesel combustion compared to conventional diesel combustion. This is due to the crevices mechanism, and furthermore, in dual-fuel operation the charge temperature is lower compared to conventional diesel operation. This results in lower combustion rates, and consequently, small quantities of fuel escape the combustion process. Furthermore, methane, the main component of natural gas, has lower reaction rates compared to other hydrocarbon fuels, and in lean natural gas-air mixtures the flame speed may be too low for combustion [5, 21].When increasing the engine load a sharp decrease of unburned hydrocarbons is observed due to an increase in combustion temperature resulting in a more efficient oxidation. However, unburned hydrocarbon emissions are still significantly higher compared to conventional diesel combustion. Engine speed does not seem to have a significant influence on the hydrocarbon emissions [6]. Furthermore, at low loads increasing the natural gas amount leads to increased HC emissions. At high loads the same results are observed up to a certain level of natural gas content. From this point on it starts to decrease again due to higher temperatures [4].

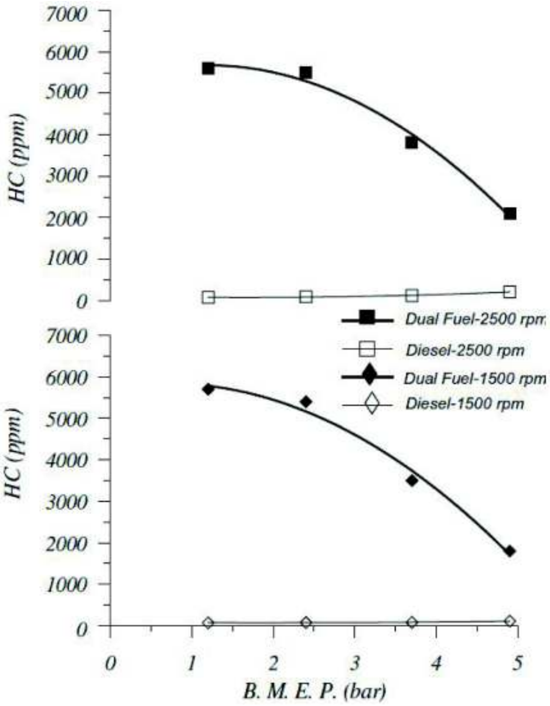

Figure 17. HC emissions (ppm) vs. load at 1500 and 2500 RPM (natural gas-diesel) [6]

Liquefied Petroleum Gas

The application of liquefied petroleum gas in a dual-fuel diesel engine shows similar results compared to a natural gas application. Hence, carbon monoxide and unburned hydrocarbon emissions tend to increase with respect to conventional diesel operation [11, 15, 22]. In the case of carbon monoxide emissions this is probably caused by the lower charge temperature compared to normal diesel operation. This lower charge temperature is a result of the higher specific heat of the lean gas-air mixture and the lack of oxidants. This results in a incomplete combustion of the LPG-air mixture which promotes the formation of carbon monoxide emissions. Furthermore, CO emissions decrease with an increasing load since the higher charge temperature and increasing LPG-air charge promotes a more complete combustion of the mixture [15]. Moreover, increasing the LPG content leads to an increase in CO emissions. Saleh found that the composition of the LPG seems to have a significant influence on CO emissions. Furthermore, it appears that increasing the butane content of the LPG has a negative effect on the emissions of CO. This is expected to be due to the higher C/H ratio of the fuel, the prolonged ignition delay, the lower adiabatic flame temperature and lower flame speed. Carbon monoxide emissions versus load and LPG composition are shown in Figures 18 and 19. The fuel composition of the different fuels tested is given in Fig. 13 [15].

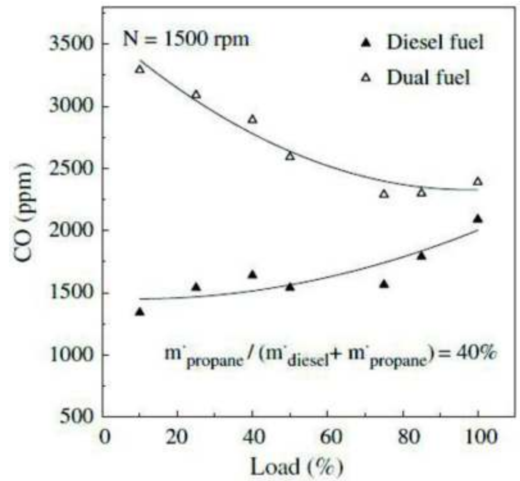

Figure 18. CO emissions (ppm) vs. load (PFI propane-diesel) [15]

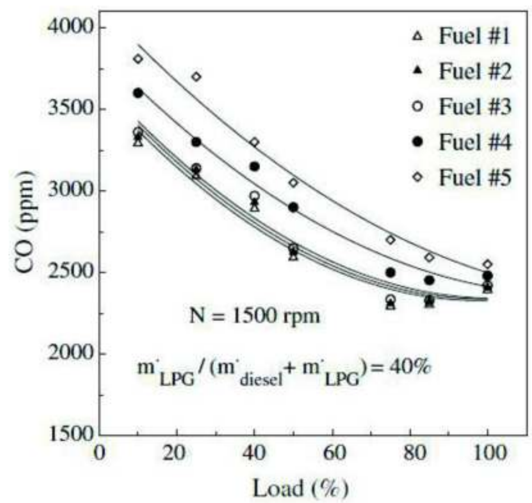

Figure 19. CO emissions (ppm) vs. load for different LPG compositions (PFI LPG-diesel) [15]

The carbon monoxide emissions of conventional dual-fuel operation, with port injected gaseous fuel, differ significantly from dual-fuel operation where a LPG-diesel blend is direct injected. This is shown in Fig. 20 where blends containing 10% LPG (L10) and 30% LPG (L30) are compared with diesel only. At low load a slight increase in CO emissions is observed, which further increases when the LPG amount is raised due to the low charge temperature. At high load, however, the emissions of carbon monoxide decrease with an increase of LPG content, and even decrease significantly compared to the conventional diesel operation levels. The flash boiling of the LPG in the blend the fuel mixtures results in better mixing with the air, and furthermore, high loads results in higher temperatures. Thereby, a more complete combustion is achieved. Engine speed does not seem to have a significant influence on the formation of CO emissions [7, 8].

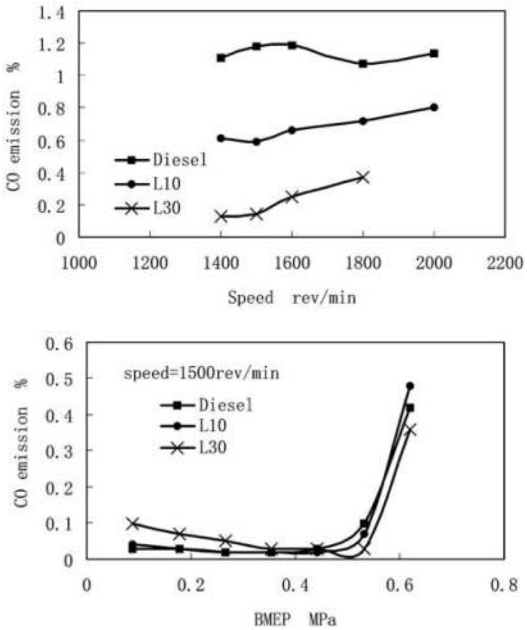

Figure 20. CO emissions (ppm) vs. loads and engine speed for different LPG/diesel blends and diesel only (DI LPG-diesel blend) [7]

In Fig. 21 hydrocarbon emissions are depicted for different loads with two different LPG/diesel ratios. Compared to conventional diesel operation hydrocarbon emissions tend to increase when operating in dual-fuel mode on LPG, both PFI and DI, and diesel [7, 8, 11, 15, 22]. Especially running on high LPG/diesel ratios and low loads results in increased emissions of unburned hydrocarbons, due to the lower charge temperature and the crevices mechanisms. Whereas direct injecting a blend of LPG and diesel has a positive effect on CO emissions, HC emissions do not show such an effect. The improved mixing due to flash boiling makes that slightly more fuel gets trapped in the crevices, and thereby, raises hydrocarbon emissions. Furthermore, increasing the LPG/ diesel ratio will result in higher HC emissions. However, at high loads the difference becomes less significant. This is probably due to the higher temperatures which lead to completer combustion of the air-fuel mixture.

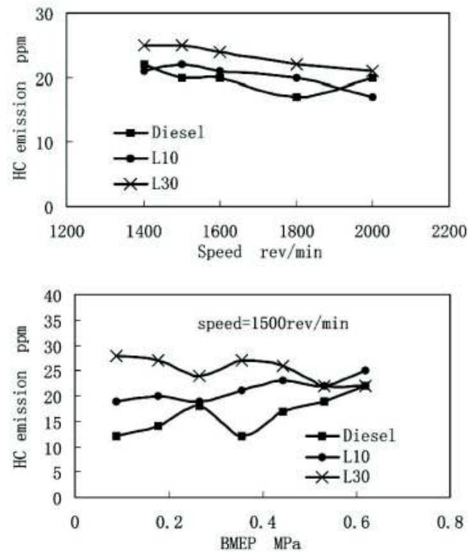

Figure 21. HC emissions (ppm) vs. loads and engine speed for different LPG/diesel blends and diesel only (DI LPG-diesel blend) [7]

Synthesis Gas

In general the emissions of carbon monoxide tend to increase under dual-fuel operation with synthesis gas and diesel compared to conventional diesel operation [16, 23]. This is probably due to the lower in-cylinder temperature caused by the lower peak cylinder pressure in dual-fuel operation this results in unburned fuel. Since synthesis gas is mixture with as main components carbon monoxide and hydrogen, the emissions of carbon monoxide and hydrogen are directly influenced by the composition of the syngas. Research done by Bika et al., shows that increasing the CO/H_2 ratio of the syngas has an increase in carbon monoxide emissions as result. Furthermore, the emissions of carbon monoxide and hydrogen increase significantly as the substituted diesel percentage is raised. As shown by Bika et el., who investigated two loads, the relative CO emissions tend to decrease as the load is increased, as shown in Fig. 22 and 23 [16]. This can be explained by the higher charge temperatures which promotes the oxidation of the unburned CO in the fuel-air mixture. However, Sahoo et al. state that at higher loads and diesel replacement rates a lack of available oxygen can lead to an increase of CO emissions due to incomplete combustion. The reduced cylinder temperatures and the decreased available oxygen in dual-fuel operation may also cause increased unburned hydrocarbon emissions due to incomplete combustion of the injected diesel fuel, as shown in Fig. 24 [23].

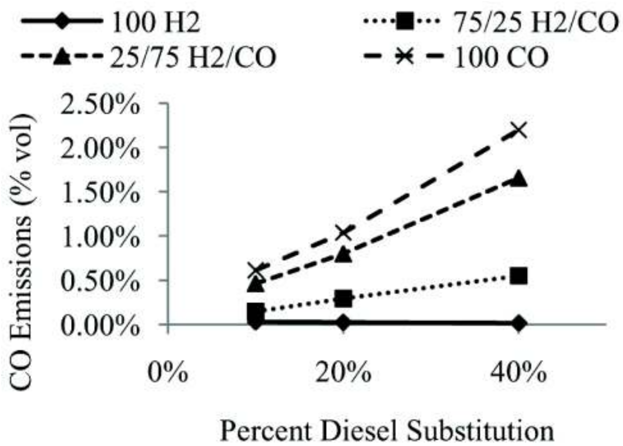

Figure 22. CO emissions vs. diesel substitution rate at 2 bar IMEP for different syngas compositions (syngas-diesel) [16]

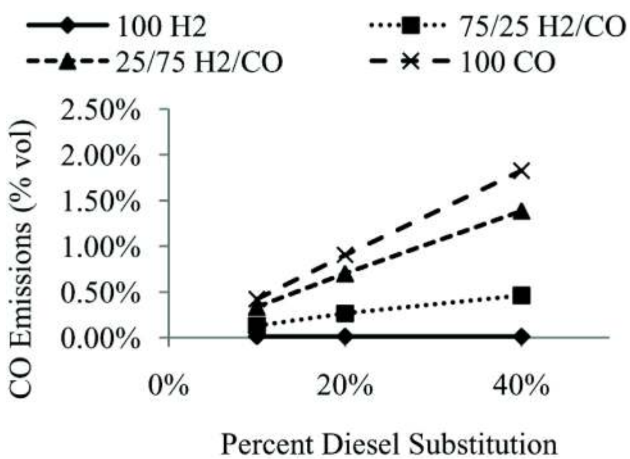

Figure 23. CO emissions vs. diesel substitution rate at 4 bar IMEP for different syngas compositions (syngas-diesel) [16]

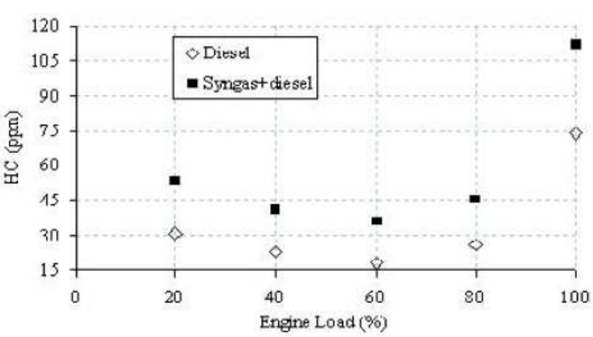

Figure 24. HC emissions (ppm) vs. load for diesel and dual-fuel (syngas-diesel) [23]

Hydrogen

In Fig. 25 and 26 CO respectively HC emissions versus loads are displayed. In general the emissions of carbon monoxides and unburned hydrocarbons are reduced in hydrogen-diesel dual-fuel operation compared to conventional diesel operation [16, 19, 24, 25, 26]. However, it should be noted that an increase in hydrogen emissions is likely to occur due to unburned gaseous fuel. Hydrogen is a non-carbon-based fuel, and thereby, it does not contribute to the emissions of carbon monoxide and hydrocarbons. Hence, the hydrocarbons and carbon monoxide emissions are a result of incomplete combustion of the diesel. Furthermore, the addition of hydrogen reduces the amount of diesel (carbon-based fuel) injected which results in a operation that is less prone to CO and HC formation [19]. Moreover, hydrogen has a higher adiabatic flame velocity compared to diesel, and it has the ability to combust in very fuel-lean environments [13]. However, it is also mentioned that the injection of hydrogen into in the inlet manifold/port may cause a lack of oxygen due to the replacement of air by hydrogen. This can result in a reduction of oxygen available for the diesel to combust with, and thereby, an incomplete combustion which increases the emission of unburned hydrocarbons [13].

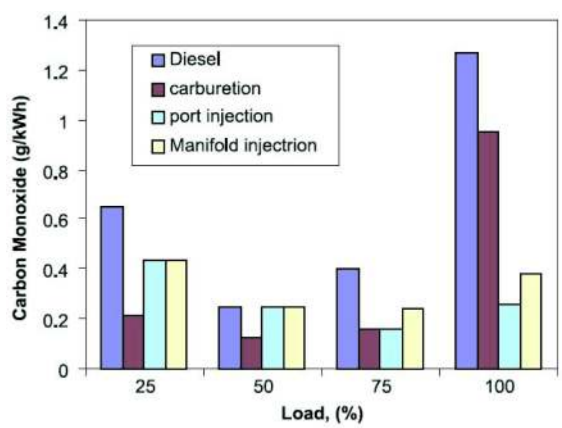

Figure 25. CO emissions (g/kWh) vs. load for diesel and four different dual-fuel methods (carbureted, port injected and manifold injected) (hydrogen-diesel) [19]

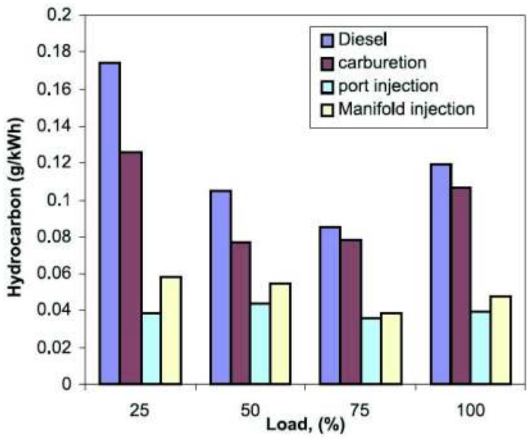

Figure 26. HC emissions (g/kWh) vs. load for diesel and four different dual-fuel methods (carbureted, port injected and manifold injected) (hydrogen-diesel) [19]

FUEL CONSUMPTION AND/OR EFFICIENCY

This part of the paper discusses the influence of a dual-fuel operation on efficiency and/or fuel consumption compared to a conventional diesel operation. As discussed earlier unburned hydrocarbon and carbon monoxide emissions tend to increase during dual-fuel combustion compared to normal diesel combustion. This directly implies a poorer combustion efficiency of the dual-fuel operation which results in an increased fuel consumption. Furthermore, it should be noted that port fuel injection of a gaseous fuel will significantly reduce the volumetric efficiency due to the fuel vapor in the intake mixture. The presence of fuel in the intake mixture reduces the amount of fresh air, and thereby oxygen, that can be trapped in the combustion chamber. Although this does not influence the engine efficiency it does decrease the maximum rated power of a dual-fuel engine compared to a normal diesel engine.

Natural Gas

The usage of port fuel injected natural gas and direct injected diesel generally results in a significantly increased fuel consumption compared to conventional diesel operation as shown in Fig. 27. In dual-fuel mode the specific fuel consumption seems to increase with natural gas content. Papagianakkis et al. and Maji et al. assumed that this is most likely due to the low lower charge temperature and lower combustion rates especially at low loads [4, 5, 6, 20]. The reduced diesel injection results in a lower premixed combustion phase, whereas the diffusion combustion rates are increased. The diffusion controlled combustion occurs later in the expansion stroke, and therefore, does not improve the engine efficiency [20]. Furthermore, poor utilization of the gaseous fuel increases the fuel consumption. At higher loads the difference between dual fuel operation and normal diesel operation decreases. Due to the higher temperatures, the decreased ignition delay, and the shorter burn duration the gaseous fuel utilization is higher. This leads to fuel consumption comparable with that of normal diesel operation.

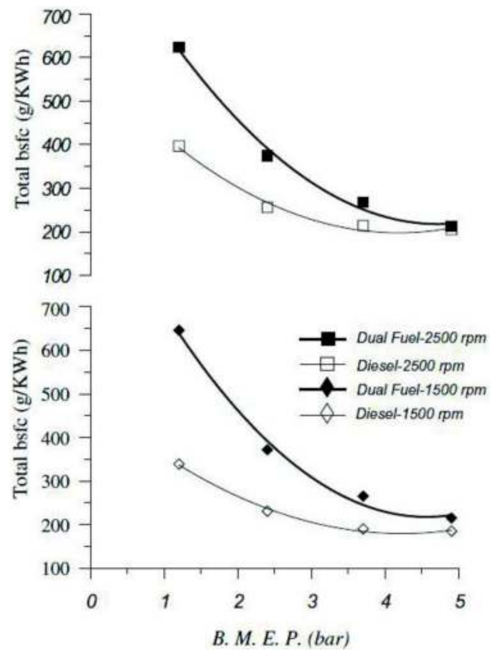

Figure 27. Brake specific fuel consumption (g/kWh) vs. load for 1500 and 2500 RPM (natural gas-diesel) [6]

Liquefied Petroleum Gas

Saleh, and many others, revealed that duel fuel combustion with LPG (PFI) and diesel does not have a significant influence on the efficiency of an engine [15]. In general the specific energy consumption at low loads is slightly increased compared with normal diesel operation. Furthermore, at low loads an increased diesel/LPG ratio results in higher engine efficiency. The increased diesel amount improves the ignition quality and leads to a completer combustion and a more rapid combustion of the gaseous fuel. At higher loads however, the specific energy consumption is decreased. Due to the higher temperatures and the more rapidly proceeding combustion an almost complete utilization of the gaseous fuel is realized. This results in a decreased specific energy consumption which is comparable or slightly improved with respect to conventional diesel operation [11, 22]. Figure 28 shows the effect of engine load on the specific energy consumption versus load for dual-fuel operation and normal diesel operation.

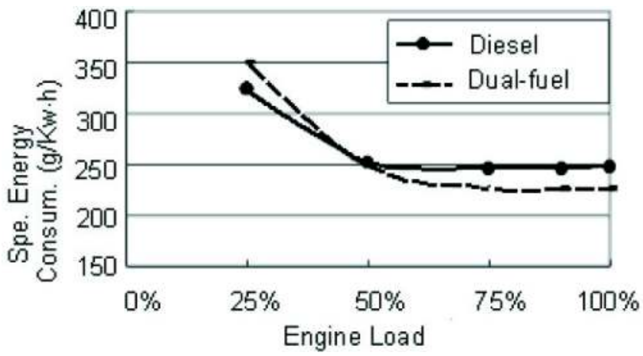

Figure 28. Specific energy consumption (g/kWh) vs. load (PFI LPG-diesel) [11]

Qi et al. found that comparable results are achieved with direct injected LPG-diesel blends. Where at low loads fuel consumption of dual fuel operation is increased compared with diesel operation. Due to a decreased cetane number of the blended fuel, which elongates the ignition delay, combustion is retarded into the expansion stroke. Consequently the fuel economy increases with LPG content of the fuel blend. At high loads the fuel economy is comparable with that of normal diesel operation [7, 8].

Synthesis Gas

The little research that is done on syngas-diesel dual fuel operation does not show promising results on efficiencies. In general the efficiency of a syngas-diesel dual-fuel engine is decreases with respect to conventional diesel operation [12, 16, 23]. This indicates poor combustion efficiency due to the CO content of the syngas [23]. This poor combustion efficiency can be originated by either a too lean mixture or a too rich mixture. When compensating the efficiencies for the unburned fractions of carbon monoxide and hydrogen the efficiencies are comparable with that of normal diesel operation [16]. Figure 29 shows the efficiency of syngas-diesel operation compared with a normal diesel operation. In this case the syngas consists of 50 vol.% hydrogen and 50 vol.% carbon monoxide. Furthermore, the composition of the syngas has a significant influence on its efficiency. Considering a syngas composed by carbon monoxide and hydrogen increasing the hydrogen fraction is thought to have a positive influence on efficiency. Moreover, contamination of the syngas with nitrogen and carbon dioxide will most likely negatively affect the engines efficiency.

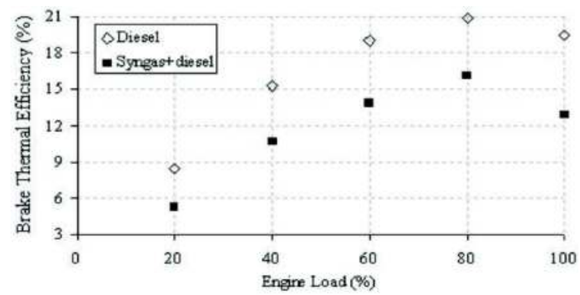

Figure 29. Brake thermal efficiency vs. load (syngas-diesel) [23]

Hydrogen

In general the efficiency of a dual-fuel engine tends to increase while running on hydrogen and diesel as shown in Fig. 30. This is probably due to the rapid combustion of the hydrogen and its uniform mixture. The rapid combustion of the hydrogen is a product of the high flame velocities [26]. Therefore, increased combustion rates are observed compared with the normal diesel operation, which is beneficial for the efficiency of the engine [13, 19, 27]. However, the research carried out by Bika et al. shows reduced efficiencies in dual-fuel mode. This is most likely due to the extreme lean hydrogen/air mixture, and thereby, no proper flame propagation is achieved. The lack of flame propagation results in unburned hydrogen that does not contribute to the produced power. When compensating for the unburned hydrogen the efficiencies are comparable with that of the normal diesel operation or even slightly improved at higher loads.

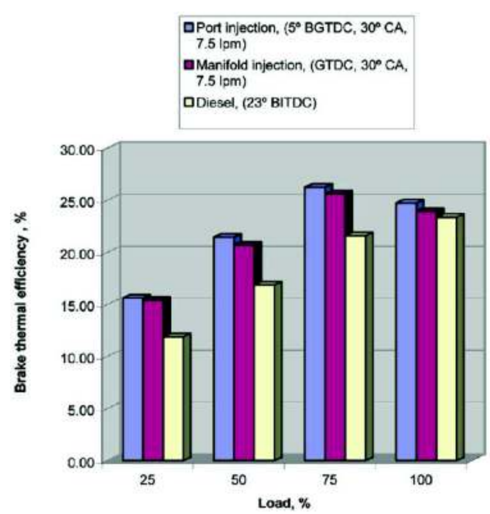

Figure 30. Brake thermal efficiency vs. load for port injected, manifold injected and carbureted hydrogen (hydrogen-diesel) [13]

RUNNING COSTS

The application of an alternative, gaseous, fuel in a dual-fuel operation with diesel can offer significant economical advantages. Since carbon monoxide and hydrogen are not common available fuels they are not included in this evaluation. Hence, synthesis gas is not included since it is a mixture of hydrogen and carbon monoxide. However, with on-board-reforming it is possible to form syngas or hydrogen on the vehicle. Nevertheless, such on-board-reforming techniques would not be beneficial for the engine efficiency since it will cost energy which otherwise would be used for propulsion. In Table 1 lower heating values and the specific energies per euro of the evaluated fuels are shown. It is clear that the amount of energy per euro for liquefied petroleum gas and natural gas is significantly higher than the specific price of diesel. These prices are based on the current suggested prices in the Netherlands. Due to the decreased efficiency of a dual-fuel engine running on natural gas and diesel an economical advantage is only achieved by the ratio of NG/diesel. High ratios of natural gas can offer a significant economical advantage especially when operating at high loads since the efficiency then approaches the efficiency of conventional diesel operation. For liquefied petroleum gas the advantage is more straight-forward. Due to the comparable efficiencies of LPG-diesel dual-fuel operation and conventional diesel operation and the beneficial specific price of LPG a significant economic advantage exists. The exact advantage depends on the amount of added gaseous fuel. Furthermore, the environmental advantages that the application of gaseous fuels in combination with diesel offers can provide economic advantages in some other way. It is not unlikely that subsidy is provided by governments with the purchase of such clean vehicles and/or possible reduced tax fares.

Table 1. Lower heating values and specific prices evaluated fuels (Netherlands, July 2011 after taxes)

	LHV [MJ/kg]	Specific Price [MJ/euro]
Diesel	44.0	26.15
LPG	46.6	32.9
Natural Gas	47.0	46.8
Carbon Monoxide	10.4	-
Hydrogen	120	-

CONCLUSIONS

The automotive industry is forced to reduce exhaust emissions, due to strict European, American and Japanese emission legislation. Most automotive industry manufacturers currently apply exhaust after treatment systems to reduce tailpipe-out emissions. However, this is an expensive way to achieve reduced emissions. Therefore, researchers worldwide have proposed alternative solutions to meet with the international emissions legislation. One of which is the application of dual-fuel combustion of gaseous fuels and diesel. Many researchers have been investigating the influences of dual-fuel operations with gaseous fuels and diesel on the engine performance. This includes the influence on emissions and engine efficiency. This review paper discusses the effect of dual-fuel combustion on engine-out emissions, engine efficiency and running costs. The fuels evaluated in combination with diesel are natural gas, liquefied petroleum gas, synthesis gas and hydrogen.

In general soot emissions can be effectively reduced in dual-fuel modes for all the evaluated gaseous fuels except for syngas. Since little research evaluates the effect of syngas on soot emissions the only results evaluated are of an impure syngas. Syngas containing only carbon monoxide and hydrogen could lead to more promising results particularly with increasing hydrogen content of the syngas. Furthermore, with increasing loads and gaseous fuel content soot emissions further decrease with respect to conventional diesel operation. Since hydrogen has a very low density, increasing the amount of syngas or hydrogen in the fuel can result in a lack of oxygen. This lack of oxygen can cause incomplete combustion and lead to increased soot emissions.

Depending on which gaseous fuel is used for dual-fuel operation significant reductions in nitrogen oxides can be achieved. Liquid petroleum gas and natural gas both offer NO_x reductions due to a more homogeneous mixture and decreased mixture temperatures. Moreover, increasing gaseous fuel percentages and loads will result in increased reduction of nitrogen oxide emissions compared to normal diesel operation. Both hydrogen and synthesis gas combined with diesel will lead to increased nitrogen oxide emissions. This is likely due to the higher flame temperatures and combustion rates of hydrogen and carbon monoxide.

The emissions of unburned hydrocarbon and carbon monoxide are mostly a result of incomplete combustion. A dominant source of incomplete combustion of the gaseous fuels is the unburned fuel in crevices volumes. Furthermore, lean gaseous fuel/air mixtures can lead to poor flame propagation. Dual-fuel operation with LPG and natural gas will both increase the emissions of hydrocarbons and carbon monoxides compared with conventional diesel operation. However, direct injected LPG-diesel blends will decrease the emissions of carbon monoxide. Furthermore, hydrogen-diesel dual-fuel show comparable results on carbon monoxide and decreased hydrocarbon emissions since hydrogen is a non-carbon-based fuel. Syngas-diesel combustion will, depending on the syngas composition, increase carbon monoxide emissions. Moreover, with a decreasing carbon monoxide content of the fuel the CO emissions decrease; however, compared with a normal diesel operation it is still increased. Hydrocarbon emissions during a syngas-diesel operation tend to increase due to a decreased combustion efficiency of the injected diesel. Furthermore, it should be noted that with the application of hydrogen or syngas an increase of hydrogen emissions is expected.

The different evaluated gaseous fuels have a different influence on the engines efficiency. Running on hydrogen and LPG can offer slight improvements on efficiency. However, natural gas will decrease efficiency due to the lower combustion temperatures and increased ignition delays. A dual-fuel operation with syngas and diesel is likely to lead to increased energy consumption due to decreased combustion efficiency. When compensating for the unburned fuel fractions the efficiencies are comparable with that of normal diesel operations. Together with the environmental advantages that the application of dual-fuel engines can offer additionally such a combustion process can offer economic advantages. Due to the low price per unit of energy of natural gas and liquefied petroleum gas significant reductions in running costs can be achieved. Furthermore, some governments provide subsidies or reduced tax rates for clean ways of transportation.

To conclude, this research shows that dual-fuel engines, using diesel and gaseous fuels, can offer significant advantages on emissions, performance and costs. Since the results of the reviewed literature already show significant advantages of the dual-fuel concept compared to conventional diesel combustion, further research at Eindhoven University of Technology will be carried out on this subject. This research will focus on the application of natural gas and LPG as gaseous fuel due to their economical and environmental advantages and their common availability. Furthermore, the dual-fuel concept will be expanded with "new" clean and efficient combustion concepts such as Premixed Charge Compression Ignition (PCCI) and/or Reactivity Controlled Compression Ignition (RCCI). The concept of dual-fuel low temperature homogeneous/premixed charge combustion has already extensively been examined, and shows promising results on PM- and NO_X-emissions as well as thermal efficiencies [28, 29]. With the application of a gaseous fuel (low reactive) and diesel (high reactive) a wide variety of overall fuel reactivity's can be achieved, and therefore, it is an interesting topic to further investigate.

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DEFINITIONS/ABBREVIATIONS

CI
Compression ignition

DI
Direct injection

DPF
Diesel particle filter

IMEP
Indicated mean effective pressure

K
Kelvin

kW
Kilo watt

LPG
Liquefied petroleum gas

NG
Natural gas

Nm
Newton meter

NSC
NO_x storage catalyst

PFI
Port fuel injection

PM
Particle matter

SCR
Selective catalytic reduction

SI
Spark ignition

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