Combustion of Alternative Vehicle Fuels in Internal Combustion Engines

A report on engine performance from combustion of alternative fuels based on literature review

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March 2015

THE SWEDISH KNOWLEDGE CENTRE FOR RENEWABLE TRANSPORTATION FUELS

Report within project "A pre-study to prepare for interdisciplinary research on future alternative transportation fuels", financed by The Swedish Energy Agency.

Sammanfattning

Ambitionen med att ersätta fossila bränslen med alternativa bränslen är ett minskat utsläpp av växthusgaser som exempelvis koldioxid. Denna rapport visar att flera olika alternativa bränslekandidater såsom metanol, etanol, högre alkoholer, RME, HVO, DME och biogas/naturgas fungerar väl i olika förbränningsmotorkoncept. Energiförbrukning är i de flesta fall i stort likartad som för diesel eller bensin med undantag för metanol och etanol som ger minskad förbrukning, särskilt i Ottomotor. De alternativa bränslena anses som säkra och erbjuder i de flesta fall kraftigt minskade risker för cancer och andra negativa hälso- och miljöeffekter - något som alltför sällan uppmärksammas. Kandidaterna skiljer sig åt hur de hanteras, dvs om de är gas- eller vätskeformiga samt vad gäller utsläpp av emissioner som sot, kväveoxider, kolväten och kolmonoxid. Även här är utsläppen lägre än för diesel och bensin. De relativt små skillnaderna mellan bränslena i motoranvändning indikerar att produktion och distribution av alternativa bränslen kommer att ha en större sammantagen inverkan vad gäller miljöfaktorer och kostnader. I detta avseende har metanol pekats ut i andra studier som ett lämpligt bränsle då den kan produceras effektivt och billigt från biomassa och integrerat med hållbar el (electrofuel). Denna studie visar att metanol fungerar väl i motor, med låg energiförbrukning, låga utsläpp och låg inverkan på hälsa och miljö. Metanolen är dock inte oproblematisk utan ställer krav på korrosionsskydd och denaturering. RME och etanol är redan etablerade och fungerar utmärkt i motorer. Biogas och RME likaså. Precis som bensin, diesel och CNG levt sida vid sida under många år, finns det flera goda skäl för ett flertal parallella alternativa bränslen. Exempelvis är en fortsatt och ökad inblandning av RME i diesel och etanol + metanol i bensin (för att passa in i E85 systemet) lämpliga initiala steg framåt med i stort sett befintlig motorteknologi. Nya förbränningsmotorkoncept ger ytterligare minskad förbrukning och kan utvecklas vidare parallellt med nya bränslen. En ökad hybridisering och integration med elnätet ger förutom direkt förbättrad energianvändning även nya möjligheter till ytterligare minskad förbrukning för motorn. Detta skapar rimliga förutsättningar för hållbar bränsleproduktion såväl som energisäkra och miljömässigt hållbara transporter.

Summary

Alternative fuels can reduce green-house-gas emissions from the transport sector. This report shows that several of the alternative fuels, such as methanol, ethanol, higher alcohols, RME, HVO, DME, biogas/CNG, work well in several different engine concepts. Energy consumption is in most cases similar to that of diesel or gasoline with the exception of methanol and ethanol that offer reductions, especially in SI-engines. Alternative fuels are considered safe and in most cases associated with strong risk reduction with respect to cancer, other health aspects and environmental issues, something that is rarely acknowledged. Apart from differences in handling, whether the fuel is gaseous or liquid, emissions of soot, NOx, HC and CO vary between the fuels, although the levels typically are lower than for gasoline or diesel. The comparably small differences during engine operation indicate that production and distribution will have higher significance when it comes to the environmental performance and operating costs of the different alternative fuels. Methanol has in other reports been suggested as a promising candidate since it can be produced effectively and affordably from biomass and as an electrofuel. This report concludes that methanol works well as an engine fuel, with low energy consumption, low emissions and low environmental and health impact. Methanol is, however, not unproblematic. It requires special attention to prevent corrosion and needs to be denatured. RME and ethanol are already established and work well in engines. So do biogas/CNG and RME. Just as diesel and gasoline co-exist, there is good reason to use several alternative fuels in parallel. For example, increased amounts of RME in diesel and ethanol + methanol in gasoline (to fit the E85 system) are relevant steps forward that essentially rely on current engine technology. New combustion engine concepts can be co-developed with new fuels and lead to further reductions in energy consumption. Increased hybridization and integration with the electricity grid provide better energy utilization as well as a potential for further reduction of fuel consumption from new engine operation strategies. This enables realistic opportunities for sustainable alternative fuel production as well as energy secure and environmentally sustainable transportation.

Contents

Definitions, Acronyms, Abbreviations

AKI: Anti knock index
EATS: Emissions after-treatment system
B7: Diesel fuel with 7% biodiesel
BTE: Brake thermal efficiency (Overall efficiency of an engine)
BTL: Biomass-to-liquids diesel fuel
CA: Crank angle
CHP: Combined heat and power
CI: Compression Ignition
CNG: Compressed natural gas
CO: Carbon monoxide emission
COV: Coefficient of variation
CR: Compression ratio
DF: Duel fuel engine concept
DI: Direct injection
DICI: Direct injection compression ignition. The conventional diesel engine
DME: Di-Methyl-Ether
DNBE: Di-n-buthyl ether
DOC: Diesel oxidation catalyst
DPF: Diesel particulate filter
DoE: Design of experiments
EGR: Exhaust gas recirculation
EN 228: Gasoline fuel meeting EN 228 standard specification
EN 590: Diesel fuel meeting EN 590:2004 standard specification
E5-E85: Fuel with 5-85vol-% ethanol and 15-95vol-% gasoline
ED95: Ethanol fuel with ignition improver
EGR: Exhaust gas recirculation
EHN: 2-Ethylhexyl Nitrate
EL: Ethyl Levulinate
ETBE: Ethyl tert-butyl ether
EURO 6: Emissions regulation for cars
EURO VI: Emissions regulation for heavy vehicles
GDI: Gasoline direct injection. Also known as DISI – direct injection spark ignition
GIE: Gross indicated efficiency
FAME: Fatty acid methyl ester, "biodiesel"
FSN: Filter smoke number
FT-BTL: Biomass-to-liquids diesel fuel made by Fischer-Tropsch synthesis
GHG: Green house gas emissions (Typically CO_2, N_2O and CH_4)
GTL: Gas-to-liquids diesel fuel made from natural gas by Fischer-Tropsch synthesis
HC: Hydrocarbon emission
HCCI: Homogeneous charge compression ignition.
HD: Heavy duty. Usually refers to truck engines
HVO: Hydrotreated vegetable oil
ICE: Internal combustion engine
λ: Lambda. Phi: Ratio between air/fuel. Unity indicates balance between fuel and air
LD: Light duty. Usually refers to car engines
LHV: Lower heating value
LPG: Liquefied petroleum gas

LTC: Low temperature combustion. Modern concept to avoid NOx formation.
M5-M85: Fuel with 5-85vol-% methanol and 15-95vol-% gasoline
ML: Methyl Levulinate
MON: Motor octane number
MPG: Miles per gallon
NEDC: New European driving cycle
NO_x: Nitrogen oxide emission
PAH: Polycyclic aromatic hydrocarbon
Phi: Ratio between fuel/air. Unity indicates balance between fuel and air
POMDME: Polyoxymethylene Dimethyl Ethers (sometimes known as **PODE** or **DMMn)**
PPC: Partially premixed combustion
RME: rapeseed methyl ester
RCCI: Reactivity controlled compression ignition.
RON: Research octane number
SCR: Selective catalytic reduction
SFC: Specific fuel consumption
SI: Spark Ignited. – The traditional gasoline (Otto) engine
SME: Soy methyl ester
SNG: Synthetic natural gas
TDI: Turbo direct injection
TERF: Toluene-ethanol reference fuel
TWC: Three way catalyst

1.Introduction

Scope
This report provides an overview of alternative fuels that are in use or have been tested in internal combustion engines. The focus is on experiences from alternative fuels in engines related to technical issues, potential engine efficiency and emissions, but not on fuel costs, production or availability, and aim at serving the reader with a background of the merits and concerns of potential future fuels and engine concepts from a technical context. The report covers the main alternative fuels and some more unusual ones but should not be regarded as a complete review since some potential fuel candidates might have been overseen by mistake, due to the limited time available for the review. The review is also intentionally limited, and publications dealing with alternative fuels or engine technology that are either outdated or not relevant for Swedish conditions have been excluded in the screening process. Examples of such excluded fuels or engine technologies are for instance coconut oil and carbureted SI engines. Publications dealing with solid fuels such as powders from coal, wood and metals have been excluded as well due to their limited success as well as the huge challenges that make solid fuels much less attractive than liquid or gaseous alternative fuels within the foreseeable future.

Review method
The material is gathered mainly by searching the Scopus databases, that covers essentially all relevant journals and publications on the field, but also from other internet sources, from our own research and experience within the research group at Lund University, from visited conferences and workshops and also through discussions with other experts in the field. A simple search on for instance google scholar using the phrase " alternative fuels engine" gives close to 400 000 hits, indicating the huge interest and also vast amount of information on the topic. Of all hits, possibly some 20 000 are articles of reasonable quality and relevance. To find the most relevant articles the search has therefore been performed in two sequences, the first focusing on the most recent research, 2010-2014, to find the relevant alternative fuel candidates and the second search very specifically on individual alternative fuels in specific engine combustion concepts. Over 250 publications, reports or presentations have been examined while around 70 of those have been read more carefully and the majority included in this report. Most of the alternative fuel sections are written in a way to provide an overview of the more well-known aspects of the fuel group, followed up by short review examples of relevant publications with the intent to exemplify current research status, important results or potential problems, but also as a path for further information and references for the reader.

2.Overview of engine combustion principles and their sensitivity to fuel properties

Basic engine operating principles
Internal combustion engines (ICE) are based on a piston and cylinder system that can exchange the working fluids, contain the combustion, and convert the in-cylinder pressure into rotational work. Combustion engines work according to either the two- or four-stroke principle. Either case involves five fundamental processes: filling the cylinder with fuel and air, compression, combustion, expansion, and emptying the cylinder of combustion gases. Other mechanical solutions for ICE's exist but since they are not available commercially and all depend on the same combustion principles as the piston engines these are not included in this investigation.

Stoichiometry
Stoichiometric operation means that there is an ideal proportion of oxygen and fuel (lambda or phi at unity) from a combustion perspective. From an engine efficiency perspective it is often better to run lean (lambda >1 or phi <1). One important advantage with stoichiometric operation is that a three-way catalyst (TWC) can be used, effectively reducing the emissions of HC, CO and NOx.

EGR
EGR or exhaust gas recirculation is one way to dilute and slow down the combustion and is usually employed in DICI engines to reduce NOx. EGR can also be employed for load control.

LTC
LTC or low temperature combustion is a strategy to maintain combustion temperature below the formation temperature of NOx and soot.

Supercharging
To increase the load of an engine, supercharging may be employed. Through supercharging, the in-cylinder mass of air and fuel can be increased and thus more work produced from each cycle. Supercharging can be achieved using a mechanically driven compressor, but it is more efficient to use a turbocharger that exploits the otherwise wasted exhaust energy. For low calorific gaseous fuels, supercharging is very useful for increasing the power output and thus the mechanical and total efficiency of the engine.

Engine efficiency
The energy flow through an internal combustion engine can roughly be divided into four parts according to the losses and efficiencies.

1. Combustion efficiency: Chemically bound fuel energy is converted through combustion into heat. If the combustion is incomplete, the exhaust will contain products that still have energy content. Combustion efficiency is usually higher than 99% in a diesel (CI) engine, while a spark ignition (SI) engine can have combustion efficiency as low as 90–95%.

2. Thermodynamic efficiency: Heat is converted through a thermodynamic cycle into mechanical work. The theoretical maximum thermodynamic efficiency is approximately 85%, but in reality it is approximately 35–40% for stoichiometric SI and 50% for CI. The main difficulty in converting heat to work is that of limiting the associated heat loss to the expelled exhaust gases and the heat transfer through the cylinder walls. In automotive applications, the excess heat is used for heating the vehicle compartment but there are also substantial research efforts on waste heat recovery systems. In stationary CHP applications, these losses can be used for district heating, while in some gasification/engine systems, the wasted heat can be used in the gasification process. In either case, the system efficiency is increased by using the waste heat.

3. Gas exchange efficiency: The burned gas needs to be replaced with fresh air (in an SI engine, with air/fuel mixture). The gas exchange efficiency indicates whether this can be done with low losses or whether high pumping work is needed. Under high loads, the pumping work is limited, but the loss can be significant in SI engines operating under lower loads due to throttling. Gas exchange efficiency is often in the order of 85–95%.

4. Mechanical efficiency: Internal friction of the engine parts consumes some of the power, as do all the auxiliaries, such as the water pump, oil pump, and generator. The mechanical efficiency relates these losses to the power produced. At full load operation, mechanical efficiency may reach 95%, but at lower loads it drops to 0% at idle (no practical work produced).

Brake (total) efficiency is the product of the four efficiencies listed above, the weakest of which is clearly thermodynamic efficiency. The main losses in the thermodynamic cycle occur during the conversion of heat into work, when heat is lost to the combustion chamber walls and into the atmosphere with the expelled exhaust gases.

There are a number of other measures of efficiencies that are relevant to understand in the presented work. In engine-related work, *gross indicated efficiency* and *net indicated efficiency* are commonly used. These efficiencies have historical significance, since they could be calculated from the indicator diagrams traditionally produced from simultaneous pressure and volume measurements. Gross indicated efficiency is the product of combustion efficiency and thermodynamic efficiency, while net indicated efficiency is defined as the product of gross indicated efficiency and gas exchange efficiency.

2.1 Commercial combustion concepts commonly used in vehicles

2.1.1 Spark Ignition (SI)

The vast majority of cars, smaller vehicles and smaller power equipment (lawn mower, chain saws etc) use SI engines. The SI engine works according to the following fundamental principles. Fuel and air are mixed before entering the cylinder. The compressed in-cylinder charge is ignited at a controlled time by an electrical spark. After a short delay, the homogeneous charge of fuel and air burns from the spark plug out to the cylinder walls through flame propagation. Engine load is controlled by a throttle in the induction channel, thus controlling the total amount of fuel and air that enters the cylinder. There are three main drawbacks to the SI engine. The first is the throttle that limits part load efficiency by increasing the pumping losses. The second is that, with a premixed charge, the compression ratio has to be limited (which means lower efficiency) and a high-octane fuel must be employed to avoid pre-ignition and knock. The third drawback is that a relatively large part of the unburnt fuel escapes the combustion by flame quenching close to combustion chamber walls and by entering crevice volumes (e.g topland crevice) and thereby decrease the combustion efficiency and increases the amount of unburnt hydrocarbons released into the atmosphere (Figure 1). The SI engine has several advantages. It is easy to control. It can be run very cleanly by using stoichiometric operation and a three-way catalytic converter after-treatment system (TWC). It lends itself very well to either liquid or gaseous fuel operation, with either lean-burn or stoichiometric operation. The fuel can be easily provided to the engine through cheap low-pressure injection systems. The conventional port injected SI engine is sensitive to the evaporation properties of the fuel since the fuel needs to be vaporized to enter the combustion chamber. As mentioned, the ignition properties are essential as well to avoid uncontrolled combustion. To have a reasonably high compression ratio, a fuel with high resistance to auto-ignition is required – the higher the better in principle. The premixed operation means that there are typically no soot emissions, thus fuel composition is less critical than for CI engines from that point of view. The carbon versus energy content in the fuel will however dictate the amount of CO_2 emissions and play a role on HC and CO emissions as well. The high engine out emissions of HC and CO is a consequence of the premixed charge and wall quenching.

2.1.2 Direct Injection Spark Ignition (DISI)

To reduce the negative consequences from fully premixing, such as high CO and HC emissions as well as pre-ignition, modern state of the art SI engines employ direct injection of the fuel. From a fuel properties perspective, evaporation properties are not that sensitive any more since fuel evaporation is not problematic when injecting the fuel directly into the hot compressed cylinder gases. Instead, the heat of vaporization can now be exploited to reduce the in-cylinder temperature, which reduces the risk for pre-ignition and knock but also has the beneficial effect of reducing the compression work. With reduced risk for pre-ignition and knock the compression ratio can be increased, that together with the reduced compression work leads to increased engine efficiency. Direct injection of fuel is not without its problems. Under certain cases, DISI engines may produce high level of soot emissions. A problem that is almost none existing in port fuel injected SI engines.

2.1.3 Direct Injection Compression Ignition (DICI)

The diesel or direct injection compression ignition (DICI) engine is, thanks to its high efficiency, the most common type of engine for commercial vehicles and marine applications. The DICI engine is also increasing in popularity for cars, especially in Europe. The DICI works by that only air is drawn through the induction system into the engine. The air is compressed, and shortly before the top dead centre (TDC) is reached, the fuel is injected directly into the cylinder and ignited by the high temperature and pressure of the compressed air. The CI has several advantages over the SI engine. The load is controlled by the amount of fuel injected rather than by using a throttle that increases the pumping losses. The combustion efficiency is usually very high, since little fuel will reach and quench against the cylinder wall and crevice volumes, thus avoiding unburned hydrocarbon and carbon monoxide emissions. Furthermore, the compression ratio can be comparatively high, since there is no risk of pre-ignition or knock. One major disadvantage of the CI engine is its comparatively complex and expensive high pressure fuel injection system. Another important problem is the great amount of NOx and soot produced by CI combustion. This is explained by the local fuel-rich zones and high local combustion temperatures that give rise to soot and NOx, respectively (Figure 1). Fuel properties are also important for the likelihood of soot production. Unfortunately, exhaust after-treatment is not as elegantly handled in the CI engine as in the SI engine, and it might require several separate catalytic converters and particulate filters for the CI engine to comply with the more stringent emissions regulations. The evaporation properties are in general of low sensitivity due to the direct injection. With very low temperatures, the low vapor pressure of diesel means that very little diesel can be evaporated. This leads to starting problems–

historically solved by adding some gasoline to the diesel. To achieve traditional CI combustion the fuel should have little resistance to auto-ignition (high cetane number).

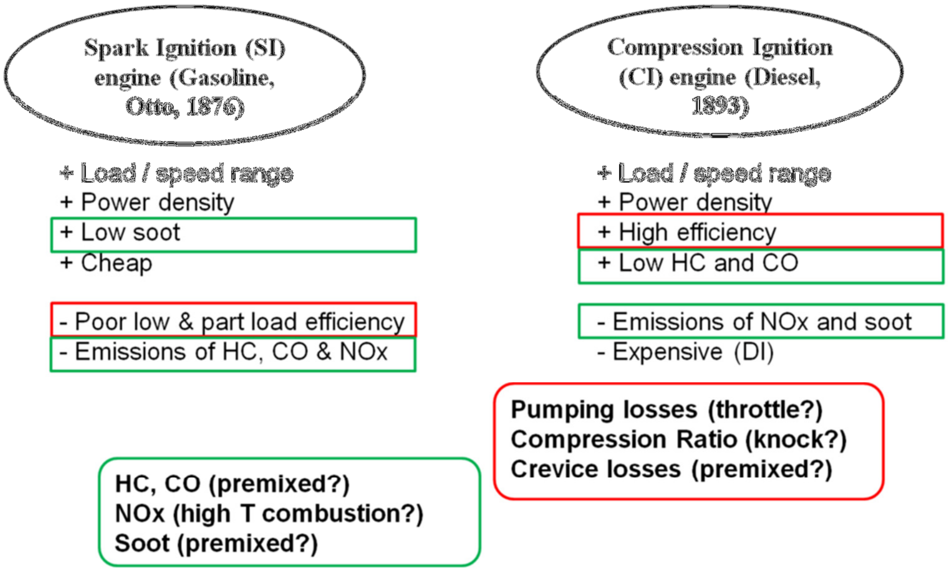

Figure 1. Overview of SI and CI engine pros and cons. Red boxes are related to efficiency while green boxes are related to emissions.

2.2 Other commercial combustion concepts

2.2.1 CI - Dual fuel engines

For larger stationary gas engines, lean-burn dual-fuel is often the combustion principle of choice for installations where gas delivery can be uneven. Total efficiency is usually very high and can be even higher than for a comparably sized CI engine due to fast combustion leading to high thermodynamic efficiency. Due to combustion close to the combustion chamber walls, the combustion efficiency is usually a bit lower, though. Gas and air are mixed and provided to the engine as in the SI engine, but instead of a spark igniting the mixture, a high-cetane (i.e., easily ignited) fuel is direct-injected and ignited by the high pressure and temperature from the compression, which in turn ignites the main gas and air charge. The ensuing combustion occurs mainly through flame propagation. The concept is gaining interest for automotive applications.

2.2.2 SI – Lean-burn pre-chamber engines

Lean-burn pre-chamber SI engines are possibly the most common type of engine for larger stationary applications (>1 MW) in which the gas supply is stable. The concept is also gaining interest for automotive applications. These engines do not require any additional fuel for ignition and have very high efficiencies. During induction, gas is also fed separately to a small pre-chamber where the gas mixture is richer than in the cylinder. At the end of the compression, the rich mixture in the pre-chamber is ignited by a spark and the flames from the nozzles of the pre-chamber in turn ignite the lean mixture in the cylinder. The lean gas charge is consumed by a flame front combustion. The reason for using a pre-chamber is that it can be difficult to ignite lean mixtures with a spark alone. Such difficulties can lead to slow combustion, misfiring, and thus high emissions and low efficiency. The advantages and disadvantages of lean-burn pre-chamber SI engines are basically the same as those of lean-burn dual-fuel engines, except for the single-fuel requirement. Emissions can be very low and efficiencies very high if the pre-chamber is carefully designed.

2.3 Combustion concepts being researched and under development

For more than two decades there has been quite active research on alternative and more efficient and clean combustion principles. HCCI, or ATAC as it originally was coined, was the first low temperature combustion strategy for engines. Although HCCI has not been commercialized, it provided extensive new insights to engine

combustion that has led to the development of many other concepts. These include RCCI and PPC that are described below, but also PCCI, PPCI, GDCI and many others that have low temperature combustion and high dilution levels and in common and, due to their similarities, are not described further.
A common feature of the new combustion principles is that they offer new opportunities for both existing and new alternative fuels. HCCI can be run on essentially any fuel by tailoring compression ratio and inlet temperature, RCCI uses two fuels with varying proportions while PPC runs efficiently on any liquid fuel by adjusting fuel injection and other parameters (Figure 2). PPC has also demonstrated excellent efficiency and very low emissions for naphtha, that has an octane rating of around 70; essentially a fuel with ignition properties in-between diesel and gasoline.

2.3.1 Homogeneous Charge Compression Ignition (HCCI)

The homogenous charge compression ignition (HCCI) principle is a comparatively new concept that has yet to find commercial success. The working principle is similar to that of the SI engine, in that the fuel and air are mixed before being induced into the cylinder. The HCCI engine does not use any specific device to ignite the in-cylinder charge. Combustion starts simultaneously throughout the cylinder through auto-ignition by compressing the charge to sufficiently high pressures and temperatures. In regular operation, the HCCI engine needs dilution of the intake charge to limit the pressure rise rate during combustion. This leads to a low combustion temperature that is beneficial for efficiency and for low soot and NOx emissions. The premixing and low combustion temperature does however lead to very high emissions of CO and HC. By carefully adjusting compression ratio and inlet temperature, almost any fuel can be used with HCCI. The challenges with controllability and low load have limited the use of HCCI to an ideal combustion research tool.

2.3.2 Reactivity Controlled Compression Ignition (RCCI)

RCCI uses two fuels with different reactivity (auto-ignition resistance) in different proportions to optimize the combustion behavior at different operating conditions. It is similar to the dual fuel concept by using one fuel with high auto-ignition resistance premixed with air and one fuel with low auto-ignition resistance direct injected. Unlike the duel fuel concept, RCCI uses dilution and low temperature combustion, in a similar way to HCCI. Very high efficiencies have been reported, combined with emissions characteristics similar to HCCI.

2.3.3 Partially Premixed Combustion (PPC)

PPC can be seen as a concept combining principles from both DICI and HCCI. Typically, PPC is associated with a separation of the direct injection event and the auto-ignition combustion. By injecting the fuel at some point during the compression, combined with air dilution and high amounts of residual gases and a fuel with some resistance to auto-ignition, fully premixed or fully heterogeneous conditions can be avoided. This leads to low emissions of soot, NOx, HC and CO together with very high efficiency. PPC exhibits substantial fuel flexibility with liquid fuels by tailoring the injection strategy towards the auto-ignition properties of the fuel. However, with low auto-ignition resistance of the fuel, sufficient premixing is difficult to achieve leading to increased emissions of soot. Gaseous fuels have not been investigated with PPC due to the anticipated difficulties associated with suitable direct injection of gas.

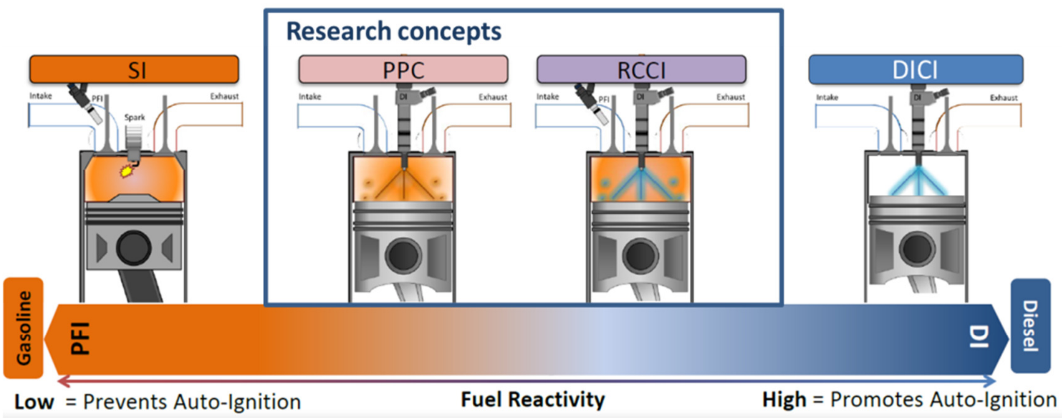

Figure 2. Engine combustion research concepts compared to conventional SI and DICI. Blue indicates a reactive fuel like diesel while orange indicates a none-reactive fuel like gasoline. Modified from [1].

2.4 Fuel relevant engine hardware

Modern engines have similar fuel related hardware configuration regardless of combustion principle, but with differences depending mainly on if the fuel is liquid or gaseous. Figure 3 shows the fuelling system of a DISI engine (often known as gasoline direct injection, GDI). In common with all other modern engines there are fuel pumps, a fuel injector, fuel lines and so on. The fuel injector is placed with direct injection into the cylinder and to overcome the in-cylinder pressure and provide sufficient air-fuel mixing the injection pressure is typically around 300 bar. DICI engines have a very similar configuration although usually with the injector centrally placed. Injection pressure is much higher at around 2000-3000 bar to provide sufficient air and fuel mixing since injection is simultaneous with combustion. The very high pressures cost energy and the high-pressure systems are both very expensive as well as sensitive to impurities in the fuel. Conventional SI engines are port injected and fuel pressure is typically around 3 bar.

Gas engines are usually port injected as well. To avoid that the gas escapes, the whole fuel system including the fuel tank is pressurized. For LPG and DME a fuel tank pressure of 5 bar is sufficient while for CNG and Hydrogen, fuel tank pressure is much higher at 200 and 700 bar respectively. Hydrogen can be liquefied similar to LNG. LNG is for instance stored at -162˚C and with just little overpressure adding quite some complexity and expense. Gas engines can also be direct injected and some are also equipped with pre-chambers having their own fuel supply.

The different energy content for various fuels means that the fuel flow rates and thus fuelling components needs to be tailored to the specific fuel. Several fuels, for instance alcohols and natural gas, have poor lubricity that require either fuel pumps and injectors with low scuffing materials or addition of lubricating additives. Alcohols, especially methanol and ethanol, and some other fuels are corrosive to certain metals, rubbers and polymers. Hydrogen is possibly the most demanding fuel, since not only is its storage complicated; it also reacts with several metals. The hydrogen molecule is so small that it simply leaks through several metals and other materials.

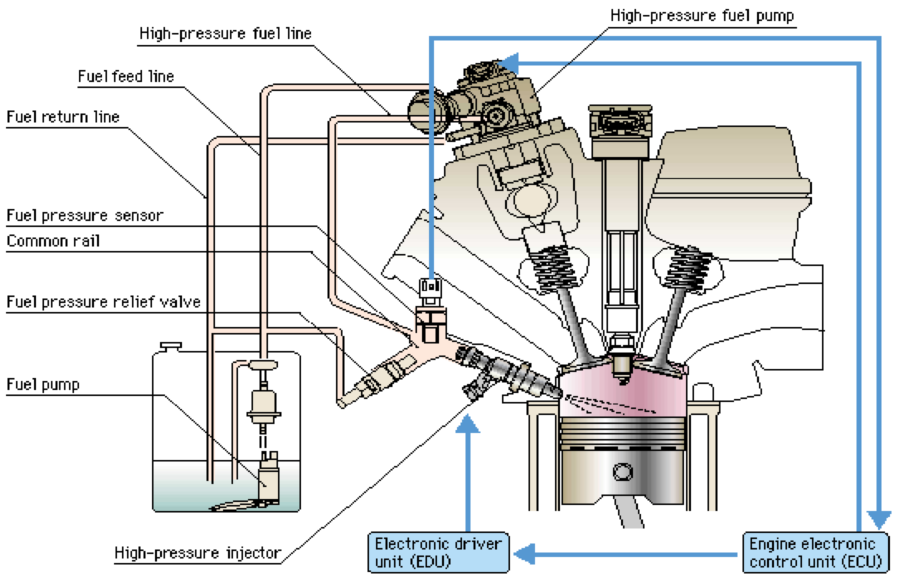

Figure 3. Fuel system of a DISI engine.

2.5 Emissions after-treatment versus engine concepts

Nitrous oxides (NOx), hydrocarbons (HC), carbon monoxide (CO) and soot or particulate matter (PM) are known as regulated emissions. The emissions legislation is increasingly getting stricter. Most markets in the world requires vehicles with some sort of emissions after-treatment system (EATS) while in US, Europe, Japan and some other places the demands requires advanced EATS to meet the regulations. SI are typically operated stoichiometric which allows the use of a three way catalyst (TWC) that is a comparably cheap and effective after-treatment device for NOx, HC and CO. SI typically operates premixed and does not produce enough soot to require a soot EATS. The emerging direct injected SI engines, can however produce significant amounts of soot, which could lead to required use of particulate filters.

DICI engines emit less HC and CO but high amounts of NOx and soot. To meet the latest and strict regulations US 10 and EURO VI for heavy duty vehicles, such as buses and trucks, advanced and expensive EATS are required (see Figure 4). EURO 6 for cars is not as strict and simpler NOx reduction and particulate filters used.
Lean burn engines may get away with only an oxidizing catalytic converter (OC or DOC) to reduce CO and HC but on some markets selective catalytic reduction (SCR) is needed to reduce NOx. Emerging combustion concepts, as RCCI and PPC, are designed to operate without the need of expensive EATS. RCCI may get away with only DOC while PPC shows the overall best emissions performance. Low load CO and HC emissions are, however, still too high from PPC to be EURO VI compliant. A DOC might be needed.

Future regulations may prove difficult to meet for DICI engines and may require adaption of RCCI and PPC strategies. Methane is also a challenge to reduce sufficiently from CNG engines, and will likely require advances on catalyst development.

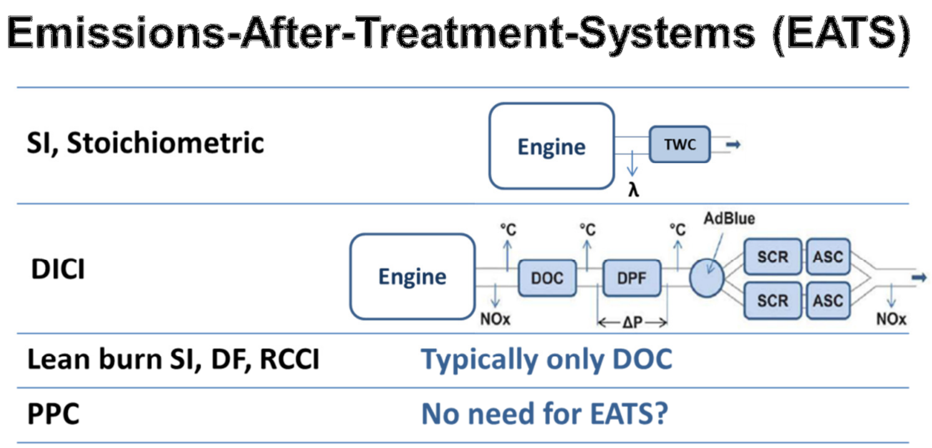

Figure 4. Simplistic overview of emissions after-treatment systems versus combustion concepts.

3.Compilation of experiences using alternative fuel

3.1 Alcohols

Alcohols and especially ethanol have more than a century long history as fuels in combustion engines. Ethanol, either neat or as E85 (15 % gasoline) has been commercially used for a couple of decades on certain markets, for instance Brazil and Sweden. Ethanol is also used as a drop-in fuel up to 10% in gasoline on several markets, including EU and USA. SI flex-fuel engines are commonly used and can switch operation from gasoline to, for instance E85, on the fly. Although more uncommon, ethanol is also used in DICI “diesel” engines in for instance public transportation [2]. Methanol has not reached the same level of use as ethanol. However, there is as quite substantial experience with methanol from several fleet studies [3-5]. Methanol is in commercial use today in China with quite some local variations. M5 to M30 are used directly in standard gasoline engines while M85 and M100 are used in dedicated methanol vehicles. The experiences in China still need to be properly evaluated [6]. Methanol is a preferred fuel in motorsports since it is considered to be safer than for instance gasoline since it can easily be extinguished with water in the case of fire. The experience with higher alcohols such as pentanol and hexanol is more limited, but in general these alcohols have properties closer to gasoline. Octane ratings and amount of low temperature reactions are similar, and just as butanol they do not mix with water.

The high octane ratings of alcohols make them less prone to engine knock or pre-ignition and they are therefore well suited as SI engine fuels. The reduced knock tendencies can be exploited with an increase in compression ratio leading to both higher efficiency and higher power output compared to gasoline operation. The high octane ratings of alcohols do also mean that they are not naturally suited to CI operation. Such engines are therefore operated with combinations of increased compression ratios, ignition improvers, inlet air heaters or assisted ignition from glow plug. Also hot residual gases have been employed. The high heat of vaporization of alcohols leads to a reduction of temperature in the charge, which can be exploited for improved cylinder filling and reduced compression work. Another interesting and beneficial property of alcohols and especially methanol is the comparably high molar expansion that provides additional pressure during the chemical reactions but without additional heat.

The lower energy content of simpler alcohols compared to gasoline does not only mean that more fuel needs to be carried onboard a vehicle, but also that the engine fuelling system needs to be designed to accommodate higher fueling rates. The energy content of simpler alcohols are, however, much higher than for energy gases or batteries. Engine operation with alcohols is associated with a couple of other challenges. Alcohols are more corrosive than either gasoline or diesel. Methanol containing water is the most aggressive while higher alcohols are increasingly less so [7]. To avoid corrosion alcohol engines use steel and certain plastics throughout the fueling system and in the case of methanol with water, stainless steel and Teflon are recommended. Metals like lead, zinc, copper, aluminum and magnesium as well as some elastomers, plastics and rubber should not be used in contact with alcohols. The low lubricity of alcohols requires additives in the fuel to avoid problems with diesel type fuel pumps and injectors – unless bespoke units are used. Alcohols are solvents and can also form acids during combustion which means higher demands on lubricant additives and possibly more frequent oil changes. Unlike gasoline or diesel, neat alcohols are single component fuels with single specific vapor pressures and boiling points that infer more challenging low temperature cold starts. It can be difficult to vaporize enough fuel to reach an ignitable mixture.

Alcohol fuels offer reduced probability for soot emissions thanks to the oxygen present in the fuel. Together with the reduced combustion temperature, alcohols offers an attractive way to operate CI engines with reduced emissions of both NOx and soot compared to regular diesel fuel. SI engines are typically run stoichiometric with a TWC that effectively reduces the emissions of HC, CO and NOx. Engine out emissions of formaldehyde, acetaldehyde and acetic acid can be high and requires an effective catalyst to be limited at the tail-pipe. Methanol is possibly the most controversial alternative fuel due to its acute toxicity, but the reduced risk for cancer and other health issues [8], a

95% reduced risk for fire damages [9] and the strongly reduced impact on environmental damages from spillage [10] indicates overall benefits for methanol versus fossil gasoline or diesel. Ethanol has similar beneficial properties.

3.1.1 Methanol (including mixtures with gasoline)

Methanol can be used in different combustion concepts, e.g. SI, DICI and RCCI engines.

SI

Sileghem et al [11] have investigated the influence of water content in MeOH on SI engine efficiency and emissions. Water removal in alcohol production can, as an example, account for as much as 14% of the energy content for 99% purity ethanol. Enabling engine operation with hydrous alcohol could therefore potentially lead to improved overall energy use and reduced fuel cost. The results show that MeOH has around 6 % higher BTE than gasoline in the experiments and that water addition up to the maximum tested 10 % hardly affect efficiency. The reasons are related to the improved cylinder filling due the water cooling effect and reduced in-cylinder cooling losses. NOx emissions are reduced but CO emissions increased due to the reduced temperature. Both emissions are above 6 g/kWh but since operation is stoichiometric, a TWC can be employed for very low tail-pipe emissions.

Lean burn and EGR in SI was investigated by Naganuma et al [12]. MeOH combustion is more tolerable to lean burn than gasoline (lambda 1.5 versus 1.25) and also offers higher EGR tolerance 30 % versus 10 %. A modified 8 valve 1.9l VW TDI engine (19.5 CR) could be operated in throttle-less stoichiometric SI mode between full load (11.6 bar) down to 3.3 bar. Peak brake efficiency of 42 % was reached, which is higher than for the std diesel DICI operation of the engine. Similar results were achieved by Brusstar et al [13] with a similar engine. BTE approached 43 % while diesel operation reached 40%. The peak efficiency area over load and speed was 5 times bigger than that for the diesel engine, clearly showing the benefits of controlling load with EGR. A large peak efficiency area is crucial for high average efficiency and millage during regular vehicle operation.

DICI

Even though presented already 1990, the work by Caterpillar on truck operation on neat methanol contains much valuable information [5]. They used two DICI 33 ton trucks that operated in regular delivery, driving the same path in British Columbia, Canada year around until they covered a total of 600 000 km (10 000 hours). Conditions varied from +30˚C and low humidity to -30˚C with heavy snow. The DICI engines were modified with for higher fueling rate and the vehicles equipped with larger stainless fuel tanks due to the lower energy content of methanol. The fuel injectors had 9 radial sprays and a tenth spray directed straight downwards to hit an impingement point on top of the piston. Two of the radial sprays were directed to the almost centrally positioned glow plug, that was used for cold start and to assist the ignition, while the tenth spray created a fuel spray ring formed by the bounced jet, to guide the flame front between the radial sprays. CR was 16.0:1, while the turbine was increased in size and the fuel injection timing advanced, relative to diesel operation. No optimization was done on the combustion chamber geometry to accommodate the MeOH operation, but still power and efficiency matched that of the original diesel engine. Emissions were below the upcoming 1994 regulations, with largely reduced soot emissions, leading to smoke free operation. Conventional engine lubricant was used with same oil change periods as for diesel operation. The methanol engines showed reduced cylinder liner wear, but increased valve face wear, the latter a consequence of the reduced soot that helps lubricating the valves, and easily solved with modified valve material. Injector life was only 1000 hours, due to buildup of deposits from contamination of MeOH and lube oil. The glow plugs had to be replaced every 500 hours on average, due to corrosion or poor quality due their more or less continues use. The drivers reported that the engines started quickly in cold weather and operated smoother and quieter than the diesels. During summer, after short stops, the hot engines could be difficult to start due to vapor lock.

A more recent investigation was performed by Roberts et al [14]. They ran neat methanol and neat ethanol in a MD engine with DICI. CR was surprisingly low at 16.8, and they used air heating to 125˚C to get ignition. There was no mentioning of ignition improver or ignition assistance. The approach was to run stoichiometric to realize the use of a

TWC and to monitor soot. Soot stayed well below the current legislation for both fuels. An energy balance model including turbo compounding indicated a BTE of 51% for the concept.

RCCI

Dempsey et al [15] investigated MeOH/diesel RCCI in 1.9 l GM engine in stationary cycle points covering 2.3-17.7bar IMEPg over 1500-2300 rpm. Load was limited by the allowed peak cylinder pressure of 150 bar. Peak GIE of 51.3% was reached with very low levels of soot and NOx. Higher loads were operated with >90% MeOH while idle was operated on neat diesel. An open combustion chamber was adapted for RCCI leading to higher efficiency but also slightly higher NOx.

3.1.2 Ethanol (including mixtures with gasoline)

Ethanol can be used in different combustion concepts, e.g. SI, DICI and PPC engines.

SI

The research trend in US is towards higher octane ratings as a means to increase engine efficiency and thus reduce fuel consumption and CO_2 emissions [16-18]. One example of this is [14] where going from E10-91RON at 10:1 CR to E30-101 RON at 13:1 CR yielded 6–9% improvement in CO_2 emissions and 2% worse to 1% better MPG fuel economy, depending on the drive cycle. The increase in MPG is related to the lower volumetric energy content of the E30 mixture but actually corresponds to an increase in engine efficiency.

Splitter et al [19] found that intermediate mixtures (E30) have a more pronounced improvement of the knock limit than can be explained by the AKI (or RON), see Figure 5. This leads, not only to increased efficiency of 10% but also to an increase in power output of more than 20%. By employing 15% EGR further improvements were achieved.

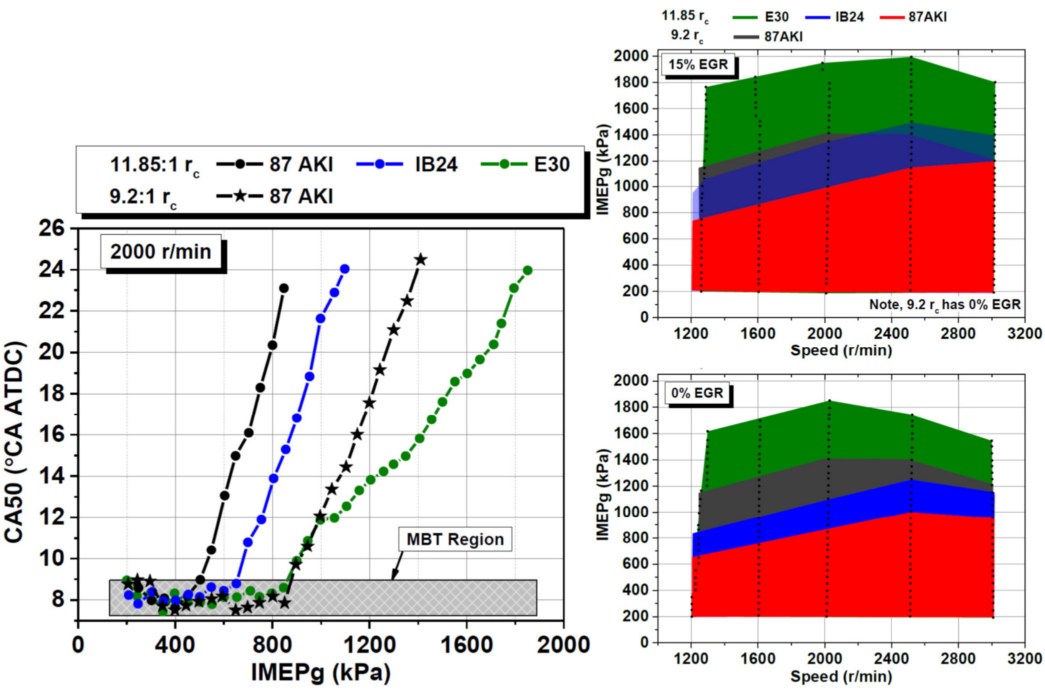

Figure 5. Comparison between regular gasoline (87 AKI), 24% isobutanol in gasoline (IB24) and E30 [15]. The figure to the left shows the surprisingly strong effect on knock limit for E30. Figures to the right show the load range of the different fuels in the tested engine.

DICI
Ethanol is not a natural diesel engine fuel but Scania has used what is known as ED95 in buses for 20 years on some markets [20, 21]. ED95 usually contains 92% wet ethanol (max 6.8% water), 3% MTBE, around 5% ignition improver (Beraid 3555) and ppm levels of corrosion inhibitor. To achieve autoignition the compression ratio is increased from 17:1 to 28:1. Power output and brake efficiency is similar to the diesel engine equivalent, while soot emissions are halved. HC and CO emissions are increased. By use of EGR and EATS, EURO V emission regulations are met.

PPC
Neat ethanol and ethanol mixtures have been investigated in PPC. Shen et al. investigated the influence from mixture strength, EGR and boost levels on HD-PPC performance for ethanol, diesel and RON69 naphtha [22,23]. All three fuels exhibited a reduction in efficiency when running at stoichiometric conditions, to determine the potential for using a TWC in PPC. Ethanol had a clear advantage with the least efficiency drop and reached a gross indicated efficiency of 49% with potential for ultra-low tailpipe emissions. The highest recorded efficiency with ethanol was 56% and was reached with a combination of 32% EGR, 2.5 bar intake pressure and lambda 1.77. The CR was 17.3:1 and the inlet temperature 90˚C. Soot emissions are essentially below detection level, while NOx, HC and CO balance on the levels for EURO VI and are sensitive to small changes in control. One of the main challenges with ethanol-PPC is the high pressure-rise rate that leads to high noise levels.

3.1.3 Butanol and higher alcohols
Toyota is investigating SI engine performance using lean boosted Atkinson cycle operation with high RON fuels [24, 25]. Butanol has properties that are closer to gasoline than ethanol. According to the results iso-butanol can give higher efficiency than 1-butanol but not as high as ethanol (see Figure 6).

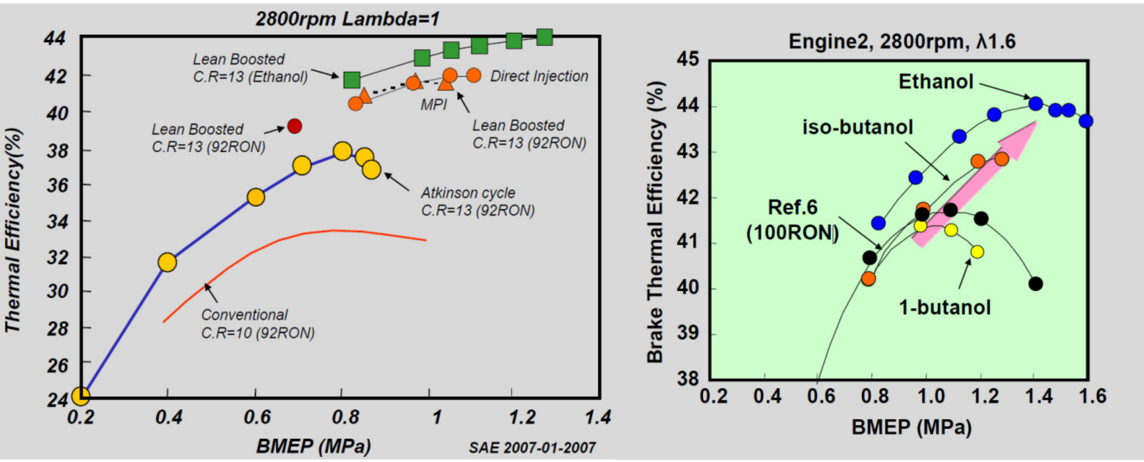

Figure 6. SI engine research at Toyota [24,25]. The left figure shows the merits of using Atkinson cycle, lean boost and high RON fuels. The right figure shows a comparison between 1-butanol, iso-butanol and ethanol at lean operation.

3.1.4 Alcohol mixtures
A range of different blends of alcohols have been tested in engine concepts such as SI, DICI and PPC.

SI
The concept of ternary blends of methanol, ethanol and gasoline, allow variation of the fractions of the individual components without changing the fundamental properties of the fuel blend (Turner et al [26]). In this work a method was employed to create mixtures of E42.5M28, E21M42 and M56(G44) that all have the same octane rating, stoichiometric AFR, density and LHV as commercial E85(G15). The four blends were tested in a flex-fuel vehicle

(SAAB 93, 1.8 BioPower) in both NEDC and real driving. No adaptions where made to the vehicle and no problems were experienced during the tests. All blends provided the same vehicle performance and cold starting was excellent. Methanol offers better cold start performance than ethanol thanks to its beneficial relation at low temperature between flammable mixture strength and vapor pressure. The conclusions of this work is that the ternary blend approach can be used in the existing vehicle fleet without recalibration; that further reduction of gasoline in transportation can be achieved and that other biofuels (for instance butanol) can be used for new ternary blends.

DICI

Isopropyl alcohol and methanol were blended with diesel and operated in a LD diesel engine at low load by Chokalingam et al [27]. The best compromise between emissions and efficiency was reached with a mixture of 60% diesel, 20% isopropyl alcohol and 20% methanol. BTE increased from 31 to 36% while soot and NOx were reduced 5% compared to neat diesel operation.

By replacing part of the diesel with ethanol to create a mixture of 70% diesel, 20 % ethanol and 10% biodiesel the average engine out soot emissions could be reduced more than 80 % both in and outside the NEDC drive cycle (Napolitano et al) [28]. NOx was also slightly decreased but HC and CO could be doubled in the NEDC although hardly affected at higher loads. By DoE optimization HC, CO, fuel flow and noise could be reduced although with increase in soot and NOx. The most sensitive parameters where; energy content in the pilot injection, rail pressure and combustion phasing.

Dual-Fuel

In [29] E85 was introduced to the engine trough the intake ports while diesel was direct injected. The ratio of ethanol could be varied up to 40-90%, depending on operating conditions and limited by pressure rise rate. Soot emissions were very low while NOx, CO and HC emissions were quite high. The highest recorded BTE was 42%.

PPC

Solaka et al [30] investigated the influence from toluene, isooctane, n-heptane and ethanol (TERF) mixtures on LD-PPC. One important result is that an increasing aromatic content in the fuel increases all regulated emissions. Soot was increased drastically while NOx was almost doubled, the later an effect of the faster combustion from increased aromatic content.

3.2 FAME

Fatty-acid methyl ester (FAME) is a group of fuels originating from vegetable oils and animal fats commonly known as biodiesel. In Europe this is typically rapeseed methyl ester (RME) while in US it is more common with soy methyl ester (SME). Since essentially any vegetable oil or animal fat can be transesterified to biodiesel or used as fuel directly there is a substantial number of different fuel feedstocks, for instance oils from algea, palm, coconut, jojoba, mustard, pongamia, tallow, lard, chicken fat, brain oil and many other. The direct use of vegetable oils in engines, for instance rapeseed oil, is possible, but the associated problems with coke formation or polymerization makes these fuel unpractical and they are therefore not discussed any further. There is also a wealth of publications referring to engine experiments using locally produced fuels from for instance palm oil etc, and applied in dated engine technology. Such publications are not included in this work unless they are judged to be of relevance for Scandinavian conditions. Many of these produced fuels have anyway similar influence on engine operation as the more common FAME alternatives.

FAME fuels have been used in engines for a long time and there is substantial knowledge when using them either neat (B100) or as drop-in fuel in diesel in conventional diesel engines (DICI). Currently up to 7% biodiesel is allowed in European diesel by the EN590 diesel fuel specification. Several properties of FAME are similar to that of fossil diesel and they can therefore be used in diesel engines with little or no modifications. FAME has similar or slightly higher viscosity than diesel and for that reason work well in DICI fuel injection systems. FAME contains roughly 10% less energy than diesel leading to a corresponding increase in fuel consumption since engine efficiency is similar. Soot emissions are typically lower with FAME since these are oxygenated, while NOx is often reported to be increased since FAME typically burns faster, the latter a result of the slightly higher cetane rating of FAME. The high cloud point and pour point of FAME make them less suited for neat operation in colder climates, unless certain additives are used. Problems with bacterial growth in the fuel tank as well as dilution and thickening of engine lubricating oil have been reported. The former is easily avoided by avoiding water while the latter is referred to the increased spray penetration length with FAME that can be aggravated by late injection strategies for DPF and DeNOx regeneration. Specially formulated engine oils are one response to this problem. FAME can be aggressive towards rubber and acts as an solvent. The high cetane rating and thus very low resistance to knock or pre-ignition is one of the reasons that make FAME not suitable as a SI engine fuel. The reduced toxic species in the emissions and very low sulfate emissions give a much lower impact on human health than from fossil fuels [8]. FAME is considered both safe and with little impact on environment from spillage.

3.2.1 RME & SME

FAME fuels produced from rapeseed and soy are commercially available diesel substitutes.

DICI

Guido et al [31] compared both RME and SME with both European diesel (CEC) and synthetic diesel from natural gas (GTL) on a GM EURO5, 2liter, DICI engine in eight steady state operating points. Much of the work was focused on investigating how well the open or closed loop combustion control strategies responded when employing the different fuels. The results indicate that the closed loop control of both 50 % burned timing and IMEP handled the changes best and could maintain good control of both engine power and engine out emissions. General observations are that both RME and SME offers similar engine efficiency as CEC, reduces PM with 90% but increases NOx with 50%. With closed loop control the NOx/PM tradeoff can be shifted so that NOx is at the same level as for CEC or GTL while PM is reduced 80%. RME shows an advantage over SME with only 20% versus 40% increase of CO compared to CEC. HC emissions are similar between CEC and SME but reduced with RME (25% reduction) and GTL (50% reduction). GTL offers otherwise very similar performance to CEC but with slightly better efficiency.

Rose et al [32] concluded that the oxygen content in FAME extends the regeneration period of the DPF for B50 with 100% compared to neat diesel.

3.3 HVO

Instead of using esterification to form FAME, vegetable oils and animal fats can be hydrotreated to form what is known as Hydrotreated Vegetable Oil (HVO). The hydrotreatment removes the double bonds and oxygen that leads to stability issues in FAME and thus gives HVO improved storage properties as well as reduced risk for oil contamination. To further improve the low temperature properties, isomerization, addition of flow improvers, control of reaction temperature or co-processing with petroleum-derivates are employed [33]. Final fuel properties are almost independent of original feedstock. HVO is an excellent DICI fuel with properties close to Fisher-Tropsch diesel and may be used either neat or blended with diesel. HVO offers reduced emissions compared to fossil diesel, especially regarding PM since HVO has much lower aromatic content, but not the same health or environmental benefits as for instance RME.

DICI

Murtonen et al [34] compared EN 590 diesel with HVO, GTL and RME in three different engines, five different buses (with five additional engines) in four different test cycles. All engines (4.5-11.9 liter displacement) use DICI combustion and the emissions before and after EATS where compared. The general conclusion is that NVO, GTL and RME reduce all legislated tailpipe emissions (after EATS) compared to diesel, even in some odd cases when the engine out emissions of soot increased. The reduction was strongest for soot while NOx was hardly affected. RME had the strongest impact by reducing engine out soot up to 50% in some cases, probably thanks to its oxygen content. Also engine out formaldehyde was typically reduced and PAH7 strongly reduced by HVO, GTL and RME. Engine efficiency was not affected although the volumetric fuel consumption increased due to lower density (HVO, GTL) or lower heating value (RME).

3.4 Other, also including synthetic gasoline and diesel

Synthetic gasoline and diesel may have several different feedstocks and names but are in general produced through the Fisher-Tropsch process. They typically exhibit slightly better emissions performance compared to their fossil equivalents. Sulfur is much lower than in fossil gasoline and diesel, which can be very high and problematic on some markets. One obvious advantage with synthetic diesel or gasoline is that no engine modifications are required.

DICI

Heuser et al [35] investigated two proposed C-8 oxygenated fuels from the "Tailor-Made Fuels from Biomass" (TMFB) cluster at RWTH Aachen University. The fuels Di-n-buthyl ether (**DNBE**) and **i-octanol** where compared to diesel in both an optical high pressure chamber (penetration lengths etc) and a single cylinder LD engine in DICI mode (emissions, engine performance, soot particle distribution). Both DNBE and octanol offer a factor 10-15 reduction of soot with retained levels of HC emissions. DNBE also strongly reduces CO and offers increased engine efficiency (up to 2 % units) . Ignition characteristics are quite different with longer ignition delays for octanol (CN 34 versus 115).

An evaluation of real world emissions from FAME, HVO, BTL and ULSD was performed in [36]. FAME stood out in the comparison with around 20% higher NOx emissions.

POMDME, Polyoxymethylene Dimethyl Ethers (sometimes known as **PODE** or **DMMn**) are relatively easy to synthesize from methanol and their physical properties are fairly similar to those of diesel fuel. Density and cetane number are higher, 1073 kg/m3 and 72, while LHV and viscosity are lower, 20.9 MJ/kg and 1.77 mm2/s. Engine screening show that neat POMDME and POMDME/diesel mixtures have a strong advantage on both soot emissions, thanks to its high oxygen content, and on NOx emissions. HC and CO emissions are maintained at low levels while engine efficiency was improved slightly [37, 38]. POMDME shares several of the benefits of DME but is more practical and require less updates to the engines since it is a liquid. Just as for DME the low energy content requires increased fuel flow rates, a larger fuel tank and lead thus to a higher volumetric fuel consumption.

Oxygenated non-cyclic and cyclic components were blended with diesel and compared in a single cylinder HD-DICI research engine [39]. The non-cyclic components **Ethyl Levulinate (EL)** and **Methyl Levulinate (ML)** where used in fractions of 10 and 20% while the cyclic components Methoxybenzene (**Anisole**) and 1,2-dimethoxybenzene (**Veratrole**) were used in fractions of 10%. All mixtures except ML10 reduced soot emissions strongly without excessive EGR rates, thus allowing a beneficial compromise between all emissions and fuel consumption. While regular diesel showed to be very sensitive for the NOx/soot trade-off when varying EGR amount, all mixtures showed much less sensitivity. With the best mixture, ML20, EURO VI emissions regulations could be met without any EATS during stationary operation combined with a volumetric fuel consumption noticeably lower than for diesel. No heating value was provided for ML but considering the low heating value of EL one might assume that engine efficiency is improved with either of the Levulinate mixtures. No adaption were made to the engine compared to diesel operation. Load and engine speed were kept constant at 6 bar IMEPg and 1200 rpm. Inlet temperature and pressure were also kept constant at 300 K and 1 bar absolute.

SI

By using different mixtures of gasoline, ethanol and Ethyl tert-butyl ether (**ETBE**) Milpied et al. [40] demonstrated that isolated effect of RON and MON has much stronger influence on knock latent heat of vaporization.

Two furan fuels (**2-MTHF** and **2-MF**) were compared to ethanol and gasoline in high boost SI operation to determine the origin of pre-ignition. Gasoline and furans are sensitive to pre-ignition from the hot spark plug electrode, while the less sensitive pre-ignition for ethanol is believed to originate from fuel-oil droplets [41].

Oxygenated cyclic components Methoxybenzene (**Anisole**), 1,2-dimethoxybenzene (**Veratrole**), **Acetophenone**, **2-phenyl ethanol** and **Benzyl alcohol** were individually used in fractions of 10% in Euro 95 gasoline and compared to Euro 95 and Euro 98 gasoline in a five cylinder LD-PISI Volvo production engine [39]. The measurements were focused on combustion stability and knock, essentially proving that each of the mixtures are possible to use in production standard SI engine with slightly degraded performance for Veratrole while 2-phenyl ethanol, Anisole and Benzyl alcohol showed slightly improved performance compared to Euro 95 gasoline. No emissions data were provided.

PPC

In [42] gasoline was blended with 5% 2-Ethylhexyl Nitrate (**EHN**) and either 10 % ethanol or 20.4 Methoxybenzene (**Anisole**) and compared to regular diesel in a single cylinder HD-DICI research engine. Both EHN and Anisole act as ignition improvers and move the gasoline mixtures closer to diesel in terms of auto-ignition properties. The experiments were run at loads of 10 or 16 bar IMEPg with different engine speeds, combustion phasing and boost pressure. EGR, injection pressure and inlet temperature were kept constant at 50%, 1500 bar and 3˚C. CR was 15.0:1. The results can be summarized with that both oxygenated gasoline mixtures provide; a lower energy consumption (higher efficiency) but higher fuel consumption (lower energy content); lower soot but at the expense of increased NOx with the anisole blend performing better; higher HC than diesel, but lower CO for anisole blend than either ethanol blend or diesel.

Naphtha refers to a light fraction between gasoline and diesel and although being of fossil origin it is more efficient to produce than regular gasoline, resulting in 5% lower overall CO_2 emissions. Naphtha with a rating of RON 70 has been investigated in both LD and HD-PPC engines [43]. The ignition characteristics suit PPC well and by running the HD engines with $\lambda \approx 1.5$ and ≈50% EGR a combination of high efficiency (up to 57% GIE) and very low regulated emissions can be achieved. The feasibility of naphtha-PPC in a commercial LD engine was demonstrated in [44]. The results show that commercial engine hardware can be used for an efficient and clean LD-PPC engine with power output, speed range and pressure rise rates similar to that of the original LD diesel engine. Gross indicated efficiency was raised from 43% to 51% and NOx reduced to extremely low levels (30 ppm). The amount of soot emissions was very sensitive to injection parameters.

3.5 Gaseous fuels

Due to the low volumetric energy density of gaseous fuels both the onboard fuel storage and fuel injection systems differs from those used with liquid fuels. Gaseous fuels are typically compressed or liquefied to allow a reasonable driving range. Gaseous fuels such as methane rich gases (natural gas or biogas) and propane or butane rich gases (LPG) have very high RON ratings and are therefore well suited to SI operation and have actually been used historically longer than gasoline. There is vast experience and several million gas fuelled vehicles in operation. An alternative approach to SI is dual fuel operation where the combustion is initiated by a small injection of diesel instead of using a spark plug. Emissions are generally favorable, especially while using a TWC combined with slightly rich operation to compensate for the low levels of CO that otherwise would reduce the effectiveness of NOx reduction. In lean burn applications engine efficiency can be increased and engine out NOx reduced sufficiently, thus only an oxidizing catalyst is required for HC and CO emissions after-treatment. Methane can be challenging to reduce sufficiently with catalytic after-treatment and there are ongoing discussions on stricter legislation on tailpipe emissions of methane.

3.5.1 CNG, SNG and LNG

Compressed natural gas, CNG, is with more than 10 million vehicles currently the most common alternative fuel to diesel and gasoline and consists mainly of methane, CH_4. Even when from fossil origin, due to its high H/C ratio, it can theoretically provide a reduction of 25% CO_2 during vehicle operation compared to fossil diesel or gasoline. In reality, the reduction of GHG is less due to methane slip and leakage (methane is a 21 times stronger GHG than CO_2). CNG is compressed to more than 200 bar and is available in more than 200 filling stations in Sweden. The 50 000 CNG vehicles in Sweden are usually of the flex fuel type and can run on either CNG or gasoline with SI engines using stoichiometric operation and TWC. Instead of extracting natural gas from gas wells, synthetic natural gas, SNG, can be produced through a number of processes from coal or other sources and has essentially the same properties as CNG. By liquefying the natural gas at -162˚C and 0.25 bar over-pressure to LNG, the energy density can be increased 2.4 times compared to CNG. This is practical for shipping of NG but the expensive cryogenic storages and the risk of fuel loss during vehicle stand still from boiling LNG means that LNG vehicles are not common. Natural gas has the benefit of not being poisonous and is also generally considered a very safe fuel.

An overview of CNG engine technologies can be found in [45]. To meet EURO VI emission regulations Figer et al discusses the merits of different CNG HD engine technologies [46]. Lean-burn SI can have brake efficiencies above 43%, thus being comparable to regular HD diesel engines, but are associated with slightly lower power and poorer transient response. To reach EURO VI, lean operation is not enough and a SCR is required to reduce the NOx emissions. The biggest challenge is however to limit the methane slip. Methane oxidation catalysts that have sufficient conversion efficiency (>90%) and a durability for 700.000 km operation are currently not cost effective. Dual-Fuel CNG diesel engines may replace as much as 70% of the diesel fuel, but suffer from the same challenges as lean-burn SI regarding methane slip. On top of that, NOx and soot emissions are higher and require after-treatment as well. Stoichiometric SI allows high loads, excellent transient response as well as cost effective handling of emissions for EURO VI requirements, unfortunately with increased thermal loads and lower brake efficiency.

SNG was compared to CNG operation in [47]. SNG lead to more stable operation and reduced fuel consumption in the WHSC, thanks to the 3% hydrogen content that reduced the risk of knock. A slight increase in NOx was observed.

By replacing the spark plug with a"turbulent jet ignition" (TJI) assembly in a LD engine, the net indicated efficiency was raised from 36.5% (lambda 1) to 42.5% in lean propane operation (lambda 1.7) where the prechamber was feed with around 2% of the fuel [48, 49]. Target efficiency of the project is 45%. Lambda >2 was possible with a COV of 3%.

Kofod et al. made a theoretical comparison between a LNG and a European B7 standard diesel blend to establish the well-to-wheel greenhouse gas (GHG) emissions [50]. Assuming similar thermal efficiency of the engines, GHG reduction potential of LNG compared to diesel is in the order of 17 ± 6%.

3.5.2 Biogas and biomethane

Biogas can be produced in several ways from several different feedstocks and is typically a methane rich gas that contains CO_2 and some other species. When cleaned and upgraded to > 90% methane, biomethane can be used as a vehicle fuel and mixed with CNG. With biogas the CO_2 emissions are typically reduced more than 90% and can sometimes even be considered to provide negative greenhouse gas emissions since the otherwise emitted methane is a stronger greenhouse gas than the CO_2 produced from combusting the methane. Around 60 % of the gas used to propel NG vehicles in Sweden is currently biomethane. The available publications do not add much and the reader is directed to the much broader range of publications on CNG since fuel properties are the essentially the same and the engine technology exactly the same.

3.5.3 LPG

Liquefied petroleum gas, LPG, is a propane rich gas that is known in Sweden as Gasol. It is only pressurized 5-20 bar and works excellent in SI engines, although it does not offer the same CO_2 benefit as CNG. For safety reasons an odor additive is added to discover leaks that undetected could lead to hazardous situations, since LPG is heavier than air. Due to the comparably low price and ease of implementation, it is quite common with retrofitted LPG vehicles in Europe. In Sweden the interest has declined steadily and does today only account for 300 vehicles and 10 filling stations.

In [51] emissions from 7 buses and one truck fuelled on LPG and equipped with TWC were measured for several different drive cycles and compared to HD diesel and gasoline trucks. The results show that the LPG vehicles have significantly lower emissions than pre 2003 trucks but that the rapid development of DPF's and SCR emissions control technology for HD vehicles means that modern diesel trucks have much lower emissions of PM, HC and CO than the LPG vehicles and almost the same levels of NOx.

3.5.4 DME

DME is a well-understood engine fuel from several fleet studies. For instance, Volvo has actively investigated and introduced DME on buses and trucks since 1999 and is launching the third generation DME trucks during 2015 in Europe and North America [52, 53]. Development of DME fuelled vehicles are going on in several countries such as Japan, China, Korea and USA. DME is a oxygenated gaseous fuel that can be handled as a liquid when pressurized above 5 bar. Due to its high cetane number it is suitable as a diesel engine (DICI) fuel, but unsuitable for SI operation. For DICI operation the fueling system needs to be designed for higher fuel flows compared to diesel operation, due to the comparably low energy content in DME, and the fuel tank pressurized. Viscosity as well as modulus of compressibility is much lower than for diesel, so fuel pumps needs to be designed accordingly. To avoid wear a lubricating agent is commonly added while an odor additive is added to discover leaks that undetected could lead to hazardous situations, since DME is heavier than air. DME has a fairly high latent heat but combined with low boiling point which promotes vaporization and lead to lower in-cylinder temperatures and thus reduced NOx emissions.

Emissions are very favorable with DME and can meet EURO 5 regulations in a passenger car drive cycle without any EATS. HC and CO emissions are even lower than for diesel operation and soot is also very low with DME thanks to the oxygen content and the lack of carbon-carbon bonds. NOx emissions depend more on the engine physical parameters than the fuel, but considering the low soot emissions, low NOx strategies (aka EGR) should be fairly easy to implement. Efficiency is typically reported to be similar to diesel operation. DME is generally considered a safe fuel with little negative impact on human health. A review of DME use in engines can be found in [54].

3.5.5 Hydrogen

Hydrogen is considered an excellent engine fuel, especially in SI engines, and has the obvious advantage of not yielding CO, CO_2, and HC emissions. It has not become more widely used due to the difficulty of economic distribution and production. The energy content in relation to volume is very small for this, the smallest known molecule, making storage and transportation expensive. Hydrogen has fairly unusual and sometimes contradictory properties. For example, its research octane rating (RON) is very high while its motor octane rating (MON) is low. This indicates that hydrogen has a very low resistance to knock, which can be explained by its low ignition energy and extremely high flame speed. In a mixture, however, hydrogen acts in the opposite way by increasing the overall knock resistance. This is explained by the trade-off that the mixture's ignitability is less improved by the hydrogen addition than are the flame speed and thermal diffusivity. Improved flame speed limits the time for knock to occur, while the high thermal diffusivity of hydrogen limits the risk of high-temperature gas pockets in the combustion chamber that could initiate knock or pre-ignition. The reduced risk of knock and pre-ignition means that the compression ratio of the engine can be increased, which increases thermal efficiency. The improved ignitability due to hydrogen addition is very beneficial as well, since this enables very lean engine operation. Under these conditions, combustion temperatures can be decreased, which results in extremely low NOx emissions. Furthermore, pure H_2 has some challenging properties regarding, for example, diffusivity, that need to be addressed if in high concentrations. Hydrogen is thus incompatible with many steels, nickel and its alloys, titanium alloys (pure titanium works well, though), and cobalt and its alloys, which can be susceptible to hydrogen brittleness or that are permeable to hydrogen, permitting it to diffuse (leak) through. Hydrogen's extreme flammability makes it important to avoid static spark discharges by properly grounding materials in contact with hydrogen. In mixtures, such as producer gas, in which the hydrogen content seldom exceeds 30%, the problems are not as extreme as in pure hydrogen. To use hydrogen on a vehicle it needs to be either compressed to 700 bar, liquefied or cryo-compressed. Range can still be an issue.

HCCI

Lee et al [55] has proved that hydrogen can be used with naturally aspirated premixed compression ignition without any inlet preheating or ignition improver. Minimum CR for cold start is 32:1 and a quite narrow band of very lean mixtures (phi around 0.2) is allowed to avoid knock on one hand and misfire on the other. Peak indicated efficiency was in the order of 45%.

4. Benchmarking of alternative fuels and combustion principles performance

Relevant data from the referenced publications are included in Figures 7-10. The purpose is to provide an overview of the relative merits of the different fuels and engine combustion concepts. Since the data set is limited, the influence from different individual engine operation conditions can be such that the presented results are not always directly comparable. An example on the sensitivity on engine efficiency from load variation can be seen in Figure 6, but many other parameters affect the efficiency. Therefore, these figures should be regarded as indicators rather than universal truths. References and background data for Figures 7-10 are found in Tables 1 and 2 in the Appendix. All emissions data are engine-out emissions, thus before any emissions after-treatment system. In vehicle applications, EATS are used to meet the applicable regulations, but depending on the engine-out emission levels and the severity of the regulations, more or less expensive EATS can be employed or even avoided.

Light-duty engine data comes in most cases from multi-cylinder engine experiments providing measured brake data, while some have been estimated brake data from measured indicated data. Most heavy-duty engine results are from single cylinder test engines and are therefore often measured as gross indicated efficiency (GIE). To translate to brake thermal efficiency (BTE, the practical engine efficiency) friction and pumping losses needs to be accounted for. The difference varies for different engine concepts and fuels, but typically gives a reduction of 2-7 %-units when going from GIE to BTE. As GIE is increased, the gap to BTE typically also increases since with the reduced energy losses, less "waste" energy is available for boosting the engine.

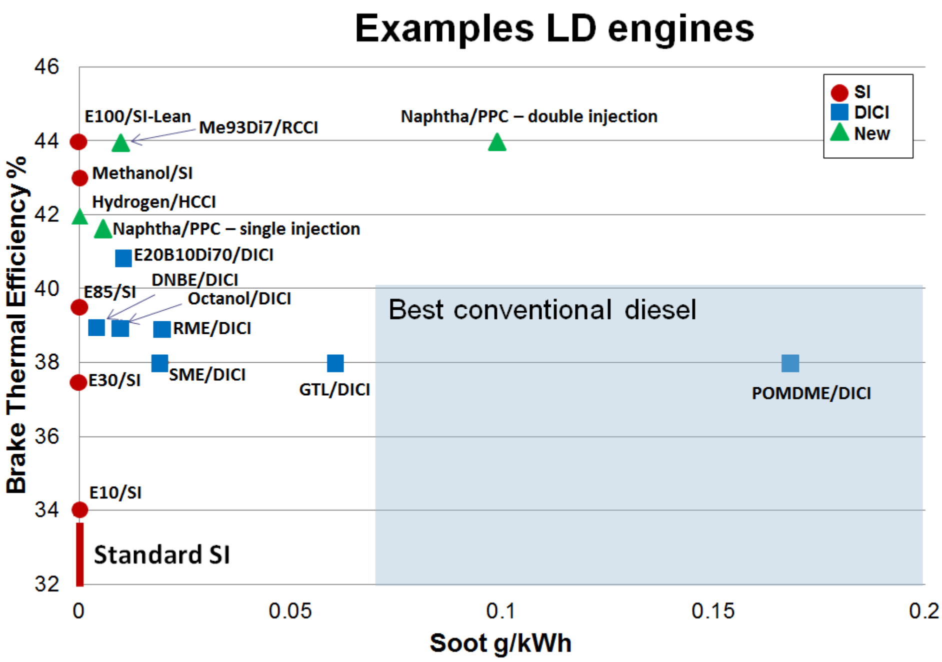

Figure 7. Brake thermal efficiency versus soot for different fuel and light-duty engine combustion concepts.

In Figure 7, one can see that going from current commercial gasoline with 5% ethanol to neat ethanol, efficiency can be increased a remarkable 30% thanks to beneficial evaporation properties and the allowed increase in compression ratio due to the increased resistance against knock. Methanol allows as well very high efficiencies and low soot emissions. The high molecular expansion of methanol should in theory lead to an efficiency advantage over ethanol. The figure shows that alcohols in SI do provide a significant benefit compared to gasoline and even surpasses diesel engine efficiency combined with essentially soot free operation. Alternative diesel-like fuels such as RME, SME and GTL provides important soot reduction but does not alter efficiency. The results on POMDME are not characteristic for DME-like fuels and are likely an effect from a less than ideal combination of operating parameters and hardware. The same set of experiments provided even much worse performance for fossil diesel fuel. POMDME is known to produce lower soot, HC and CO than diesel.

The emerging combustion concepts such as HCCI, RCCI and PPC provide high efficiencies and comparably low soot emissions. Naphtha/PPC with double injection showed higher efficiency but also quite high soot compared to single injection.

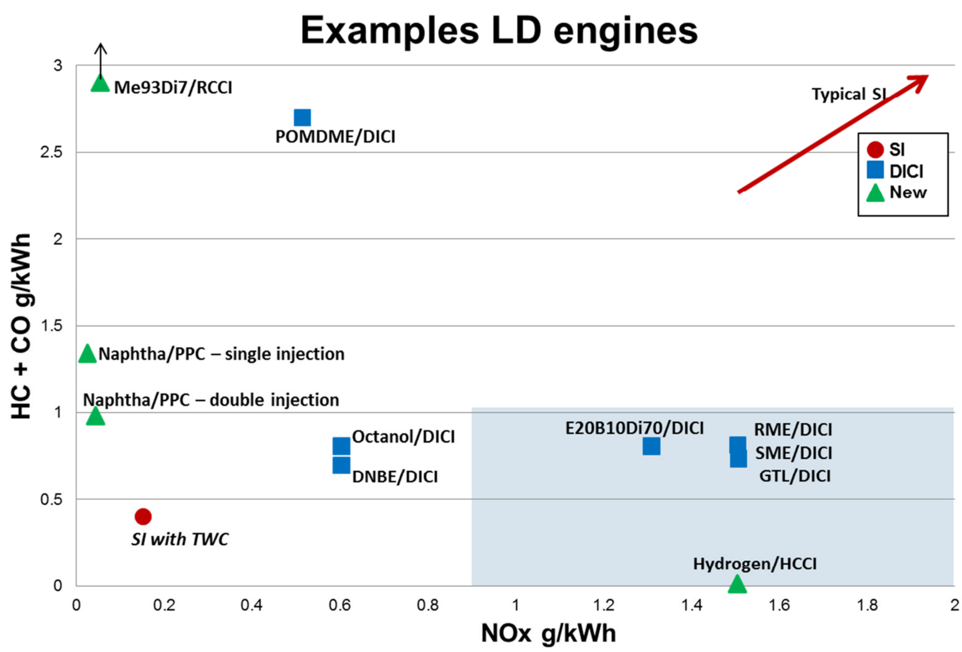

Figure 8. HC+CO versus NOx emissions for different fuel and light-duty engine combustion concepts.

Figure 8 shows HC+CO versus NOx emissions for different fuels and light-duty engine combustion concepts. The scales in the figure are low so conventional gasoline engines (SI) that typically have quite high HC, CO and NOx emissions are outside the scales (see red arrow). SI engines depend on stoichiometric operation and TWC emissions after-treatment to comply with regulations. Conventional diesel engines (DICI) can be controlled for either low NOx or low soot, but not at the same time. The lower limits are presented as blue areas in Figures 7-10. Heavy-duty DICI engines have much stricter emissions regulations that typically requires the use of more advanced EATS including selective catalytic reduction (SCR). Since premixing is avoided in DICI, much less engine out HC and CO is produced than in SI engines, which is confirmed by the experiments included in Figures 8 and 10. RCCI and PPC are low temperature combustion (LTC) concepts designed for low NOx, which is confirmed by the results in figures 8 and 10. Unlike PPC, RCCI depends on premixing (of one fuel) and this leads to very high levels of HC and CO emissions. HCCI is also a LTC but with a compression ratio of 36:1 for the hydrogen fuelled HCCI, temperature gets high and thus NOx too (Fig. 8). Hydrogen has the obvious advantage of not forming CO, HC or soot at all.

Figure 9 reveals that most alternative fuels have an advantage compared to fossil diesel regarding soot emissions. Just as for LD engines, the alcohols show a strong advantage. There are some variations in efficiency between fuels using the DICI principle, but this is mainly an effect of using different hardware or operating conditions. Alternative liquid fuels, such as synthetic diesel (GTL), HVO or RME should in principle have the potential to reach similar peak efficiency as the state-of-the-art DICI engine included in Figure 9. This engine has 51.6% GIE and 47.0 % BTE. There are essentially no combustion losses, while pumping losses are 1.6 % and friction losses are 3.0 % and thus represent the drop from BTE to GIE of 4.7% from the used 100% fuel energy. PPC is expected to have a larger drop in efficiency down to 48-50% BTE while the loss might be even bigger for RCCI due to the use of extensive Miller timing and high boosting requirements.

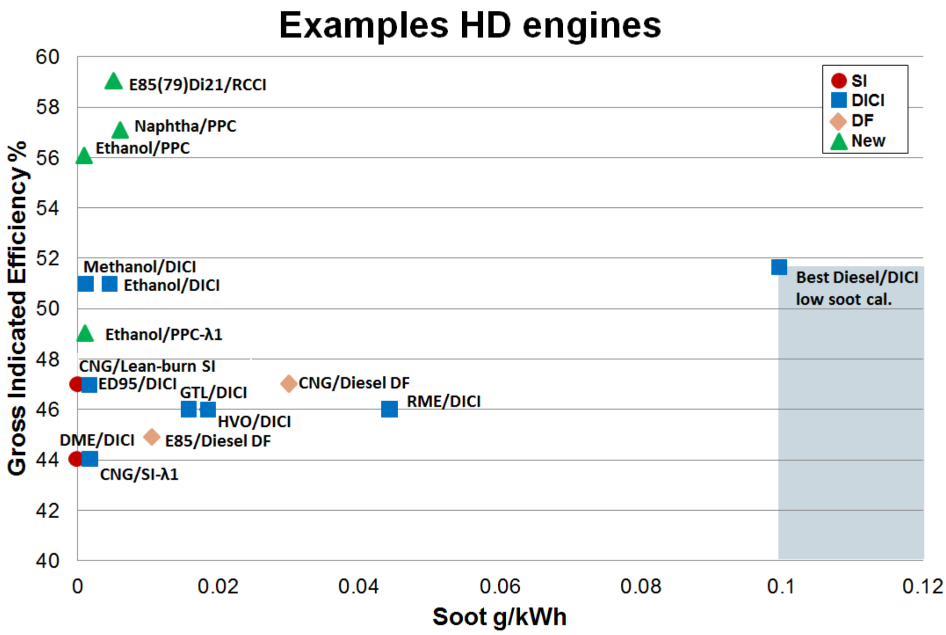

Figure 9. Gross indicated efficiency versus soot for different fuel and heavy-duty engine combustion concepts.

The DICI engine running on neat ethanol or methanol is actually a medium duty engine showing good potential for efficiency and soot. The indicated efficiency estimated in Roberts, Johnson and Edwards [14] is based on the assumption of turbo-compound. No data on HC, CO or NOx were available, however. The largest stationary CNG/SI engines, used for production of electricity, exhibits GIE above 55% while their smaller contemporary truck engines shown in Figure 9 have more modest efficiencies. Soot is essentially none-existent. Dual-fuel engines with diesel pilot produce soot from the diesel fuel and in the case of CNG show diesel-like efficiency. The E85/diesel dual fuel engine has slightly lower efficiency and very high emissions of HC, CO and NOx. The reason is likely related to the yet limited amount of research spent on this concept. Soot is low though. The new combustion concepts RCCI and PPC show substantially higher efficiencies and lower soot levels.

Looking at Figure 10, the typical emissions performances for different HD engine combustion concepts are confirmed: - Low HC and CO for DICI and the opposite for SI and DF. - High NOx for DICI and SI, while lower for lean SI and CNG/DF. RCCI has also very low NOx, but as already explained very high HC+CO. PPC has the lowest combination of HC+CO and NOx and is essentially emissions regulations compliant without any after-treatment system.

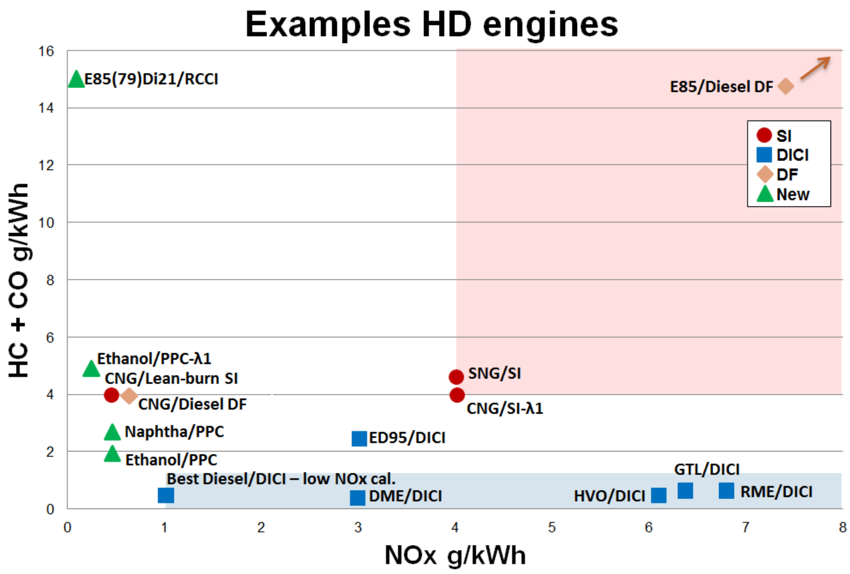

Figure 10. HC+CO versus NOx emissions for different fuel and heavy-duty engine combustion concepts. The pink area represents typical stoichiometric SI.

5. Analysis - knowledge gaps, challenges and opportunities

One important conclusion is that internal combustion engines can be adapted to a wide range of alternative fuels. In addition, efficiency and emissions performance does not need to be degraded either, compared to the currently existing commercial engine concepts. In fact, efficiencies can be increased substantially with alcohol use in SI engines, which is the most common engine solution today for passenger cars globally. Efficiency is important not only from a fuel cost perspective, but also to realize a reduction of CO_2 emissions. With a hydrocarbon fuel engine out emissions of CO_2 cannot be avoided or even reduced with emissions after-treatment systems. Efficient engine/fuel combinations and fuels with low C/H ratio do provide some advantages and may reduce CO_2 up to 30% in theory, but from a GHG perspective, the fuel feedstock and fuel production efficiency is of even higher importance than the engine technology. The question here is the fossil carbon balance of the fuel. In this context, hydrogen is obviously a great fuel since it doesn't have any tailpipe emission of CO_2, CO, HC or soot, however these might still be present in the production phase.

Alternative fuels are considered safe and in most cases associated with strong risk reduction with respect to cancer, other health aspects and environmental issues. Ahlvik et al. [8] even claim that "Probably, the risk of cancer together with the daily casualties from particulate emissions, are responsible for the majority of deaths caused by the emissions from traffic". Other examples are provided in [8], such as an example where 80 000 liters of methanol was spilled into the river Rehn in Germany. When the experts arrived they could not find any traces of the spillage. A similar spillage of diesel or gasoline would have resulted in much worse environmental damage.

The biggest difference between the different alternative fuels and engine combustion concepts possibly comes down to regulated emissions performance. These are soot, NOx, HC and CO emissions. The SI principle leads to low emissions of soot but high emissions of NOx, HC and CO. These are on the other hand treated effectively with TWC after-treatment. The DICI principle provides low CO and HC but suffers from high NOx and especially soot emissions, which poses some challenges of cost effective and efficient combination of emissions after-treatment systems. The alternative fuels, that can replace fossil diesel, such as RME, HVO, GTL or alcohols do all show strong reduction of engine out soot and can be exploited for simplified and cheaper EATS. If this is enough is not entirely certain. There is increasing debate and research on the health effects from soot particles, which could lead to demands for much stricter emissions legislation regarding soot or other particulates stemming from engine combustion (as well as from industry and energy production). Methane combustion is also facing challenges. Methane is particularly difficult to reduce in an EATS and partly since it is a strong GHG there are ongoing discussions to introduce strict regulations on methane emissions. This would have an impact on CNG, LPG, SNG and biogas combustion.

The emerging combustion concepts HCCI, RCCI and PPC demonstrate both higher efficiency and lower emissions than conventional SI or DICI. These concepts do also provide further emission benefits when operated on alternative fuels. RCCI demonstrates the highest gross indicated efficiencies, although measured brake efficiencies at high levels still need to be presented. Load and speed range is not an issue with RCCI since the whole concept is built around the idea of using two fuels on-board to regulate the engine requirements at both high and low loads. At low loads a high reactivity fuel such as diesel is used, which could pose problems with soot. Higher loads are dealt with premixed low reactivity fuels such as gasoline or alcohols, but problems with extreme emissions of HC and CO are yet to be solved satisfactorily. PPC on the other hand uses only one fuel and has better overall emissions performance. PPC suffers from low load performance where emissions get too high for operation without EATS. Cold starting and pressure rise rates (noise) are also not resolved satisfactorily yet. Just as for RCCI, measured high brake efficiencies need to be presented. Both RCCI and PPC show substantial fuel flexibility and are enablers for use of future alternative fuels. The research on both concepts provides important new understanding for the development of future combustion engines, and the concepts could eventually be introduced on their own or possible combined with SI or DICI for mode-shift strategies. One such example could be a combined PPC-SI where SI is used for starting and low load operation while PPC is used for part load to high load operation. Further research is however required to answer such questions.

Coming back to engine efficiency, peak engine efficiency has limitations as a comparator. The average efficiency for an engine in its operation is a more important measure. Passenger cars, for instance, typically operate at low loads and low engine speeds, and it is well-known that DICI has higher part load efficiency than throttle controlled SI. Unfortunately, it is not easy to find such average efficiency for all fuels currently, although some drive cycle averaged data is available. A simple standard method to determine and present average efficiency rather than using a whole drive cycle, would be welcome. DICI, as mentioned, but also RCCI and PPC have high part-load efficiencies. SI, however, does require further research, although attempts with EGR have demonstrated impressive part load efficiency results. The downside here has been sluggish transient response, but also limitations to how low in load EGR is actually effective.

Several of the newer alternative fuels have been investigated to a limited extent, so much more research in different engine concepts is required. Many of these fuel components could provide further benefits if mixed with each other or with the more well-known alternative components. For instance could a mixture of octanol and DNBE possibly provide good results in DICI. Gasoline fuel, for instance, is a mixture of hundreds of components that together give a spread in evaporation and ignition properties that are beneficial for cold starting and controlling combustion rate. With this in mind it is probably beneficial, as well, to combine several alternative components for SI and PPC fuels.

Another issue is that standard methods for fuel testing and quantification are lagging behind. It is not so easy to predict engine performance or emissions performance for all emerging fuels and different engine combustion principles in a real engine application from the existing standards. The traditional RON and MON give reasonable indication on the knock performance of a fuel in SI combustion, but these indices are measured under operating conditions that are outside operating conditions of modern SI engines. Besides, fuels that in principle are good SI fuels may have RON and MON ratings that are outside the range of the calibration and definition of the test methods, namely RON 100 defined by isooctane. Methanol, ethanol, natural gas and some other good SI fuel candidates all have RON and MON above 100. RON, MON, AKI and CN have also been shown to be of limited value for LTC concepts such as HCCI, RCCI and PPC, and several researchers have looked into finding new relevant measures for these combustion concepts [56-58]. As an example Lund University has worked on developing a HCCI number [59]. The CFR engine that is used as the defined test equipment for RON, MON and CN is from the 1930´s and has little in common with modern efficient and often boosted engines. The question here is if it's time to find new standard test engine(s) and methods that can be used to quantify combustion behavior (ignition delay, low temperature reactions, flame speed), evaporation behavior, gross indicated efficiency, NOx, HC, CO, soot, other emissions and much more, for different fuels with different combustion principles. New indices that have been proposed are for instance new additional octane numbers (Bengt Johansson, Lund University) and phi-sensitivity (John Dec, Sandia National Labs). With a new set of fuel definition test methods, much more fundamental understanding of engine fuels can be realized. Currently much of the fundamental research on fuel behavior in engines are performed on many none standardized types of engines, which makes direct comparisons difficult, as seen in the benchmarking chapter. Standard engines and methods would facilitate direct comparisons. Fuel research performed on different engines will still be important to quantify effects from changes in hardware, such as engine sizes, injection systems and others, that are continuously developed.

The technical challenges with alternative fuels will likely be related primarily to corrosion issues, fuel injection issues and ignition related issues. The EATS will also be facing challenges with new emission components. Starting with corrosion issues, alcohols possibly provide the biggest challenge. Ethanol both neat and in mixtures is corrosive and the E85 use has meant special consideration to all parts in contact with the fuel. Typically, this has meant use of stainless steel, more advanced polymers in gaskets and special lubricants. Methanol, that is even more aggressive, could raise this challenge. Measures to deal with corrosion obviously come with added costs and potential guarantee risks. The fuel injection systems are sensitive to injector fouling, purity of the fuel and pump lubrication. RME and many other alternative fuels provide some challenges here with required redesign of the fueling system and potential use of additives. Spark plugs and glow plugs have been reported to be susceptible to erosion during operation from some alternative fuels. Since the development is towards more powerful engines where new operation strategies and new engine combustion concept pose new and tougher demands, lifetime of some ignition system components can be a challenge. Finally, new fuels may produce specific components in the exhaust stream that are either toxic, cancerogenic or otherwise unwanted. These could become a challenge to remove with an EATS, since the development towards more efficient engines typically reduces exhaust temperatures that are needed for effective catalytic conversion. Emerging and stricter emissions legislation may pose further challenges, not only on the EATS and the engine system, but also on the fuel.

From a Swedish perspective, several challenges can be identified for the introduction of sustainable vehicle fuels.

1. *Harmonized global vehicle technology or specific vehicle technical development for Swedish requirements.*
   The vehicle fleet in Sweden is mainly based on imported vehicles. These come from manufacturers in Europe, Asia and North America and it is not unlikely that we will continue to import a large share of the vehicles in the future as well. Swedish automotive manufacturers on the other hand export most of their produced vehicles and will likely continue to depend on export to be competitive. For these reasons, the introduction of alternative fuels in Sweden could, at least in the short perspective and to some extent, depend on global engine technology development. Special adaption of engines for specific Swedish fuels is one option, but this option will likely lead to additional expenses for Swedish customers and higher risks for the automotive and fuel producers. One key issue here is to find a sustainable fuel that also has a future outside of Sweden.
2. *Time scale.*
   The Swedish Government has set the target that Swedish road transports should be fossil independent by 2030, i.e., a reduction of fossil fuel use from the 2010 years level. Considering that the average lifetime of Swedish cars is 10 years and that there are only 15 years left to 2030, actions need to be taken immediately to support development of vehicle technology that can meet the requirements.
3. *One of the major challenges is finding sustainable national policies and regulations that promote a constructive co-operation between state, citizens, companies, researchers and other actors.*
   Trying to convince private companies to develop and market products that are less mature and thus susceptible to guarantee risks and with much higher selling price and operating cost than the conventional alternatives and on top of that could be discouraged by the state after a year or so, is obviously not a realistic venture or even an ethical one. Vehicle manufacturers and potential fuel producers face these challenges with all the different emerging fuels and engine combustion concepts. To find willing investors, there must be a reasonable chance to make at least some profit. This requires a narrowing down to a few and preferred alternative fuels and also stable rules.

There are also a number of opportunities. Sweden has substantial biomass resources as well as world leading vehicle and engine manufacturers. Sweden has also proved the strength and ability to introduce a national system for alternative fuel distribution in the recent past. This is the national fully functional secondary distribution system with more than 1800 fuel pumps for E85 capable of handling more aggressive and corrosive fuels than gasoline or diesel. This system allows additional freedom for introducing new alternative fuels. Sweden does also have a strong electrical infrastructure with essentially fossil free produced electricity. This means that further electrification of the transport sector lowers the total energy demand that needs to be produced from alternative sources. Plug-in hybrid electric vehicles are already available and have the potential to be a cost effective and energy secure system for passenger cars where most of the daily travels can be managed on electricity alone and longer travels on sustainable fuels [60]. Long haulage trucks will depend on ICE and sustainable fuels and possibly partly on electric drive if electric motorways are realized. The hybridization offers also potential benefits for improved combustion engines. With reduced requirements on engine load and speed range, the combustion engine can be optimized for very high efficiency in one prioritized operating point. Such optimization has the potential to reduce fuel consumption up to 30%. Public transportation in urban areas is probably best handled with battery electric/electric grid hybrid buses to avoid local emissions altogether. But, one important strength with engine fuels is that they can be stored in large quantities for use in case of emergency situations such as electric production breakdown from natural catastrophes or in worst case war. In this particular aspect, electrification of the transport sector is more vulnerable and a combination with ICEs desirable.

The Swedish market can provide a unique opportunity as an introduction market for automotive manufacturers to introduce and demonstrate environmentally friendly world leading technology. Swedish customers have high environmental awareness and comparably high economical latitude. Biomass resources and infrastructure are in many ways much better than in many other countries. Technical leadership on both biofuel production and engine technology as well as global leading companies are all present. Finally, such a role for Sweden be would in-line with the targets for the Swedish government as a leading country on environmental issues.

5.1 Alternative fuels for current conventional engine technologies

Current conventional engine technology refers to engine technology that is commercialized, which includes mainly SI and DICI engines. Development is both continuous and very rapid to meet legislation updates, customer demands and competitor's products. Legislative development influencing engine development is mainly towards new emissions standards while customer demands are mainly related to purchase and operating costs (fuel consumption) and refinement in operation. In the case of cars there is also emotional factors such as demand for sporty performance and thus more powerful engines[61].

So, how will engine technology develop in the short perspective? The future is always difficult to predict but one prognosis that agrees with others is provided by Delphi, one of the major global automotive suppliers and specialists on for instance fuel injections systems [62]. Their prognosis in Figure 11 shows that the worldwide market share of SI engine LD vehicles will increase, especially for direct injected SI engines (DISI or GDI), and DICI engines will also continue to be important. Technology development is indicated to be through evolution rather than through revolution with the introduction of new concepts. For the short term future it seems relevant to focus on alternative fuels that can be used in SI or DICI engines. A plausible path is to increase the amount of drop-in fuels in gasoline and diesel to eventually phase out the fossil fuels in the mixtures.

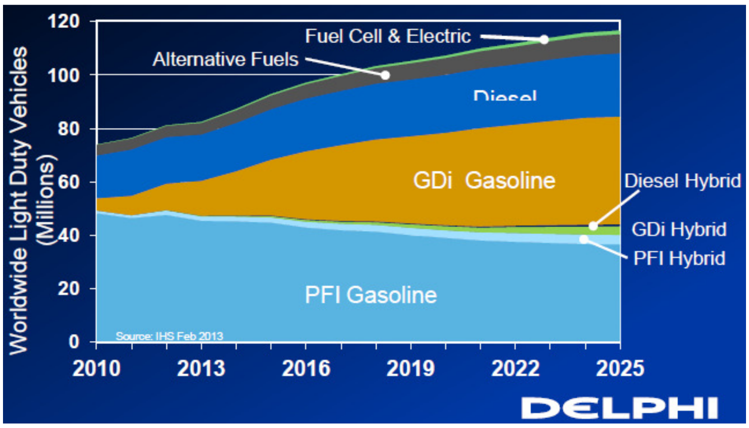

Figure 11. Prognosis of LD vehicles annual sales for various energy technologies [62].

The presented engine research shows that SI engines work even better on alcohols than on gasoline if efficiency and emissions are accounted. Both peak efficiency and part load efficiency for methanol-EGR SI even surpasses that of diesel engines. Emissions can be ultra-low with TWC and stoichiometric alcohol operation. Negative aspects are cold start performance, corrosion issues and increased volumetric fuel consumption due to the lower energy content of alcohols. To solve the cold starting issues alcohols are currently not used neat in Sweden, but in mixtures with gasoline, aka E85. Newly developed tip heated fuel injectors is one example of emerging technology that in this case currently allows cold starting of E100 down to -5˚C [62]. Corrosion issues have been sufficiently handled for E85 but require suitable materials in the fuelling systems that are more expensive than for diesel or gasoline. Engine lubrication oil and its system do also require attention. The lower energy content means that the increased fuel flow needs to be delivered from injectors and pumps with higher capacity than for diesel or gasoline engines.

Considering the several positive qualities of alcohols combined with the experiences of E85 and the currently existing distribution system of E85, the concept of GEM, (gasoline, ethanol, methanol) ternary blends seems very attractive [26]. The basic idea of the concept of ternary blends enables interesting opportunities for continuous fuel reformulation without any requirements on updates either to the vehicle or to the fuel distribution infrastructure. Ideally, the driver does not even need to know anything about the fuel even though the actual composition may vary substantially both regionally and over time. The concept allows for a gradual replacement of none wanted components and for several alternative fuel candidates to be used simultaneously. Although the base point of the E85 properties is meaningful, other base points should be sought as well as new combinations of both existing and emerging alternative fuel components. Ideally, the concept could evolve together with both current engine technologies and the emerging ones. To eventually reach a fully fossil free SI fuel, the solution would be to find a substitute for the remaining gasoline that has similar or even improved properties especially for low temperature vaporization. Synthetic gasoline is obviously one option and should be investigated in ternary blends or alcohol mixtures, but also other potential candidates should be sought and investigated.

On the DICI engine side HVO as well as alcohol mixtures seem the most relevant ones to investigate further in the short perspective. HVO is an excellent fuel that can be used directly in DICI engines. HVO is however currently more expensive and has worse health performance than FAME and the consistent, high quality has attracted the interest from the aviation industry possibly leading to that all produced HVO will be used for aviation [63]. Alcohols can be used in DICI engines but requires quite other engine specifications and are thus not directly exchangeable with diesel. To run alcohol in DICI, higher CR, larger injectors and alcohol bespoke fuel pumps as well as ignition improvers are needed. Bigger fuel tanks are required as well if a diesel like range is to be realized. The research should focus in finding better ignition improvers and possibly the use of alcohols in LD DICI engines. If the current trend with lower CR continues for DICI this will require fuels with higher cetane number [64]. DMMn and its derivatives are candidates that at least theoretically could be good candidate for clean DICI operation. Further research is needed though.

Ternary blends are also relevant for DICI where a baseline specification should be sought and investigated. Current but not yet published work at Chalmers University investigates the performance in DICI with blends of diesel, HVO and n-butanol [65].

The introduction of hydrogen as an alternative fuel still seems to be far away. Hydrogen's advantages make it relevant to monitor the future developments on hydrogen technologies, though. The extremely low volumetric energy content and current on-board storage technology means that both engine and vehicle efficiencies are very important. On efficiency alone vehicles with hydrogen fuelled combustion engines cannot compete with fuel cell vehicles [66]. If costs are considered there is a more equal competition, but considering the complexity and cost of injection systems and high pressure storage a hydrogen ICE vehicle will be much more expensive than with other alternative fuels.

5.2 Alternative fuels for emerging engine technologies

The engines we use today, the gasoline (SI) and diesel (DICI) engines, have been adapted to gasoline and diesel fuel for more than a century. Most of the alternative fuel research is therefore focused on adapting fuels to the current mature gasoline and diesel engines. With the emerging engine combustion technologies there is, however, an opportunity to adapt both fuels and engines to each other.

One such opportunity would be to find a match of alternative fuels and blends that can be matched with PPC engine adaption. For instance, it would be relevant to find and investigate alternative fuels with properties similar to those of naphtha – a fuel with combustion properties somewhere in-between gasoline and diesel. Naphtha is therefore not a suitable SI or DICI engine fuel, but works very well in PPC. PPC has demonstrated outstanding fuel flexibility with similar very high peak efficiencies while operated on diesel, gasoline, naphtha or ethanol. What differs between the fuels is the emissions performance and load range. FAME and DMMn, which both are oxygenated, and HVO show a strong reduction of soot compared to diesel in CDC. These are fuels that can possibly combine low enough emissions of soot, NOx, HC and CO with very high efficiencies, excellent load range and good cold start performance in PPC. Ternary blends of various alcohols, HVO and others are also of relevance to investigate further in PPC. Methanol is an obvious candidate, due to its excellent performance in SI, its effectiveness in production from biomass and use as electrofuel. Methanol's potential has been acknowledged and a project on methanol PPC just started at Lund University.

RCCI, and the to some degree similar dual-fuel concept, are fuel flexible in the sense that they employ two fuels with different reactivity. Several different alternative fuel combinations can be considered. But, the requirement of two fuels makes these concepts overall less fuel flexible.

Another potential path that does not require two large fuel tanks, is in-injector ignition-improver blending, targeted at improved low load operation. Such approach can be considered a bridge between PPC and RCCI.

Fuels that can be integrated into the sustainable energy production, and be efficiently produced and provide the dual roles of energy storage and fuel (electrofuels), are enablers of a future sustainable society. The fuel flexibility of the new combustion concepts should here be exploited and adapted together with the best fuels that can fill such dual role.

6.Summary

Alternative fuels

- No single alternative fuel can be identified as an ideal replacement of fossil fuels. The various candidates all have positive and negative aspects.
- Apart from the obvious benefits in reducing GHG emissions, many of the alternative fuels (RME, ethanol, methanol, DME and methane gases) provides strong reduction of risks related to cancer, other health issues and negative environmental impacts compared to fossil diesel and gasoline.
- Alternative fuels that replace diesel, such as FAME and HVO, works comparably well in DICI engines and offer mainly reduced GHG and soot emissions but no improvements in engine efficiency.
- Alcohols show great potential to reduce GHG, improve engine efficiency and reduce regulated emissions in essentially any engine concept. The best candidates, methanol and ethanol require, however, anti-corrosion measures.
- Gaseous fuels offer reduced GHG, sometimes even when of fossil origin (CNG). Biogas offers a win-win reduction of GHG since it is better to burn the strong GHG methane to CO_2 rather than emitting it. DME demonstrates excellent emissions performance and might be introduced on a larger scale.
- Several emerging fuels have interesting properties but require further research and have yet to prove their worth.
- The parallel use of several alternative fuels can be beneficial not only from a supply point of view but also with respect to combustion performance – mixtures of several components (as diesel or gasoline) can allow better combustion performance and control.
- The relatively small variations in engine efficiency between different alternative fuels indicate that GHG emissions and operation costs could be more affected by Well-To-Tank (fuel production, distribution) than from Tank-To-Wheel (engine and vehicle).

Engine (vehicle) technology

- Traditional engine concepts such as SI and DICI are quickly improving while new concepts such as PPC and RCCI are intensively researched.
- New engine concepts show good potential for high efficiency (low CO_2) and low regulated emissions.
- New engine concepts are easier to adapt to new alternative fuels than the traditional ones.
- New fuels may introduce challenges on the engine fueling systems, lubrication systems and EATS due to corrosion, fuel degrading and problematic fuel components.
- Increased hybridization of vehicles reduces the amounts of required alternative fuels but requires integration between engine and hybrid system. Such integration can be exploited for up to 30% reduction in engine fuel consumption by optimizing the engine for one primary operating point.

Research methods and potential research activities

- Improved fundamental understanding of fuel properties is essential for the research and development of clean and efficient engines. The current methods and standard tools are to some extent insufficient to provide such understanding or meaningful comparisons of fuels in different combustion strategies, and should therefore be complemented and developed further.
- Increased fraction of drop-in fuels in fossil fuels for traditional SI and DICI should be considered as first measures.
- Further development of the concept of ternary blends, to achieve high fractions of alternative fuels without upsetting engine calibration or functionality of control systems or EATS in SI and DISI, could be relevant to investigate further.
- Research into solving methane slip in LNG, CNG and biomethane engines is required.

- Scanning relevant and emerging alternative fuels together with the best emerging engine concepts is needed. Integration towards electrofuels is an important factor.
- Integration between several research disciplines is required to understand the best alternative fuel candidates.

Other considerations

- Stricter emissions legislation will pose additional challenges on both fuels and engine systems.
- The large uncertainties on what policies that will be introduced for alternative fuel both in Sweden and in other countries makes it difficult for all relevant parties to focus their activities or find funding and thus slows down research and technical development.
- Sweden targets fossil independent vehicle fleets by 2030, which is only 15 years away considering the lifetime of vehicles and the need for research and development.
- Sweden has a better potential to be a leading market for introduction of sustainable fuels and vehicles than many other countries.

Research demonstrates that combustion engines can be adapted to efficient and sustainable operation with a large variety of alternative fuels, albeit with some trade-off in costs and performance. This adaptability makes ICEs part of the sustainable future for the move from fossil fuel dependence into sustainable systems that integrate cost effective fuels, energy grid and transportation.

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Appendix

Table 1. References and comments for Figures 7 and 8.

	Reference	Comment*
Methanol/SI	[13]	
DNBE/DICI	[35]	Estimated BTE
Octanol/DICI	[35]	Estimated BTE
GTL/DICI	[31]	
RME/DICI	[31]	
SME/DICI	[31]	
E10/SI	[18]	
E30/SI	[18]	
E85/SI	[18]	
E100/SI-Lean	[25]	
E20B10Di70/DICI	[29]	
POMDME/DICI	[37]	
Hydrogen/HCCI	[55]	
Me93Di7/RCCI	[15]	Estimated highest potential BTE from 51% GIE
Naphtha/PPC	[44]	Estimated highest potential BTE from 51% GIE

* Unless specified, estimations are made by the author of this report.

Table 2. References and comments for Figures 9 and 10.

	Reference	Comment*
Methanol/DICI	[14]	Estimated GIE incl turbocompound by original authors
Ethanol/DICI	[14]	Estimated GIE incl turbocompound by orignal authors
HVO/DICI	[34]	Estimated GIE. Real driving emissions
GTL/DICI	[34]	Estimated GIE. Real driving emissions
RME/DICI	[34]	Estimated GIE. Real driving emissions
79E85Di21/RCCI	[67]	
Ethanol/PPC	[23]	
Ethanol/PPC-λ1	[22]	
Naphtha/PPC	[43]	
Best Diesel/DICI	[68]	Estimated lowest possible emissions
ED95/DICI	[20,21]	Estimated GIE from 43% BTE
CNG/Lean-burn SI	[45, 46]	Estimated GIE from 43% BTE
CNG/Diesel DF	[46, 69, 70]	Estimated GIE from 43% BTE
CNG/SI-λ1	[46]	Estimated GIE from 40% BTE
DME/DICI	[52,53]	Estimated GIE, older engines
E85/Diesel DF	[29]	75%EtOH, Estimated GIE from 42% BTE.

* Unless specified, estimations are made by the author of this report.