Fuel 222 (2018) 278–286

Contents lists available at ScienceDirect

Fuel

journal homepage: www.elsevier.com/locate/fuel

Full Length Article

GTLine – Gasoline as a potential CN suppressant for GTL

Jos Reijnders[a,*], Michael Boot[a], Bengt Johansson[b], Philip de Goey[a]

[a] Eindhoven University of Technology, Mechanical Engineering, Combustion Technology, PO Box 513, 5600MB Eindhoven, The Netherlands
[b] King Abdullah University of Science and Technology, Clean Combustion Research Center, Thuwal 23955-6900, Saudi Arabia

ARTICLE INFO

Keywords:
Gas to liquid (GTL)
Gasoline
Cetane number
Aromaticity
Efficiency
Emissions
Partially premixed combustion (PPC)

ABSTRACT

The main driver to investigate low temperature combustion concepts, such as partially premixed combustion (PPC), is the promise of low particulate matter (PM) and nitric oxide (NOx) emissions. A critical prerequisite for PPC is to temporally isolate the fuel injection and combustion events. In practice, exhaust gas recirculation (EGR) is applied in order to sufficiently extend the ignition delay to that effect. Hereby, in general, higher EGR rates are necessary for fuels with higher cetane numbers (CN).

Against this background, the objective of this paper is to investigate the efficacy, with respect to PM-NOx emissions and engine efficiency, of gasoline as a potential gas-to-liquid (GTL) CN suppressant in various dosages. The performance of the resulting GTLine blend will be evaluated under PPC operating conditions in a heavy-duty direct-injected diesel engine.

Setting aside for a moment any potential practical issues (e.g., flash point, vapor pressure) that fall outside the scope of this study, our data suggest that blending gasoline to otherwise high CN GTL appears to be a promising route to improve not only the efficiency, but also PM and NOx emissions, particularly when operating in PPC mode. Interestingly, this benefit is notwithstanding the high aromaticity of the gasoline compared to GTL.

Given the ongoing dieselization trend and associated surplus of gasoline in many regions, notably Europe, along with the fact that the cost price of gasoline is significantly lower than that of GTL, the proposed GTLine approach promises to be a cost effective way to accommodate GTL in a world wherein low temperature combustion concepts, such as PPC, appear to be really taking off.

1. Introduction

Low temperature combustion (LTC) concepts such as homogeneous charge compression ignition, premixed charge compression ignition and partially premixed combustion (PPC) are seen as promising routes to achieve both low emissions and high efficiency in future compression ignition engines. For practical reasons, including controllability of the combustion phasing and thermal loading of the engine, fully premixed combustion, as is the case for the former two concepts, is considered here to be less promising in real-life applications. This study will therefore focus on the latter combustion principle, PPC.

PPC can be defined as a combustion process in a compression ignition engine, whereby a temporal separation exists between the fuel injection and combustion events, thereby implying that a long ignition delay (ID) is the single most important prerequisite [1–10]. A shared conclusion found in all these studies is that PPC is most readily realized with a low CN fuel, else prohibitively high EGR rates are likely necessary to adequately extend the ID (Table 1). Other key findings from the before mentioned studies, along with associated data on engine specifications, operating conditions and fuel matrices, are presented in Table 2.

In our previous work [13], we evaluated the performance of two Fischer–Tropsch (FT) GTL diesel fuels with CN's of 52 and 72 in various combustion modes from high (i.e., conventional diffusion) to low (i.e., PPC) temperature regimes. The results demonstrated that, at equal fuel aromaticity, a high CN yields no discernible benefit in terms of PM-NOx trade-off in high temperature combustion modes and even becomes a serious handicap when transitioning into the low temperature regime.

While GTL is best known and often explicitly marketed for its exceptionally high CN, it is possible to produce GTL with lower, more diesel-like values by means of a combination of shortening and branching the paraffinic chains intrinsic to the FT process [13]. While future GTL plant owners might take notice of aforementioned insights, producers of high CN GTL diesel must necessarily add low CN compounds in order to decrease the CN.

Earlier, we investigated the use of ethanol [14] and oxygenated aromatics [15] as potential CN suppressants for GTL. Shell too acknowledged that for some engine operation conditions the otherwise

* Corresponding author.
E-mail address: j.j.e.reijnders@tue.nl (J. Reijnders).

https://doi.org/10.1016/j.fuel.2018.02.111
Received 17 March 2017; Received in revised form 3 February 2018; Accepted 15 February 2018
0016-2361/ © 2018 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY license (http://creativecommons.org/licenses/BY/4.0/).

Nomenclature

ϕ	equivalence ratio
aTDC	after top dead center
CA	crank angle
CA50	50% of total heat released
CAD	crank angle degree
CN	cetane number
CO	carbon monoxide
CR	compression ratio
EGR	exhaust gas recirculation
FT	Fischer–Tropsch
GTL	gas-to-liquid
GTLine	blend of GTL and gasoline
HC	hydrocarbons
HD	heavy-duty
HDDI	HD direct-injection
ID	ignition delay
IDw	ignition dwell
IQT	Ignition quality tester
NOx	nitrogen oxide(s)
PM	particulate matter
PPC	partially premixed combustion
RoHR	rate of heat release
rpm	revolutions per minute
SOC	start of combustion
SOI	start of injection
T	temperature

high CN of their GTL product should be lowered and therefore proposed to blend in oxygenated and nitrated aromatics [16]. A well known approach to lower the CN of diesel fuel in general is to blend it with low CN fossil or biofuels [11,17–23].

When reviewing Table 2, one practical and relatively low cost fuel looks particularly promising, gasoline. Commonly referred to as Dieseline in literature, this mix of fossil fuels already has a proven track record as a PPC fuel. What is more, there exist, in Europe at least, a surplus of gasoline, thereby partially compensating for both the limited availability of GTL as well as its relatively high cost price.

As no earlier engine results on GTL-gasoline blends could be found in the literature, the objective of this study is to investigate the efficacy, with respect to improving the PM-NOx-efficiency trade-off, of gasoline as a GTL CN suppressant. The performance of the resulting GTLine blends will be evaluated under both conventional and PPC operating conditions.

2. Methodology

2.1. Experimental setup

All experiments are carried out on a modified 12.6 liter HDDI DAF XE 355C in-line six diesel engine (see Table 3 and [13,24]).

The first cylinder is used as a test cylinder and is equipped with a dedicated in- and outlet manifold, EGR circuit and fuel injection system. Cylinders 2 and 3 have no function, while numbers 4 through 6, operating on the stock engine control unit (ECU) and conventional fuel, are responsible only for setting and maintaining the desired engine speed. For optimal EGR dosage, temperature control and mixing in fresh air, several surge tanks and coolers have been incorporated into the design. A schematic overview of the test engine is shown in Fig. 1.

Fresh air (up to 5 bar) for the test cylinder is provided by an external compressor, the mass flow of which is measured by a Coriolis mass flow meter. The fuel injection system consists of a Resato double-acting air driven fuel pump (up to 2500 bar), a second Coriolis mass flow meter and a prototype Delphi common rail injector with eight 0.151 mm diameter holes.

Gaseous emissions of CO, HC, NOx, CO2 (intake and exhaust), along with the filter smoke number (FSN), are recorded by a Horiba Mexa 7100 DEGR and AVL smoke meter (415S), respectively. EGR is calculated in wt.% using both CO2 sensors (intake and exhaust). Gaseous emissions, along with common pressure, temperature and mass flow sensors are logged for 40 s at 20 Hz for each operating point. Data acquisition for in-cylinder pressure and heat-release analyses is achieved by a SMETEC Combi system, which logs in steps of 0.1 crank angle degree for 50 continuous cycles. Variables measured by this system are in-cylinder pressure via an AVL GU21C, calibration value 36,87 pC/bar, intake and fuel pressure, and injector current. For each operating point, the FSN is averaged over three measurements.

Table 1
Minimum required EGR rate to achieve PPC.

Source	Fuel	CN	EGR (wt%)
[1]	Gasoline	±15	0
[5]	Gasoline	±15	5
[11]	Diesel	±56	25
[2]	Diesel	±42	30
[10]	Diesel	±43	40
[12]	Diesel	±54	48

2.2. Fuel matrix

In total, five fuels will be evaluated in the engine tests: neat GTL, three GTLine blends (e.g., 10, 20 and 50 vol.% gasoline), and EN590 diesel as a reference fuel. Fuel properties, as measured by ASG-Analytik GmbH Germany, can be found in Table 4.

2.3. Experimental procedure

All tests are conducted with a single injection per cycle, at a fixed engine speed of 1200 rpm, and a constant engine oil and coolant temperatures of 90 and 85 °C, respectively. For all fuels, EGR rates are varied from 0 to 50%. Hereby, the CA50 is kept constant at 10° CA after top dead center by adjusting the start of injection (SOI). An overview of the operating conditions is provided in Table 5.

2.4. Repeatability and accuracy

Various engine operation points have been re-measured on a regular basis in order to assess the repeatability. First, the complete data set has been measured, where after some points were repeated. In all cases, new results were in good agreement with older ones. In earlier work [13], the repeatability of the engine setup and data acquisition system used in this study is discussed in greater detail. Associated data on accuracy is summarized in Table 6.

3. Results

3.1. Rate of heat release

Fig. 2 shows the rate of heat release (RoHR) for all fuels at 15 wt% EGR. As might be expected, when maintaining a constant CA50, lower CN fuels yield a longer ID,[1] higher peak rate and shorter combustion duration.

[1] Time expressed in CA between SOI and SOC, whereby SOI and SOC are defined as the CAD at which the fuel first enters the combustion chamber, as evidenced by RoHR first going negative as a result evaporative cooling, and the moment at which the RoHR first rises above the 50 J/CAD threshold, respectively.

Table 2
Summary of literature review on PPC.

Ref. #	Engine specifications	Operating conditions	Fuels	Key findings
[1]	HD, CR = 14	4–9 bar IMEP, 0–25% EGR	Diesel, Gasoline	Engine can run on gasoline in PPC mode with a much higher IMEP while maintaining low NOx and smoke
[2]	HD, CR = 16.1	4 bar IMEP, 5–60% EGR	Diesel	The LTC models show a longer liquid-fuel penetration and longer ID for PPC. Moreover, reduced and altered soot formation regions are observed
[3]	LD, CR = 16.1	5 bar IMEP, 0–65% EGR	Diesel, Gasoline, n–Heptane, n-Butanol	Soot emissions are strongly related to injection timing Higher intake pressures counteract EGR soot penalty
[4]	LD, CR = 15.5	5 bar IMEP, 20–35% EGR	Diesel, Propane	NOx and particulate matter (PM) emissions are reduced with early split injection strategy using high propane ratios
[5]	LD, CR = 14.7	3–7 bar IMEP, 5–15% EGR	Gasoline	Double injection improves PPC spark assisted combustion efficiency Lower pilot fuel mass injection reduces CO and UHC emissions
[6]	LD, CR = 16.5	1–5 bar IMEP, 0% EGR	Diesel, Ethanol	Combustion mode moves from two-stage to three-stage increasing the premixed ratio
[7]	HD, CR = 17.1	4–12 bar IMEP, 0% EGR	Diesel, Methane	Start of injection (SOI) significantly affects emissions in LTC mode Heat release shifts from two-stage to Gaussian profile when advancing SOI
[8]	LD, CR = 15.0	6 bar IMEP, 0% EGR	DME	Dual injection strategy shows extremely low NOx emissions while maintaining moderate engine output
[9]	LD, CR = 17.5	8 bar IMEP, 0–20% EGR	Diesel, n-Butanol	The joint action of a longer ignition delay and a better fuel volatility reduces smoke at moderate injection pressures
[10]	LD, CR = 16.0	4 bar IMEP, 40–45% EGR	Diesel	Theoretical analysis of the reaction rates suggests that soot formation is insensitive to equivalence ratio at temperatures below 1500 K

Table 3
Test engine specifications.

Engine type	HDDI
Engine model	XE355C
Cylinders	6, with 1 isolated for research purposes
Capacity [l]	12.6
Bore [mm]	130
Stroke [mm]	158
Compression ratio [–]	15.7

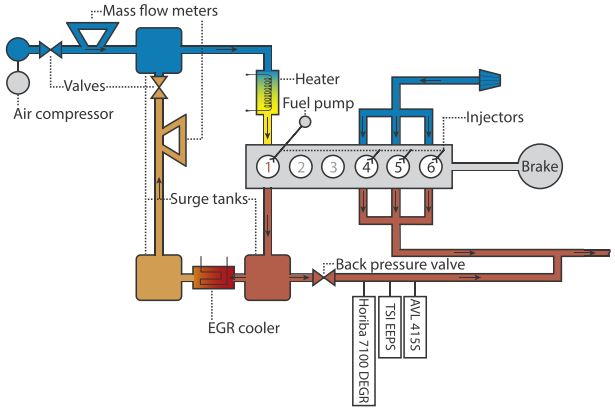


Fig. 1. Test engine rig.

The RoHR signal can be unimodal (e.g., 50/50 blend; steep rise and fall) or more bimodal like (e.g., 100/0; steep rise and slow fall, even with a plateau), whereby the first and second modes represent the contribution of premixed and subsequent diffusion combustion, respectively.

Ceteris paribus, wider RoHR curves are indicative of a more dominant role for diffusion combustion, which tends to be slower than its premixed counterpart. A greater prevalence of diffusion combustion, in turn, is to be expected for high CN fuels, owing to their relatively short ID's.

Table 4
Fuel properties.

Property	Unit	Fuels				
		100/0	90/10	80/20	50/50	Ref. (EN590)
GTL	[%V/V]	100	90	80	50	0
Gasoline	[%V/V]	0	10	20	50	0
CN (IQT)	[-]	79.8	68.2	62.6	45.5	51.6
LHV*	[MJ/kg]	44.6	44.4	44.3	43.7	42.5
Density*	[kg/m^3]	777.3	773.5	769.7	758.3	835.4
C*	[wt%]	84.6	84.6	84.5	84.4	85.1
H*	[wt%]	15.1	14.9	14.7	14.1	13.1
Aromatic content*	[%V/V]	<0.1	2.6	5.1	12.5	16.3
AFRstoich*	[–]	14.9	14.8	14.7	14.5	14.2
Sulfur*	[mg/kg]	0.5	0.9	1.3	2.4	14.2

* Blend values calculated from those measured for neat compounds

Table 5
Engine operating conditions.

Parameter	Unit	Value
Engine speed	[rpm]	1200
IMEP	[bar]	5.5–6.0
CA50	[CAD aTDC]	10
Intake pressure	[bar]	1.0
Exhaust pressure	[bar]	1.3
Intake temperature	[°C]	40
EGR	[wt%, CO2/CO2]	0–50
Lambda (λ)	[–]	2–1
Injection pressure	[bar]	1500
Injection duration	[μs]/ [CAD]	950-1050/ 6.9-7.6

As the CN drops, however, the premixed phase begins to play a more dominant role in the heat-release event. In fact, particularly for the GTLine fuels with the highest blend ratios of gasoline, the very nature of the RoHR curve changes from bi- to unimodal as the contribution of diffusion combustion wanes and the combustion type gradually shifts into PPC territory.

Table 6
Data acquisition accuracies.

Data type	Brand	Type	Unit	Accuracy
Temperatures (intake, exhaust, etc.)	Omega	k-type thermocouple	°C	±1.1 ° C
Pressures (intake, exhaust, etc.)	GE	PMP 1400	Pa	±0.25% of value
Air mass flow	Micro Motion	Coriolis CMF200	g/s	±0.35% of rate
Diesel mass flow	Micro Motion	Coriolis CMF010	g/s	±0.2% of rate
In-cylinder pressure	AVL	GU21C	bar	±0.3 % FS (250 bar)
Gaseous analyzer	HORIBA	7100 DEGR	%, ppm	±0.5% Full Scale
Smoke meter	AVL	415S/ Filter method	FSN	±0.01 FSN (<6 FSN)

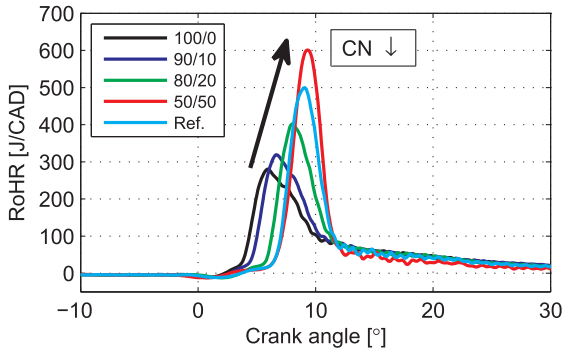


Fig. 2. RoHR as a function of CAD at 15% EGR.

3.2. Ignition dwell

An important drawback of diffusion combustion is the so-called diesel dilemma or PM-NOx trade-off. Measures to decrease diffusion flame temperature (e.g., by using EGR) tend to curb NOx and promote PM emissions, and *vice versa*. LTC concepts therefore aim to switch to a new paradigm, wherein this trade-off no longer manifests. To this end, measures are undertaken to increase the role of premixed over diffusion combustion.

The rationale for this is quite straightforward; as fuel is more widely dispersed in the combustion chamber, local equivalence ratios drop and combustion heat is released more homogeneously throughout the cylinder. Former and latter phenomena, in turn, generally result in lower PM and NOx formation rates.

In order to measure the relative importance of both combustion modes, we will evaluate the so-called ignition dwell (IDw) of the combustion event. The IDw is defined as the difference (e.g., expressed in CA) between the end of injection (EOI) and the start of combustion (SOC) (Eq. (1)). Hereby, a negative and positive value signifies classical (i.e., lifted diffusion flame) and PPC diesel combustion, respectively [25].

$$IDw = CA(SOC) - CA(EOI) \quad (1)$$

Fig. 3 shows the IDw as function of EGR. Data points below the dashed line indicate diffusion combustion is more dominant. Conversely, data points positioned above this line will most likely be void of this combustion mode and are considered to be of the PPC type. As discussed earlier when reviewing the PPC literature and is further evidenced in Fig. 3, all investigated fuels can be pushed into PPC territory by means of EGR, irrespective of their CN.

Nevertheless, as found in literature (Table 1), the data in Fig. 3 demonstrate that far less EGR is required for the lower CN fuels (e.g., those with a higher concentration of gasoline). As can be seen in Fig. 4, a minimum ID (e.g., 7–8 CAD) is required to breach this threshold, with associated EGR levels falling with CN.

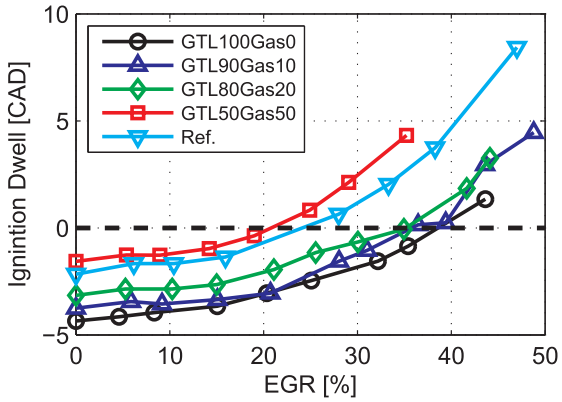


Fig. 3. Ignition dwell as a function of EGR.

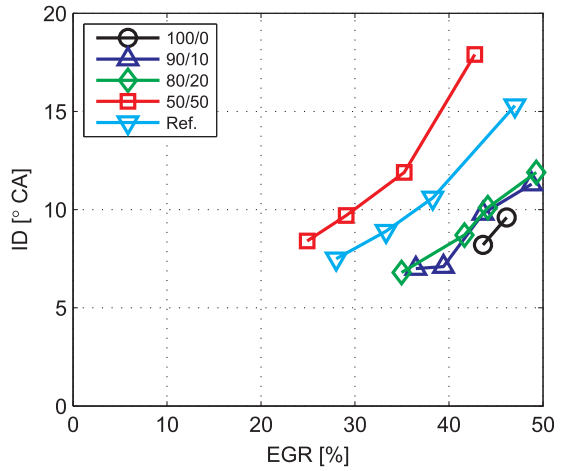


Fig. 4. ID as a function of EGR.

Note that for the remainder of this paper, only measurements with IDw values greater than zero will be considered. Complete EGR sweeps are provided in Appendices A–D, and associated data on HC and CO emissions in Appendix E.

3.3. Indicated efficiency

Indicated efficiency is calculated as follows:

$$\eta_{ind} = P_{ind}/(\dot{m}_{fuel} * LHV), \quad (2)$$

where

P_{ind} is the indicated power, $\dot{m}_{fuel}$ is the mass flow of the fuel, and LHV is the lower heating value.

The penalty of heavy EGR use is quite tangible in Fig. 5. As might be expected, EGR weighs on efficiency. Particularly for rates in excess of 35–40 wt%, efficiency drops rapidly when approaching stoichiometric conditions, coinciding with a rapid increase in both CO and HC emissions (E).

Accordingly, in our data set at least, the higher the CN, the higher the drop in efficiency when operating in PPC mode. Note that the authors have not attempted to further optimize the efficiency by, for example, modifying the CA50 or intake pressure. Interestingly, comparable efficiencies are found for all fuels at any given EGR level.

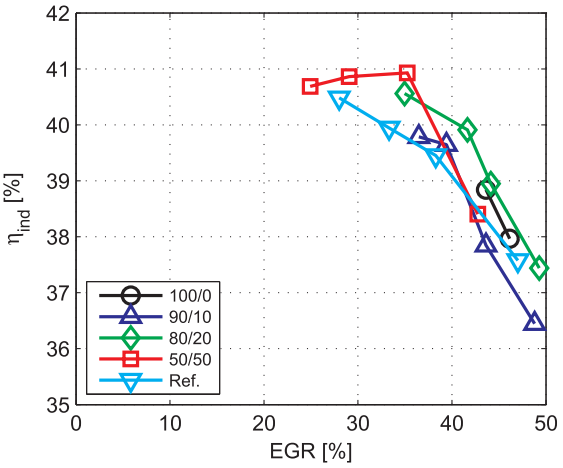


Fig. 5. Indicated efficiency as a function of EGR

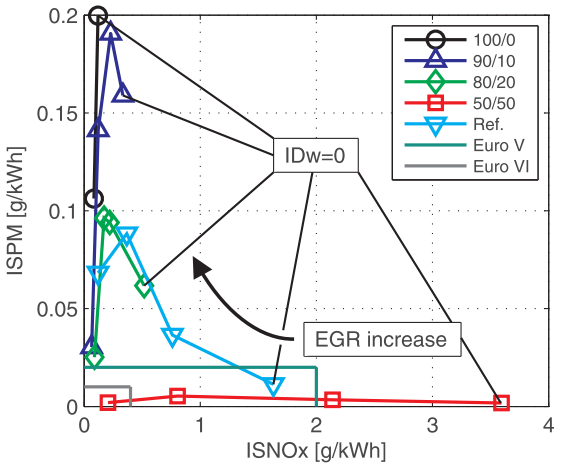


Fig. 6. PM-NOx trade-off in PPC regime.

3.4. PM and NOx

Notwithstanding taking into account only higher than zero IDw data, aforementioned PM-NOx trade-off is still present in varying degrees for all fuels (Fig. 6). Nevertheless, striking differences can still be observed, with generally more favorable curves found for the lower CN fuels. In fact only the two lowest CN fuels, EN590 and 50/50 GTLine, are found capable of achieving combined Euro V engine out emissions for PM and NOx. The number of fuels drops to one for Euro VI.

For all fuels, there appears to exist a tipping point, whereby the emissions trade-off no longer holds and even goes into reverse. The significance of this tipping point with respect to the validity of the aforementioned IDw boundary between classical and PPC diesel combustion will be discussed in the next section.

4. Discussion

4.1. PPC threshold

The PPC threshold of zero in the IDw equation has been defined in accordance with the literature consensus with respect to the definition of this combustion concept. Judging from the PM-NOx emissions data (Fig. 6), however, a classical trade-off is still clearly present in many data points for which the aforementioned IDw criterion has been met. As the PPC concept is praised by the combustion community for the very absence of this trade-off, its existence here suggests that diffusion combustion may still play a role even well after the EOI.

Although detailed optical engine experiments would be required in order to fully comprehend this discrepancy, a possible contributing factor might be attributable to the last fraction of fuel injected near the EOI still burning as a lifted diffusion flame. Given that the onset of auto-ignition is generally a local event in the spray, this theory would appear to be a promising candidate for further scrutiny in optical experiments.

4.2. Cetane number and aromaticity

Going against conventional wisdom, the two best performing fuels, both with respect to efficiency and emissions, are those with the higher aromaticity and lower CN. This is in line with the conclusions of our previous work [13], which stated that both high CN and aromaticity have a negative impact on aforementioned parameters when operating in PPC mode, although the latter fuel characteristic appears even more detrimental than the former. In other words, purposefully increasing aromaticity with the objective to lower CN appears to be a sound approach for this particular LTC concept.

Looking at the PM-NOx trade-offs shown in Fig. D.1 in the Appendix, it would appear that neat GTL performs worst of all fuels. This trade-off improves with higher concentrations of gasoline and thus even in the face of falling CN and increasing aromaticity. Interestingly, the 80/20 blend and reference fuel show comparable behavior, notwithstanding a lower CN for the latter fuel (e.g., 63 vs. 52, Table 4).

A plausible explanation for this performance parity, achieved here at dissimilar CN values, might be found in the associated aromaticity of the fuels in question. As it happens, the lower CN reference diesel fuel contains more than three times the amount of aromatics as is true for the 80/20 GTLine blend (e.g., 16.3 vs. 5.1%, Table 4).

As concluded in an earlier study [13], given an equal CN, the fuel with the lowest aromaticity will generally yield the more favorable PM-NOx trade-off. It would appear here that a higher aromaticity can be offset by a lower CN, whereby the respective negative and positive impacts on the trade-off cancel each other out. As the results in Fig. D.1 would suggest, this is indeed the case for the reference diesel fuel and the 80/20 GTLine blend.

4.3. Equivalence ratio and temperature

The origin of PM and NOx emissions are often discussed in the context of a ϕ-T diagram. Herein, ϕ and T denote the local fuel/air ratio and temperature, respectively. In an optically accessible engine, these fundamental parameter that lead to NOx and PM, can be determined with (advanced) laser diagnostics. However, for a full metal engine the local ϕ and T can not be measured. Nevertheless, when it is assumed that for PPC, *ceteris paribus*, the impact of CN and EGR on local ϕ-T conditions is qualitatively similar to that measured for the charge as a whole,[2] some insights might emerge that could help explain aforementioned PM-NOx behavior (Fig. 6, IDw = 0).

In Fig. 7, the bulk equivalence ratio is plotted against the bulk gas temperature, which has been estimated from application of the ideal gas law to the measured pressure and volume[3] history.

From Fig. 7 it becomes clear that temperatures at the SOC are all similar and slightly below 700 K. After the auto-ignition event, temperatures rise rapidly to the respective apices. Here, obvious differences are visible amongst the fuels, as well as a clear trend with CN. As discussed earlier, the higher the CN of the fuel, the higher the amount of EGR required to breach the zero IDw threshold (Figs. 3 and 8).

EGR, which has been cooled to approximately ambient conditions in our experiments, so as to maintain a constant charge temperature, has a cooling effect on the combustion process, owing to the relatively high

[2] As determined via air/mass flow meters and in-cylinder pressure sensor.

[3] Derived from engine geometry and crank angle position sensor.

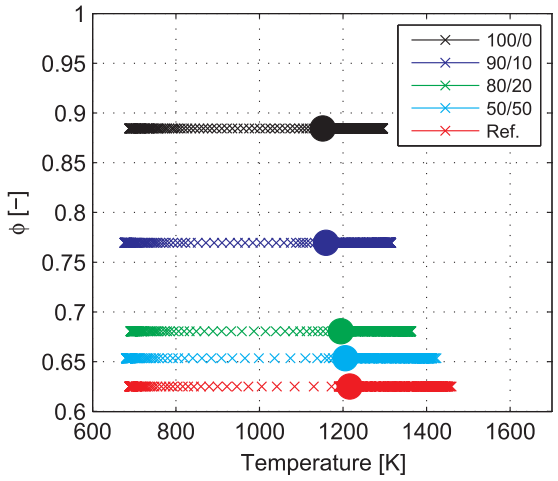


Fig. 7. Bulk temperature and equivalence ratio trace during combustion at IDw = 0. Large dots indicated average values.

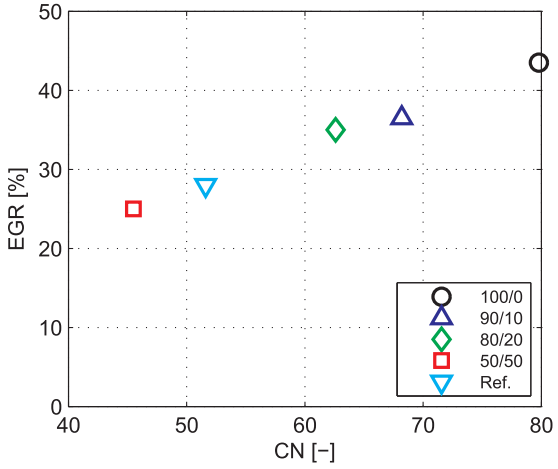


Fig. 8. EGR as function of cetane number for IDw = 0 conditions.

specific heats of CO_2 and H_2O. Moreover, given that EGR suppresses oxygen-rich fresh air, the equivalence ratio naturally increases with its dosage.

Combining Figs. 6 and 7, it is fair to assume that the high PM and NOx values seen at IDw = 0 for the high and low CN fuels can at least in part be traced back to a less favorable equivalence ratio and temperature, respectively.

4.4. Indicated efficiency

The main drawback of using high CN fuels in combination with PPC is most evident in Fig. 9. Here, the indicated efficiency is plotted for the various fuels at IDw = 0. A sharp drop in efficiency can be observed for

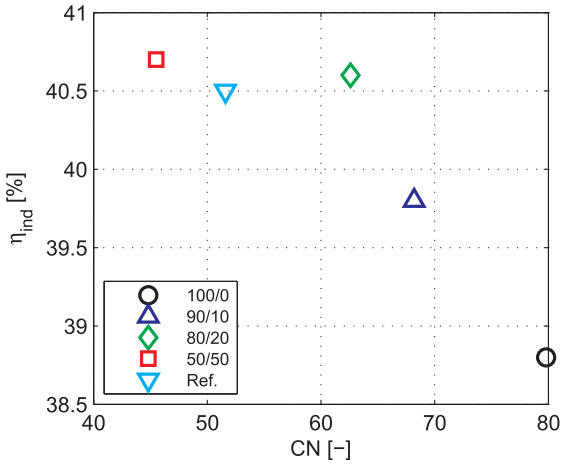


Fig. 9. Indicated efficiency as function of cetane number for IDw = 0 conditions.

the two fuels with the highest CN (e.g., >60). Note that the penalty is even more pronounced for IDw values in excess of the zero threshold; a fact which, given the previous observation that a higher ignition dwell than IDw = 0 is necessary to have an appropriate PPC border, appears all the more relevant now.

To complicate matters even further, recall that the emissions trade-offs for the higher CN fuels are far less favorable than those measured for the less reactive fuels (Fig. 6).

5. Conclusions

Careful analysis of the experimental engine data for various GTL-gasoline blends in PPC mode has led to the following conclusions:

- The higher the CN, the higher the amount of EGR required to sufficiently extend the ID (Fig. 4)) into PPC territory (Fig. 3) and achieve associated low PM-NOx emissions (Fig. 6), whereby the ignition dwell should be somewhat greater than zero.
- A CN higher than 60 cq. EGR rates above 30–40 wt% have a negative impact on indicated thermal efficiency (Fig. 5), most likely as a result of incomplete combustion (Figs. E.1 and E.2).
- Blending in relatively low cost and abundantly available gasoline thus improves the efficiency and emissions behavior of GTL when operating in PPC.

Acknowledgments

The authors gratefully acknowledge the financial support of SER-Brabant (New Energy House project), who was solely responsible for the finances and has not interfered with selecting Journal, content, conclusions or whatever. Furthermore, we would like to acknowledge our technical support team, Gerard van Hout, Theo de Groot and Hans van Griensven.

Appendix A. Ignition delay

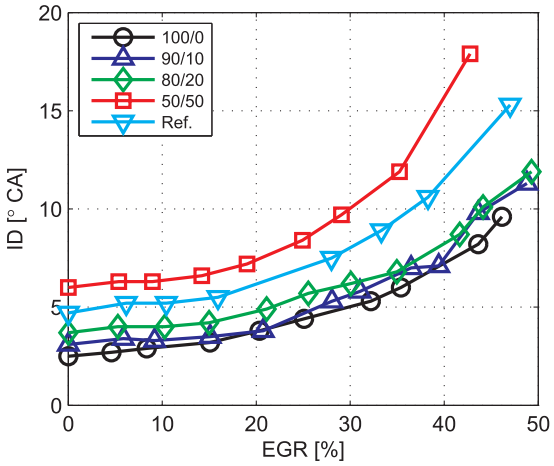


Fig. A.1. Ignition delay as function of EGR.

Appendix B. Indicated efficiency

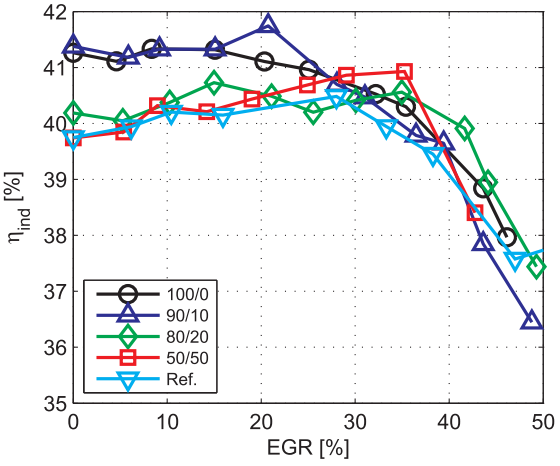


Fig. B.1. Indicated efficiency as function of EGR.

Appendix C. PM and NOx emissions

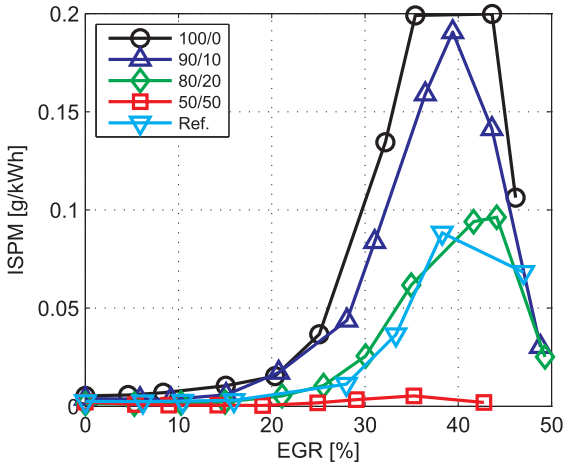


Fig. C.1. PM emissions as function of EGR.

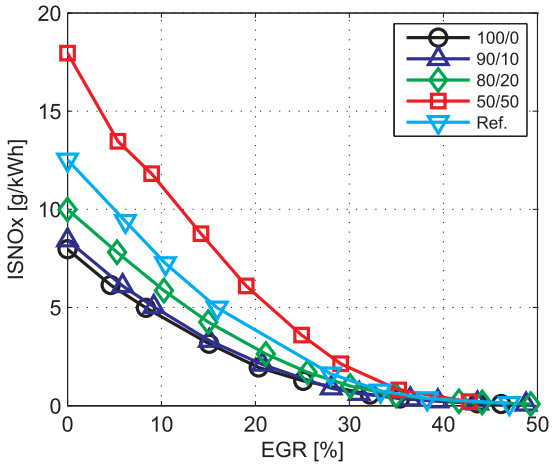


Fig. C.2. NOx emissions as function of EGR.

Appendix D. PM-NOx trade-off

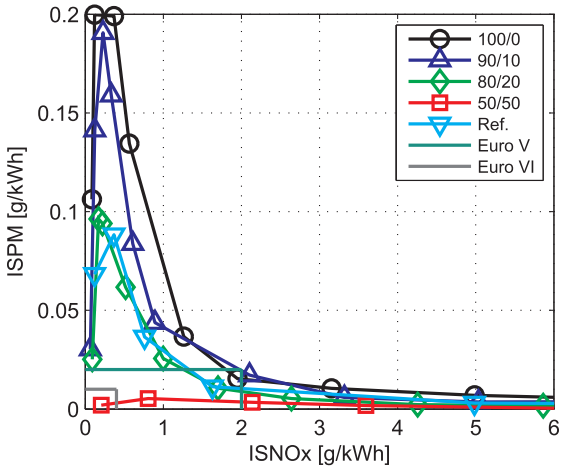


Fig. D.1. PM-NOx trade-off.

Appendix E. HC and CO emissions

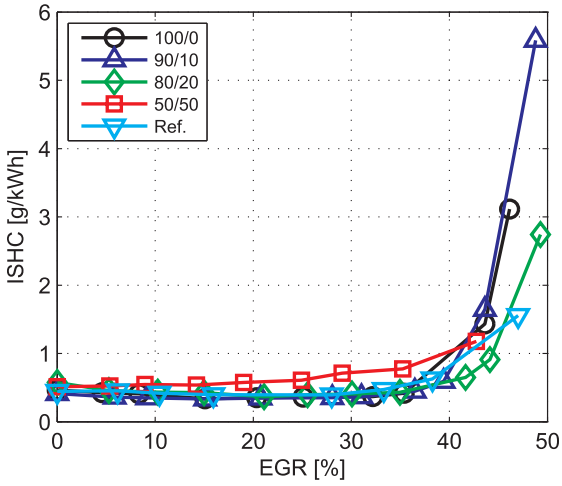


Fig. E.1. Unburnt hydrocarbon emissions as function of EGR.

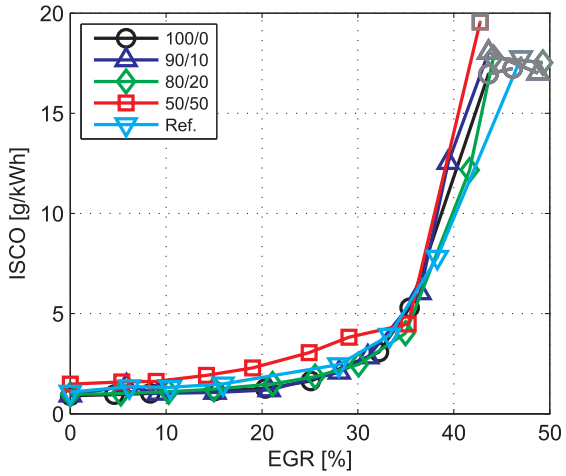


Fig. E.2. Carbon monoxide emissions as function of EGR (gray markers are out of range of the measurement equipment).

References

[1] Kalghatgi GT, Risberg P, Angstrom HE. Advantages of fuels with high resistance to auto-ignition in late-injection, low-temperature, compression ignition combustion. SAE Technical Paper: 2006-01-3385 (2006). doi:http://dx.doi.org/10.4271/2006-01-3385.

[2] Musculus MP, Miles PC, Pickett LM. Conceptual models for partially premixed low-temperature diesel combustion. Prog Energy Combust Sci 2013;39(2–3):246–83. http://dx.doi.org/10.1016/j.pecs.2012.09.001.

[3] Liu H, Ma S, Zhang Z, Zheng Z, Yao M. Study of the control strategies on soot reduction under early-injection conditions on a diesel engine. Fuel 2015;139:472–81. http://dx.doi.org/10.1016/j.fuel.2014.09.011.

[4] Lee J, Chu S, Cha J, Choi H, Min K. Effect of the diesel injection strategy on the combustion and emissions of propane/diesel dual fuel premixed charge compression ignition engines. Energy 2015;931(Part 1):1041–52. http://dx.doi.org/10.1016/j.energy.2015.09.032.

[5] Benajes J, Molina S, Garća A, Monsalve-Serrano J, Durrett R. Performance and engine-out emissions evaluation of the double injection strategy applied to the gasoline partially premixed compression ignition spark assisted combustion concept. Appl Energy 2014;134:90–101. http://dx.doi.org/10.1016/j.apenergy.2014.08.008.

[6] Mancaruso E, Vaglieco BM. Spectroscopic analysis of the phases of premixed combustion in a compression ignition engine fuelled with diesel and ethanol. Appl Energy 2015;143:164–75. http://dx.doi.org/10.1016/j.apenergy.2015.01.031.

[7] Guerry ES, Raihan MS, Srinivasan KK, Krishnan SR, Sohail A. Injection timing effects on partially premixed diesel-methane dual fuel low temperature combustion. Appl Energy 2016;162:99–113. http://dx.doi.org/10.1016/j.apenergy.2015.10.085.

[8] Kim MY, Lee JH, Lee CS. Combustion characteristics and NO_x emissions of a dimethyl-ether-fueled premixed charge compression ignition engine. Energy Fuels 2008;22(6):4206–12. http://dx.doi.org/10.1021/ef800221g.

[9] Valentino G, Corcione FE, Iannuzzi SE, Serra S. Experimental study on performance and emissions of a high speed diesel engine fuelled with n-butanol diesel blends under premixed low temperature combustion. Fuel 2012;92(1):295–307. http://dx.doi.org/10.1016/j.fuel.2011.07.035.

[10] Jacobs TJ, Assanis DN. The attainment of premixed compression ignition low-temperature combustion in a compression ignition direct injection engine. Proc Combust Inst 2007;31(2):2913–20. http://dx.doi.org/10.1016/j.proci.2006.08.113.

[11] Liu H, Wang Z, Wang J, He X. Effects of gasoline research octane number on premixed low-temperature combustion of wide distillation fuel by gasoline/diesel blend. Fuel 2014;134:381–8. http://dx.doi.org/10.1016/j.fuel.2014.06.019.

[12] Shen M., Tuner M, Johansson B, Cannella W. Effects of EGR and intake pressure on PPC of conventional diesel, gasoline and ethanol in a heavy duty diesel engine. SAE Technical Paper: 2013-01-2702 (2013). doi:http://dx.doi.org/10.4271/2013-01-2702.

[13] Reijnders J, Boot M, de Goey P. Impact of aromaticity and cetane number on the soot-NOx trade-off in conventional and low temperature combustion. Fuel 2016;186:24–34. http://dx.doi.org/10.1016/j.fuel.2016.08.009.

[14] Boot MD, Frijters PJ, Klein-Douwel RJ, Baert RS. Oxygenated fuel composition impact on heavy-duty diesel engine emissions. SAE Technical Paper: 2007-01-2018 (2007). doi:http://dx.doi.org/10.4271/2007-01-2018.

[15] Boot M. Liquid fuel composition and the use thereof, USPTO, 2015, patent US 8,968,426.URLwww.google.com/patents/US8968426.

[16] Griffins C, Clark R, Clayton C, Stevenson P, Wardle R. Fuel compositions, USPTO, 2014, patent US 8,771,385. URLhttps://www.google.com/patents/US8771385.

[17] Han D, Ickes AM, Assanis DN, Huang Z, Bohac SV. Attainment and load extension of high-efficiency premixed low-temperature combustion with dieseline in a compression ignition engine. Energy Fuels 2010;24(6):3517–25. http://dx.doi.org/10.1021/ef100269c.

[18] Rezaei SZ, Zhang F, Xu H, Ghafourian A, Herreros JM, Shuai S. Investigation of two-stage split-injection strategies for a Dieseline fuelled PPCI engine. Fuel 2013;107:299–308. http://dx.doi.org/10.1016/j.fuel.2012.11.048.

[19] Zhang F, Xu H, Zhang J, Tian G, Kalghatgi G. Investigation into light duty dieseline fuelled partially-premixed compression ignition engine. SAE Int J Eng 2011;4. http://dx.doi.org/10.4271/2011-01-1411. 2011-01-1411.

[20] Lu X, Qian Y, Yang Z, Han D, Ji J, Zhou X, Huang Z. Experimental study on compound HCCI (homogenous charge compression ignition) combustion fueled with gasoline and diesel blends. Energy 2014;64:707–18. http://dx.doi.org/10.1016/j.energy.2013.10.068.

[21] Yu C, Wang J-X, Wang Z, Shuai S-J. Comparative study on gasoline homogeneous charge induced ignition (HCII) by diesel and gasoline/diesel blend fuels (GDBF) combustion. Fuel 2013;106:470–7. http://dx.doi.org/10.1016/j.fuel.2012.10.068.

[22] Wang J, Yang F, Ouyang M. Dieseline fueled flexible fuel compression ignition engine control based on in-cylinder pressure sensor. Appl Energy 2015;159:87–96. http://dx.doi.org/10.1016/j.apenergy.2015.08.101.

[23] Cracknell R, Bardon M, Gardiner D, Pucher G, Hamje H, Rickeard D, Ariztegui J, Pellegrini L. Vapour space flammability considerations for gasoline compression ignition vehicles operating on dieseline blends. SAE Int J Fuels Lubr 2016;9. http://dx.doi.org/10.4271/2016-01-2266. 2016-01-2266.

[24] Zhou L, Boot M, Johansson B, Reijnders J. Performance of lignin derived aromatic oxygenates in a heavy-duty diesel engine. Fuel 2014;115:469–78. http://dx.doi.org/10.1016/j.fuel.2013.07.047.

[25] Hildingsson L, Johansson B, Kalghatgi GT, Harrison AJ. Some effects of fuel auto-ignition quality and volatility in premixed compression ignition engines. SAE Int J Eng 2010;3. 2010-01-0607.