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Kappel, Jannik; Mathiesen, Brian Vad

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**SCREENING OF TANK-TO-WHEEL EFFICIENCIES FOR CNG, DME AND
METHANOL-ETHANOL FUEL BLENDS IN ROAD TRANSPORT**



Screening of tank-to-wheel efficiencies for CNG, DME and methanol-ethanol fuel blends in road transport

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Authors:
Jannik Kappel
Brian Vad Mathiesen

Publisher:
Department of Development and Planning
Aalborg University
Vestre Havnepromenade 5
9000 Aalborg
Denmark

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Abstract

The purpose of this report is to evaluate the fuel efficiency of selected alternative fuels based on vehicle performance in a standardised drive cycle test.

All studies reviewed are either based on computer modelling of current or future vehicles or tests of just one alternative fuel, under different conditions and concentrations against either petrol or diesel. No studies were found testing more than one type of alternative fuel in the same setup. Do to this one should be careful when comparing results on several alternative fuels. Only few studies have been focused on vehicle energy efficiency.

This screening indicates methanol, methanol-ethanol blends and CNG to be readily availability, economic feasible and with the introduction of the DISI engine not technologically challenging compared to traditional fuels. Studies across fuel types indicate a marginally better fuel utilization for methanol-ethanol fuel mixes.



DEN EUROPÆISKE UNION
Den Europæiske Fond for Regionaludvikling



ENERGIÖRESUND

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1 Purpose of This Paper

In a society based 100 % on renewable energy, e.g. as described in the recent CEESA project (2013) the transport sector must undergo a radical change. Currently 95 % of the global transport sector is dependent on oil [Mathiesen et al. 2008]. As shown in the CEESA report no single fuel technology is able to replace the fossil derived fuels. Due to the relative low energy density of batteries, fuels derived from biomass must be used, especially for heavy vehicles, ships and airplanes as well as a feedstock for chemical applications and plastics. This is essential as most renewable energy e.g. from wind, photovoltaic or hydro harvests energy in the form of electricity directly. The choice of fuel must be based on among other things; energy costs of “harvesting” the fuel, cost of using the fuel, energy density as well as environmental concerns. Studies on the entire fuel pathway are called Well-To-Wheel (WTW) studies and are often separated in Well-To-Tank (WTT) and Tank-To-Wheel (TTW) studies.

This report compares studies on the last part of the pathway; the tank-to-wheel studies, with respect to the fuel utilization of alternative fuels. Only studies using a standardized drive cycles are included. The report also summarizes specific studies on Methanol, CNG and DME since these fuels are deemed to have high potential. The unit of comparison is fuel utilisation in MJ/km and the parameters are type of vehicle, type of engine and type of fuel. Engine designs will be characterised in three different categories. Piston Injection Spark Ignition (PISI), Direct Injection Spark Ignition (DISI) and Direct Injection Compression Ignition (DICI). The DISI engine is currently the dominating petrol engine and the DICI is the engine used in diesel vehicles.

Several alternative fuels are studied. Ethanol fuel blends are written as e.g. E85 where 85 is the share of ethanol in %, the rest being petrol. The same is the case for methanol where M100 would be pure methanol. The study focuses on personal cars and trucks. However conclusions regarding fuel utilisation are expected to be transferable to other means of transport.

2 Literature review

This review includes both "large" general studies on many vehicles and many fuels as well as more specific studies on few or single vehicles and fuels. Characteristic for the large studies is that they are to some extent based on computer modelling and not actual laboratory testing. Many of the studies also include estimated data for "future" vehicles.

2.1 General studies

The report "Well-to-Wheels Analysis of Advanced Fuel/Vehicle Systems — A North American Study of Energy Use" from May 2005 by Norman Brinkman et al. is an updated version of the original work from June 2001 [Brinkman 2005]. As then the vehicle modelled is a "future" 2010-model-year, full-sized GM pickup truck. The truck was selected because it was a high seller among light-duty vehicles (cars and trucks) in the U.S. market, and because light-duty trucks accounted for a large proportion of the fuel used in the U.S. vehicle fleet. In the study, the authors attempt to estimate the energy use and emissions for the 2010-model-year truck fleet over its lifetime. The WTW calculations were based on a fuel-cycle model developed by Argonne National Laboratory for an older 2001 study and updated for the current. The study included fuel utilisation data for a PISI engine running on petrol, CNG, and H₂, a DISI engine running on petrol and E85 and a DICI engine running on diesel.

Another report; the "Well-to-wheels analysis of future automotive fuels and powertrains in the European context – The Tank to wheels report" was carried out jointly by representatives of EUCAR (the European Council for Automotive R&D), CONCAWE (the oil companies' European association for environment, health and safety in refining and distribution) and JRC/IES (the Institute for Environment and Sustainability of the EU Commission's Joint Research Centre), assisted by personnel from L-B-Systemtechnik GmbH (LBST) and the Institut Français du Pétrole (IFP) [CONCAWE 2011].

The 3c version of the CONCAWE report from 2011 is the second updated version of the first report from 2003. The report is split in a WTT edition and a TTW edition. The TTW report summarises laboratory tests of 2002-vehicles using different fuel types and engine design. Data such as lag time to 100 km/h in different gears and fuel efficiency of the type MJ/100 km are summarised. All presented data are based on a common, "virtual" vehicle, representing a typical European compact size 5-seater sedan, comparable to e.g. a VW Golf. The theoretical vehicle is used as a tool for comparing the various fuels and associated technologies. It is not claimed to be representative of the European fleet. The reference is a 2002 Port Injected Spark Ignition petrol (PISI) powertrain. The report includes projections of the same data for the same vehicles as well as FCHEV vehicles. The report also states its projections of how technology is expected to be in 2010 and beyond. These data are called 2010+ and are still widely used in many studies. The numbers used in this study are however the known values from 2002. PISI vehicle data included from the study are: petrol, CNG bi-fuel and CNG dedicated, DISI-petrol and DICI Diesel, DME and synthetic diesel.

In 2007 the Danish Energy Agency (DEA) launched the "Alternative Propellants" project [DEA 2012]. The purpose of the project was to provide a systematic foundation to evaluate which alternative propellants for transport means seemed to have the greatest technological and economical long-term potential. This was the first project of its kind by a Danish governmental agency. In 2012 the project and the underlying model were upgraded to a more comprehensive edition. The Danish Energy agency is planning to keep updating the model to secure a good source of information on the matter. The report is mainly based on the "2010+ vehicles" from the CONCAWE study as well as datasheet data from auto producers. All data are aggregated to year

2030. The report contains data on PISI vehicles running on CNG and H₂, DISI vehicles running on petrol and E85, and DICI vehicles running on diesel, DME and synthetic diesel.

The database and model "Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model", GREET is maintained by the Argonne National Laboratory and can be used for simulating vehicle data such as emissions and consumption data for the years 1990-2020 and for three different vehicle classes: passenger cars, Light Duty Truck 1 (<2,7 tons) and Light Duty Truck 2 (< 3,9 tons) and several engine types [GREET 2013]. Data from an example file of the model from 2012 is included in the below comparison. The data includes utilisation data for PISI-petrol and dedicated CNG, DISI-E85 and DICI-diesel and synthetic diesel.

2.2 Specific studies

This section contains specific studies on CNG, methanol or DME. Contrary to the previous section the data here are based on real-life driving or laboratory tests using the New European Drive Cycle (NEDC) or another drive cycle. CNG vehicles are generally separated in two categories. Dedicated CNG engines run on CNG alone, where as bi-fuel engines run mainly on CNG but have a back-up petrol engine. Bi-fuel vehicles thus have two separate fuel tanks.

Other alternative fuel vehicles are of the Flex-fuel type. A Fuel-flex vehicle is, as the name suggest flexible in the types of fuel it can use. After refuelling the vehicle a virtual and/or physical system determines the volume and density of the new fuel and adjust compression accordingly. Fuel-Flex vehicles can typically run on petrol with as much as 85 % ethanol and can easily be upgraded to run on M85 or even M100 [Bromberg and Cheng 2010]. Upgrading a DISI to fuel-flex capability is in the range 100\$-300\$ [Turner 2013] and may even be as low as 70\$ [Stephens 2011], and thus very cheap compared to the additional costs choosing the CNG version of a new car which cost app. 1750€ [Concawe 2011].

Since the cetane number for DME is almost the same as Diesel, DME can typically be used directly in a DICI engine and methanol can be used in much the same way due to its high octane (RON 109) and high heat of vaporization (RON 24 eq). In this respect, DME and methanol has several advantages over Diesel. PM emissions are very few, decreasing the need for a particulate filter. DME and methanol have a low carbon content (C/H ratio: 0.33 and 0.25 respectively) and produces less CO₂ during synthesise from NG compared to diesel produces via the Fisher-Tropsch process [Sato 2009]. Methanol further has the advantage of being a liquid whereas DME is a gas. The ED95 concept used by Scania can easily be modified to a MD95 concept [Bromberg and Cheng 2010]. Comparisons made by Brusstar [Brusstar 2002] shows that higher efficiencies can be achieved when using methanol in a slightly modified diesel-engine than when using diesel. The engine had the same efficiency as on diesel when ethanol was used. Since both ethanol and methanol is Research Octane Number (RON) 109 the difference origins from the differences in heat of vaporizations.

2.2.1 CNG

In an attempt to compare actual consumption data for a city refuse truck transformed from using traditional Diesel to CNG, a full life cycle analysis were conducted in the Canadian city of Surrey, British Columbia [Rose et al. 2013]. The LCA found no net gain in energy, however significant reductions (approximately 24% CO₂-equivalent) in GHG and criteria air contaminant (CAC) emissions were obtained. In addition fuel cost estimations based a 5-year lifetime for both vehicles reveal that considerable cost savings may be achieved by switching to CNG. The paper concludes: "Thus, CNG RCVs are not only favourable in terms of reduced climate change impact but also cost

effective compared to conventional diesel RCVs, and provide a viable and realistic near-term strategy for cities and municipalities to reduce GHG emissions.”

The CNG truck was seen to have a marginally better fuel utilization. However the values include starts and stops, pauses and handling the garbage containers. Thus although the study is valid for comparing CNG and diesel in the concrete example, the study is not comparable with other studies on other types of vehicles.

Naturgas Fyn has 15 natural gas vehicles. Eight are VW Caddy, four are VW Transporter, two are VW Passat and one is a Fiat Panda. All vehicles are fuelled at the same company fuelling station and the consumption and kilometres driven has been written down from November 2011 to November 2012. All vehicles are bi-fuel meaning that they are also fitted with a back-up petrol engine. The back-up engine is reportedly used very seldom and it is thus possible to calculate the average CNG consumption for each vehicle type. The consumption compared to the data sheet is seen in Figure 1.

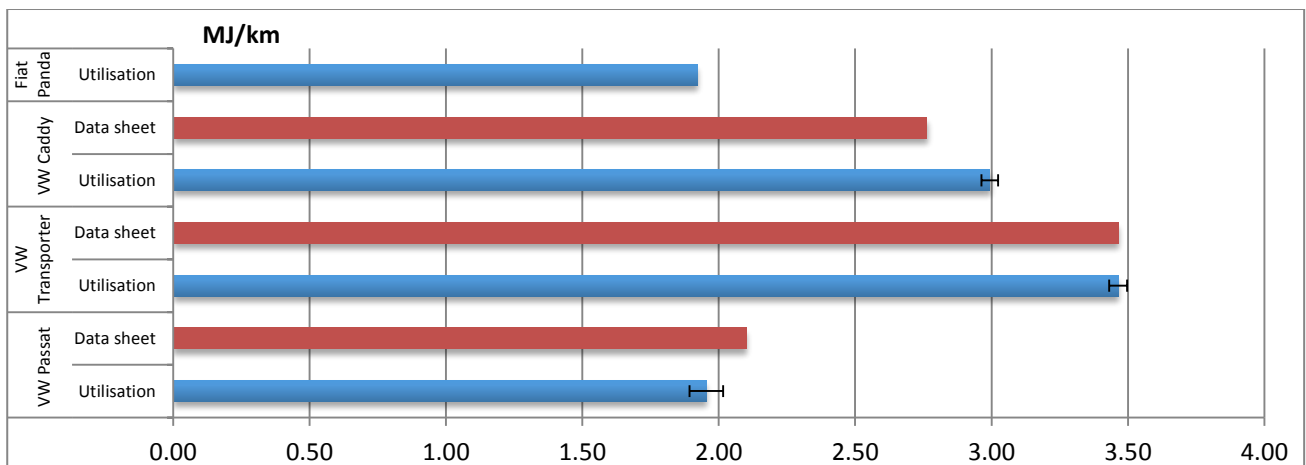


Figure 1: Average fuel consumption with standard error for CNG vehicles and VW data sheets for the same CNG vehicles. Data from Naturgas Fyn, 2012

The standard error for the measured data is seen to be small and the values are very close to the data sheet values.

2.2.2 Fuel-flex vehicles

Using methanol as a fuel for vehicles is not a new idea. Volkswagen has conducted test at least since 1972. Up until the mid 1980’s the purpose of the proposed fuel shift were [IFP 1986]:

1. Environmental concerns including the phase out of leaded petrol and reduction of smog.
2. Strategic needs to reduce the heavy dependency on imported oil.
3. Developing new markets for NG, coal and agricultural products to reduce surplus production.

Several large regional tests were carried out in the period 1972 to 1988 with ~ 1000 cars in field trials in Germany, Sweden and New Zealand as well as ~ 500 vehicles in China [Methanol Institute 2013] with fuel mixes of M15 ED30/MD30, E100 and M85. The studies found most vehicles to have travelled more than 160.000 km and some more than 350.000 km without any considerable corrosion and wear in the methanol engine. Cold-start issues were reduced using electric PTC heaters to heat up the inlet manifold. No utilisation data were recorded.

A very recent study compared the fuel efficiency of different methanol and ethanol mixes in a flex-fuel vehicle [Turner 2013]. E85 has an Air Fuel Ratio (AFR) of 9,69. By mixing different concentrations of Gasoline, Ethanol and Methanol (named GEM blends) Turner et al. tested how several fuel-mixes with similar AFR performed in an unaltered flex-fuel vehicle. The purpose of the tests was to extend the ethanol supply – not to increase energy efficiency. The tested fuel mixes were: G100E0M0, G15E85M0, G29.5E42.5M28, G37E21M42 and G44E0M56. Except for pure petrol the AFR, density, gravimetric LHV, volumetric LHV, carbon intensity was very similar for all mixes. Two test vehicles were used: A SAAB 9-3 station wagon fitted to Euro IV with a manual gear box and a SAAB 9-3 station wagon fitted to Euro V with an automatic gear box.

Turner found the mixes to cause very few issues. Issues with cold-start were only a problem for the pure E85, and only in harsh winter conditions and not with any of the methanol mixes. Three drive cycles (NEDC) were performed, one cold and two warm, overall the mixes were found to have a better fuel utilisation than pure petrol in all tests. The authors argue that the extra cost of upgrading a vehicle to Flex-fuel capability is only \$100-\$300, and thus very limited compared to e.g. CNG or hydrogen fuel cell vehicles. The cost is coherent with GM Denmark who charged 1000 DKK (\$174) including tax (180 %) and VAT (25 %) for upgrading a 2010 Opel Insignia to Fuel-Flex [Opel Denmark 2013]. Excluding VAT and tax the added cost is reduced to 286 DKK (\$50) which is fully in line with GMs former Vice Chairman Tom Stephens claiming an additional cost of upgrading a gasoline car to FFV of 70 \$ [Stephens 2011].

Vancoille et al. (2012) like we did, found most existing WTW studies to be based on out-dated technology and thus modified a spark ignition engine to perform as a flex-fuel vehicle. This vehicle was used to compare renewable transport fuels, hydrogen and methanol formed from hydrogen, with gasoline. The authors found the ability to employ qualitative load control instead of throttling giving relative efficiency improvements compared to gasoline between 10 and 20% due to reduced pump control. The highest efficiencies were attained when operating on hydrogen and using qualitative load control, especially at low loads, where improvements up to 40%, relative to gasoline were achieved. Due to higher NO_x emissions, throttled stoichiometric operation were required on higher loads, this resulted in efficiencies comparable to those of gasoline. Methanol efficiencies were found to be only 5-10% relative to gasoline, but could be retained over the entire load range. The authors found these improvements mostly to be due to reduced pumping losses, increased burning velocities and decrease in cooling losses. Since measurements are only done on the engine and thus not using a drive cycle, only the conclusions and not the data from the study can be included in this report.

2.2.3 DME

A recent Japanese study tested DME as a fuel in five trucks of different size and on different roads [Sato 2009]. The purpose of the study was to compare emissions from diesel and DME, but fuel consumption was also noted. For the heavy truck, mainly travelling on highways the average fuel consumption was found to be 12,7 MJ/km, the average fuel consumption for a light truck travelling on ordinary roads were recorded as 6,7 MJ/km and a light duty truck travelling mainly on highways had an average fuel consumption of 5,4 MJ/km. The authors note the fuel consumptions to be "virtually the same as current diesel vehicles".

3 Comparison of the data

In comparing data from different sources it is important to assure that the conditions under which the measurements are performed are sufficiently similar. The first step when looking at vehicle data is to ensure that the engine types are the same. In this comparison engine types are separated in to three types: PISI, DISI and DICI. However as choice of vehicle and method of measurement differ between the studies only the relative difference between fuels are compared.

3.1 Piston Injection Spark Ignition engine

The Piston Injection Spark Ignition is the “old-fashion” engine with a carburettor and sparkplugs. This engine is cheaper and simpler than more advanced engines but also in general less efficient. From the data studied it seems to be rather common in use in Asia and other non-westerns countries currently, whereas it is seldom used in western-country vehicles anymore.

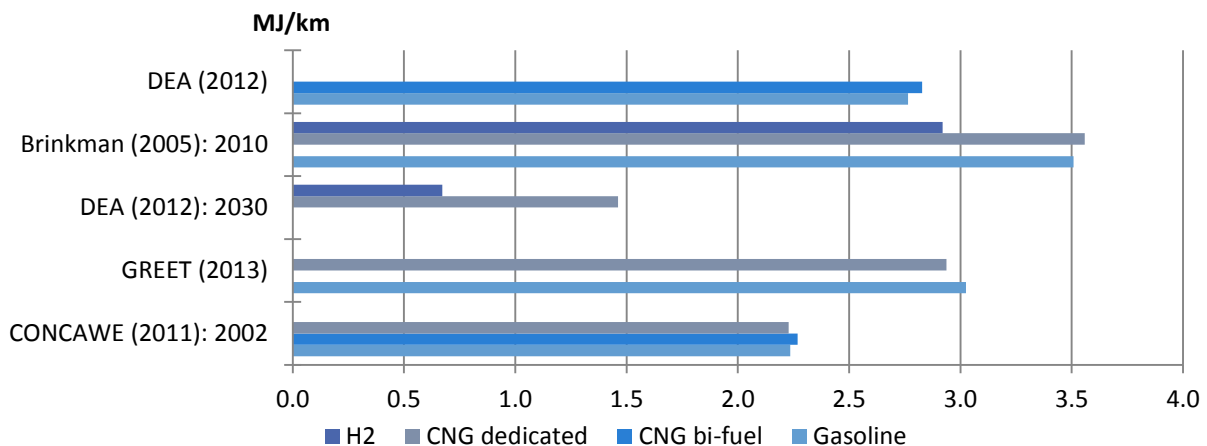


Figure 2: Fuel efficiency for Piston Injection Spark Ignition engines with data-year if not the same as publication year.

Figure 2 compares fuel consumption of different fuels and literature sources. It is seen that the dedicated CNG engine has a marginally lower fuel consumption per kilometre from the data from CONCAWE and the GREET model. Contrary Brinkmans results showed petrol to be a little more efficient.

Both the non-forecasted DEA data and the CONCAWE study suggest the bi-fuelled CNG to be marginally less efficient than the petrol engine.

Data from Brinkman suggested H₂ in a PISI engine to have lower energy consumption per km than both CNG and regular petrol. DEA has the same conclusion regarding H₂ and CNG.

3.2 Direct Injection Spark Ignition engine

The Direct Injection Spark Ignition engine employs no carburettor but instead uses electronically controlled injection to give a more efficient use of the fuel. This engine type has been dominating in petrol vehicles in the western world since the beginning of the 2000's. By using DI cold start problems of FFVs are virtually eliminated since there is no longer a need for vapour pressure, as is the case for PISI engines.

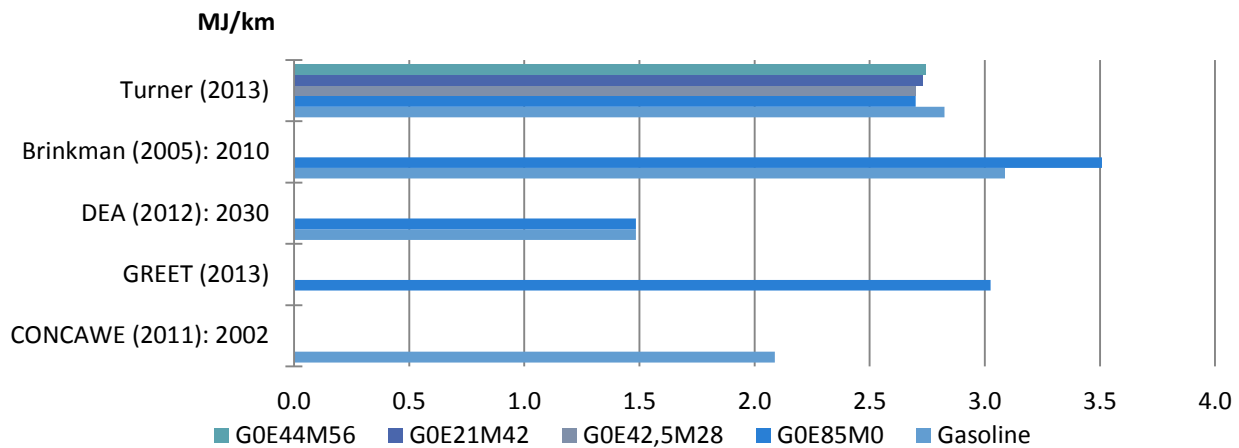


Figure 3: Fuel efficiency for Direct Injection Spark Ignition engines with data-year if not the same as publication year.

Figure 3 compares the different literature sources and fuel types for the DISI engine. DEA expects the petrol engine and the E85 to be equally efficient in 2030. Brinkman assumed the E85 to be less efficient than the petrol engine. This is in contradiction to Turner et al. who performed three engine tests per fuel and found the E85 and methanol mixes to be marginally more efficient than petrol.

3.3 Direct Injection Compression Ignition engine

The Direct Injection Compression Ignition engine, or the “Diesel Engine” does not employ spark plugs but instead ignites the fuel by compression. This limits the possible fuel types but allows for an even higher efficiency compared to other engine types due to the higher compression.

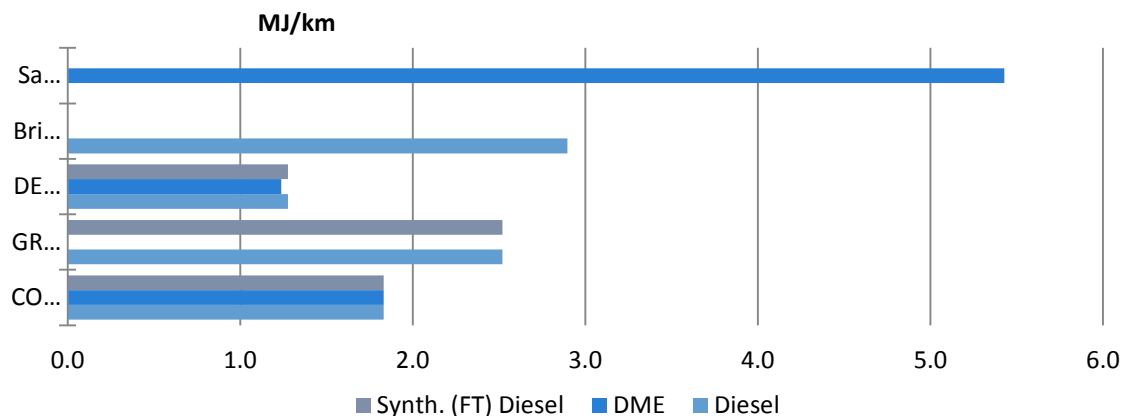


Figure 4: Fuel efficiency for Direct Injection Compression Ignition engines with data-year if not the same as publication year.

Figure 4 contains a comparison of fuel types from different sources using the DICI engine. The GREET project and DEA expects synthetic diesel and fossil fuel derived diesel to have the same engine efficiency in year 2013 and 2030 respectively. DEA assumes DME to have a slightly better efficiency than traditional diesel in year 2030, where as CONCAWE saw no difference in 2002. Sato found all tested DME trucks energy consumption to be comparable to that of diesel.

3.4 Tank size requirements of CNG, Diesel and methanol

The range of a vehicle obviously depends on the size and the content of the fuel tank. The available cargo space on CNG trucks depends heavily on pressurisation of the gas. The volume can be estimated as follows. The density of methane at 250 bars is roughly 190 kg/m^3 . Liquid Methanol has a density of 790 kg/m^3 . The gravimetric heating value is approximately 50 MJ/kg for NG and 20 MJ/kg for methanol. Thus CNG takes up twice the space as methanol for the same energy content at 250 bars, the standard pressure of CNG for vehicles. At 1000 bars the volumetric energy content is comparable, however this high pressure might cause safety issues with regards to loading and storage. Roughly 15-20 % energy is lost when converting NG to methanol, however energy cost from electricity to CNG or methanol is comparable for the two and the energy cost of compressing CNG is only a few MJ/kg. Thus the critical factor in choosing between the two is the energy utilization in vehicle which. CNG was shown to be slightly more efficient than Diesel by Sato (2009).

If only looking at the heating value, Diesel should take up roughly half the volume of methanol, however methanol has a higher oxygen-content, leading to a theoretical higher engine efficiency.

4 Conclusion

All studies reviewed are either based on computer modelling of current or future vehicles or tests of just one alternative fuel, under different conditions and concentrations against either petrol or diesel. No studies were found testing more than one type of alternative fuel in the same setup. Do to this one should be careful when comparing results on several alternative fuels. Only few studies have been focused on vehicle energy efficiency.

DME is most often produce via a two-step process from NG via methanol and syngas to DME. According to Sato (2009) the fuel efficiency is comparable to that of DME, however PM emissions are fewer and the energy costs of producing DME are lower than diesel produced via the Fischer-Tropsch method.

CNG vehicles have approximately the same energy efficiency as petrol engines. However emissions are lower and NG is not a scarce resource to the same scale as oil. Rose found CNG to be marginally more energy efficient than diesel and the total lifecycle economy to be in the favour of CNG. No studies were found comparing neat M100 to other fuels in the same vehicle.

The Chinese auto manufacture Geely, selling cars in Russia, Turkey, Nepal, Venezuela, Ukraine, Chile, South Africa, Syria and Uruguay, started production of its first methanol-powered vehicles in 2012 [Ewoks 2011]. Chery another Chinese auto manufacture sells vehicle that run on different mixtures of methanol up to M85 [Methanex 2011]. Using pure methanol M100 have previously given problems with cold start, this can however be solved by using DI, a technology which has been widely used since the early 2000's.

Methanol-ethanol fuel mixes seems promising since the fuel efficiency seems to be marginally better than fossil derived fuels and the costs of upgrading a DISI engine to flex-fuel capability is very small compared to the total price of the vehicle [Turner et al. 2013].

Methanol may increase the efficiency of vehicles due to higher oxygen content [Vancoillie et al. 2012 and Turner et al. 2013]. CNG seems to be comparable to existing petrol vehicles. Hence this screening finds a dire need to conduct laboratory test or computer modelling on the matter. There is a specific need for an analysis of such fuels in heavy vehicles as these vehicles are hardly electrifiable.

This screening indicates methanol, methanol-ethanol blends and CNG to be readily availability and with the introduction of the DISI engine, not technologically challenging compared to traditional fuels. Studies across fuel types indicate a marginally better fuel utilization for methanol-ethanol fuel mixes.

Ethanol, methanol, CNG and DME can be derived from non-fossil sources. Currently the last three can be derived easily from NG, which in the future can be substituted with synthetic fuels based on renewable energy.

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