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Feasibility of Alternate Fuels for Use on Pilot Boats

Research Project

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ABSTRACT

Swedish pilot vessels are small, high powered craft that operate in and around populated port areas. Their primary function is to ensure the safe delivery and transfer of marine pilots to and from vessels transiting the port. In doing so, pilot vessels perform an important and challenging safety function which promotes the safe transit of vessels through Swedish waterways.

Recent years have seen increased interest in the reduction of the environmental impacts from waterborne trade, including from small harbor craft such as pilot vessels. One approach which has seen considerable development is the reduction of emissions via the implementation of alternate fueled marine craft that utilize fuels other than the marine gas oils (MGO) and heavy fuel oils (HFO) upon which the industry has hitherto relied. Particularly promising is the category of low flashpoint fuels which includes CNG, LNG, LPG, methanol, DME, and hydrogen (H_2). The advantages of these fuels include positive emissions reductions, a relatively well developed state of technology in both marine and non-marine sectors, and the possibility of synthesis from biomass feedstock.

This study considers the problem of reducing the emissions and environmental impacts associated with the operation of pilot vessels in Sweden. The issue is approached from the standpoint of a near term construction or conversion for a vessel to burn low flashpoint fuels which can eventually be sourced from biomass.

The first part of the project investigates CNG, LNG, LPG, methanol, DME, and hydrogen as possible fuel choices. The chemical and physical properties, handling and combustion characteristics, and availability of each of the candidate fuels are summarized. Based upon the information presented, LNG, methanol, and DME are selected as the most promising candidates for further investigation. The second part of the study examines the feasibility of a near term implementation of an LNG, methanol, or DME fueled pilot vessel wherein feasibility is defined as the ability of the vessel to deliver reliable and economic performance while in commercial service. The question of feasibility is examined from a number of perspectives: currently available technology in terms of engine concepts and fuel systems, safety hazards and implications of handling the selected fuels, proposed regulations for low flashpoint fueled vessels, past experience with various test installations, and the uncertainty of fuel markets and cost predictions.

Based upon the investigation of feasibility, the study finds that the technology required to implement an alternate fueled pilot vessel is well developed and has the potential to be commercially available in the near future. Pilot boats that are fueled by alternate fuels are expected to demonstrate a reduction in emissions and the concept will benefit from the well developed infrastructure for biofuels in Sweden. All three fuels are currently available in Sweden and in many instances are available as sourced from biomass.

However, and despite the potential synergy due to technical similarities with road vehicles such as heavy duty trucks, this study concludes that Swedish pilot vessels are not the best suited platform for the implementation of these technologies. The hazards associated with the handling of the low flashpoint fuels necessitate the installation of many additional systems and components. The added level of complexity is expected to contribute significantly to the initial acquisition and operating costs of the vessel and to negatively affect the overall reliability of the vessel. Since pilot vessels perform a

critical role in ensuring the safety of pilots and thereby promote safe commerce within ports, any potential compromise in reliability is a significant concern.

A significant level of uncertainty is also encountered as a result of the ambiguity associated with the regulatory requirements for the vessel. The regulations governing gas fueled vessels are still under development and it is not certain to which extent Swedish pilot vessels will need to comply with these regulations. Nonetheless, the standards which are currently being proposed have been adapted from much larger scale installations and therefore have the potential to render the project infeasible.

Although it is possible that there will be tenable technical solutions to the aforementioned problems, there are two particular issues which are of special concern and which do not lend themselves to the application of the respective fuels to small marine craft. The first relates to LNG and the fact that the homogenous charge type engines which are used to burn LNG have a tendency to pass unburned methane via the exhaust which has 21-25 times greater a global warming potential than CO_2 on a 100 year time scale. The second relates to methanol and DME, which are problematic because their vapor is heavier than air. This means that released vapor will pool and collect in the low and crenellated spaces that are typical of small craft machinery spaces.

Further work on the low flashpoint fueled concept will require an assessment in order to determine to which standards the vessel will have to be built and whether these standards will render the project infeasible. On the basis of this assessment, a more detailed design concept should be developed in order to assess the economic feasibility of the concept, including fuel supply and storage. An alternate approach which should be considered is the partial blending of liquid fuels such as biodiesel or biomass derived GTL fuels.

Sammanfattning

Svenska lotsbåtar är små, har hög installerad effekt och används mycket i och runt befolkade hamnområden. Den primära funktionen är en säker transport av lotsar till och från fartyg som trafikerar hamnen, vilket är en orsak till att det ställs krav på hög effekt.

De senaste åren drivkrafterna för att minska hälso- och miljöpåverkan från sjötransporter ökat. Detta gäller speciellt för trafik i områden nära kuster och med hög befolkningstäthet, det vill säga områden där större delen av lotsbåtarnas verksamhet bedrivs. En viktig strategi för utsläppsminskning är använda andra bränslen än de traditionella inom sjöfart; marin dieselolja (MGO) och tjockolja(HFO). Särskilt lovande alternativ är bränslen med låg flampunkt som CNG (komprimerad naturgas), LNG (flytande naturgas), LPG (gasol), metanol, DME (dimetyleter) och vätgas (H2). Fördelarna med dessa bränslen är, förutom att de ger utsläppsminskningar, en relativt väl utvecklad motorteknik, samt möjligheten till syntes från bioråvara.

Denna studie fokuserar på möjligheter att minska utsläpp och påföljande miljökonsekvenser i samband med driften av lotsbåtar i Sverige genom att byta bränsle. Utgångspunkt är en nybyggnation eller ombyggnad till drift med bränslen med låg flampunkt som på sikt kan produceras från biomassa.

I den första delen av projektet har en studie av potentialen hos CNG, LNG, LPG, metanol, DME och vätgas som möjliga bränslen utförts. De kemiska och fysikaliska egenskaperna, hanterings -och förbränningsegenskaper samt tillgången på bränslen har utvärderats. Utgående från den informationen har LNG, metanol och DME identifierats som de mest lovande kandidaterna för en fördjupad utredning. I den studeras möjligheten att i en nära framtid implementera LNG, metanol eller DME som bränsle på fartyg där genomförbarheten definieras som driftsäkerhet och ekonomisk rimlighet.

Frågan granskas ur flera perspektiv: tillgänglig teknik i fråga om motorkoncept och bränslesystem, säkerhetsrisker och konsekvenserna av att hantera de utvalda bränslena, befintliga och förslagna föreskrifter för användning av bränsle med låg flampunkt, tidigare erfarenheter från olika testkoncept och osäkerheten i bränslemarknad och kostnadsläge.

Utgående från denna genomgång kan man konstatera att teknik som krävs för att byta till de studerade bränslena finns och är väl utvecklad/har potential att bli kommersiellt tillgänglig inom en snar framtid. Lotsbåtar som drivs av alternativa bränslen kan förväntas ge minskade utsläpp och konceptet kommer att gynnas av väl utvecklad infrastruktur för biobränslen finns i Sverige.

Alla tre bränslena används för närvarande i Sverige och i många fall finns kvaliteter som som baseras på biomassa tillgänglig.

Men trots synergieffekter av tekniska likheter med vägfordon som tunga lastbilar, kan man konstatera att svenska lotsbåtar är inte den bäst lämpade plattformen för införande av de föreslagna bränslena. De risker som är förknippade med hanteringen av bränslen med låg flampunkt kräver installation av många ytterligare system och komponenter. Den extra

nivån av komplexitet kan förväntas höja anskaffnings-och driftskostnader för fartyget och även minska den totala tillförlitligheten hos fartyget.

Eftersom lotsbåtar har en avgörande roll för att garantera säkerheten för lotsar och därigenom främja säker verksamhet i hamnarna, är eventuella kompromisser i tillförlitlighet en allvarlig nackdel.

En betydande grad av osäkerhet finns också genom oklarheter i regelverk för användning ombord. Regelverket för gasdrivna fartyg är fortfarande under utveckling och det är inte säkert i vilken utsträckning svenska lotsbåtar måste följa dessa regler. De normer som för närvarande föreslås har anpassats från installationer i mycket större skala, vilket potentiellt kan omöjliggöra användning till lotsbåtar.

Även om det är möjligt att man kan finna hållbara tekniska lösningar på dessa problem, återstår två frågor att beakta och som gör att bränslet inte lämpar sig väl för små marina farkoster. Den första rör LNG och det faktum att den typ av motorer som används för LNG har en tendens att ge stora utsläpp av oförbränd metan via avgaserna (”metanslip”). Metan har 21-25 gånger större en global uppvärmningspotential än CO_2 på en 100 årig tidsskala. Det andra handlar om metanol och DME, vilkas ånga är tyngre än luft. Det innebär att det finns risk att explosiva blandningar uppstår i maskinrum och liknande utrymmen på små båtar.

Ytterligare studier av konceptet med användning av bränslen med låg flampunkt kommer att kräva en utvärdering av vilken standard fartyget måste byggas och om till och om detta kommer att göra projektet omöjligt. På grundval av den bedömningen bör ett mer detaljerat designkoncept utvecklas för att kunna bedöma de ekonomiska förutsättningarna, inklusive bränsleförsörjning och lagring. Ett alternativ som bör tas med är att göra en partiell inblandning av flytande bränslen som biodiesel eller biomassa-baserade GTL bränslen.

ABBREVIATIONS

ASD	Azimuth stern drive
BLEVE	Boiling liquid expanding vapor explosion
CBD	Central business district (cycle)
CFC	Chloroflorocarbon
CH_3CH_3OH	Ethanol
CH_3OCH_3	Dimethly ether
CH_3OH	Methanol
CH_4	Methane
CNG	Compressed natural gas
CO	Carbon monoxide
CO_2	Carbon dioxide
DF	Dual fuel
DI	Direct injection
DING	Direct injection natural gas
DITA	Direct injection turbocharged aftercooled
DME	Dimethyl ether
DNV	Det Norske Veritas
ECA	Emissions Control Area
ECM	Engine control module
EEDI	Energy Efficiency Design Index
EEOI	Energy Efficiency Operational Index
EGR	Exhaust gas recirculation
FLT	Forklift truck
GHG	Greenhouse gas
GRP	Glass-reinforced plastic or polymer
GTL	Gas-to-liquids fuels
GWP	Global warming potential
H_2	Hydrogen, liquid or gaseous
H_2S	Hydrogen sulfide
H_2SO_4	Sulfuric acid
HAJI	Hydrogen assist jet injection
HAM	Humid air motor
HCCI	Homogenous charge compression ignition
HFO	Heavy fuel oil
HHV	Higher heating value
HS&E	Healthy, safety, and environment
HSI	Hot surface ignition
HPDI	High pressure direct injection
HSSI	Homogenous stoichiometric spark ignition
IMO	International maritime organization
J	Joule
kPa	Kilopascal
kW	Kilowatt
LBG	Liquified biogas

LBSI	Lean burn spark ignition
LCA	Life-cycle assessment
LEL	Lower explosive limit
LEV	Low emission vehicle
LHV	Lower heating value
LNG	Liquified natural gas
LOA	Length overall
LPG	Liquified petroleum gas
M90	Fuel blend of 90% methanol and 10% gasoline
MARPOL	Marine Pollution Act
MEP	Mean Effective Pressure
MGO	Marine gas oil
MN	Methane number
MON	Motor octane number
N_2O	Nitrous oxide
NMHC	Non-methane hydrocarbon
n-mi	Nautical miles
NOK	Norwegian Krone
NO_X	Nitrous oxides
NREL	National renewable energy laboratory
PM	Particulate matter
PTO	Power take off
RON	Research octane number
RPT	Rapid phase transfer
SECA	Sulfur Emissions Control Area
SEEMP	Ship Energy Efficiency Management Plan
SING	Spark Ignition Natural Gas
SO_2	Sulfur dioxide
SO_3	Sulfur trioxide
SO_X	Sulfur oxides
T&D&S	Transportation and distribution and storage
ULEV	Ultra low emission vehicle
USD	United States Dollars
VCE	Vapor cloud explosion
VOC	Volative organic compound
W	Wobbe index
λ	Fuel-to-air ratio

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1 INTRODUCTION

Recent years have seen an increase in the awareness of and emphasis on reducing the environmental impacts associated with the maritime transport sector. As evidenced by the staggering array of both local, national, and international regulations that have recently come into effect or are currently under consideration, there is both a real pressure to affect positive improvements and a great deal of uncertainty as to which technical and legislative instruments will be the most effective means of doing so.

On a global scale, the situation is complicated by the fact that there is not a single, overriding executive body to coordinate, oversee, and direct maritime emissions reduction directives. As a result, the regulations have been either decentralized and regional in their application or the result of intense compromise amongst competing interests. Even on a vessel scale, there are tradeoffs that must be made between conflicting operating interests: for example, nitrous oxides (NO_X) vs. vessel efficiency and the utilization of cleaner burning distillate fuels vs. the profitability of the voyage. This situation is made more challenging by the global nature of the shipping industry and the fact that any technologies that are to be adopted globally must be supported and supplied regardless of the possibility of shifting trade patterns and ports of call.

In recent years, there have been a number of successes in smaller scale projects that have demonstrated the feasibility of emissions reduction technologies while minimizing the scope of the application; for example LNG (liquefied natural gas) fueled ferries in Norway and cold-ironing for liner service container ships in California. These projects have been successful precisely because they have been able to minimize the uncertainties of a truly global application while successfully demonstrating the technical feasibility of their respective technologies. In doing so, these small scale projects have had the added benefit of stimulating the interest that is required to develop the infrastructure necessary for a large scale implementation.

One approach which has garnered interest and demonstrated great potential is the widespread introduction and implementation of alternate fuels for marine applications. Most recently this interest has been the byproduct of the challenges that are associated with the meeting of marine environmental regulations that have been and are coming into force.

Although maritime regulations have historically lagged behind their shore-based counterparts, the challenges that are faced by shore-based and marine transportation industries are in many ways similar. One of the advantages of employing alternate fuels is that while there may only be a limited level of development and implementation in the marine sector, there is a wealth of data and experience regarding alternate fuels that can be applied from previous development in the shore-based transportation sector. In the case of small vessels, such as pilot boats, which have a much lower installed power relative to most other commercial vessels, this analogy to shore side transportation vehicles is particularly appropriate since, in a sense, a pilot vessel can readily be compared to a local delivery truck that operates from a home depot.

Pilot vessels are small harbor craft, typically in the range of 15m length overall (L_{OA}), whose purpose is to deliver marine pilots to and from vessels that are transiting a waterway, be it a harbor, river, or channel. On a daily basis, marine pilots are faced with a challenging task: not the least of which involves climbing up the side of a moving ship on a precariously fixed rope ladder, guiding an unfamiliar vessel through often constricted, crowded, and shallow harbor waters, and coordinating between the vessel and multiple ship-assist tugboats in order to safely and securely moor the vessel. (See Figure 1.)

Figure 1 - Typical pilot ladder arrangement for embarking and disembarking a pilot. (Picture courtesy of 1.)

In accomplishing their task, marine pilots are responsible for ensuring the safe and pollution free movement of vessels and goods through the ports of the world. When things go wrong, however, the results are not only highly visible to the general public, but also have the potential to incur huge costs to personnel, property, and the environment.

Although the statistics are not readily available, the possibility of pilot fatality or serious injury during the pilot transfer is well known (1) and cases of pilot fatalities are not unheard of especially in cold water environments (2). In the event that a pilot does fall from the ladder, risks include landing on the pilot boat, being struck by either vessel's propellers, hypothermia, and drowning. (Refer to Table 1.) These individual risks are further compounded by the fact that both vessels will need to maneuver without hesitation in order to avoid striking the pilot, the larger vessel will very likely abort its passage, and that the pilot vessel will need to react quickly to retrieve the pilot from the water.

Just as large marine vessels rely on pilots to ensure safe transit through harbor waters, so do marine pilots rely on pilot vessels and their crews to effect the pilot's safe transfer between vessels and ensure that they arrive in a suitable condition to take command of the vessel. As such, it is readily apparent that any new technologies for pilot vessels must be carefully scrutinized in order to ensure that the critical safety functions of the boat are in no way compromised.

Water Temperature [°C]	Expected Time Before Exhaustion	Expected time of Survival
0.3	**< 15min**	**45min**
0.3 – 3.3	**15 – 30min**	**30 – 90min**
3.3 – 10	**30 – 60min**	**1 – 3hrs**
10 – 15.6	**1 – 2hrs**	**1 – 6hrs**
15.6 – 21.1	**2 – 7hrs**	**2 – 40hrs**
21.1 – 26.7	**3 – 12hrs**	**3hrs – indefinite**
>26.7	**Indefinite**	**Indefinite**

Table 1 - Exhaustion and survival expectations for various water temperatures. (Adapted from 3.)

This project investigates the feasibility of operating Swedish pilot boats on alternate fuels, including methane based fuels such as LNG and CNG, LPG, methanol, DME, and hydrogen. The advantages of selecting Swedish pilot boats as a testing platform for alternate fuels include:

- A small scale application with relatively high fuel consumption;
- Close proximity to coastal population centers;
- The relatively developed state of the engine and fuel system technologies in this power range; and
- A relatively developed infrastructure and availability of alternate fuels within Swedish ports which have a significant biofuel capability.

The goal of this project is to ensure a feasible application of alternate fuels with the intention of transitioning to the utilization of biofuel feedstock.

The technologies that are considered must be both feasible and functional from an operational perspective while safeguarding the essential safety function of the pilot boat. The project includes a comprehensive discussion of the various alternate fuels and considers the relative advantages and disadvantages of the fuels from a variety of perspectives, including chemical properties, energy density, and technology available, hazards involved with the storage and handling, and life cycle perspective. On the basis of this discussion, LNG, methanol, and DME are selected as the most promising technologies for the short term and are discussed and evaluated in further detail.

2 BACKGROUND

In recent years, the reduction of emissions from marine commerce has received increasing attention. Although the carbon dioxide emissions from commercial marine operations are low relative to the quantity of goods carried, the emissions of NO_X and SO_X are collectively high compared to other modes of transportation (4). Because shipping routes are concentrated near areas of high population density, there is also a significant cost to society from the adverse health effects of marine generated emissions. Corbett et al. have shown that the emissions from vessels as far as 200 n-mi offshore have the potential to affect air quality within coastal communities (5) and have further estimated that the particulate matter (PM) emissions alone were responsible for between 19,000 and 64,000 premature deaths annually related to lung cancer and cardiopulmonary disease (6). Not surprisingly, the highest density of these fatalities was found in Asia and Europe in those areas adjacent to the world's busiest shipping lanes. (See Figure 2.) More recently, McArthur and Osland have estimated that the total cost of emissions in the port of Bergen for 2010 are in the range of 4.75 and 21.5 million Euro per annum (7) which corresponds to a cost of approximately 660 NOK per resident per year. And while the majority of attention has been given to the emissions from large, ocean-going vessels, the influence of emissions from inland waterborne commerce should not be underestimated nor discounted. Corbett and Fishbeck suggest that 54% to 78% of vessel generated NO_X emissions found in the twenty busiest states in the United States with waterborne commerce are the result of marine engines operating on inland waterways (8).

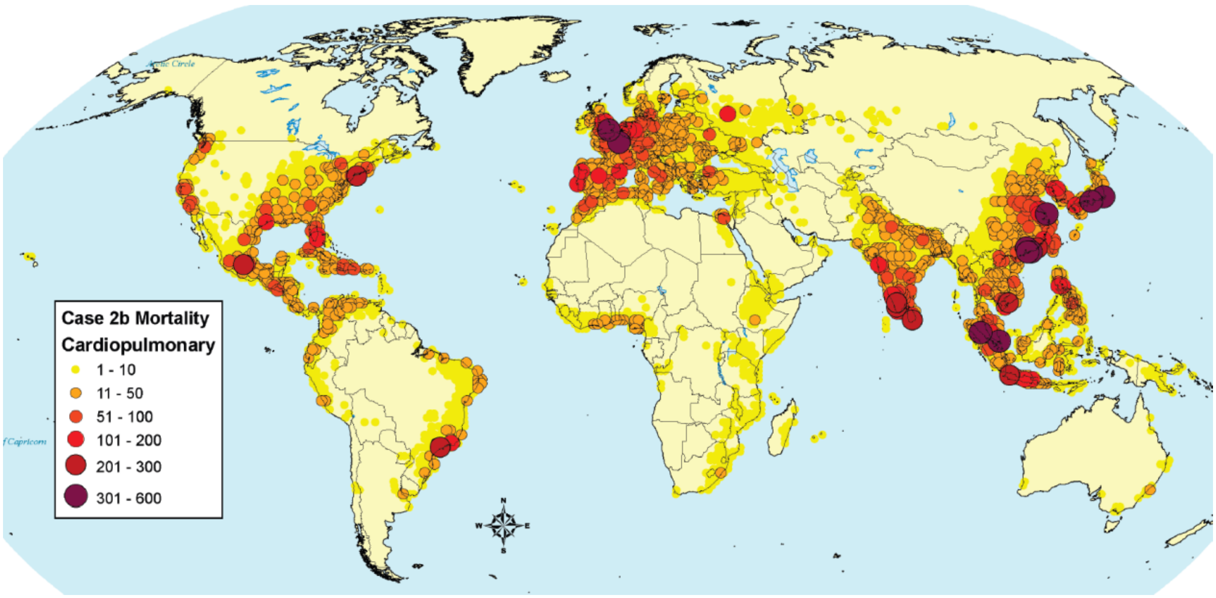


Figure 2 – World map showing concentrations of cardiopulmonary mortality that can be attributed to ship PM2.5 emissions. (6)

For small and large vessels alike, exhaust emissions are only a portion of the total effect that marine commerce has on the environment. Other sources of impact include, but are not limited to:

- The energy and raw materials associated with the building of new vessels;
- The release of oil, chemicals, and volatile organic compounds (VOCs);
- The disposal of wastes including sewage and garbage;
- The transport of non-native species between ports;

- The life cycle costs associated with the production and transportation of fuels; and
- The means by which old ships are recycled and disposed.

Consensus on how best to mitigate many of these impacts has been reached by the international community through the vehicle of the International Maritime Organization (IMO). MARPOL 73/78 is the convention that has formed the basis of these environmental regulations and which has been amended with several annexes in order to address additional environmental impacts and concerns. The most recent developments have been focused on the reduction of airborne emissions from marine vessels through implementation of MARPOL Annex VI. In addition to this set of international conventions, several state and provincial governments have elected to adopt localized and often more stringent emissions reduction schemes through a variety of measures which include subsidies, economic incentives, taxes, penalties, and legislated requirements.

2.1 Vessel Emissions

The emissions that are of the greatest concern are a byproduct of the combustion systems upon which most vessels rely for power and propulsion and include CO_2, NO_X, SO_X, and PM. The release of unburned methane (CH_4) from engines that burn natural gas is a topic which has not received much attention to date, but is one which will be central to this paper quite simply because methane has 21-25 times the global warming potential (GWP) of CO_2 on a hundred year time scale. (9)

The relative quantities of emissions that are produced from vessel propulsion, power generation, and auxiliary systems are affected by a number of factors including the quantity and chemical composition of the fuel being burned, the condition of the combustion equipment, and the temperature and pressure within the combustion chamber. The following subsection summarizes the main emissions of concern and how they are formed.

CO_2: The amount of CO_2 produced is a direct result of the carbon content of the fuel being burned in combination with the amount of fuel being burned. Fuels are classified according to their carbon content. See Table 2, below.

Hydrocarbon	Chemical Formula	State
Methane	CH_4	Gaseous
Ethane	C_2H_6	Gaseous
Propane	C_3H_8	Gaseous
Butane	C_4H_{10}	Gaseous
Pentane	C_5H_{12}	Liquid
Hexane	C_6H_{14}	Liquid
Heptane	C_7H_{16}	Liquid
Octane	C_8H_{18}	Liquid
MGO	$C_{12}H_{23}$	Liquid
HFO	$C_1H_{1.58}S$	Liquid/Solid

Table 2 – Carbon content of various fuels and state at ambient conditions. (10)

Fuels up to butane will be gaseous at standard conditions while pentanes (C_5) and greater will be liquid at standard conditions. Assuming complete combustion, Eq. 1 shows that fuels with a higher carbon content will produce more CO_2.

Eq. 1. $C_XH_Y + \left(X + \frac{Y}{4}\right) * O_2 \rightarrow X * CO_2 + \frac{Y}{2} * H_2O$

In the event of incomplete combustion, some of the carbon is converted into carbon monoxide (CO) or particulate matter (soot) which is basically unburned fuel. (11)

SO_X: The amount of SO_X produced is directly proportional to the sulfur content of the fuel which is first converted into SO_2 (See Eq. 2). Approximately 3-8% of SO_2 produced further reacts with oxygen to form SO_3 (See Eq. 3) which then reacts with the water in the combustion gases to form H_2SO_4 or sulfuric acid (See Eq. 4). When the exhaust stream comes into contact with cool air or cool surfaces, the sulfuric acid condenses and, when further diluted, becomes extremely corrosive. (10)

Eq. 2. $S + O_2 \Leftrightarrow SO_2$

Eq. 3. $SO_2 + \frac{1}{2}O_2 \Leftrightarrow SO_3$

Eq. 4. $SO_3 + H_2O \Leftrightarrow H_2SO_4$

NO_X: Nitrous oxides are the byproduct of the combustion reaction that occurs when the nitrogen content of the air is oxidized. Unlike with CO_2 and SO_X, the amount of NO_X produced is dependent upon the temperature within the combustion chamber rather than the chemical composition of the fuel. The Zeldovich mechanism (See Eq. 5 through Eq. 7.), which is responsible for 80 - 90% of NO_X production is primarily active at temperatures above 1,400°C and becomes more selective as temperature increases. (11, 12)

Eq. 5. $O + N_2 \Leftrightarrow NO + N$

Eq. 6. $N + O_2 \Leftrightarrow NO + O$

Eq. 7. $N + OH \Leftrightarrow NO + H$

NO_X production is particularly problematic for diesel engines because of the high compression ratios at which these engines operate. The high compression ratio allows for a much greater mass of air in the combustion chamber prior to ignition and thereby accounts for the high efficiency (i.e. low CO_2 production) of diesel engines. However, since the temperature of the charge air increases with increased compression pressure, this in turn leads to higher combustion temperatures which result in much higher levels of NO_X production.

PM: Particulate matter is the result of unburned fuel and other matter passing through the combustion chamber. This can either be the result of less than optimal combustion conditions in regions in the combustion chamber or of contaminants which pass through the combustion chamber. (11)

In a diesel engine, atomized fuel is sprayed into and ignited by the temperature of the compressed air charge. The complete combustion of the fuel is dependent on the evaporation of the fuel droplets and the transport of these vapors to regions within the combustion chamber with sufficient oxygen to sustain combustion. Any condition which adversely affects this process has the potential to result in incomplete combustion.

The other possible cause of particulate emissions is incombustible matter which passes through the combustion chamber. This can be a result of fuel or air contamination. Another common cause is damaged piston rings which can cause engine lubricant to be drawn into the combustion chamber. This type particulate emissions is the result of the incombustible qualities of some of the oil additives.

2.2 EMISSIONS CONTROL STRATEGIES

There are many approaches which can be used to effect a reduction in emissions from marine engines.

First and foremost, all engine emissions are either directly or indirectly related to the quantity of fuel being burned. If the amount of fuel being burned is reduced, then likewise, so will the emissions that are being produced. This can be accomplished in a number ways: for example by improving the efficiency of the engine and/or plant, running the engine less or at lower loads, and reducing the number of rapid load changes. Also pertinent to this approach are operational changes which affect how the vessels are being operated. These might include changes in routing to avoid areas of higher resistance (storms or currents) or of reductions in transit speed. In the case of pilot boats these changes need to be considered with caution so as not to add excessive transit time which might impede the pilot’s ability to complete the pilotage.

In the case of conventional diesel engines, a well-developed approach to emissions reduction has been the optimization of the combustion cycle to reduce emissions. Improvements have included optimized combustion chamber design, improved control systems, more efficient or variable turbocharging, and altered injection timing in order to reduce combustion chamber temperatures.

Since NO_X emissions are of particular concern, considerable effort has been devoted to developing the means to decrease the temperatures within the combustion chamber. Examples of such technologies include Exhaust Gas Recirculation (EGR) and various means for injecting water into the combustion chamber; the latter include the Humid Air Motor concept (HAM) in which water vapor is injected with the charge air and assorted methods of emulsifying water into the fuel oil. A major disadvantage of these technologies is reduced fuel efficiency and therefore increased CO_2 production.

Another option for reducing emissions is the installation of exhaust after treatments. There are various options available depending on the size and type of engine installations; these include a variety of systems such as catalytic reducers, scrubbers, and electrostatic filters. Although a number of these technologies are still in development for large marine applications, variants of the same technologies have been used regularly in road and shore-based applications for many years: for example, catalytic reducers have been a standard installation for road applications since the 1970’s.

A disadvantage of many exhaust gas after-treatments is the added complexity is introduced into the system as well as the relatively narrow operating limits within which many of these technologies operate. These issues can be problematic when attempting to combine different technologies and when engines are operating in warm-up or transient cycles. Additionally, because of the pressure drop across components that are installed in the exhaust system, the power and fuel consumption of the engines are negatively impacted.

An option that has received significant attention is the introduction of cleaner burning fuels. Current marine fuels are derived from the last refinement stages of petroleum feedstocks and therefore have a much higher allowable proportion of contaminants than road fuels. Cleaner burning fuels can be produced from a number of different sources, including from the processing of coal, natural gas, and biomass, and are often free of such contaminants as sulfur. Two of the major disadvantages associated with alternate fuels are the development of sufficient distribution networks and, since many of the fuels are gaseous at standard conditions, the added storage requirements to ensure an equivalent operating range.

Lastly, technologies which partially or fully integrate electric drives have the potential to reduce vessel emissions; however, these types of propulsion systems tend to have appreciably lower transmission efficiencies than either direct or geared drive systems. The success of these technologies depends on the development and installation of robust batteries and charging systems. Fully electric vessels would need to be charged at the dock and, given the relatively low energy density of batteries, have to date resulted in vessels with limited operating ranges.

Technologies which involve partial integration of electric drives include hybrid and fuel cell powered drives. Hybrid drives utilize diesel engines for both propulsive power and to charge batteries. Depending on the required load, the vessels can operate on the power from the diesel engine and use the excess power to charge the batteries. If more power is required, then the batteries are discharged in order to supply make-up power to the grid. This configuration results in significant fuel savings because it allows a smaller sized diesel engine to run at a load point that gives optimum fuel efficiency while still being able to provide peak power as required. Fuel cells, on the other hand, are used to generate electricity without a combustion reaction. Fuel is oxidized by air in the presence of a catalyst and an electrical current is generated. Hydrogen is the most common fuel for fuel cells, but variants can operate on methanol, methane, and syngas. The disadvantages of fuel cells include the extremely low power density as well as the difficulties inherent in handling hydrogen as a fuel (13).

2.3 Regulatory Approach

The IMO approach to regulating vessel emissions was originally centered on limiting the sulfur content of fuel. This also served to theoretically limit the levels of particulate emissions because there is a strong correlation between sulfur content of fuel and the amount of particulates emitted (5). Additional sulfur emissions control areas (SECAs) were defined which were subject to more stringent limits on maximum sulfur content of fuel being burned, such as the North Sea, the Baltic Sea, and within 24 miles of the California Coast. The limits for SECA and non-SECA areas are provided in Table 3.

Zone	Sulfur Limit (m/m)	Effective Dates
SECA	1.50%	Before 01 July 2010
	1.00%	Between 01 July 2010 and 01 January 2015
	0.10%	After 01 January 2015
Non-SECA	4.50%	Before 01 July 2012
	3.50%	Between 01 July 2012 and 01 January 2020
	0.50%	After 01 January 2020

Table 3 – Limits for SECA and non-SECA areas.

In 2008, the IMO adopted the NO_X Technical Code in order to address the problems associated with NO_X emissions. The NO_X Technical Code was similar in approach to previous SO_X regulations in that it called for a successive reduction in the maximum allowable NO_X emissions for diesel engines as defined by engine speed. Likewise, provisions were made for special emissions control areas (ECAs) which were to be subject to more stringent limits. The limits as per the IMO NO_X technical code are listed in Table 4. It is worth noting that Tier III limits represent a further 80% reduction of NO_X emissions with respect to the Tier I levels.

	Specific NO_X Production Allowed by Engine Speed in g/kW-hr		
	n < 130rpm	130rpm ≤ n < 2000rpm	n ≥ 2000rpm
Tier I	17.0	$45*n^{-0.2}$	9.8
Tier II	14.4	$44*n^{-0.23}$	7.7
Tier III	3.4	$9*n^{-0.2}$	2.0

Table 4 – Limits for NO_X-ECA areas, where n is the engine speed in rpm.

The IMO approach to limiting greenhouse gas emissions is focused mainly on the reduction of CO_2 emissions and is to be accomplished by limiting the fuel consumption of vessels. January 2013 saw the implementation of the Energy Efficiency Design Index (EEDI) for newbuilt vessels. The EEDI limits the allowable installed power for a vessel depending on size, capacity, and speed according to specified reference curves based on ship type. The current EEDI reference values are intended as a baseline value which will be subject to further reductions. Operational efficiency is being quantified by the Energy Efficiency Operational Index (EEOI) which is currently voluntary but intended to quantify the efficiency of a given vessel voyage relative to the quantity of goods carried. Concurrent with the implementation of the EEDI was the requirement for a Ship Energy Efficiency Management Plan (SEEMP) which applies to all vessels and seeks to document ship specific operational measures for reducing fuel consumption. Finally, the IMO has stated an intent to pursue market based measures such as carbon credits and fuel taxation in order to stimulate the development of less energy intensive shipping. (14)

In addition to international regulations, many local governments have elected to impose more stringent regulations within their jurisdictions. Examples of local regulations include Environmentally Differentiated Fairways in Sweden, the Norwegian NO_X tax scheme, and more stringent sulfur regulations that were adopted by California prior to the implementation of the North American ECA.

2.4 Technical Advances

The technical challenge posed by this slew of variable and inconsistent regulations is considerable, and even more so considering the short time frame in which they have come into force. A direct effect of these new regulations has been the stimulation of interest in and development of a number of technologies for which there was previously no market. This point is illustrated in Figure 3 which chronicles the growth of LNG fueled vessels starting in 2000.

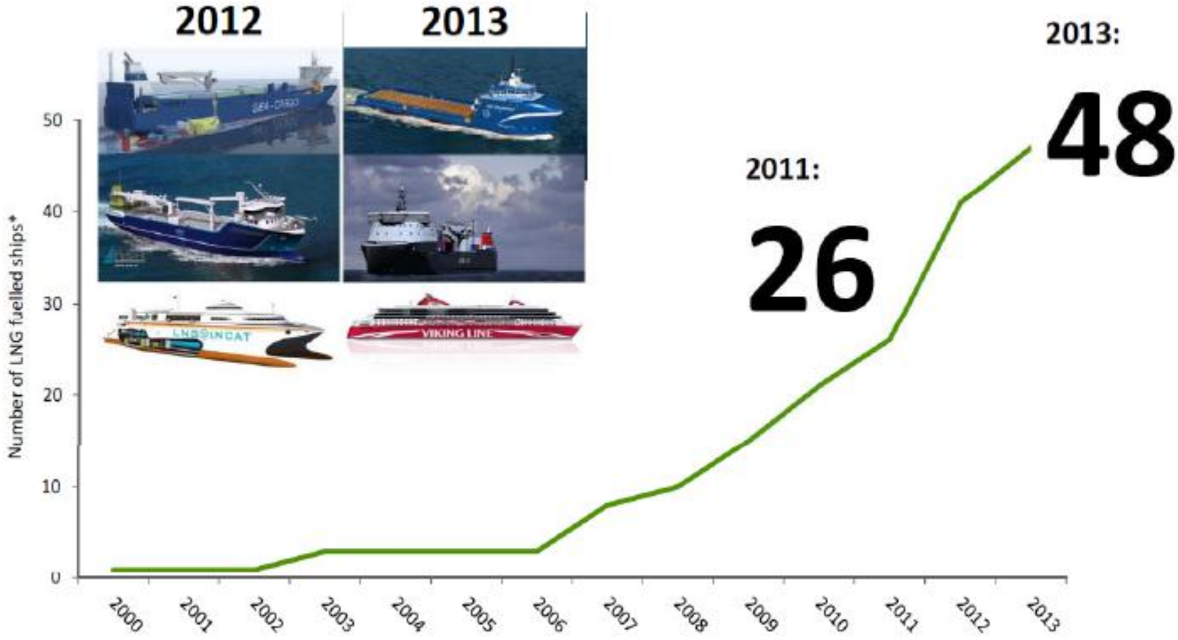


Figure 3 – Number of LNG-Fueled ships in operation. (Chart courtesy of 15.)

Due to the relative complexity of and difficulties involved with the integration of many of the options being considered, the concept of running marine vessels on cleaner burning alternate fuels has garnered much interest. Notwithstanding the complexity of the fuel distribution systems, both shoreside and onboard, the principle advantage of alternate fuels is the relative simplicity of the application.

Perhaps the project that has received the most attention has been the development of LNG-fueled ferries in Norway (See Figure 4.). The first LNG-fueled ferry was delivered in 2000. As of April 2012, there were 26 LNG-fueled vessels in operation, most of which are ferries or platform supply vessels operating in or near Norwegian waters. As of 2013, a further 29 vessels had been placed on the orderbooks, including some intended for markets outside of the North Sea (16).

LNG fueled vessels utilize either lean-burn, spark-ignited engines or dual-fuel engines which operate in the medium speed range. LNG is stored in cryogenic tanks and refueling is most commonly carried out via delivery by an LNG tanker truck.

The use of LNG as a fuel has also seen wider application in the form of boil off from the cargo of LNG carriers. Originally the boil off gas was burned in main propulsion boilers, however more recently there has been development with large medium speed dual- and tri-fuel engines and the concept of a gas injection low speed diesel engine is being actively pursued.

Figure 4 - One of the LNG-fueled ferries operating in Norway, the *M/F Bergensfjord*. (Photo courtesy of DNV 16.)

There has been considerably less development of the field of large scale marine application of alternate fuels other than LNG, however a recent project in the Port of Gothenburg has tested a technology which allows for onboard processing of methanol to a mixed methanol/DME fuel. The systems, including the fuel storage and delivery systems, on board processing system, and modified auxiliary engines were installed on board short sea engine Ro-Pax ferry (17).

There have also been a number of other successful small scale projects that have demonstrated the feasibility of alternative emissions reduction technologies and many of these projects have been applied to so-called "small boats" such as tug boats and other intercoastal craft.

The application of fuel cells for marine propulsion and power generation has been the subject of periodic interest. Recently, there have been a number of developments along this front, including a somewhat less than economically advantageous installation aboard a 12-passenger UK ferry boat at a cost of £225,000 for 12kW of installed power. (18) (See Figure 5.) Other projects have included the successful testing of a 330 kW molten carbonate fuel cell aboard a Norwegian supply boat and the installation of two 120 kW proton exchange membrane fuel cells aboard the German-built Type 212 submarine. (19)

Figure 5 - The *Hydrogenesis* is the UK's first hydrogen powered fuel cell passenger ferry. (Picture courtesy of 18.)

There has also been recent progress in demonstrating hybrid technology on ship assist harbor tugs. In California, two azimuthing stern drive (ASD) tugs have been converted to hybrid drives which use their engines to drive generators which could either use the power for propulsion or to charge their batteries. (See Figure 6.) The tugs are each rated in the range of 3800 kW and were in demanding service as harbor tugs in San Pedro since 2009 and 2012 respectively. The project, however, suffered a setback in 2012 when one of the tugs suffered a major fire while in service which was believed to be a consequence of a software error which caused the batteries to overcharge (20).

Figure 6 - *Carolyn Dorothy* is one of the hybrid haror tugs operating in California, USA. (Picture courtesy of Foss Maritime.)

Although there has been much development in recent years, is worth noting that many of the technologies under consideration are shockingly not new. For example, it may come as a surprise that the first fuel cell was invented fifty-five years before the first diesel engine!

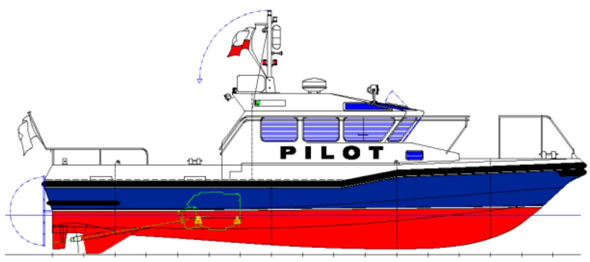
3 PILOT BOATS

3.1 General Description

Although pilot boats operate under a variety of different conditions in different ports the world over, the basic function of a pilot boat is relatively simple: to deliver a pilot safely and in good condition to take charge of the transit of the vessel they have just boarded (21). The actual job of a pilot boat, however, is complicated by many factors, not the least of which include weather conditions, congested traffic, and the notoriously variable nature of vessel arrival and departure schedules.

Typical pilot vessels range in size from 10 to 25 meters in length with the majority of boats being between 15 and 20 meters in length. Depending on the service, pilot vessels operate at a variety of speeds; in the case of ports where there is the possibility of a long pilotage and/or long distances to the pilot station, the current trend has been towards high-powered, high-speed craft with speeds approaching and occasionally surpassing 30 knots.

Typical propulsion configurations include direct drive twin screw and twin waterjet (See Figure 7.). Waterjet arrangements are considered to be advantageous in applications over 28 knots while propellers are considered more efficient at speeds below 25 knots. The window between 22 knots and 28 knots is considered suitable for either water jets or propellers (22). Other advantages of waterjets include improved maneuverability, decreased susceptibility to damage by objects or debris that are floating in the water, decreased risk of casualty in the event a pilot goes overboard, and decreased stress on engines and gearboxes. In spite of these advantages, waterjet systems are not suitable for low speed applications and incur a higher initial cost.



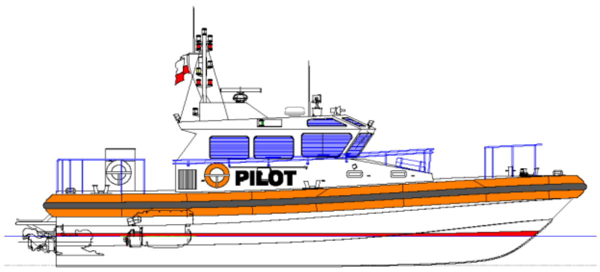


Figure 7 - Examples of twin screw and twin waterjet pilot boat configurations. (Pictures courtesy of 21)

Propulsion power is usually supplied by two high- or medium-speed diesel engines that are direct coupled to either the propeller or waterjet via a gearbox and, in the case of direct drive vessels, a clutch arrangement. Typical engine sizes range from 200kW to over 500kW for main engines and a smaller engine for generating electrical power. Common engine manufacturers for Swedish pilot boats include Scania, Volvo Penta, and Caterpillar.

The weight of the vessel is relevant to fuel consumption and is greatly affected by the choice of hull material and the scantlings thereof. The design of the vessel must strike a balance between the weight of the vessel and ensuring that the hull has adequate strength to withstand not only the stresses that are introduced by the normal motions of the vessel in a seaway, but also the mechanical impacts that are likely to occur as a result of the vessel coming alongside. Steel is considered an excellent material, especially with regards to toughness and impact resistance.

Particularly in high speed applications, the major disadvantage of steel is its weight. In addition, steel structures require increased maintenance for corrosion prevention relative to other choices of materials. Aluminum and glass reinforced polymer (GRP) are used for applications where weight is a restriction and are considered to have similar weight, strength, and powering requirements (21). The weight of the vessel is also affected by the design, the scantlings of structural members, and the quantity of fuel and equipment carried aboard. It is for this reason that smaller fuel tanks which are refilled more frequently might be considered advantageous in certain applications.

In terms of outfitting, pilot vessels are generally designed for the short term movement of personnel rather than long term comfort. The major function of the auxiliary equipment is to support the primary function of the boat. This includes navigation, communication, and lighting equipment; vessel fendering; and rescue and lifesaving equipment.

Due to the differences in port operations, however, there are a number of different configurations of pilot vessels in operation. Certain ports, which have high traffic densities or particularly long distances to the pilot boarding area, sometimes employ a mother-ship concept in which a larger and more comfortable vessel is kept on station and pilot transfers are managed by launching smaller, more maneuverable craft. In other parts of the world, including Sweden, pilot vessels also must contend with ice in the water up to and including some icebreaking capability (See Figure 8.). These boats have a radically different design than their warm water counterparts and are built with a single propeller to avoid ice getting caught in between propellers, shafts and struts, or in waterjet intakes; a deep keel to help break ice and direct it away from the propeller; and a heavier boat weight in order to help with breaking the ice and maintaining course through floating ice. Not surprisingly, these boats operate at significantly lower speeds, but have a high fuel consumption when operating in ice due to the added resistance of the ice field.

Figure 8 - Swedish pilot boat operating in harsh ice environments. (Picture courtesy of Peter A. and MarineTraffic.com.)

Another option which has seen application particularly in areas with severe weather conditions has been the use of helicopters as a means of pilot transfer. Helicopters are currently being used for pilot transfers certain ports in the United States, South Africa, France, Germany, and Belgium.

3.2 MANEUVERABILITY

Under normal conditions, the pilot boat must be maneuvered alongside a larger vessel while it is underway, typically at a reduced maneuvering speed. The maneuver is made challenging by the interaction of the smaller pilot vessel with the flow of water around the larger vessel. Both vessels, will have regions of relatively high pressure at their bows and sterns, and relatively low regions of pressure along their parallel midbodies (23). Since the pilot boat is the smaller of the two vessels, the dynamics associated with the water flow around the larger ship will dominate the interaction between the two vessels. Originally, the pilot boat will experience turbulence and an unsteady course as it crosses the area of mixed flow that is bounded by the bow wave. As the pilot boat nears the side of the ship, the combined effect of the regions of low pressure causes it to be sucked in alongside of the ship until it has merged into the larger vessel's boundary layer. If the larger vessel is turning, for example as when forming a lee, the effect can be further exacerbated and can cause the pilot boat to "walk" up the side of the larger vessel. Both situations can cause hard contact and can be especially dangerous if personnel are on deck (Capt. M. Dindio, personal communication, July 10, 2013). Once the pilot boat is alongside the larger vessel, it is effectively held in place by the flow around the vessel. In order for the pilot boat to separate from the larger vessel, it must create a wedge between itself and the larger vessel whereupon it is peeled off the side of the ship by a region of high pressure that is created between the two vessels.

A recent accident in Galveston, Texas in which a pilot boat operator lost his life after the pilot boat that he was driving overturned while approaching a ship demonstrates the inherent risks involved in the maneuver (24) and demonstrates importance of adequately powered pilot boats. These maneuvers are often complicated by weather conditions including wind, seas, and swell, which can cause relative and often unpredictable motion between the two vessels.

Wind and weather conditions can also affect the pilot transfer by making it difficult for a pilot to climb the ladder and, in the worst case scenario, significantly affect the survivability of a pilot if they should fall in the water. (See Figure 1, presented previously.) The effect of water temperature upon survivability is provided in Table 1, presented previously.

It should be noted that the survivability in water temperatures that correspond to typical Swedish water temperature is on the order of minutes. It is therefore of the utmost importance that the pilot vessel be able to maneuver quickly to avoid and retrieve a pilot that has fallen into the water. This critical function necessitates a vessel with adequate powering and response.

3.3 SWEDISH PILOT BOATS

In Sweden, pilot boats as well as pilotage services are maintained and operated by the Swedish Maritime Administration (Sjöfartsverket). Approximately 75 boats serve a total of 24 pilot stations that are divided among seven regions. Because many Swedish harbors operate in ice conditions in winter, most ports have different boats for summer and for winter operations. In addition, several standby boats are strategically located in the various regions in order to ensure that pilotage service is not disrupted by a boat breaking down.

The Swedish pilot boats are procured for long-term operation and some of the boats in service were built as early as 1968. However the bulk of the fleet is considerably younger.

Typical summer boats have maximum speeds in the range of approximately 20 knots, although there are at least 5 waterjet boats with speeds in excess of 30 knots. The remainder of the boats are either winter boats or older vessels with maximum speeds in the range of 10 knots. The split between high speed (20 knots+) and low speed boats is approximately half and half.

Common engine manufacturers include Scania, Volvo Penta, and Caterpillar and the current approach to engine overhaul is complete replacement rather than in-place rebuild. The boats are built to classification society standards but inspected and regulated by the Swedish Transportation Department (Transportstyrelsen).

4 ALTERNATE FUELS

4.1 SELECTION OF FUELS

This section considers various alternatives which could serve as a replacement for marine gas oil (MGO), the current fuel in use on Swedish pilot boats. Although there are myriad alternate powering options that might be considered along with these fuel alternatives, with the exception of hydrogen, this paper focuses solely on those fuels most appropriate for use with internal combustion engines. Hydrogen is considered most feasible in the context of a fuel cell. Due to the difficulties in storage, hydrogen is not currently a viable fuel; nevertheless, it is worth discussing because it is the only fuel that does not emit CO_2 when burned.

The fuels that are under consideration are loosely termed “alternate” fuels. They include liquefied natural gas (LNG), compressed natural gas (CNG), liquefied petroleum gas (LPG), methanol, dimethyl ether (DME), and hydrogen. This section considers the possible fuel choices from a number of perspectives, including the chemical and combustion properties, considerations for storage and handling and the hazards associated therewith, the equivalent sizing for typical pilot boat fuel tank, and the life cycle impact of the fuel. Whenever possible, the fuels are compared with MGO, which is currently the standard fuel for all Swedish pilot boats in operation and on the basis of these comparisons, the most promising fuels are to be selected for further discussion and technical review.

Although alternate fuels are often portrayed as radical developments, it will be demonstrated that these fuels and the technology used to burn them are anything but new. Successful demonstrations and tests with many of these fuels often go back twenty years or more. It should be noted that, under the right conditions almost anything will burn - a fact that is attested to by the daily burning of heavy fuel oil (HFO) by thousands of ships worldwide.

Perhaps the most important step in conducting a pertinent analysis is the careful consideration and definition of the criteria by which the fuel is to be judged. In the case of this study, the motivation for fuel switching is to affect the transition from petroleum to biomass derived fuels. This paper readily acknowledges that a transition phase which utilizes petroleum derived fuels might be the most expedient means of accomplishing a full switch to biofuels.

An important distinction that must therefore be made between the identity of the fuel and the origin of the fuel. For each of the fuels considered, the common name of the fuel identifies the makeup and sometimes the conditions at which the fuel is stored. Most of the fuels are simple fuels that can be produced from a variety of sources including petroleum products, natural gas, coal, and biomass. The relative life-cycle emissions for a fuel will differ based upon the source of the fuel even though the chemical makeup of the fuel might be the same. As such, implications of superior or inferior environmental performance should not be inferred from the name alone.

Table 5 summarizes the physical properties of the alternative fuels that are being considered. MGO is used as a baseline to compare the various fuels because it is the current standard fuel in use aboard the Swedish pilot boats. The properties listed in the table are explained in greater detail below.

Fuel \ Property	LHV	HHV	Boiling Pt.	Storage Pressure	Density	Equivalent Volume	Flammability Range
MGO	42.791	45.766	154 – 372	1	0.8366	1.00	0.7 – 6
LNG	48.632	55.206	-161.5	1	0.4282	1.72	5 – 15
CNG	48.632	55.206	-161.5	250	0.1942	3.79	5 – 15
LPG	46.607	50.152	-0.5	7.5	0.5080	1.15	1.8 – 8.5
Methanol	20.094	22.884	64.5	1	0.7941	2.24	6 - 36.5
DME	28.882	31.681	-23.7	5	0.6652	1.86	3.4 - 27
H_2	120.7	141.8	-253	1	0.0708	4.19	4 – 76
H_2 (gas - LP)	120.7	141.8	-253	345	0.0308	9.63	4 – 76
H_2 (gas - HP)	120.7	141.8	-253	700	0.0625	4.75	4 - 76
Units	MJ/kg	MJ/kg	°C	Bar	g/cm^3	rel to MGO	% by vol.

Table 5 – Compiled physical properties of the alternate fuels under consideration (11, 25, 26).

4.2 Fuel Properties

The lower and higher heating values (LHV and HHV respectively) are a measure of the energy content of the fuel. The difference between the two values lies in the test methods employed. The higher heating value measures the energy content but negates energy that is required to evaporate the water content of the exhaust gases (see Eq. 1). In order to do so, the combustion products are returned to 25°C as part of the test procedure. The lower heating value does not consider the energy content contained in the evaporated water and therefore obtains measurements when the exhaust gas gases are at 150°C. In the case of the combustion of elemental carbon, the LHV and HHV are the same since no water is produced during the combustion of the fuel. In all other cases the LHV is the value of practical interest since the exhaust gases are not cooled to temperatures where the water content will condense. (11)

The boiling point of the fuel is given at standard atmospheric pressure. The boiling point is an indication of whether the fuel is liquid or a gas at standard conditions (101.325 kPA and 20°C). The lower the boiling point of the fuel, the more energy it will take to liquefy the fuel and likewise, the greater the driving potential for the fuel to absorb heat and regassify.

The pressure refers to the pressure at which the fuels are typicaly stored. Diesel and LNG are stored at atmospheric pressure while most of the other fuels are stored at moderate pressure. CNG and hydrogen are both stored as gaseous fuels, albeit at extremely high pressures. Hydrogen can also be stored cryogenically, but it must be cooled to much lower temperatures than even natural gas, thus resulting in a high energy cost to do so.

The density of each fuel is provided at typical storage conditions relative to temperature and pressure.

The equivalent volume compares the volume required for a given energy content relative to a marine gas oil standard. This is a theoretical comparison of the relative fuel tank sizing requirements but does not take into account the differences in efficiency between different engine types. In particular, the values cited do not reflect the 25% penalty in fuel efficiency which is associated with the type of spark ignition engines which are typically used with methane based fuels such as LNG and CNG.

The flammability range of a fuel is measured on a percent volume basis and is an indicator of how easily the fuel will burn when mixed with air. A fuel with a wide flammability range will be more likely to ignite when in the presence of an ignition source. Flammability range is an important parameter in determining the precautions needed to safely handle the fuel.

4.3 METHANE BASED FUELS

Methane based fuels include LNG, CNG, and LBG and are derived from methane based mixtures which are either liquefied or compressed in order to enable less voluminous storage. Most commonly, LNG and CNG are produced from fossil fuel sources and are referred to as natural gas. Both fuels can be produced from biomass as well, and are then referred to as biogas. Biogas is most commonly distributed either by direct injection into existing gas networks or by liquefaction and mixing with LNG stock. For the purposes of this report, methane fuels are simply considered as either LNG or CNG regardless of origin. It should, however, be noted that LNG and CNG are by no means a homogenous fuel. Depending on its origin, natural gas can contain significant proportions of higher level hydrocarbons such as ethane, propane, and butane. Likewise, depending on the source from which it was derived, biogas can contain significant proportions of contaminants and inert gases. Care must therefore be taken when selecting methane based fuel sources in order to ensure that the installed engine can accommodate the different characteristics of the fuels being supplied.

4.3.1 Availability and resources

Historically, natural gas was considered a nuisance byproduct of oil production and large quantities of natural gas were and to a certain extent are disposed of in oil fields via flaring. In recent years, there has been a concerted effort by the oil industry to capture and process the gas that had previously been flared into useful products. Thus in some life-cycle assessments (LCAs) the production of fuels from flare gas is assigned a different life-cycle cost relative to similar fuels which are produced from wells that are specifically dedicated to natural gas production. (27)

A typical LNG chain involves the development of gas production and liquefaction sites, development and acquisition of a shipping infrastructure, and storage and regasification terminals which supply the gas to distribution grids. (See Figure 9.) As of 2009, the total cost of a newly developed LNG train was estimated at between 6 – 8 billion USD (28).

Given the low density of natural gas and the fact that gas reserves were located in remote locations relative to distribution networks, the natural gas market has been limited by the challenges of economically transporting natural gas to consumers. Currently natural gas is generally transported via pipeline or as liquefied natural gas via LNG carriers. From an economic standpoint, pipelines are considered preferable for short distances whereas an LNG supply chain is considered advantageous for longer distances. The break-even point is estimated to be somewhere between 3000 and 4000 km (28).

In recent years, the development and exploitation of shale gas reserves in North America has had a significant effect on the natural gas market. For many years the outlook has been that the United States would be a net importer of and a large market for natural gas. Since the development of the shale gas reserves, the outlook has changed to the point that some of the terminals that were constructed to import gas are now applying for export licenses. Additionally, the effect of the temporary shutdown of Japanese nuclear reactors after the incidents at the Fukushima nuclear power plant have served to create a substantial increase in demand in the Japanese LNG market. The combination of these factors has led to the decoupling of LNG prices from oil prices and led to pronounced price variations between different geographical markets which has resulted in significant modifications to historical trade patterns. (29)

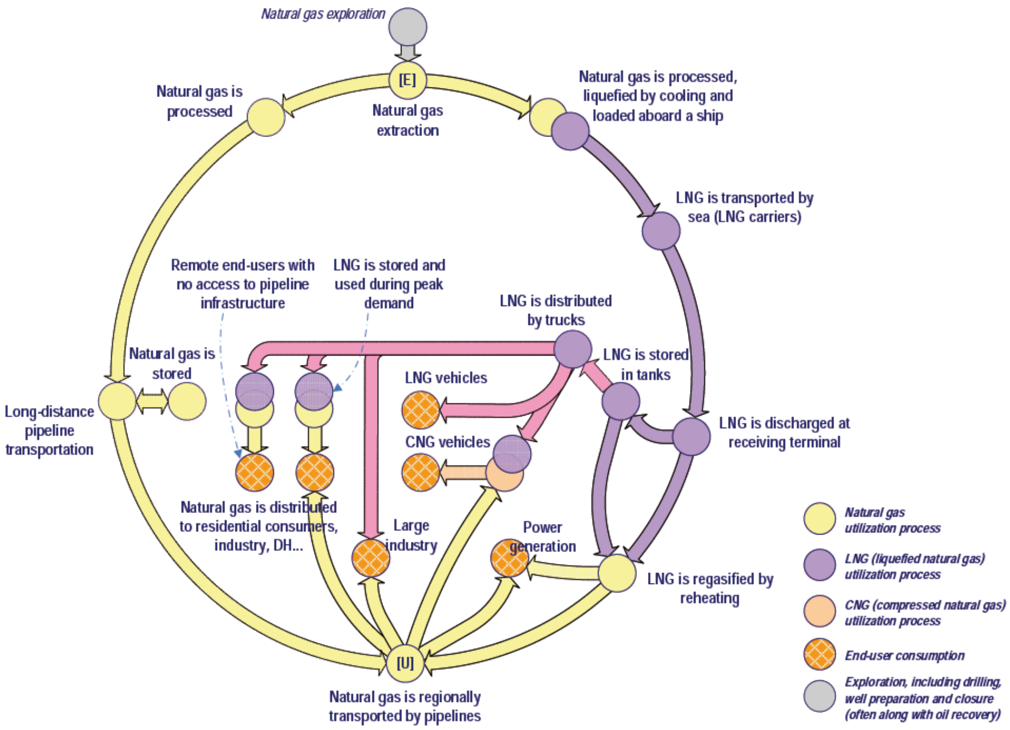


Figure 9 - Overview of the general production, transportation, and use of natural gas. (Picture courtesy of JRC 2009 28)

An alternate source of methane based fuel is biogas. Biogas is the result of the microbial degradation of biomass. Biogas can be produced from a number of sources including landfills, agricultural waste, slaughterhouse waste, fish ponds, sewage, and the remnants of logging operations. The waste is fed into an anaerobic digester where it is broken down into a mixture of methane, CO_2, and other gases by the resident bacteria. The biogas is collected, treated, and stored while the residual sludge from the process is nitrogen rich and can be used as fertilizer. (30)

Given the range of sources and the relatively high level of impurities, biogas must be treated prior to being suitable for energy consumption. The basic treatment process involves filtration of impurities, removal of hydrogen sulfide (H_2S); separation of carbon dioxide and other gases; and finally dehumidification (25).

Typical properties of biogas from different sources are given in Table 6, below.

4.3.2 Properties of Methane based fuels

Regardless of source, a number of key indicators must be defined in order to enable a comparison of methane-based fuels and evaluate their suitability for combustion. Amongst the principal indicators that determine the suitability of a fuel for a given combustion application are the Wobbe Index and the methane number (MN). (25, 31)

Property \ Source	Sewage Gas	Agricultural Gas	Landfill gas	Unit
Methane	65-75	45-75	45-55	% by vol
CO_2	20-35	25-55	25-30	% by vol
CO	<0.2	<0.2	<0.2	% by vol
N_2	3.4	0.01-5	10-25	% by vol
O_2	0.5	0.01-2	1-5	% by vol
H_2	Traces	0.5	0	% by vol
H_2S	<8,000	10-30,000	<8,000	mg/Nm^3
HHV	6.6-8.2	5.5-8.2	5.0-6.1	kWh/ Nm^3
LHV	6.0-7.5	5.0-7.5	4.5-5.5	kWh/ Nm^3
Normal density	1.16	1.16	1.27	kg/Nm^3
Density rel. to air	.9	.9	1.1	kg/Nm^3
Wobbe Index	7.3	n.a.	n.a	kWh/ Nm^3
Methane number	134	124-150	136	

Table 6 - Typical properties of biogas from various sources (25).

Wobbe Index is an indication of ability of a particular fuel to deliver heat through a given nozzle. It is therefore a measure of the interchangeability of gaseous fuels with different compositions. (32)

The Wobbe index is based upon two relations:

1. The heat delivered through a nozzle is proportional to the heating value and the volumetric flow of the fuel.
2. The flow through the nozzle is inversely proportional to the square of its density.

As such, the Wobbe index can be expressed as:

Eq. 8. $$W = \frac{HHV}{\sqrt{sg}}$$

Where: HHV is the higher heating value of the fuel
sg is the specific gravity of the fuel

Methane number (MN) is used to describe the knock or detonation characteristics of a fuel relative to a reference mixture of methane and hydrogen. Of the two fuels, hydrogen is knock prone while methane is extremely knock resistant. A pure methane fuel is given a methane number of 100 while a pure hydrogen fuel has a methane number of 0. In practical terms, the lower the methane number, the more prone a fuel will be to knocking. Since higher order hydrocarbons such as ethane, propane, and butane are each successively more knock prone, the methane number is an indication of the non-methane hydrocarbon content of the fuel. (31) Methane number is used in conjunction with coolant water temperature in order to determine the permissible rating of the engine. (25)

4.3.3 Technology

Whether fueled by LNG or CNG, natural gas engines run on similar principles. The two main engine types that have been developed are the lean burn spark ignition (LBSI) engines and the dual fuel engines. LBSI engines use electronic control systems to meter and inject fuel into the air intake ports. The mixed air and fuel charge is then compressed during the compression stroke and ignited by means of spark ignition. Dual fuel engines utilize a pilot injection of diesel fuel to ignite the fuel-air mixture. Various other combustion concepts have also been tested and developed, but these will discussed in greater depth in subsequent sections of this paper. (33, 34, 35, 36)

4.3.3.1 Fuel systems

Although LNG and CNG are essentially the same fuel, they are handled quite differently. Since LNG is liquefied rather than compressed, it is stored at near atmospheric pressure but at significantly lower temperatures than CNG. The advantage of this approach is a significantly higher energy density without the need for high pressure storage tanks. The disadvantage of the LNG systems is that the fuel is stored at extremely low temperatures (-161.5 °C). This presents a challenge not only from the standpoint of needing to control heat leakage into the tank but also from the hazards that are associated with the handling of fuel at such a low temperature, such as cold burns and instantaneous brittle fracture of mild steel upon contact.

Typical LNG systems utilize a double-wall vacuum insulated cryogenic tanks which are equipped with a number of fittings including a safety valve, level gauge, fill line, and shutoff valves. The valves are located in an enclosure that is known as the cold box. The liquid fuel is then supplied to the engine via a vaporizer in which the fuel is either heated by ambient air or by the vessel's cooling system. (37) (See Figure 10.)

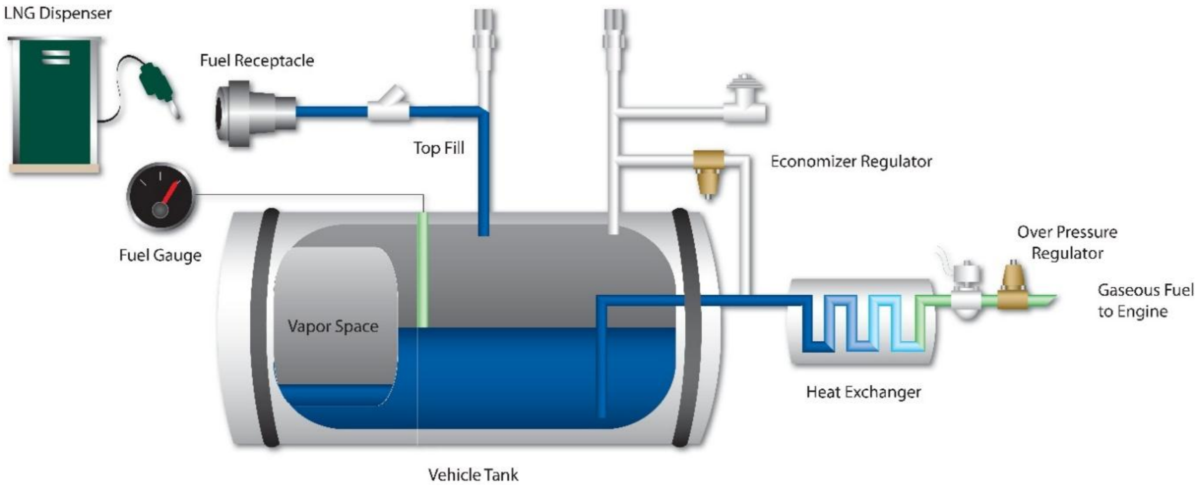


Figure 10 - Diagram of a typical LNG tank to engine system layout. (Picture courtesy of ChartLNG.)

Because of the low system temperatures and the fact that even the best insulated tanks cannot eliminate all heat ingress into the tank, one of the limitations of LNG applications is that the fuel tanks cannot be allowed to sit idle for long periods of time. If the tanks are allowed to sit, they will absorb heat from their surroundings. This heat will cause some of the LNG to evaporate which will in turn increase the pressure in the tank. If the pressure builds sufficiently then it will be relieved by the relief valve which will cause a release of methane into the atmosphere. As was mentioned previously, methane is a greenhouse gas with a large global warming potential. (38)

On the other hand, CNG is supplied to the engine via a pressure reducing valve or regulator. (See Figure 11.) A pump is not needed because of the high tank pressure. However since CNG systems utilize natural gas which is not liquefied, the energy density of CNG is about 2.2 times less than that of LNG. From a practical standpoint, this means that CNG fuelled vessels will require more than double the space that is required for a similar LNG fueled vessel and almost four times the fuel storage space that is required for a similar MGO fueled vessel. This is a very real disadvantage and one that is compounded by the heavy weight of the storage tanks. Despite the development of composite materials and improved designs for similar storage tanks for road applications (39), the size and weight of storage tanks pose a real limit for CNG fueled vessels.

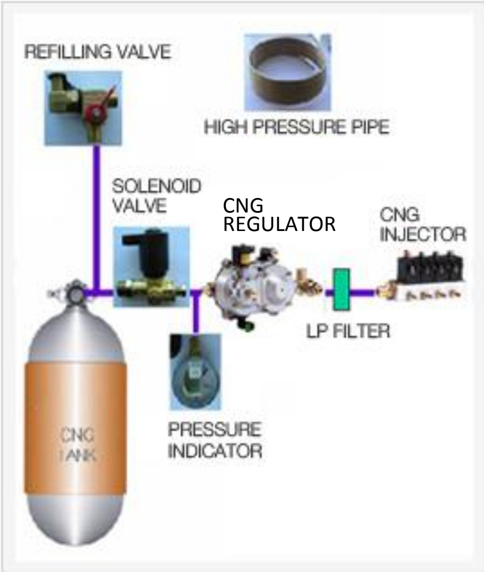


Figure 11 - Diagram showing a typical CNG tank to engine system layout. (Picture adapted from ENK, Co, Ltd.)

4.3.4 Emissions

One of the main advantages of burning natural gas is the reduction of emissions from the combustion process. Based upon the reduced carbon content of methane (CH_4) as opposed to MGO ($C_{12}H_{23}$), the combustion of natural gas reduces CO_2 production by approximately 20% (33). Additionally since natural gas has virtually no sulfur content, SO_X and particulate emissions are reduced by approximately 95 – 99%. (40) Due to lean combustion schemes, NO_X emissions are reduced by approximately 75 – 90% (40). These reductions are significant when compared with diesel engines and are advantageous for vessels operating in harbors and near population centers.

However, the total greenhouse gas emissions benefit from natural gas is often misleading due to the high level of methane slip from many natural gas engines. Methane slip refers to unburned methane that passes to the atmosphere through the exhaust. Estimates place methane slip as high as 8-10% for some engines. (41). Unburned methane in the exhaust gases is primarily the result of flame quenching as the flame front nears the cooler cylinder wall. Unburned methane can also reside in crevices such as those formed around piston rings and between the cylinder wall and the piston crown where proper combustion is difficult to achieve (41). Methane slip is problematic because methane is a greenhouse gas; on a twenty year time scale, methane has a global warming potential (GWP) of 72 relative to CO_2 and on a hundred year time scale, the GWP of methane is still 21-25 times that of CO_2. (41, 30). As such, methane slip is an important factor that must be considered when evaluating the overall benefit of switching to natural gas as a fuel for internal combustion engines. (9)

It should also be noted that dual fuel natural gas engines will have higher overall emissions, including CO_2, than straight gas engines on account of the diesel pilot fuel.

4.3.5 Life cycle

An important attribute of LNG that needs be considered carefully is the long and energy intensive supply chain that is required to produce and deliver it. In addition, the LNG market has recently been subject to instabilities that were created through the introduction and development of new sources, the practice of negotiating historically long contract terms, and recent instability due to political unrest and natural disasters. Despite these concerns, recent progress in the development of shale gas and the possibilities associated with natural gas hydrates suggests that LNG will continue to be an important energy source in the future. (29)

From a life-cycle perspective, the performance of CNG relative to LNG depends greatly upon the source of the gas. The compression of the gas is energy intensive, though not as intensive as liquefaction. If the gas is sourced from an LNG supply, then production of CNG is extremely energy intensive because it incorporates the LNG train as well. On the other hand, CNG produced from relatively local sources would have a significantly improved life-cycle performance (42). Likewise, there is the possibility of producing CNG from biogas sources.

4.4 LPG

4.4.1 Availability and resources

Liquefied petroleum gas, also known as LPG, is another fuel that has seen widespread use in many segments of the transportation sector. For years, LPG has been the fuel of choice for indoor forklifts due to its superior emissions performance relative to gasoline or diesel. In 2000, there were nearly 800,000 LPG fueled forklift trucks in operation with approximately 85% of new forklifts being supplied with LPG fuel systems (43). As of 2002, LPG was also the primary fuel for approximately 4 million vehicles is use worldwide (44). As such, LPG has a distinct advantage relative to other alternative fuels is a long history of vehicle applications as well as a developed and dispersed distribution network.

LPG is produced either as a byproduct of the oil production or refining processes; it is a mixture of different gases, the relative proportions of which depend on the source of the gas. The main components of LPG are propane and butane (C_3H_8 and C_4H_{10}) and the heavy nature of these components has a significant effect on the handling characteristics of the gas. In Europe propane content of LPG can be as low as 50% while in the US, LPG must contain at least 85% propane (34). Typical compositions of LPG fuels by country are listed in Table 7.

Country	Propane	Butane
Austria	50	50
Belgium	50	50
Denmark	50	50
France	35	65
Greece	20	80
Ireland	100	0
Italy	25	75
Netherlands	50	50
Spain	30	70
Sweden	95	5
United Kingdom	100	0
Germany	90	10

Table 7 – Standards for LPG Fuels.

4.4.2 Properties

The relatively low vapor pressure of LPG is an important property because it allows LPG to be stored as a liquid at modest pressures of around 15 bar without the need for refrigeration. At atmospheric conditions, the boiling point of LPG is somewhere between -42°C and 0.5°C and depends upon the relative proportions of propane and butane in the mixture.

Another important attribute of LPG is that it is heavier than air in its vapor phase. From a practical standpoint, this means that if LPG vapors are released, they tend to pool and collect in low lying areas. This is a concern in marine applications due to the fact that LPG vapors could possibly collect and pool in bilges and other internal compartments. Likewise, the greater density of LPG relative to air inhibits the ability of LPG to disperse in the event of a release.

A major benefit of LPG relative to the other fuels is its relatively high energy density. For an equivalent energy content of MGO, the volume of LPG fuel tanks would only need to be increased by about 15% versus 70% for LNG and an additional 270% for CNG. These estimates, however, are based solely upon the energy density of the fuel and do not take into account the reduced efficiency of gas engines and the fact that LPG is generally stored in pressurized cylindrical tanks which have the potential for significant broken or inefficient stowage relative to a conventional liquid filled fuel tank whose shape can be adjusted to accommodate the shape and structure of the hull.

4.4.3 Technology

The majority of information regarding the performance of LPG fueled engines is available from the testing and development of engines built for road applications. LPG fueled engines have been tested and produced in a variety configurations, including purpose-built and retrofit applications. Various designs have incorporated both gas phase and liquid phase direct injection systems, throttle body and port fuel injection systems, and both lean burn spark ignition and direct injection jet ignition systems. Engines have also been produced that can be operated in multi-fuel modes, such as the LPG/CNG flex fuel engine developed by Boretti and Watson (35).

4.4.4 Emissions

Emissions from LPG fueled engines are heavily dependent upon the working principle of the engine, particularly the the design of the fuel system (45). One of the major differences between LPG and natural gas is that LPG has a much higher flame speed. This means that LPG has a higher knock potential than LNG and results in engines will lower compression ratios or derated outputs.

Since LPG has a ratio of carbon to hydrogen content in between that of methane and diesel, LPG is expected to have lower tailpipe CO_2 emissions than MGO, but higher CO_2 emissions than LNG (35). A reduction of 20% in CO_2 emissions has been demonstrated in a test engine that was converted from diesel to LPG service (36).

SO_X emissions are limited by the low permissible sulfur content of the fuel and, due to the good mixing properties of gaseous fuels, LPG fueled engines also produce significantly less particulate emissions than diesel engines, especially at low loads (36). This latter is a feature that is especially attractive for vessels that spend significant time operating at partial loads or while maneuvering.

In terms of NO_X emissions, LPG fueled engines have shown significant potential for reduction when operating in lean burn mode. Several studies have shown that extremely low NO_X levels can be achieved when operating at λ = 1.4 - 1.6, where λ is the air-to-fuel ratio. These engines are known as lean burning spark ignition engine (LBSI), and the reduction in NO_X is effected by cooling the combustion gases with the excess air that is supplied to the combustion chamber. Lean burn engines entail a trade-off between NO_X emissions and PM emissions. As λ becomes progressively leaner, the opportunity for engine misfire increases, and the quantity of PM emissions likewise increases. In engines where liquid LPG is injected directly into the cylinder, a partial reduction of NO_X is achieved when the charge air is cooled by the evaporation of the injected fuel (45).

4.4.5 Life cycle

Relative to the other fuels that are being considered, LPG has relatively low energy consumption per unit of energy produced but somewhat higher energy costs associated with the transportation, distribution, and storage of the fuel (T&D&S). According to a study by Wu et al. that focused on the conversion of a fleet of State operated vehicles in Texas, LPG was produced using only 64% of the energy relative to an equivalent energy content of diesel. Although the energy consumed in the transportation, distribution, and storage of the fuel was slightly higher, the total energy consumed was still only 69% versus that of road diesel (46).

Although LPG is an attractive fuel from a number of perspectives, a major drawback is that there is not a well-developed path for transitioning to biofuels. To date, the synthesis of biogas and/or methanol/dimethyl ether is more attractive option and has seen greater development in terms of facilities and infrastructure. Of these alternatives, DME is the most similar in handling characteristics to LPG and could be a viable alternative to expand upon the technology that has been developed for the distribution and utilization of LPG.

4.5 METHANOL

4.5.1 Availability and resources

Methanol is unique relative to the fuels discusses thus far because it is a simple alcohol which is liquid at ambient conditions. Methanol is further differentiated by fact that it is a synthesized fuel whose quality can be controlled rather than a fuel derived from naturally occurring resources which must be processed and purified. Currently, methanol is synthesized and widely distributed as a feedstock for various chemical processes and it has begun to see limited application as a transportation fuel. Methanol is of further interest because it is a feedstock for dimethyl ether (DME) which is a fuel that is considered an attractive replacement for diesel fuel for compression ignition engines (26).

The chemical formula of methanol is CH_3OH; it is similar in handling and characteristics to ethanol, a related alcohol whose chemical formula is CH_3CH_2OH. Both methanol and ethanol have seen application as transportation fuels for years. Some of the earliest internal combustion engines, including those designed by Otto and Benz, were designed to operate on alcohol rather than petroleum fuels (26). More recently, countries such as Brazil and the United States have actively developed transportation networks that operate either exclusively on ethanol or with ethanol-gasoline blends. Meanwhile, methanol has been used for years in the types of high performance engines that are typical of motorsport franchises such as the Indianapolis 500, Monster Trucks, and Top Alcohol Dragsters.

Although methanol and ethanol can be used to similar effect, a significant objection to the implementation of ethanol as a widespread transportation fuel is that it is a first generation biofuel which shifts agricultural resources away from food cultivation (26). While ethanol can be produced synthetically by a process that is similar to that which is used to produce methanol, this pathway is not preferred because it operates at a lower efficiency and higher cost than the process for synthesizing methanol (47).

A benefit to methanol as a fuel is that it can be produced from a variety of feed stocks. The original method of producing methanol was as a byproduct of charcoal production through the destructive distillation of wood. Today methanol is more commonly produced by catalyzing syngas, which is a mixture of H_2, CO, and CO_2 that can be produced by either the reforming or partial oxidation of common feed stocks such as natural gas, coal, coke, biomass, and petroleum (26).

Perhaps the most interesting option for methanol production is a technology which involves the capture and recycling of CO_2 from stack emissions that is currently being demonstrated at a plant in Iceland. (See Figure 12 and Figure 13.) The plant, which started up in 2011, recycles 85% of the CO_2 emissions from an associated geothermal power plant; the methanol plant has a production capacity of 2 million liters of methanol per year, including a significant export capacity (26, 48).

Figure 12 - George Olah Renewable Methanol Plant located near Reykjavík, Iceland converts CO_2 stack gas to methanol. (Picture courtesy of Carbon Recycling Int'l)

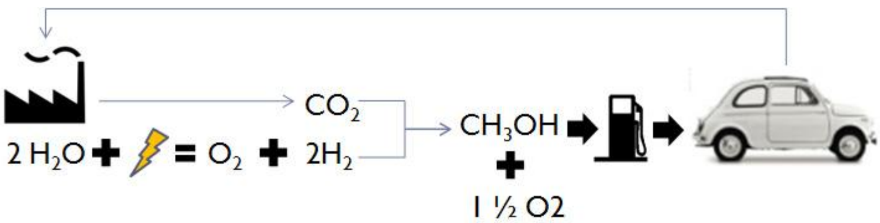


Figure 13 - Process diagram for the recycling of CO_2 stack gas to methanol and use for vehicles. (Diagram courtesy of Carbon Recycling Int'l)

4.5.2 Properties

In terms of chemical properties and handling, methanol is a liquid fuel with a boiling point of 64.5 °C. This is a significant advantage because it means that methanol can be stored without the need of expensive pressurized or refrigerated tanks. Despite being a liquid, methanol has a relatively low calorific value, which means that methanol would require approximately 2.2 times the storage volume for an equivalent energy content of MGO.

Because of its low boiling point, and coupled its relatively wide flammability range, methanol is classified as a low flashpoint fuel by the IMO; this means that methanol must be handled in a manner that is similar in most, but not all, respects to other low flashpoint fuels.

4.5.3 Technology and Emissions

In terms of combustion, the fact that methanol is a synthesized fuel means that it is free from sulfur and other contaminants. Another of the characteristic properties of methanol as an alcohol based fuel is that it has a very high heat of vaporization. In practical terms, this means that there is a significant cooling effect when using methanol, especially if it is injected into the cylinder. This has a twofold effect of reducing NO_X emissions and suppressing engine knock. The latter means that methanol engines can be designed with much higher compression ratios than their diesel counterparts. Research suggests that methanol engines can be significantly downsized relative to their diesel counterparts resulting in smaller, lighter engines. (47)

One of the issues with methanol combustion is the formation of formaldehyde as a byproduct of incomplete combustion. Formaldehyde is a carcinogen which is usually removed by use of an oxidation catalyst in road applications and which would also need to be dealt with for marine applications.

4.5.4 Life cycle

From a life-cycle perspective, the performance of methanol is highly dependent on the source from which the syngas is produced. The extremes range from renewable methanol plants which are reporting CO_2 reductions in the range of 65-95% relative to what is required to produce methanol while using conventional fuels (48) to the considerably more energy intense production of methanol from coal. Ellington et al estimated that methanol produced from biomass in the United States would require 37,596 x 10^6 J of energy in the form of woodchips for every ton of methanol produced and would require an additional 10,792 x 10^6 J per ton of additional energy input. This corresponds to a conversion rate of 53% of the raw energy stock to the final product with a further 22.3% of this value being required to process the raw feed into the final product. With regards to CO_2 emissions, 4,561 kg of CO_2 are generated per ton of methanol produced, with only 1,373 kg per ton of CO_2 being produced by the actual combustion of the fuel (49).

Relative to CO_2 emissions from the combustion process, a spark ignition direct injection engine operating on M90 (90% methanol/10% gasoline mixture) has similar levels of CO_2 emissions as a comparably sized diesel engine (27).

Lastly, a significant advantage of methanol is the fact it is in wide use as a chemical feedstock for a number of industrial processes, including the production of plastics. As such, methanol is already being produced in a geographically diverse network of production plants and is supported by an existing and global distribution network. This, in conjunction with the fact that methanol is already handled as a liquid rather than a compressed or liquefied gas, suggests that setting up a fuel infrastructure will be less complex than other fuels, especially in the case of a small scale, regional application like the Swedish pilot boats. (50)

4.6 DME

4.6.1 Technology

Dimethyl ether (CH_3OCH_3) is a gaseous fuel that is produced from the dehydration of methanol. Unlike methanol, which is suited for use in internal combustion engines and which can be readily mixed with gasoline, DME is better suited for use in compression ignition (diesel) engines and, because of its physical properties, can be mixed with LPG. (See Figure 14.)

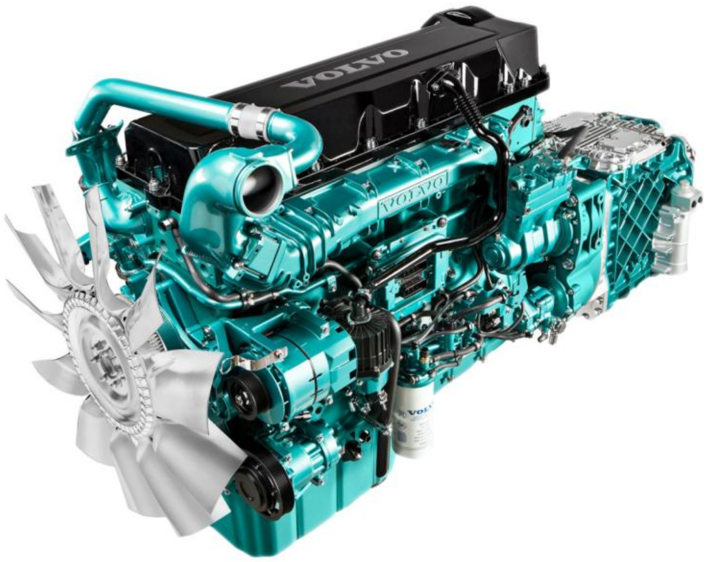


Figure 14 - Volvo DME Engine based on the Volvo D13. (Picture courtesy of Volvo.)

Similar to LPG, DME is a gaseous fuel with a boiling temperature of -24.9 °C. Likewise, many of the physical properties of DME are similar to LPG: including density, vapor pressure, and viscosity (see Table 8). As such, DME is stored in moderately pressurized tanks in much the same way as LPG and is suitable for injection via jerk-type injection systems which are likewise common for diesel engines (51). However, and similar to LPG, DME is denser than air which presents a challenge in that any vapor that escapes will tend to collect, or pool, in confined spaces and depressions.

4.6.2 Properties

Table 8 compares the properties of DME with diesel and LPG.

Similar to many of the other fuels that have been discussed, DME has a low energy density relative to MGO. For an equivalent content of energy, a DME fuel system will need to hold 85% more fuel by volume than a comparable MGO system. As for the other fuels, this is a serious disadvantage and also presents a challenge in designing the fuel injection system because the fuel injectors must deliver approximately twice as much fuel per injection cycle.

Relative to methanol, DME has a much higher energy density and only requires 83% of the storage space for an equivalent energy content. Since the production and distribution pathways for DME are virtually the same as those of methanol, this makes DME a more attractive fuel while still retaining the production benefits of methanol, including the possibility of synthesis from CO_2 stack emissions.

Property	Propane (LPG)	Butane (LPG)	DME	Diesel	Units
Boiling Point	-42	-0.5	-24.9	180 – 360	°C
Vapor Pressure	8.4	2.1	5.1		Bar at 20°C
Liquid Density	501	610	668	840 – 890	Kg/m^3 at 20°C
Viscosity	0.1	0.18	0.15	3.79	cP
Cetane Number			55 – 60	40 – 55	
Octane (RON)	111		35		
Octane (MON)	100		13		

Table 8 - Comparison of the properties of DME, diesel, and LPG. (26)

4.6.3 Emissions

Similar to methanol, DME has low sulfur content and therefore low SO_X emissions. A diesel test engine demonstrated a 50% reduction in NO_X emissions after being retrofitted with an optimized DME direct injection system. Low NO_X emissions are a result of the heat release characteristics of DME; specifically, the shift of the rate of heat release from the earlier to latter segments of combustion and the corresponding decrease in the maximum rate of heat release. In the same series of tests, CO_2 emissions were reduced by approximately 15% relative to operations on diesel. In addition, since DME burns without the formation of soot, a normal limit for the high load operation of diesel fueled engines, it is also possible to increase engine output by 10% relative to the base diesel configuration (51).

Figure 15 – Volvo tractor truck designed to operate on DME. (52)

4.6.4 Life cycle

From a life-cycle perspective, Wang and He estimate that a DME fueled engine will produce 12% less CO_2 than a similar sized diesel engine during the combustion process (27). This agrees with the 15% reduction that was reported in the test results from Sato. From a full-cycle perspective, and considering synthesis from natural gas, both Wang et al and Louis agree that the greenhouse gas emissions are similar for diesel fuel and DME. Wang estimates that the life-cycle emissions for DME are 1.5% lower than for diesel oil (27) and Louis estimates that life-cycle emissions for DME will be 6.7% higher than for diesel oil (53). Both studies estimate similar total GHG emissions for DME at 156 and 165 g CO_2/km respectively, but differ somewhat in their estimates for diesel (178 and 152 g CO_2/km). Given the vast array of variables that must be taken into account to conduct a life-cycle analysis of any fuel, the estimates from Wang and Louis show very good agreement. More importantly, while DME production from natural gas may be considered the median path between DME produced from recycled CO_2 emissions and DME produced from coal, the differences in these studies highlight the importance of the source and the method of production of the fuel.

4.7 HYDROGEN

Hydrogen is considered briefly in the context of this paper because it is the only potentially viable alternative fuel which does not contain any carbon. As such, it is also the only fuel which does not produce carbon dioxide during combustion. Since the goal of this project is to reduce the life cycle CO_2 emissions associated with pilot boat operations, this is obviously a fuel that must be considered.

Hydrogen, or H_2, is a gaseous fuel with an extremely high energy content. With a lower heating value of 120.7 MJ/kg, hydrogen has almost three times the energy content per equivalent mass of diesel. However, hydrogen has an extremely low density which means that it must either be compressed or liquefied to extreme temperatures or pressures.

4.7.1 Resources and availability

There are a number of different processes by which hydrogen can be produced. The most commonly used is via steam reformation from various hydrocarbon sources including methane and coal. Another method which has significant potential is the production of hydrogen via electrolysis of water. Although the process is energy intensive, and therefore currently not widely used, the potential lies in coupling hydrogen synthesis facilities with electricity produced from renewable sources, including hydroelectric, geothermal, and wind power. The latter is particularly interesting because hydrogen synthesis could be used to balance loads when there is a difference between peak loads, i.e. when there is a difference between production and demand. Photobiological processes which use green algae and cyanobacteria to produce hydrogen have also been developed. (26)

Liquefied hydrogen is produced via a multistep compression-expansion system which uses ammonia and then helium to successively cool the hydrogen to -253°C. The process is extremely energy intensive; 30 – 40% of the energy content of the fuel is expended upon the liquefaction process. In addition, the liquified fuel still has a very low energy density relative to the other fuels. Because liquefied hydrogen is stored at extremely low temperatures, the fuel is also extremely susceptible to boil-off from heat leakage into the storage tank (26).

4.7.2 Properties

Another important characteristic of hydrogen is its extremely wide flammability range. For most gaseous fuels the flammability range serves to limit the risk of explosion in the event of a release. In practical terms, this means that the risk of explosion is limited by the availability of oxygen to initiate the combustion reaction. The risk of explosion is therefore limited by the dispersion and diffusion of the gas-air mixture. In the case of hydrogen, however, the flammable range spans mixtures from 4 – 76% hydrogen by volume. In addition, hydrogen has an extremely low ignition energy relative to other fuels. The ignition energy of hydrogen is only 0.02 mJ as opposed to 0.24 mJ for gasoline and

0.29 mJ for methane. This means that in the likely event that a flammable mixture of hydrogen is formed, it will take less than a tenth of the energy to ignite the mixture relative to the energy required to ignite a mixture of air and gasoline or methane. This problem is then further compounded by the fact that hydrogen is much more prone to leakage from fuel system components and fittings due to its small molecular size which means hydrogen can easily diffuse through many materials, including some metals (26).

4.7.3 Technology

Although hydrogen is most commonly considered as a fuel in conjunction with fuel cell technology, it is also possible to use hydrogen as a fuel for internal combustion engines. While it is possible to use hydrogen in compression ignition engines, it is best suited for spark ignition engines. The most common fuel systems are either carbureted or port fuel injection systems.

Compressed hydrogen is typically stored at pressures between 345 and 700 bar. Depending on the pressure at which compressed hydrogen is stored, a storage system requires anywhere between four and ten times the volume to store an equivalent energy content of MGO. The high storage pressures are also problematic from the standpoint of fuel tank cost and design.

Alternative storage concepts are also currently under development, including the storage of hydrogen by adsorption to metal hydrides or in borohydride ($NaBH_4$) or organic liquids such as methylcyclohexane (C_7H_{14}). An important advantage of the metal hydride technology is the elimination of free gaseous hydrogen which limits the risk of unintended explosion or combustion. This technology was selected for the development of a hydrogen fueled ferry concept for the San Francisco Water Transit Authority (13).

4.7.4 Emissions

With the exception of carbon content from the combustion of lube oil, hydrogen engines emit virtually no CO_2, SO_X, or particulate matter. Since NO_X, production is related to temperature, there is a potential for NO_X generation; however, at fuel air ratios (λ) greater than 2.0, NO_X are no longer generated. Peak NO_X generation occurs at λ=1.3. As an alternative, direct injection systems have also been demonstrated with a brake efficiency of 43% (54).

4.8 DISCUSSION OF ALTERNATIVES

Although tradeoffs are to be made, each of the fuels presented is a credible alternative to diesel fuel. Through successive testing and development, each of the fuels considered has demonstrated the potential to burn in an internal combustion engine with reduced emissions.

The question at hand is which, if any, of these fuels are feasible for use on Swedish pilot boats. The notion of feasibility is one that must be approached with a degree of care because it is a characteristic that is not intrinsic to the fuel itself, but rather to the circumstances in which the fuel is being used. While the state of readiness of the available technology is a critical factor, the demand for the technology and the economics of development are just as important

An example which illustrates this point is found in the modifications that were performed on many Swedish road vehicles during World War II. (See Figure 16.) Because gasoline was scarce, it was common practice to convert Swedish cars to run on gasified charcoal which was generated in trailers that were towed behind the vehicles. While this may not seem a feasible application by current standards, given the right circumstances, it became not only a feasible but also functional solution.

Figure 16 – One example of a wood-gas fired automobile available around the time of WWII. (Picture courtesy of *Lowtech Magazine*.)

This example also highlights the fact that none of the technology associated with alternate fuels is particularly new in its conception. The difference, therefore, is that there has not been a market or a demand for further innovation because petroleum based fuels have, to date, been relatively easy to exploit. These influences are discernable even in the oil industry itself as the price of oil affects which resources are economically feasible to develop; for example recent price increases have enabled the development of shale gas, oil sands, and various deep water reserves (26). In the case of alternative fuels, the development of the requisite infrastructure and consumption technologies is only expected to happen if there is sufficient demand to justify their widespread implementation.

It is also important to consider the relative states of development of alternate versus conventional diesel technologies. A common concern with alternate technologies is whether they are reliable and developed enough for full scale implementation. It is worth noting that due to market demand conventional diesel technologies have benefited from over a hundred years' worth of research and development versus the relatively recent interest and more limited implementation of the fuels and technology that are being considered in this paper. This is a distinction that must be kept in mind when considering the current performance of a technology versus future potential.

An important goal of this project is to select a fuel which can be sourced from biomass. With the exception of LPG, all of the fuels considered in this project can and are currently produced from biomass, although in limited quantities relative to production from fossil fuel sources. Nevertheless, if biomass derived fuels are not available, the use of fuels from fossil fuel sources is still attractive from two standpoints: first, the distribution, storage, and handling of the fuels are similar regardless of the source, and second, there are still emissions reduction benefits to be realized from the burning of cleaner fuels. Regarding the first point, it is then be possible to leverage off the developments required to implement fossil fuel sourced alternate fuels in order to develop the infrastructure for the wider scale implementation of the same fuels, albeit sourced from biomass.

Methane-based fuels are attractive from the standpoint of reduced emissions and wide scale availability. The recent expansion of the natural gas market, including from unconventional sources such as shale gas and coal bed methane, suggests that natural gas will be available for many years to come. The downside of natural gas is that resources are often located in remote locations and are therefore extremely energy intensive to transport. From a life-cycle standpoint, LNG is estimated to have similar although slightly CO_2 equivalent emissions to MGO (27). However one of the main drawbacks associated with LNG and CNG fueled engines is methane slip since methane is estimated to have between 20 and 25 times the warming effect of CO_2 on a 100 year timescale. Of the two fuels, or perhaps more precisely, fuel delivery systems, CNG is disadvantageous because of its low energy density and therefore the comparatively large storage tanks that are required. Since CNG is stored at pressures in excess of 250 bar, the size, weight, and configuration of the storage tanks is problematic. CNG is ruled out as a feasible choice of fuel for pilot boats for this reason.

LPG is an attractive fuel with a number of advantages when compared to LNG and CNG. Relative to the other fuels considered LPG has the highest energy density and, because LPG has a relatively high boiling point, the storage requirements for LPG in terms of temperature and pressure are much more reasonable. One of the main disadvantages of LPG is that it is heavier than air. This means that in the event of leakage, there is risk that explosive gases will pool in low areas such as engine room bilges or in other interior compartments. From a practical standpoint, more robust and carefully designed ventilation leak detection systems will be needed to mitigate this hazard. In addition, LPG is the one fuel which is not produced from biomass; therefore it does not meet the requirements of this project.

Methanol and dimethyl ether are attractive fuels from the standpoint of having low emissions and the fact that they can easily be sourced from biomass. Methanol is also interesting because it is a liquid fuel at standard conditions and therefore much simpler to handle than the other fuels that are being considered. On the other hand, DME, which is a gaseous fuel, is noteworthy because it has combustion characteristics that are similar to MGO. Despite design challenges due to its density being heavier than air, DME is still a good candidate for further development.

Lastly, hydrogen is included in this discussion because it is the only fuel which does not produce CO_2 as a byproduct of combustion. There is also significant potential in the development of hydrogen produced from renewable energy sources, especially during periods of peak supply. Nonetheless, because hydrogen is extremely difficult and hazardous to handle and does not have a good distribution system, it will not be considered further within this project.

The remaining fuels which that further consideration are LNG, methanol, and DME. In the subsequent sections of this project, each fuel considered in greater detail relative to an actual application aboard a Swedish pilot boat. The factors that are considered and evaluated are the technology in terms of engines and fuel storage and distribution systems, the availability and distribution of the fuel in Swedish ports, and the potential for development from biomass sources.

5 PROBLEM STATEMENT

In the previous section of the project, methanol, dimethyl ether, and LNG were selected as the most promising fuels for further consideration as replacements for MGO aboard Swedish pilot boats. In the following sections, a more detailed analysis of each of the selected fuels is performed with a focus on the practical implementation of these fuels. The problem is approached from the standpoint of a near term test installation on one or more pilot boats within the Swedish fleet. As such, the project focuses on the implementation of currently available technology and considers this technology from the perspective of regulations that are currently under development and with regard to the current and near term availability of these fuels within Swedish ports.

Because of the critical role that pilot boats play in promoting and assuring safe commerce within Swedish ports, the repowering of Swedish pilot vessels is not a project that has room for diminished reliability due to growing pains or trial and error. A review of various road fleet alternate fuel testing and implementations is conducted in order to determine whether the pilot program can or will meet the stringent performance requirements of the application.

Finally, the implementation of methanol, DME, and LNG are considered relative to the operating profile of Swedish pilot boats in order to determine which boats are most suitable for replacement with boats that are powered using alternate fuels.

6 AVAILABLE TECHNOLOGY

This section investigates the implementation of LNG, methanol, and DME aboard Swedish pilot boats from a practical perspective.

The technical review focuses on three main subject matters:

First, the available technology is considered and an overview of possible engine concepts and fuel systems is presented. This section approaches the installation from a generic viewpoint but aims to present the development and different engine types and fuel system options which have been developed to date.

Second, the impact of regulations upon the design is considered. Although marine systems of regulation and standardization for alternate fuel installations and infrastructure are still under development, the final design will have to conform to some level of regulatory oversight and inspection. Since these regulations have the potential to have a significant impact on the viability of the concept, their current status and development is discussed and considered.

Finally, since operational reliability is of utmost importance, a review of literature describing road fleet test installations is discussed in order to determine best practices and lessons learned from past implementation experiences.

Although there has been considerable interest in LNG as a fuel for the maritime sector, there has been relatively limited development in the field of high-speed marine diesel engines which utilize alternate fuels. There has, however, been considerable development and interest in high-speed diesel engines for road applications such as heavy duty trucks and service fleets which include vehicles such as buses and garbage trucks. From an engine and fuel system perspective, these smaller installations are more similar to the systems that would be installed on a pilot boat than the much larger medium-speed configurations which are currently the focus of development within the maritime industry for commercial ships. As such, this section considers and draws heavily from literature which describes the development of alternate fueled engines and systems for road applications.

6.1 ENGINE CONCEPTS

Extensive literature is available regarding the development of various engine concepts for heavy duty alternate fueled replacements for diesel engines. From the standpoint of ease of adaption, these concepts are mainly developments of a basic diesel engine framework with modifications to the combustion chamber, fuel system, ignition system, and control systems (33). Many of these engines are capable of burning more than one alternate fuel, including relatively different fuels such as CNG and LPG (35).

An indication of the interchangeability of a gaseous fuel is obtained from the Wobbe Index (32); this describes the relative volume of the fuel that must be injected via a given orifice in order to deliver a similar amount of energy. Given the other cylinder constraints, if the fuel system can deliver an equivalent amount of energy as with the base fuel, then it is feasible to operate the engine on another fuel without a noticeable change in performance.

Several other parameters have significant effects on whether an alternate fuel will burn well within a given engine. The most significant of these properties include the knock suppression characteristics of the fuel and the specific volume of the fuel to be injected. Another important property that applies to all gaseous fuels is the power loss that results from the displacement of a portion of the air charge by the increased volume of the gaseous fuel (55). In the case of methane, low flame speed is a characteristic which has a major impact on the design of the engine. This particular fuel quality has several major effects which include high mean effective pressures (MEP) in methane fueled spark ignition engines (56) and the tendency for methane to remain unburned and therefore pass through the engine in the form of methane slip (35).

Although the basic hardware is similar, there is considerable diversity in engine concepts and designs. Designs can loosely be differentiated according to two basic categorizations: the method of fuel delivery and the means of ignition. The mechanism of fuel delivery relates to whether the fuel is introduced into the intake air or injected directly into the cylinder. The means of ignition relates to how the fuel-air mixture is ignited: i.e. spark ignition, glow plugs, jet ignition, or via compression ignition. Overlap exists and the two categories are by no means exclusive. For example, spark ignition systems can be found both on engines that inject fuel into the intake manifold as well as those that inject the fuel into the cylinder itself.

6.1.1 Engine Type By Fuel Delivery System

6.1.1.1 Fuel delivery via intake air

Several engine concepts involve the mixing of the gaseous fuel into the intake air upstream of the combustion chamber. These include lean burn spark ignition, homogenous stoichiometric spark ignition, dual fuel, and homogenous charge compression ignition engines. The options available for delivering and controlling the fuel-air mixture are either throttle or port fuel injection. Of the two, throttle injection is considered less desirable because of the efficiency losses that are incurred during partial load operation, whereas multiport fuel injection offers more precise control of the mixing process (33).

The engine types which utilize intake manifold or port injection include homogenous stoichiometric spark ignition engines, lean burn spark ignition engines, and homogenous charge compression ignition engines, and dual fuel engines.

6.1.1.1.1 Homogenous Stoichiometric Spark Ignition Engines

Homogenous stoichiometric spark ignition engines (HSSI) operate on the concept of a perfectly mixed fuel air mixture which is ignited by a spark plug. An important characteristic of HSSI engines is that that they operate at an air-fuel ratio (λ) of one; this means that the entire fuel/air charge is at stoichiometric conditions. Control of the air-fuel mixture is based on an oxygen sensor in the exhaust.

When operating on natural gas, typical compression ratios range from 11.1 to 11.5 and are limited by the possibility of engine knock. HSSI engines have been reported to have approximately 20% less power on an energy basis than a comparable diesel engine which translates to an increase in fuel consumption of up to 50% at low and idle engine loads (33).

HSSI engines are similar to homogenous charge compression ignition (HCCI) and dual fuel (DF) engines with the exception of the source of ignition.

6.1.1.1.2 Lean-Burn Spark-Ignition Engines

Lean burn spark ignition engines (LBSI) operate on the concept of a non-homogenous mixture with an overall excess of air in the combustion chamber. Although much higher air-fuel ratios have been tested, typical air to fuel rations are in the range of 1.6 – 1.7. One of the major difficulties associated with lean burn spark ignition engines is that they operate within the relatively narrow band between the knock limits and the misfire curve of the engine. As such, when lean burn spark ignition engines operate at low loads, there is a much greater proportion of misfires. This serves to limit the practical range of λ. See Figure 17.

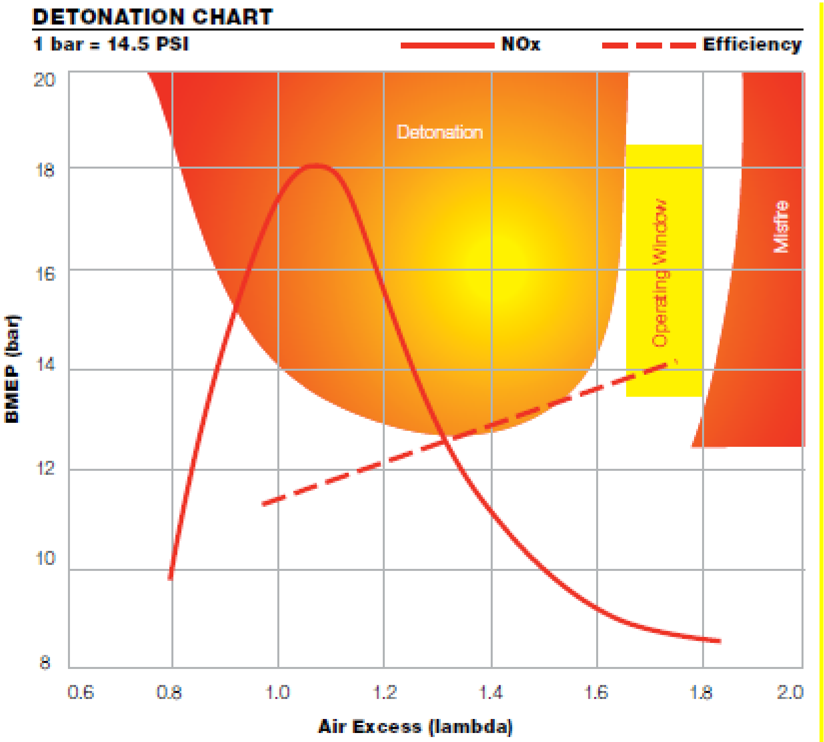


Figure 17 - Fuel-Air ratio and knocking. (57)

A lean burn stratified engine witnesses the start of combustion in the relatively stoichiometric region around the injector. As combustion progresses, the flame moves through the remainder of the cylinder which is at a lean equivalence ratio. A benefit of this approach is that the high temperature combustion gases are kept away from the relatively cool cylinder walls, which minimizes heat loss and the quenching of combustion gases. The latter is significant because it affects the emission of unburned fuels, including methane slip. A further advantage is that the combustion gases are cooled and diluted by the relatively cool compressed air. As such, LBSI engine operate with lower temperature and decreased emissions relative to HSSI engines.

LBSI engines also achieve extremely high thermal efficiencies - around 40% - which are due to the fact that lean burn engines operate at a much higher compression ratio than typical HSSI engines. Compression ratios for optimized LBSI engines are in the range of 11.7 to 13 (33). This translates to a fuel economy which is only 10% less than for a similar diesel engine.

Figure 18 - Detroit Diesel 60G natural gas engine has been used in LNG fuelled trucks and buses. (Picture courtesy of Detroit Diesel)

A significant disadvantage of LBSI engines is the low power that is produced relative to HSSI engines. In order to compensate, LBSI engines require higher pressure turbocharging and an intercooler in order to boost power output. An additional drawback is that LBSI engines are significantly affected by throttling losses, especially at low loads. Even in engines that are equipped with multiport fuel injection systems, a practical λ of 1.1 to 1.3 is the best that can be achieved at partial loads (33). In practical terms, this means that the efficiency and emissions reduction potential of LBSI engines is greatly reduced when operating at partial loads.

6.1.1.1.3 Dual Fuel Engines

Dual fuel (DF) engines operate on gaseous fuels and use a small direct injection of diesel fuel to ignite the gas-air mixture. A typical fuel configuration involves the injection of gas into the intake air plenum and utilizes a smaller quantity of diesel that is directly injected into the cylinder to ignite the mixture. Typically, DF engines are started on diesel operation and transition to operating in dual fuel mode once parameters have stabilized. An advantage of this configuration is that the engine is capable of running on just on diesel in case of a malfunction of the fuel gas system. In addition, this arrangement makes the dual fuel configuration particularly suited for retrofit installations.

At full load, the ratio of gas-to-diesel is approximately 80 – 85% (58) and as load decreases, the proportion of gas to diesel is reduced. Some engine manufacturers have also developed alternate strategies, for example a skip fire configuration in which cylinders are alternately fired but with a higher proportion of gas to fuel (58). Although dual fuel engines have higher particulate and CO_2 emissions than pure gas engines, they are still reported achieve NO_X reductions of 28% and PM reductions of 22% when operating at loads higher than 25% (58).

6.1.1.2 Fuel delivery via direct injection

Direct injection (DI) engines rely on the direct injection of fuel into the combustion chamber rather than mixing the fuel with intake air. The choice of injection timing is important because it affects the design of the fuel delivery system; fuel can either be injected early or late in the compression stroke, depending upon the properties of the fuel being used (59). Late stroke direct injection is similar to a conventional diesel engine, however a significant difference exists in that an external source of ignition is required for the fuels that are being considered in this study. A major advantage of the direct injection system is the reduction of methane slip due to fuel in the intake air bypassing the engine during valve overlap (35).

Direct injection of gaseous fuels necessitates the use of early injection timing in order to allow for adequate mass flow through the injector. Early injection systems generally utilize spark ignition and are quite similar to the HSSI concept previously discussed with the exception that the fuel is injected into the combustion chamber as opposed to the intake manifold. These early phase DI engines are well suited for gas phase injection because they offer the additional time that is required for fuel injection due to the decreased delivery rates that result from the lower system pressures and higher specific volume of the gaseous fuels (35). Early phase gas injection systems can be applied to either HSSI or LBSI concepts; however, they are most commonly applied to HSSI engines.

High pressure direct injection (HPDI) systems are conceptually similar to the fuel systems of a conventional diesel engine. Since the HPDI systems are designed to inject fuel just before top dead center, these systems necessitate the use of onboard high pressure pumps and utilize components which typically operate in the range of 200-300 bar (59). The high injection pressure is nevertheless beneficial because it reduces the power losses that are associated with displacement of charge air by the additional volume of the fuel gas. In addition, the evaporation of the fuel charge has a significant cooling effect on the cylinder. The effect is especially pronounced in methanol engines and accounts for how these engines can be operated at such high compression pressures. The practical result is that methanol engines can be downsized dramatically; literature suggests that methanol engines can theoretically be downsized by as much as a third when compared to a diesel engines of similar output (47).

High pressure direct injection (HPDI) systems are best suited for liquid phase and supercritical fluids. For fuels that are difficult to ignite, HPDI engines require an external source of ignition; the best sources are either glow plugs or via a jet of gas that is ignited in a pre-combustion chamber on account of the fact that spark ignition systems are not well suited to the high temperature and pressures that are found in the combustion chamber of an HPDI engine (33, 60).

The most common combustion concept for late cycle direct injection engines is the lean stratified jet ignited engine. This approach maximizes the emissions reduction benefits that were presented in the discussion of the LBSI engine.

6.1.2 Engine Type by Means of Ignition

Further distinction amongst engine types can be derived according to the means by which the fuel air mixture is ignited. Although certain methods may be better suited to some applications rather than others, most of the engines described above have been tested with various configurations of the different ignition systems.

Of the possibilities, spark ignition is commonly used for many engine concepts but is not suitable for high pressure applications in which case common alternatives are compression ignition, glow plugs, hot surface ignition (HSI), or jet injection. One of the characteristics of spark ignition engines is a high cycle to cycle variability of combustion and mean effective pressure (MEP). This is a result of the fact that a spark ignition cycle has a single point of ignition from which the flame proceeds randomly and is mainly influenced by the velocity of the reaction at the beginning of combustion. Cycle to cycle variability is another factor which is responsible for increased fuel consumption and elevated emissions of unburned hydrocarbons (56).

Compression ignition is the method that is used in dual fuel engines. The most common configuration involves the injection of the gaseous fuel via multiport injection and ignition via a lesser amount of diesel pilot injected into the combustion chamber via a standard diesel engine injection system. An advantage to this system is the option to run in diesel only mode; a disadvantage is the increase in emissions that are due to burning of the pilot fuel.

Jet ignition involves the pre-ignition of a small amount of fuel and air in a pre-combustion chamber and can be used with any of the combustion concepts. The products from this reaction form a jet of combustion gases which ignites the main mass of fuel. The volume of the pre-combustion chamber is typically small – in the range of 1 cm^3 and fuel and air mixture is ignited by either a spark plug or a glow plug (35). In certain applications such as the hydrogen assist jet injection (HAJI) engine, the fuel in the pre-combustion chamber can be of a different quality than the main fuel.

6.1.3 Current designs relative to choice of fuel

With respect to the fuels which are being considered, the following are the most common configurations currently available:

Fuel	Engine Configuration Options
LNG	Lean burn spark ignition
	Homogenous stoichiometric spark ignition
	Dual fuel with fuel injection into intake air
	High pressure direct injection
Methanol	Direct injection with glow plug
DME	Direct injection with glow plug

Table 9 - Engine configuration options by fuel type.

6.2 Fuel Systems

6.2.1 LNG Fuel Systems

For any of the fuels considered, the design of the fuel storage and delivery system represents a significant portion of the challenges that will need to be reconciled in order to achieve a successful and viable installation. The following sections discuss the various technologies related to fuel storage and delivery systems.

The design of LNG fuel delivery system strategies is dependent on the pressure requirements of the engines that have been installed and on the thermodynamic properties of the fuel itself. The majority of fuel systems used for road applications are saturated systems that use economizer valves to regulate the pressure. (See Figure 10.) There are, however, a number of alternatives, some of which are better suited to some particular engine concepts than to the others. The following section summarizes a paper by Weins, et al (37) which presents a comprehensive review of LNG fuel systems.

6.2.1.1 Storage tanks

The base component of the fuel system is the storage tank; this is normally a double-walled, vacuum-insulated vessel. One of the important functions of the tank is to minimize the ingress of heat into the tank. Since LNG is often stored at saturated conditions, the energy absorbed from the ambient surrounds is transferred to the natural gas and causes the equilibrium point of the contents to shift. As more gaseous LNG is formed, tank pressure increases unless the vapor can somehow be drawn off.

Storage tanks are fitted with a number of features which are critical to their function: fill connections, level gauges, overfill protection, excess flow valves, and relief valves. (See Figure 19.)

Figure 19 – Cold box and fittings of an LNG fuel storage tank. (61)

6.2.1.2 Fuel supply systems

The pressure requirements for an engine vary by combustion concept. Older naturally aspirated engines typically require fuel supply pressures of less than 1.4 bar and older turbocharged engines require a fuel supply pressure in the range of 2.0 – 2.75 bar. Modern turbocharged engines require a significantly higher supply pressure of 4.1 – 6.8 bar and dual fuel engines typically require a supply pressure of 6.8 – 8.9 bar. Direct injection engines require over 20.5 bar for early cycle (low pressure injection) and over 200 bar for late cycle injection. The vast majority of engines, fall into the spark ignition natural gas (SING) and dual-fuel engine categories which means that typical supply pressures for most engines are in the range of 6.8 – 8.9 bar.

The pressure inside the tank is established as the vehicle is being fueled. This process is known as conditioning and it involves the addition of heat to the fuel in order to increase the saturation pressure within the tank to meet fuel delivery system requirements. Fuels can either be conditioned on board the vehicle or at the storage or filling station. Two plausible concepts for fuel station conditioning are batch conditioning and on the fly conditioning. Batch conditioning involves the conditioning of the entire capacity of the storage tank while "on the fly" conditioning involves a high rate addition of heat as the vehicle is being fueled.

Once the fuel is in the tank, any energy addition into the tank, whether via heat ingress due to imperfect insulation or kinetic energy from the vehicle's motion, results in an increase of pressure within the tank. If the pressure becomes too high, then the pressure relief valves will open in order to reduce the pressure and protect the tank. (See Figure 10.) This is undesirable because it means that unburned methane is release to the surrounding areas. At best, this means that a strong greenhouse gas has just been emitted to the atmosphere and at worst, this could result in a flammable atmosphere which could endanger personnel and equipment.

6.2.1.2.1 Saturated systems

The majority of LNG systems in use in commercial vehicle applications are saturated systems that include an economizer valve that controls tank pressure. The system is filled at a saturation temperature and pressure that is high enough to satisfy the requirements of the engine installation. If the pressure increases past a certain set point, the economizer valve opens and vapor is withdrawn from the vapor space, thereby lowering the pressure inside the tank. The vehicle needs to be operated within certain time intervals in order to regularly reset the system's "hold-time clock". The latter is an important consideration because it means that this type of fuel system is not suitable for a vessel which is expected to sit idle for long periods of time. Typically, fuel tanks are designed to be able to sit idle for a maximum of one weeks at ideal conditions (62). (See Figure 20.)

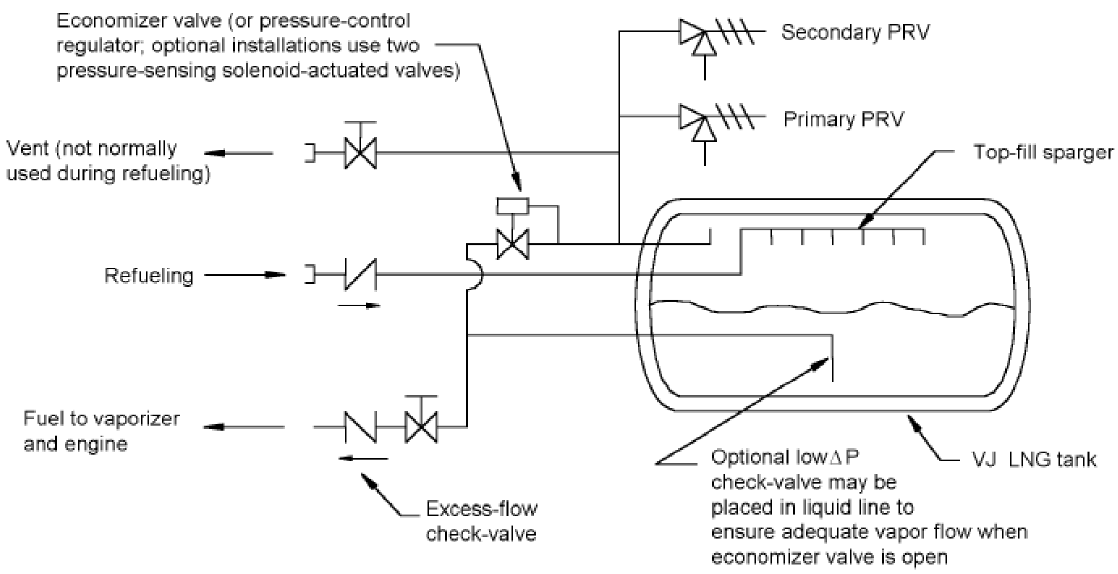


Figure 20 - Saturated LNG fuel system with vaporizer and relief valve. (Adapted from 37.)

Weathering is a phenomenon which can significantly affect the function of the saturated/economizer type of fuel system. Weathering occurs with LNG fuels that contain a portion of higher order hydrocarbons such as ethane, propane, and butane. For fuel systems that draw vapor from the vapor space in order to control the tank pressure, the relative proportion of higher order hydrocarbons within the fuel mixture tends to increase due to the methane preferentially being drawn off in the form of vapor and then being burned. Since the higher order hydrocarbons have much higher flame speeds than methane, the heat release characteristics of weathered fuels are extremely different and there is a risk that engine components will be damaged in the process.

Saturated/economizer systems have been proven with many years of service and are simple, robust, and economical. However, they are disadvantaged in that they offer no capability for building the higher pressures that some engine types require.

6.2.1.2.2 Liquid pump

An alternative system concept utilizes a cryogenic pump which is submerged in the system and delivers the fuel to the engine at the requisite pressure. This type of system is generally reserved for engines that require high fuel supply pressures. Advantages of the system are that the fuel does not need to be conditioned prior to delivery to the vehicle and that the fuel onboard the vehicle can be stored in its densest form, which effectively extends the range of the vehicle. Disadvantages include the fact that cryogenic pumps are not fully reliable, incur additional costs to the system, and are an additional source of heat ingress.

6.2.1.2.3 Alternative Designs

Additional concepts and designs have been developed with the aim of improving pressure control and eliminating the need for conditioning.

6.2.1.2.3.1 Non-saturated systems

Non-saturated systems operate with a sub-cooled liquid portion and superheated vapor content in the tank. This condition is accomplished by maintaining a false head on the system which is imposed during fueling via the throttling of a backpressure valve. If the tank pressure drops, an installed heat building circuit heats some of the liquid in the tank and injects it into the vapor space in order to build pressure. While the advantage of a system such as this is that it can be designed to accept the coldest and therefore densest LNG fuels, there is some debate as to whether a non-saturated system will be able to maintain non-saturation conditions due to the equilibration forces that are a result of heat ingress due to sloshing and tank movement.

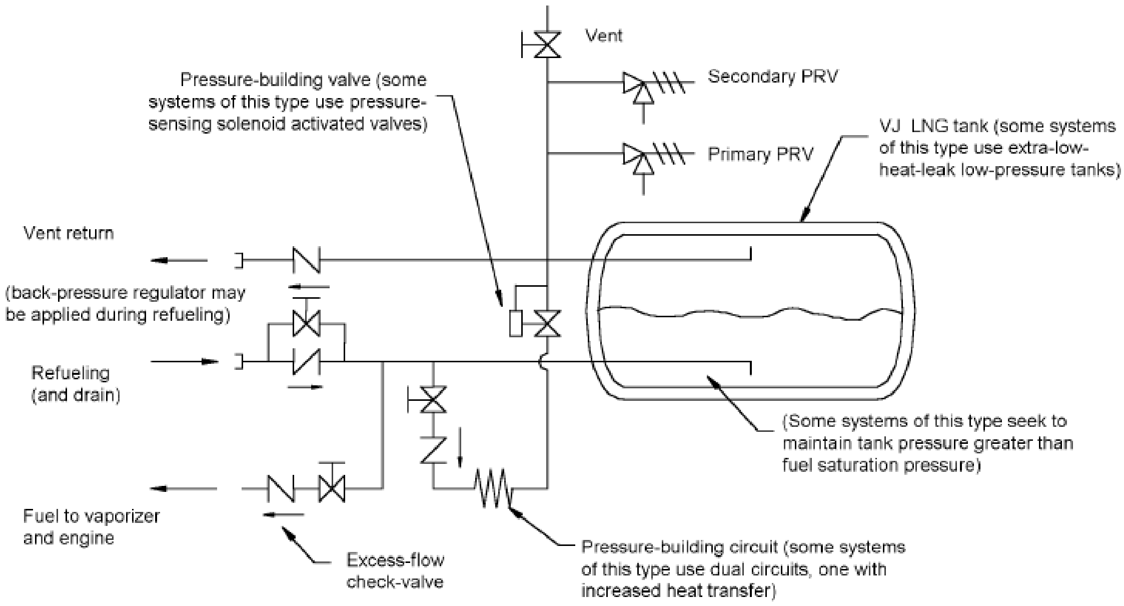


Figure 21 - LNG Fuel system with pressure building circuit. (Adapted from 37.)

6.2.1.2.3.2 Two-way pressure regulating systems

Another option is a system that provides two-way pressure regulation. This is accomplished by either using a vapor injection system or an in-tank heat exchanger. These systems have two-way pressure building and pressure reducing capabilities. Both systems use an economizer valve which draws vapor from the vapor space in the event of high tank pressure and both systems are equipped with means to increase the system pressure via the addition of energy into the tank. In the case of the vapor injection system, liquid fuel is drawn out from the tank and heated using a vaporizer, i.e. heat exchanger that uses the engine coolant as heating medium. The heated vapor is then injected into the vapor space in order to increase the tank pressure. In a system with an in-tank heat exchanger, liquid is drawn off from the tank and passed through two vaporizers prior to being delivered to the engine. After passing through the first vaporizer, the gas is circulated through a heat exchanger in the tank in order to raise the temperature and therefore the pressure within the tank prior to being routed to the second vaporizer and onto the engine(s). Both of these systems can theoretically supply fuel in the 8 bar range.

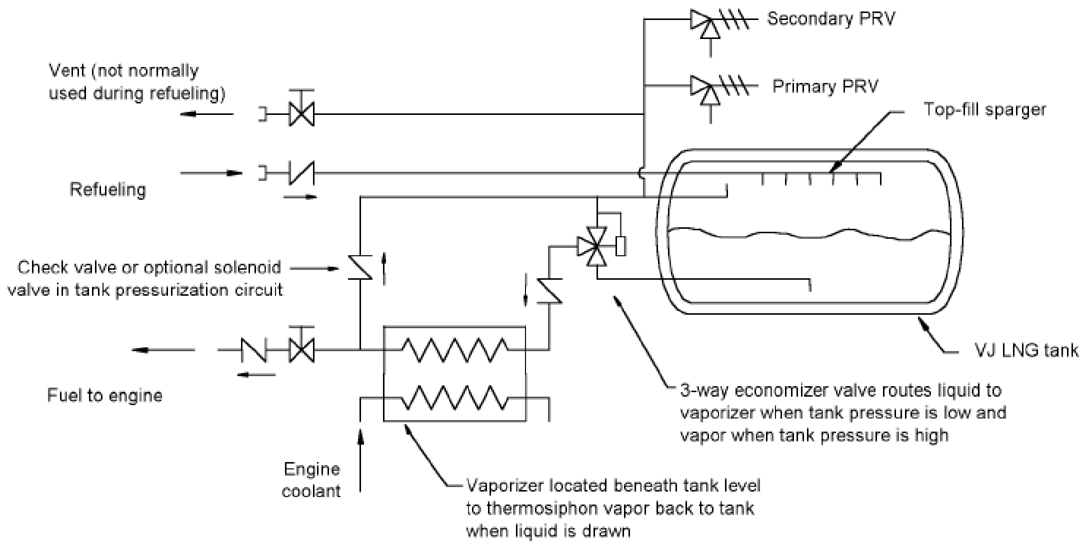


Figure 22 - LNG Fuel system with two-way pressure regulating system. (Adapted from 37.)

6.2.2 Methanol Fuel Systems

From a comprehensive review of methanol related literature, the main concerns related to the design of methanol fuel systems is the low energy density of the fuel, the incompatibility of methanol with many conventional fuel system materials, the low lubricity of the fuel, and the propensity of methanol to absorb water.

The effects of the low energy density of methanol are partially mitigated by the combustion properties of the fuel; since methanol engines can be designed with extremely high power densities (63). Nevertheless, methanol fuel injection systems must be designed in order to accommodate a larger volumetric flow rate of fuel; the geometry of fuel injectors and injection pumps must be altered in order to assure the delivery of the necessary quantity of fuel to the combustion chamber (60).

Since methanol is extremely corrosive to conventional engine materials, care must be taken in selection of suitable materials including the components used for sealing materials as well as the metals and alloys themselves. Materials containing magnesium are particularly vulnerable, as are those that contain aluminum when in the presence of water. Though not as severe, steel and other ferrous metals also exhibit pitting when exposed to methanol in the presence of water (63). The latter becomes an issue when moisture, for example from the condensation of ambient humidity upon internal tank structures, dissolves in methanol and then proceeds to corrode tank internals. The problem is best controlled by the careful application of corrosion resistant coatings or by the selection of austenitic stainless steel for vulnerable components when choosing materials (64).

Methanol can likewise be detrimental to soft sealing materials such as gaskets and o-rings. Yuen et al. (64) recommend that soft sealing materials are evaluated on the basis of performance with an M20 mixture (20% Methanol, 80% gasoline) as this is the most chemically aggressive blend of methanol based fuel available. Fluoroelastamer o-rings are considered a suitable, though expensive, sealing material although care must be taken to select the correct grade of fluoroelastamer is selected on the basis of the material specifications. Additionally, an AR-12 based polyacrylate material is promising in fuel-oil mixtures.

The effect of methanol upon incompatible O-rings is shown in Figure 23.

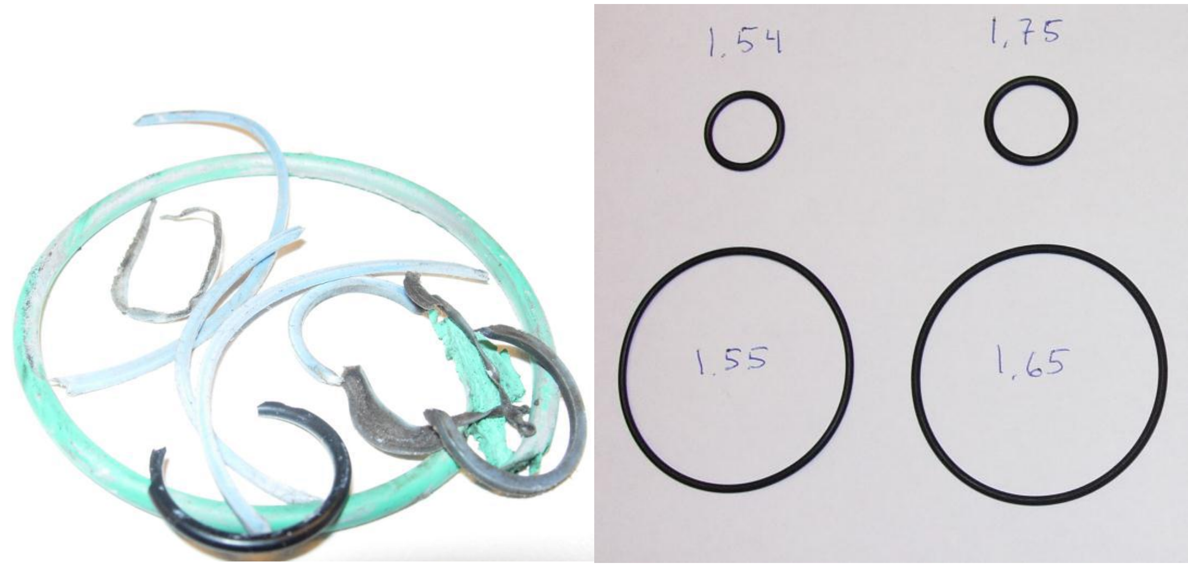


Figure 23 - O-Rings manufactured of typical materials having failed after contact with methanol. (50)

The challenging nature of the material selection process is attested to by the recommendations of Yuen et al. (64). Recommendations include that each material which is associated with the fuel system, down to the coating of the electrical connections for the submerged fuel pump, must be scrutinized for compatibility with methanol. Care is also to be exercised with the selection of sealing components of the lubricating system as the potential does exist for contamination of the lube oil system by methanol. Finally, the design and manufacturing processes for tubing and other similar components must be controlled in order to eliminate the micro cracks that result from bending and other forming processes as these will be greatly exacerbated by the corrosive compounds within methanol to the point of failure.

Despite the considerable challenges associated with material selection, methanol still has significant advantages relative to LNG and DME. In particular, because methanol is the only fuel that is handled as a liquid at ambient conditions, it does not need to be stored in specialized cylindrical tanks. The latter means that the fuel tanks can be better integrated into the vessel layout and therefore minimize the broken stowage associated with stand-alone cylindrical tanks.

Another significant characteristic that must be considered when evaluating methanol as a fuel is that the flash point of methanol is within the range of ambient temperatures. This means that the atmosphere within an enclosed fuel tank may very well be flammable (65) A means of inerting the dead space in the fuel tank and in the fuel lines must be included in the fuel system design and care must be taken when selecting fuel system components in order to eliminate potential sources of ignition.

6.2.3 DME Fuel Systems

Because of its similar physical properties, DME fuel systems are loosely based upon well proven LPG systems and include some common components such as the fuel tank (66). Nevertheless, DME also has a number of key characteristics which are different from LPG which necessitate special handling. The following section summarizes the work of Sato et al. (51) which describes the development of the fuel system for a heavy duty DME fueled truck engine.

Since DME is one of the only fuels which is utilized in compression ignition engines, the in line jerk type fuel system is the most promising candidate for a DME fuel injection system on the basis of satisfying power requirements at all loads and on the basis of prior development with low lubricity fuels. From a practical standpoint, some of the issues that must be addressed include the high compressibility of the fuel within the fuel injection pipes, the increased circulation and injection volumes, the tendency of DME to vaporize and vapor bind the fuel lines, the possibility of the fuel to dissolve in the engine circulating oil, the low lubricity of the fuel, and the propensity of the fuel to attack sealing materials and thereby result in the leakage of fuel.

These issues have been addressed via a number of engineering measures including the implementation of a pressurized fuel system with fitted fuel coolers in order to better control system pressures and guarantee the delivery of the fuel in a liquid state. Special care must be taken in the design of fuel system components in order to avoid the sticking and scuffing of parts due to the low lubricity of the fuel. Means by which these problems can be controlled include the surface treatment of various components to improve durability, the fitting of additional means of lubrication, and the use of lubricity additives which can be mixed into the fuel itself (51, 66, 67).

A significant concern is the unwanted mixing of lube oil and DME. Contamination of fuel by lube oil is the major factor that accounts for any particulate matter that is produced from the combustion of an otherwise sootless fuel. On the other hand the contamination of the lube oil sump by fuel involves the significant safety risk of a crankcase explosion and leads to degraded performance lube oil performance As such, special care has been taken when designing the fuel system in order to minimize the interface between the general circulating oil system and especially the final high pressure jerk pump and drive (i.e. camshaft) lubricating systems. A practical solution involves the installation of a secondary segregated lube oil system which is fitted with a means of disposal or of extracting the fuel.

Another well documented issue is the incompatibility of DME with conventional sealing materials. This is an engineering issue which can be mitigated via the careful selection of fuel system sealing materials. According to various authors, Teflon, graphite, Kalrez, and NBR (nitrile butadiene rubber) are the most suitable sealing materials (51, 66, 67).

The final concern that must be addressed is the tendency of DME to vaporize in fuel lines after shutdown of the engine. This process not only results in vapor bind and poor starting characteristics, but since the fuel nozzles do not have a perfect ability to seal against the gaseous form of DME, can result in the presence of fuel in the combustion chamber upon restart and can lead to significant engine damage. This problem is mitigated by the integration of a purge system which is designed to collect and eventually recompress the residual DME which is left in the fuel system after engine shutdown.

A typical fuel system is shown in Figure 24.

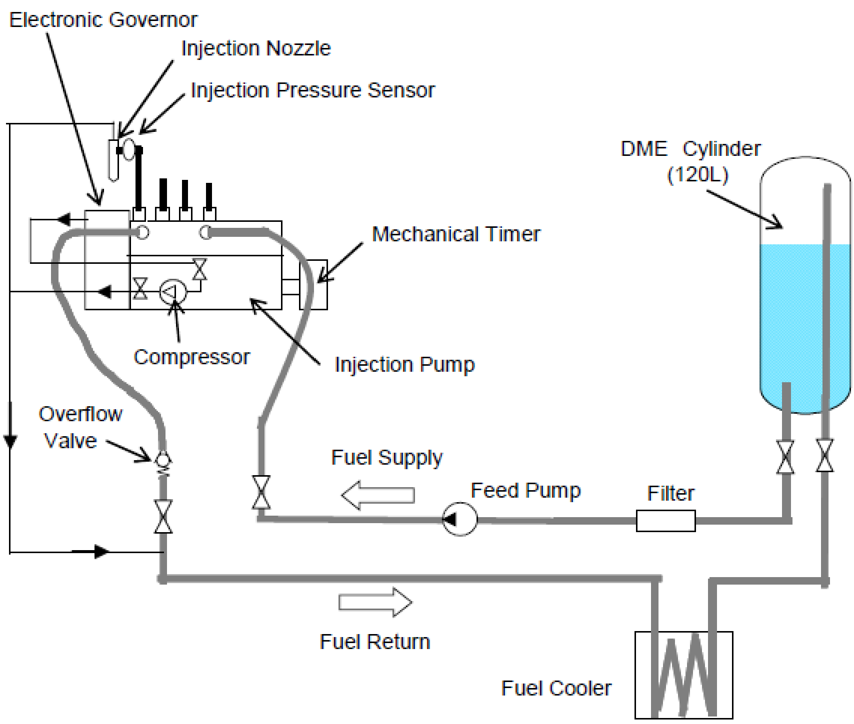


Figure 24 - Typical DME Fuel Supply Schematic. (Diagram courtesy of Sato 2004 51.)

The system includes one or more fuel tanks which are similar to LPG storage tanks and are kept pressurized at approximately 5 bar. Fuel is supplied via a low pressure fuel pump which takes suction from the liquid portion of the tank space and supplies fuel to a high pressure feed pump which in turn feeds the fuel manifold. High pressure jerk pumps take suction from the manifold and supply the cylinders via fuel injectors. The system is fitted with a fuel return line which contains a back pressure regulator and a fuel cooler in order to better regulate the pressure and temperature of the fuel supplied to the manifold and thereby control the mass of fuel injected (51). A purge system is fitted to collect vapors from the fuel system upon shutdown and return them to a purge tank. The tank is fitted with level sensor monitoring in order to allow for the detection of internal fuel leaks. A reliquefaction compressor is fitted to the fuel pump drive which returns reliquefied DME from the purge tank to the storage tank.

A typical DME storage tank is shown in Figure 25 and is fitted with a fill line, level sensor, an in tank low pressure feed pump, return lines for both the vapor and the liquid spaces, and at least one relief valve.

Figure 25 - Typical DME fuel tank on board Volvo DME Truck. (Adapted from 68.)

7 OPERATIONAL CRITERIA

7.1 SAFETY

There is a level of risk inherent to the handling of any fuel; this risk is mitigated via a combination of engineering controls and practices that moderate the hazards associated with the fuel. A key component of this strategy is a thorough risk assessment that seeks to identify key hazards and develop countermeasures that will reduce the frequency and/or severity of their impacts. Counter measures generally fall into two categories: engineering and procedure controls. Examples of engineering controls include physical devices such as fire and gas detectors, pressure relief valves, and intrinsically safe electrical components. Procedural controls include measures which may include the standardization of product specifications, the formalizing of standard operating procedures, and requirements for crew training.

The safety concerns related to the handling of a fuel are usually evaluated with respect to health, safety, and environment (HS&E). Health concerns relate to the toxicological and physical hazards that are presented by the material. Examples of health hazards include carcinogenic and mutagenic effects as well asphyxiation or burn hazards in the event of a release or fire. Safety hazards pertain to the handling of the fuel and are related to the physical properties of the fuel. Examples of safety hazards include reactivity, a wide flammable range, and how permeable various substances are relative to the fuel, therefore resulting in an increased likelihood of leakage. Environmental hazards are most commonly considered in the context of a short to medium term time scale. The most obvious scenario is the effect if a measurable quantity of the substance is released into the environment. Also of concern are the effects of smaller and perhaps routine operational releases, for example from incompletely purged fueling connections, and from the byproducts of handling and combustion processes.

Presented below is a summary of the major safety concerns related to the handling of LNG, Methanol, and DME. Many of the risks that are discussed are directly related to the physical properties which were presented in earlier sections of this report.

7.1.1 LNG

The safety concerns associated with the introduction of large scale LNG facilities in various ports around the world have been the topic of considerable debate. Nevertheless, the LNG shipping industry has maintained a very strong safety record with no loss of containment in over 50 years of LNG transport. This safety record has been attributed to the use of aggressive engineering controls and strong safety procedures (70) and the expertise from this experience is being applied to smaller scale LNG projects such as LNG fueled vessels and bunker terminals.

7.1.1.1 Fire

One of the most significant concerns regarding the use of LNG is the risk of fire and explosion. The perception of this risk is elevated by the fact that the fuel is gaseous at ambient conditions and by the relatively high energy content of the fuel. However, LNG handles and burns differently than many conventional fuels. A challenge associated with LNG, and also with other low flashpoint fuels, is a misconception or lack of understanding regarding the combustion, and likewise the handling, properties of the fuel.

Figure 26 demonstrates the progression of an LNG pool fire during a firefighting training exercise. This provides a good illustration of the major differences between the behavior of an LNG fire relative to a conventional (liquid) fuel fire.

Figure 26 - Sequential photographs taken during an LNG pool fire trial and demonstration. (71)

The first notable difference is the behavior of LNG as the initial pool is formed. At this stage the LNG boils rapidly and the rate of vaporization is determined by the large temperature difference between the ground and the liquid natural gas. Eventually, the rate of vaporization slows and approaches a slower but steady rate as the ground under the pool has cools to a temperature nearer to that of the pool itself (72).

At this point, the flammable limits of natural gas are significant since the vapor cloud must be sufficiently but not overly diluted to burn. Dispersion models are used to predict the rate of dispersion and boundaries of the gas cloud in order to determine the possible range of the affected area in the event of an ignition scenario. (70)

Once the gas cloud has been ignited, the fire is characterized by a low laminar flame speed and will burn back to the source of the leakage (70). A significant difference is that pure methane initially burns with a colorless flame and without smoke (See Image 4 in Figure 26). Nevertheless the presence of such flames can readily be detected via a combination of gas sensors, and a combination of heat and infrared flame detectors. Additionally, and as can clearly be seen in Images 5 and 6, once the fire starts to encompass materials other than natural gas, the flames become visible and are readily detectable.

The temperature differential between the liquefied pool and its surroundings is critical to understanding the continued behavior of an LNG fire. Image 6 illustrates the effects of heat addition upon the fire. In this case, the source of heat the water that is being used in conjunction with well intentioned, but nevertheless misinformed firefighting efforts. The heat in the water actually increases the rate of vaporization of the LNG and therefore increase the intensity of heat output from the fire.

7.1.1.2 BLEVE, VCE, and RPT

There are also a number of extreme phenomena that are often cited as concerns in the event of major gas fires, including vapor cloud explosions (VCE), boiling liquid expanding vapor explosions (BLEVE), and rapid phase transfer (RPT).

Vapor cloud explosions occur in unconstrained gas clouds when the flame speed accelerates sufficiently to create expanding pressure effects. According to a position paper presented in 2004, DNV does not consider VCEs to be a credible event in the case of a large scale spill of LNG over water due to the fact that the combustion mechanism of methane do not include an acceleration mechanism. The paper does, however, express some concern regarding the possibility of a VCE if a gas cloud were to drift into a constrained environment, such as a port or terminal area containing process equipment which could limit the free movement of the cloud and fire. Given the small quantity of fuel that is will be carried aboard pilot vessels, this is not a credible scenario; nevertheless, the behavior of a gas cloud within a confined environment such a machinery space is cause for real concern and must be contended with in the vessel design. (70)

BLEVEs are most commonly associated with the carriage of pressurized liquefied gases. BLEVEs occur when the impingement of flames cause the eventual material failure of the pressure vessel and results in the release of liquefied flammable gas which vaporizes and is ignited by the flames. This results in a large flash fire but with no significant pressure wave. (70). The early stages of the fire are characterized by an increase in pressure in the storage vessel as heat from the fire is absorbed by the liquefied gas. Eventually, the excess pressure is vented via the relief valve. During this process, the tank material adjacent to the liquid level in the tank is effectively cooled by the vaporization of the gas within the tank. The gas space within the tank, however, has no such cooling mechanism and is therefore prone to failure. Since the contents of the tank are pressurized, when the tank fails the resulting gas cloud has the mechanism to not only spread quickly, but also has a ready ignition source from the already present flames. The resulting explosion has the potential to be extremely violent. But because BLEVEs depend on the release and flashing of pressurized contents to spread the gas cloud, they are not considered a credible event for LNG storage tanks since the contents of LNG tanks are not kept under pressure. So long as the relief valves are adequately sized and in functioning order, a failure of the containment during a fire should result in a spill and vaporization scenario rather than a BLEVE. (70)

Rapid phase transition (RPT) refers to the rapid and potentially violent generation of vapor clouds when LNG is spilled upon water. Although an understanding the violent nature of the interaction between LNG and water is critical to firefighting strategies, there is still considerable uncertainty in the modelling of pool fires of LNG over water. One possible scenario is that convective currents under the surface of the water will delay or prevent the attainment of the steady state conditions that are eventually reached in the case of LNG spillage over land. This scenario can potentially to lead to much higher sustained rates of combustion – with as much 2.5 times the heat release rate of a similar fire over land - and the possibility of rapid phase transfer (70). And although DNV does not consider a large explosion due to rapid phase transfer to be a credible scenario, the violent nature of even small quantities of LNG when spilled into water has been well documented (73) and would certainly presents a hazard to personnel in the vicinity.

Despite the uncertainty regarding the effects of a large scale spill of LNG, a particular benefit of the pilot boat project is that the scale of the implementation falls within the range of the actual tests which have been performed to validate and tune theoretical models for predicting much larger scale spill and release scenarios. For example, PItblado et.al. (70) cite experiments in which 415kg and 2000 kg of LNG were spilled on land. The pools generated were 14 and 16 meters in diameter respectively and in the case of the 2000 kg trial, the pool was found to dissipate within 80 – 90 seconds. Although these trials do not account for the uncertainties of a spill over water, they do give a good indication of the scale and duration of effects that can be expected.

7.1.1.3 Environmental concerns

In the event of a spill, the tendency of LNG to vaporize is beneficial from a short term clean-up point of view. Unlike most liquid fuels, spilled LNG quickly vaporizes and evaporates. Because of this, there is also not a concern with LNG contaminating ground water. In the long term, however, methane is a powerful greenhouse gas and the uncontrolled release of LNG must be avoided. Another hazard that is encountered with spilled LNG is the effect that it has on many standard marine building materials. Mild steel, in particular, is extremely susceptible to low temperature embrittlement. As a result, any structures that might be expected to come into contact with LNG or spilled LNG, including drip trays and scuppers, must be fabricated from cryogenic tolerant materials such as stainless steel.

7.1.1.4 Personal safety

The main hazards that are presented by LNG in terms of personal safety are primarily related to the physical properties of the fuel. In addition to the more obvious risk of burns from fire, there is also the risk of cold burns and frostbite from accidental contact with spilled liquid or supercooled fuel transfer components. (See Figure 27.) Another concern is the risk of asphyxiation in the event of a leak into an insufficiently ventilated space. From this standpoint, it is important to note that methane, at ambient conditions is lighter than air. For this reason, ventilation systems for enclosed spaces such as machinery rooms must be carefully designed to thoroughly ventilate the space in the event of a release and, in particular, to avoid pockets which may be difficult to ventilate.

7.1.2 DME

Because DME is handled similar to LPG, it shares many of the same hazards that are associated with handling LPG. In particular, since DME is stored in pressurized containers, the risk of explosion and/or BLEVE is significantly greater than with LNG. However, since DME has a much higher boiling point than LNG, the risk of rapid phase transfer is not considered significant. One primary difference between the two is that DME vapors are heavier than air. This means that not only will the vapors more readily displace oxygen in a confined space, but that vapors will tend to pool at the lowest points of a given space. This can be problematic in areas such as machinery spaces because of the complex geometry of the bilges. Although it is possible to arrange ventilation systems such that air is either supplied to or drawn from the bottom of a particular space, the nooks and crannies associated with typical machinery spaces may prove difficult to ventilate.

Similar to LNG, spilled DME is expected to vaporize quickly and therefore leave little environmental impact. Likewise, DME is considered to have low toxicity, and is used in medical applications and is considered safe for use in the food industry (74). However, similar to LNG, there is still a risk to personnel in the form of frostbite injuries.

Figure 27 – Bunker station onboard an LNG fuelled ship in Norway. (15)

7.1.3 Methanol

Methanol is handled similarly to ethanol and in some respects is very similar to gasoline. One of the significant differences between methanol and many of the other fuels available is its wide flammability range. Depending on the ambient temperature, a closed and non-inerted container of methanol is likely to contain a flammable atmosphere (72). Another significant difference between methanol and other fuels is that methanol burns with a colorless flame, which makes it difficult for personnel to detect a methanol fire. Additionally, the risk of explosion is significant, and even more dangerous since the fire may not be immediately obvious to personnel or emergency responders. (75.)

This point is illustrated with great clarity in Figure 28 which shows images from an overturned methanol tanker truck that caught fire. Both images were taken at approximately the same time and immediately prior to the tanker exploding. The image on the left shows the fire as visible to the naked eye while the image on the right shows the actual extent of the fire via an infrared camera.

Another hazard associated with methanol is that it is water soluble. While this may be a benefit when it comes to cleaning up a spill, burning methanol can be diluted by water and still remain flammable even as a mixture. In addition, methanol vapors are slightly heavier than air. As with DME, this means that it may be difficult to arrange ventilation systems so as to be certain that methanol vapors are properly purged.

Figure 28 - Methanol tanker truck fire filmed in the visible spectrum (left) and at approximately the same time in the infrared specturm (right). These pictures highlight the inherent danger and difficulty in indentifying and fighting accidental fires. (Adapted from 76.)

A major concern with methanol is that it is be toxic at relatively low dosages, including via inhalation and through skin contact (75). According to the US EPA, "Workers repeatedly exposed to methanol experienced several adverse effects. Effects range from headaches to sleep disorders and gastrointestinal problems to optic nerve damage." (77)

7.2 REGULATORY

It is not a requirement for Swedish pilot boats to be classed by one of the major classification societies such as Det Norske Veritas (DNV), Lloyd's Register (LR), Germanischer Lloyd (GL), or American Bureau of Shipping (ABS). Nevertheless, the vessels are built to classification society standards and instead of being classed, their compliance is assured through periodic inspections that are conducted by the Swedish Transportstyrelsen.

The regulatory climate and current state of regulations regarding the implementation of alternate fuels is therefore important for a number of reasons. At a fundamental minimum, the purpose of regulations is to ensure the safe and reliable (in other words, insurable) operations of a particular vessel through the specification of minimum standards for materials, system layout and design, and requirements for safety devices. As such, the regulations are significant from two standpoints. First, the regulations are the result of an intensive risk analysis and are designed to incorporate best practices from service experience. The regulations are therefore a good guideline regarding the risks associated with the proposed systems as well as how best to mitigate those risks through design and procedural controls. In this sense they are also an indication of the requirements that need to be fulfilled in order to convert technology from a stationary or road application to the marine sector. Second, because the regulations contain actual requirements for equipment and systems to be installed, they are a good guideline for deciding the scope of the project and whether the proposed installation will be feasible in light of the regulatory requirements. In other words, the scope and flexibility of the regulations can and will directly affect the feasibility of the project.

A challenge that is common between the road and marine applications of alternate fuels is the relatively immature state of regulations and standards. Even in the road industry, where the application of alternate fuels is much more developed than in the marine industry, there is still a need to develop a more standardized approach to such critical components as fueling systems, fuel quality, and general availability. In the marine industry, this is exacerbated by relatively recent development of concepts and technology and by the intense pressure to deliver regulations for the technology that does exist. An example of the distortions that this pressure can cause is the recent petition by Sweden to include methanol and DME in the regulations for low flashpoint fuels. Although methanol and DME are low flashpoint fuels, the committee which as preparing the forthcoming low flashpoint fuel regulations had intended to exclude methanol and DME due to time constraints and the pressure to produce the regulations. In doing so, a viable alternative to LNG would effectively have been excluded from the market due to the fact that a methanol or DME fueled vessel would need to apply for exemptions for every single country in which it sought to trade (Dr. J. Ellis, personal communication, August 7, 2013).

7.2.1 Regulatory Approach

Though the individual classification societies are free to establish their own individual sets of guidelines, there is good general agreement between different classification societies regarding approach and best practices. Vessels are also required to comply with various IMO regulations when operating in the territorial waters of signatory nations. Although receiving an exemption to the rules is possible, these are problematic in that they must to be submitted to and approved for each country in which the vessel operates.

The regulations and guidelines which cover the fuels considered in this project are lumped under the heading of “low flashpoint fuels” or systems for “gas fueled vessels.” LNG and DME are covered under either heading since they are both gaseous fuels, but the treatment of methanol is slightly more problematic because it is a liquid at ambient conditions but nevertheless needs to be handled carefully because of its low flashpoint. As was mentioned above, the draft IMO code for gas fueled ships (78) is currently being modified in order to accommodate the use of methanol as a fuel. If methanol is to see use as a marine fuel, then the classification societies will follow suit and furnish rules to provide guidelines for methanol fueled installations.

A significant aspect of the rules and regulations that have been developed to date is that they are an adaptation of previous experience with gas carriers which, in many circumstances, have utilized boil-off gas as a fuel source. As such, the rules are a *progression* from earlier steam powered configurations and may present a different approach than if they had been written specifically for diesel powered installations. In addition, the regulations are written from the perspective of larger scale installations for which it is easier to accommodate the many restrictions and additional safety systems. As such it is possible that the requirements specified therein might be complex and restrictive enough as to render a small scale application such as a pilot vessel practically infeasible.

Both classification society rules and the draft IMO guidelines do, however, include provisions to approve alternate designs if they can be shown to “meet the intent of the requirements concerned and provide an equivalent level of safety as the relevant chapters.” (78?) This provision opens the door to alternate designs provided that they satisfy the intent of the safety standards. The industry accepted practice for demonstrating equivalency is by conducting a detailed risk assessment which uses a systematic approach to identify the hazards, estimate severity of consequences and likelihood of occurrence, identify topics which require detailed study, and includes a detailed operational assessment (79). (See Table 10.) Although time consuming, this type of risk assessment would be valuable to this project even if it were not required for the purpose of proving compliance with existing regulations. Nevertheless, even with provisions for alternate arrangements, there is still the risk that the proposed modifications would not be acceptable to the classification society or inspecting body and that the existing standards would be too onerous for the scale of the installation involved.

Assessment of the collision risk (risk = frequency x consequences) => definition of accepted risk

- Assessment of the required collision risk (risk = frequency x consequences) => definition of accepted damage conditions
- Equivalence between storage tank systems => fixed, installed, and portable
- Assessment of risk during bunkering procedure => definition of accepted risk
    - Limiting of consequences => limiting of reasonable amount of gas
    - Reduction of failure frequencies => safety of connection system (couplings, flexible pipes/hoses, etc.)
- Exclude gas release in the vessel:
    - Limiting failure consequences => secondary barrier for subsystems (failure of primary barrier does not lead to safety relevant consequences)
    - Reduce failure frequency => reliable storage systems, connections, valves, etc.
    - Control of accidental gas releases:
        - Gas release in case of tank failure
        - Gas release by safety devices
        - Gas release from process equipment (leakages)

Table 10 - Procedure for a typical risk assessment. (78)

From a high level review of both classification society rules, including DNV, GL, and Lloyds, as well as the most recent draft of proposed IMO IGF code, the main goals of the regulations include minimizing hazardous areas and the equipment installed in hazardous areas. Additional goals of the regulations include the prevention and minimization of the consequences of a possible explosion, arranging the systems so that power and propulsion can be restored in the event of fuel system malfunction, and ensuring that adequate standards are available for the design, construction, and installation of gas system components, including fuel lines, storage tanks, and bunkering systems (78). While a detailed discussion of the code is outside of the scope of this project, it is useful to consider certain requirements as an indication of the added complexity that the requirements would impose upon the system. Examples of specific requirements are taken from the draft IGF code and are discussed below.

One of the central themes of the regulations is the distinction between hazardous spaces and non-hazardous, or gas safe spaces. From the GL rules, a hazardous area is "an area in which an explosive gas atmosphere is or may be expected to be present in quantities such as to require special precautions for the construction, installation, and use of electrical apparatus." (78) A gas safe space is a hazardous space which is "not considered to be hazardous provided that certain provisions are met."

In order for machinery spaces to be considered gas safe, they must either be fitted with intrinsically safe equipment or protected by an emergency shutdown (ESD) system. Intrinsically safe equipment is designed to eliminate any possible sources of ignition. Typically the term intrinsically safe refers to electrical components and the design of the systems and enclosures so that sparks or flames cannot propagate outside the enclosure. Means of making equipment intrinsically safe include using low voltage direct current for control circuits, the use of zener barriers, and the design of enclosures to allow for controlled release of explosions and prevention of flame propagation. From a practical standpoint, intrinsically safe spaces would need to be simplified and kept to a minimum because of the added costs associated with the extra materials and engineering required to make components intrinsically safe. Also, intrinsically safe spaces are problematic because they limit the operations that can be conducted in the space while the system is in service. As an example, electrical tools including power tools, voltmeters, and even flashlights cannot be used in the space unless they, too, were classified as intrinsically safe.

An alternate arrangement would be an ESD protected space. An ESD protected space is one which is not required to contain intrinsically safe equipment, but which is protected by a system which automatically disconnects any possible sources of ignition (again electrical) upon the detection of a gas leak. Effectively, this would require the automatic and immediate shutdown of all equipment within the space. Although the ESD approach is more straightforward to implement, it is problematic for an application such as a pilot boat because the ability to maintain maneuverability while conducting a pilot transfer is critical. Additionally, and according to the draft IGF code, ESD protected spaces are not acceptable for gases which are heavier than air or for low flashpoint liquid fuels. This means that methanol or DME fuel installations would be required to be fitted with intrinsically safe machinery spaces.

At a minimum, all fuel piping within machinery spaces must be enveloped in a gas tight enclosure, typically in the form of double walled piping. (See Figure 29.)The enclosure is to be ventilated to a vent mast using fans which maintain negative pressure within the double walled enclosure. While there is fuel gas in the system, the ventilation fan must be kept running at all times. The fuel system is to be further protected by a “double block and bleed” arrangement which ensures that any residual fuel contained within the fuel system after shutdown is isolated from both the fuel supply and engine and purged to the vent mast using an inert gas such as nitrogen, CO_2, or argon. (See Figure 30 and Figure 31.) This arrangement necessitates not only the installation of an inert gas generating and storage system, but also of a system for the safe venting of gas. The vent system would also typically accommodate any fuel that would be discharged through pressure relief valves and the requirements, as currently written, state that the vent system must discharge to a safe location that is at least 1/3 the beam or 6 meters, whichever is greater, above the weather deck or sources of ignition and working areas and walkways, and at least 10 meters from features such as air intakes and openings. Given the scale and maneuvering characteristics of a typical pilot boat, these requirements would be particularly difficult if not impossible to fulfill.

The regulations also discuss a wide variety of requirements which include, but are not limited to, stipulations regarding the installation of fire and gas detection systems, design of ventilation systems for machinery and fuel connection spaces in terms of minimum number of air changes, provisions regarding independent access to machinery and tank connection spaces, requirements for the minimum spacing of fuel tanks relative to the hull, and criteria for the selection of materials in order to avoid brittle fracture of steel due to accidental contact with cryogenic fuels. (78)

When the regulations are considered as a whole, it soon becomes evident that the regulatory approach which is being developed is considerably more complex than that of the LNG or DME fueled truck upon which the alternate fueled pilot boat concept is based. On the one hand, the simple layout and relative roominess of a pilot boat engine room could be advantageous because it might prove simpler to convert to an ESD protected or intrinsically safe arrangement. Despite this, a significant concern is whether the added cost of the additional systems and components will render the pilot boat economically infeasible considering the relatively low cost of pilot vessels relative to other commercial marine vessels. It is certain, however, is that at least some of the requirements will have to be modified. Since the technology is in a state of development, there is a good possibility that classification societies and inspection bodies would be open to alternate arrangements, however the degree of flexibility is not certain, and the proposed designs would need to be proved using a detailed risk analysis methodology (J. Ellis, personal communication, August 7, 2013).

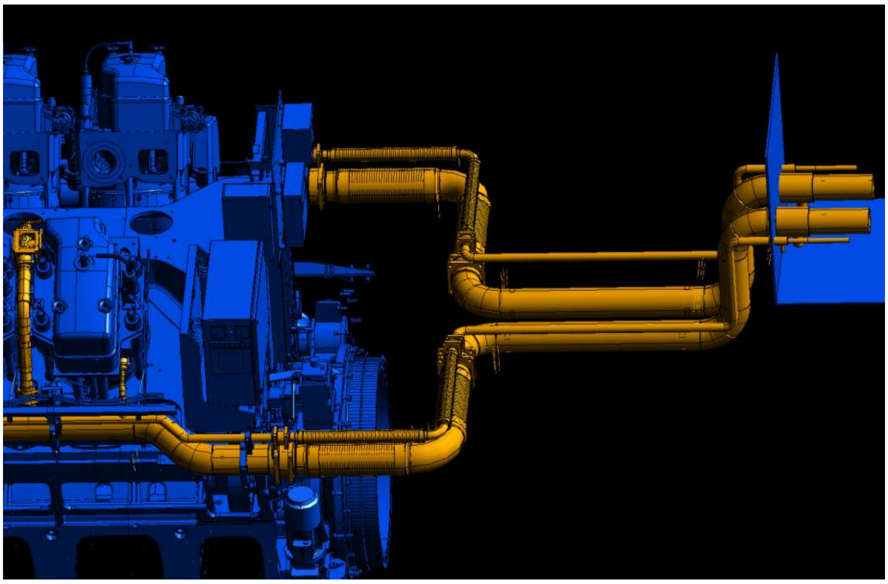


Figure 29 - Example of a double-walled piping on main gas supply and pre-chamber gas for an Inherently Safe Installation. (Figure courtesy of 80.)

Figure 30 – Automatic double lock and bleed valve (Courtesy of Young & Franklin, Inc.)

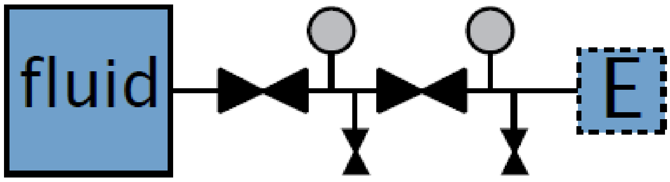


Figure 31 – Schematic of a double block and bleed valve aligned as show in Figure 30. (Adapted from 81.)

8 TEST INSTALLATIONS

Although there are a number of notable differences between the road and marine applications of high speed diesel engines, a particular advantage of the pilot boat project is that the application of such engines is quite similar to the types of road applications for which alternate fuels have been best suited. Not only are the engine and fuel system technologies similar, but likewise, the issues of fuel availability, vehicle maintenance and reliability, and overall functionality and profitability are the same.

At the time of writing, alternate fueled vehicles for such applications such as metropolitan buses, municipal vehicles such as garbage and refuse haulers, and short haul and fixed route trucking have been well proven and gained varying levels of acceptance. From the testing and development of these alternate fueled road applications, there is a wealth of practical information available that is pertinent to this project. This information is useful not only because it often discusses the pitfalls and challenges associated with various test installations, but because actual data is presented which offers comparison between the alternate fueled vehicles and similar diesel control vehicles, both in terms of emissions and operating costs, as well as in the form of driver feedback and comments.

The data was collected from a variety of projects which span a time frame from 1987 to 2000. With the exception of the preliminary development and testing of a methanol fueled versions of a Caterpillar 3406 DITA (direct injection turbocharged aftercooled) engine, most of the projects focused on the testing and evaluation of LNG, CNG, and LPG variants. In addition to a project in Texas which evaluated the potential of various CNG and LPG conversion kits for light duty vehicles to meet United States low emission vehicle (LEV) and ultra low emission vehicle standards (ULEV), there were a number of projects that were coordinated through the National Renewable Energy Laboratories (NREL) in the United States. The projects associated with NREL documented field testing, experience, and emissions measurements for heavy duty vehicles with a number of different engines including the Detroit Diesel series 60G LNG, Mack E7G, Cummins L-10, and Caterpillar 3176B Dual-Fuel engines. An advantage to this data set is that many of these vehicles were operated for upwards of 200,000 km. Although this is nowhere near the full service life of a tractor engine, this interval does represent a significant portion of the operating cycle and allows for a more complete evaluation than that what is presented in either manufacturer's sales and publicity publications or the short duration conceptual development projects that are typical of most academic research studies.

The latter acknowledges the fact that an engine which may demonstrate promising emissions results in ten or even a hundred hours of operation on the test bed may not be able to deliver satisfactory results over its intended service life. This point is reinforced by Wu et al. from the Texas Project when describing the methodology for evaluating whether a given conversion kit has the potential to meet LEV or ULEV standards (46). Wu notes, "It is important to note that the LEV standards must be complied with at the end of the useful life of the vehicle."

Additionally, Clark et al. present results from the testing of vehicles fueled by Cummins L-10 natural gas engines which show significant variability in the emissions from natural gas (LNG and CNG) fueled engines. In one particular fleet of vehicles which was tested, and including the diesel control vehicles, the three highest NO_X emitters were buses that were powered by natural gas engines. These engines emitted 35.82, 35.03, and 42.01 g/mile respectively, while the average NO_X emissions from the diesel control buses was only 27.6 g/mile. Although this anomaly was eventually attributed to a lack of sensitivity in the O_2 sensor, the more important point is that alternate fueled engines alone are not a guarantee of reduced emissions, especially if they are not correctly tuned or maintained (69).

Nevertheless, these studies did show that alternate fueled vehicles are capable of delivering reasonable performance in commercial service with a significant reduction in emissions. In particular, alternate fueled engines demonstrated low NO_X emissions and extremely low PM emissions. The emissions tests results are summarized in Table 11 below.

Emission	Quantity	Engine	Source
NO_X	50% less NO_X than diesel	Detroit Diesel Series 60G	Wiens (59)
	1/6th NO_X production relative to diesel	Cummins L-10 (Natural gas)	Clark et al. (69)
	1/6th NO_X relative to diesel	Cummins L-10 (Natural gas)	Chandler (84)
CO	4x higher	Cummins L-10 (Natural gas)	Clark et al. (69)
	Influenced by rich operation	Cummins L-10 (Natural gas)	Clark et al. (69)
	Elevated CO emission	Cummins L-10 (Natural gas)	Chandler (84)
HC	15.41 g/mile methane	Cummins L-10 (Natural gas)	Clark et al. (69)
	0.6 g/mile non-methane	Cummins L-10 (Natural gas)	Clark et al. (69)
	3.7% NMHC	Cummins L-10 (Natural gas)	Chandler (84)
	Very low NMHC	Cummins L-10 (Natural gas)	Chandler (84)
PM	10% of diesel	Cummins L-10 (Natural gas)	Clark et al. (69)
	Very low PM	Cummins L-10 (Natural gas)	Chandler (84)
	PM emission from burned lube oil	Caterpillar 3406 DITA (Methanol)	Richards (60)
	No smoke under any condition	Caterpillar 3406 DITA (Methanol)	Richards (60)

Table 11 - Emissions performance summary.

The studies are also significant because they quantify methane emissions for natural gas engines. Chandler and Clark reported non-methane hydrocarbons accounting for 3.7% and 3.9% of total hydrocarbon emissions respectively; the remainder of the hydrocarbon emissions was in the form of methane (69, 84). It is worth noting that a number of these studies were themselves a compilation of a number of different test programs and installations. As such, it is significant that good agreement was shown between the various studies.

This emissions reduction benefit was one of the main justifications that was given by various operators for pursuing the commercial development and utilization of alternate fueled vehicles. Particularly in regions that were susceptible to poor air quality, there was significant interest in reducing NO_X and PM emissions (59, 60). Other motivations included the need to comply with local or national air quality regulations (46, 69), and the desire to effect a reduced dependence on fossil fuels (59, 60). While the latter concern predates the current emphasis on climate change, the goal is the same in searching out non-fossil based fuels.

Despite these benefits, a number of papers documented considerable reluctance on the part of industry in accepting alternate fueled vehicles. This reticence is best summarized by Wiens et al.:

"Consequently, the trucking industry has been reluctant to use alternative fuels and engines which may be associated with 1) higher costs, 2) compromised performance, 3) a limited fuel infrastructure, and 4) poorer durability and fuel efficiency."

These concerns relate to the functionality and profitability of the alternate fueled platform as a whole and are often hampered by the economy of scale and infrastructure changes that would be required for a full scale implementation. As such, Wiens et al. rightly note that the implementation of alternate fueled vehicle fleets is best suited to a set of trucks which operate in the following relatively constricted operating profile:

"Engines powered by LNG look especially attractive in Class 8 (<33,000 lb Gross Vehicle Weight) short-haul truck applications where large quantities of fuel are used, vehicles are centrally fueled, and routes contain multiple starts and stops."

In other words, alternate fueled vehicles are best suited for applications where the difficulties associated with setting up a large scale fuel distribution network can be minimized and where the opportunities for capitalizing on savings associated with fuel cost can be maximized.

The statements of Wiens et al. offer a good summary of both the concerns and potential benefits of the alternate technology, especially with regards to an application which, as in the case of pilot boats, mirrors the suggested operating profile.

Once the decision had been made to utilize alternate fuels, there were a number of possible alternatives which needed to be considered in order to determine how best to approach the conversion. Although referenced to a methanol engine, Richards offers a good summary of the options that are available for the implementation of many different alternate fuels:

"The modification options include methanol/diesel blends, dual fuel systems (emulsification, fumigation, dual injection), ignition-improver additives, and neat (100%) methanol with ignition assist."

In the case of the development of the methanol engine, neat methanol with ignition assist was chosen because it best fulfilled the goals of the project, including maximizing the emissions reduction and the fossil fuel substitution potentials (60). Dual fuel technology was an option that showed great technical promise, but, at best, dual fuel technology offers only a partial reduction in the goals of emissions reduction and fossil fuel substitution.

A further and somewhat counterintuitive insight into one of the limitations of dual fuel technology was obtained from the experience with dual fuel CNG trucks that were operated by Pima Gro in Southern California in 1999. Although the trucks were used heavily, CNG usage was only 5% on an energy equivalent gallon basis. This low level of usage was attributed to a lack of availability of suitable filling stations and also some maintenance issues (84). According to Chandler et al.:

"Also, when a maintenance problem arises on the CNG system, there is no need to have it repaired immediately since the truck will still operate on diesel fuel only."

Although the ability to run in diesel-only mode might be desirable from a reliability standpoint, this example illustrates how the convenience of a dual fuel engine might undermine the emissions reduction intent of an alternative fueled engine. It this case it would have been more cost effective to simply operate the truck with a well-tuned conventional diesel engine.

Another significant drawback which was noted in several studies was the low fuel economy of alternate fueled engines relative to diesel control vehicles. This reduced fuel economy was attributed to a number of factors, including the thermodynamic differences between Otto and Diesel cycle engines, non-optimized and malfunctioning fuel equipment, fueling and venting losses, and inaccurately calibrated fuel dispensing equipment (59, 69, 60, 84). Good agreement was found between the various studies regarding fuel penalties. These results are significant because they are an indication of the added fuel capacity that will be required above and beyond the increased volumes that are necessary as a result of the decreased density and energy content of the fuel. These results are summarized in Table 12.

Engine	Penalty	Factors	Source
LNG tractor	27%	Throttling losses	Wiens (59)
		Spark ignition engine	
		Non-optimized relief valves and components	
		Excess venting	
	29%	Lack of sensitivity of O_2 sensor	Clark (69)
	28%	Differences in duty cycle	Chandler (84)
		Fueling losses	
		Measurement errors	
Dual fuel CAT	22%		Addy (85)
LNG fueled waste hauler	17%		

Table 12 - Sumary of fuel penalties and sources when using alternate fuels.

Not surprisingly for a series of development projects, a number of maintenance issues were reported. One of the most common precipitators of maintenance items and repairs was problems with the fuel system. Examples included a low power, surging, and misfiring issue that was reported by Wiens et al. and that was eventually traced to a conflict in the engine control module (ECM) instructions between maintaining correct idle speed when a PTO-drive accessory was engaged and the instructions for shutting off fuel flow when motoring (59). Other problems that required maintenance or repairs included fuel flow irregularities due to poor manufacturing tolerances in the fuel oil regulator (59), high variability in carburetor performance due to wear, maladjustment, and fuel variations (69), faulty venting of pressure relief valves (59) frequent maintenance on glow plugs (60), and leakages due to material incompatibilities methanol (60). These items underscore the importance of a thoughtfully designed and well matched fuel system and are significant because each maintenance item, even if it is simple to fix, nevertheless affects the overall perception of the functionality and reliability of the concept.

Despite these drawbacks and concerns, most studies did report overall satisfaction on the part of drivers with regards to the drivability of the vehicles. Wiens et al. reported that overall acceleration was adequate for Central Business District testing cycles (CBD). Although some acceleration lag was noticed, this was later attributed to a mismatch between engine and transmission and not to the performance of the engine itself. Once the engines were running at sufficient load, drivers reported good power and torque characteristics (59). Richards also reported positive driver feedback including comments regarding smooth and quiet driving characteristics of methanol fueled trucks, however Chandler et al. did report some driver complaints regarding low power and rough running, most of which were rectified via warranty type repairs and replacements.

A major challenge that was reported with LNG fueled vehicles in particular was fuel management. A number of studies reported problems with trucks running out of fuel, the consequences of which are significant since the trucks cannot be refueled on the road and therefore needed to be towed to a fueling facility for refueling. A related problem was encountered when maintenance was needed to be done on the fuel system in a facility that is not equipped to handle LNG trucks. Not only are there difficulties associated with vehicle storage and ventilation of the facility, but once maintenance was completed, the trucks again needed to be towed to a fueling facility. Wiens et al. stressed the importance of driver and staff education in minimizing the impacts of the difficulties and limitations associated with fuel management (59).

Despite the fact that there are some major differences between pilot vessels and the applications described in these papers, the literature cited in this section provides a good overview of the challenges and benefits that an operator might expect to encounter when testing and developing an alternate fueled vehicle and introducing it into commercial service. First and foremost, these papers have presented solid evidence that these platforms are functional and that significant emissions reductions can be achieved. Nevertheless, these benefits are not without cost. Perhaps the most important lesson to be drawn from these test installations is the importance of a carefully considered and well-engineered fuel system. However, despite the potential, many studies reported limited usage due to a number of factors, including a lack of filling stations, lower fuel efficiency, and a lower energy density of the fuel. Clark et al. also cited an almost twofold increase in operating costs relative to similarly sized diesel control trucks (69). This suggests that alternate fueled vehicles do not currently fulfill the economic and operational reliability standards set by conventional diesel engines.

9 ECONOMICS

From an economic standpoint, the question which must be considered is whether the total cost of implementing the new technologies will be in a suitable range as to support the current function of the pilot vessels. Even if fuel prices are well established, there are a number of uncertainties that must be considered in order to determine the overall economic feasibility of the design. These include not only the cost of the fuel, but also the security of supply and market volatility. Other costs include the capital costs associated with the purchase and implementation of the technology, including the cost of the required safety systems, additional operational costs in the form of possibly more expensive consumables and spare parts, more expensive and specialized labor required to repair equipment and systems, and further operational costs such as result from possibly increased down time and additional complications with fuel handling procedures.

The single most important factor in the context of the economic analysis is cost differential between the MGO and the alternate fuel of choice. Although historical data for the cost of MGO is readily available, the costs and future trends for the alternate fuels are much more difficult to predict (38). In particular, the uncertainty associated with LNG markets in recent years has been notoriously uncertain. A number of factors including a series of cold winters, the Fukushima accident and subsequent temporary shutdown of Japanese nuclear power plants, and the development of unconventional resources such as shale gas have drastically altered the dynamics of the LNG market. In recent years, the LNG market has been characterized by divergence in spot market prices between different geographical regions (82, 28, 83). This is particularly pronounced in the Asian market where LNG prices have been considerably higher than either European or North American markets. (See Figure 32.)

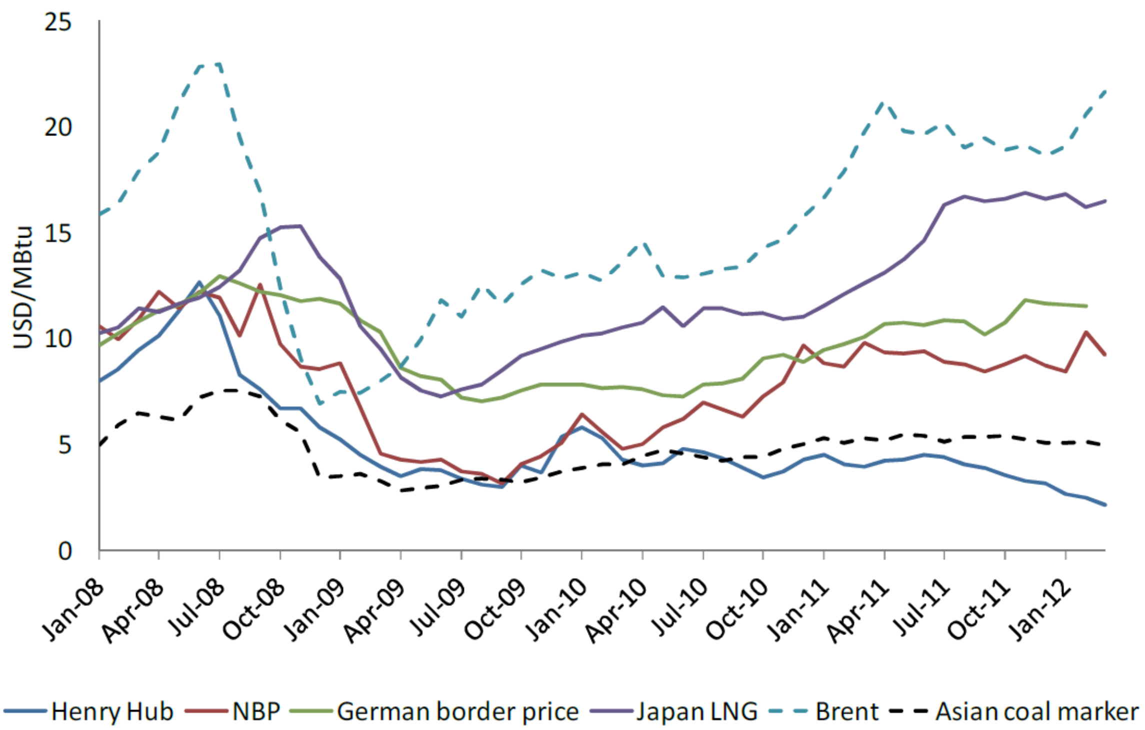


Figure 32 - International Gas Prices from 2009 through 2012 with Brent representing the Brent Crude reference oil price. (Adapted from 83)

The uncertainties within the base of price of the fuel are further multiplied by the uncertainties in the present and future cost of distribution. For example, although LNG is touted as a reasonable cost alternative to MGO, current LNG projects are heavily subsidized (38). One of the reasons that methanol and DME are considered as a feasible as a marine fuels is that they are competitive in price relative to low sulfur fuel oils (LSFO) and less expensive than MGO (17). However, and as we have seen with the LNG market, it should be noted that current prices are not necessarily an indication of long term price stability.

Ultimately, a relevant economic analysis will require information which is outside of the scope of this project, including a detailed building specification and quotation, quotations regarding consumables and repair costs, and a secured fueling contract.

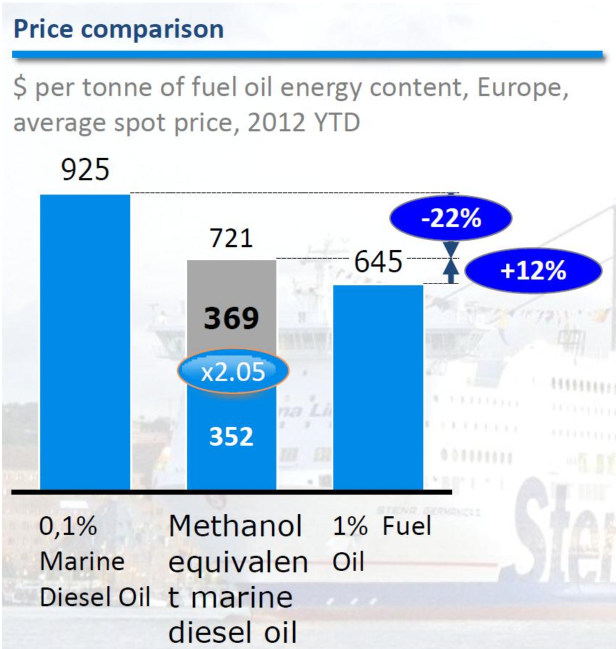


Figure 33 - Price comparison of Methanol, MDO, and LSFO. (Adapted from 17.)

10 PATHWAY TO BIO-FUELS

One of the commonly cited problems with the implementation of alternate fuels is the “chicken and the egg” scenario in which the development of fuel infrastructure is limited by the demand for the fuel, and the development of demand is limited by the development of fuel infrastructure. Since both LNG and methanol (and therefore DME) can be produced from a number of different sources, it is possible to transition from fuels which are derived from conventional sources to those which are produced from biomass. The advantage of this approach is that the introduction of equipment which burns alternate fuels from conventional sources can be used as a means to create a demand for fuels derived from biomass.

A necessary requirement for the success of any alternate fueled project is the easy accessibility of the fuel. While this is true for any project, in the case of this project which aims to transition to biofuels, the situation is further complicated by the need to secure a steady source of biofuels which are often produced in relatively small batches and in non-central locations. If fuel must be trucked in from remote locations, this can add significantly to the overall cost of the fuel (84, 86).

One of the advantages of this particular project is that there has been considerable development in the field of biofuels in Sweden. Not only are there LNG and methanol facilities located near many Swedish ports, but there is also the infrastructure for the production and distribution of biomass derived fuels. For example, biogas is injected into Swedish natural gas pipelines in many locations and biomass derived methane is available in some locations for vehicle use, for example by Fordonsgas in Gothenburg. (30) (See Figure 34 and Figure 35.)

Figure 34 - Typical LNG filling station operated by Fordonsgas. (Picture courtesy of Fordonsgas.)

Additionally, in central Sweden, Värmlands Methanol AB has started production of biomethanol from the gasification of wood waste. Although production from these sources is limited relative to the general demand, the fact that biofuels are being brought to market represents a significant step in bridging the gap between theoretical possibility and practical reality. An important advantage of this type of project is the stimulation of development of technology that will enable a greater demand for fuels derived from biomass.

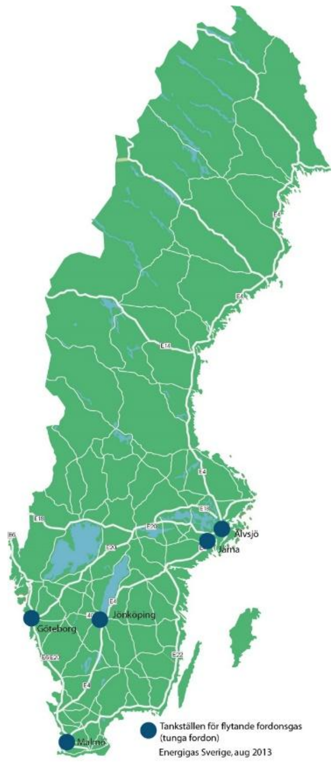


Figure 35 – Locations in Sweden offering LNG for road vehicles. (Map courtesy of Fordonsgas.)

11 DISCUSSION

The purpose of this study is to determine feasibility of operating Swedish pilot vessels on alternate fuels. Although there are many possible benefits which can be derived from the switching of fuels, the primary motivation for the proposed conversion is to stimulate the development of technology in order to facilitate a further transition to the use of alternate fuels that are derived from biomass as opposed to conventional sources.

The project is intended as the initial scoping of possibilities prior to embarking upon the formal design and acquisition process. As such, the scope of the project is confined to fuels which have seen sufficient development in terms of distribution networks and in each fuel's state of readiness regarding technology, including associated subsystems, to be brought to market.

Although seemingly intuitive, the latter point illustrates the type of conundrum which is typical of a project such as this. None of the fuels considered are particularly novel, however due to a variety of factors including economics which are uncompetitive relative to conventional fuels and limited distribution networks, very few have seen widespread acceptance in the marketplace. As such, even though technology might exist which is ready to be brought to market, as long as there is not a demand for the technology, it is impossible to predict how long it will take for it to be brought to market and readily available. The latter is of course highly dependent upon the cost of conventional resources, and, as we have seen, is likewise extremely difficult to predict.

Because of this, the project focused on fuels that utilize technology that had already been brought to market in one form or another. As such, the project exploited the similarity in engine size between pilot vessels and heavy duty trucks, the similarities in handling between gaseous fuels such as LPG and DME, and the current momentum within the maritime industry with respect to gaseous fuels.

The project is organized into a broad survey of alternate fuels which is followed by a more specific analysis of the most promising candidates. Central to the latter discussion is the concept of feasibility. As with any engineering project, there are always trade-offs that need to be made. The criteria for feasibility must therefore be carefully defined because in a complex system such as this, which involves technical, operational, logistical, and economic considerations, there can often be conflicting conclusions based upon which feasibility criteria are prioritized.

The evaluation of the feasibility of the proposed solutions is based upon the requirement that the alternate fueled pilot vessel be able to reliably and economically perform its assigned function, that the solution is constructible within the near term, and that there is the potential for transition to fuels which are produced from biomass.

The question of feasibility is therefore approached from two standpoints. First, the availability of the technology is established; and second, the possible solutions must be considered from a systemic point of view in order to ensure that there are no conflicts which would prevent the vessel from reliably and economically performing its function.

In determining the initial scope of the project, liquid fuels such as gas to liquids (GTL) fuels synthesized from biomass and biodiesel were discounted for a variety of reasons. In the case of GTLs, a decisive factor was data from various life cycle analyses which showed that it is an inefficient use of resources (53). On the other hand biodiesel was discounted because it entails of the inefficient use of biomass, i.e. with a practical limit of how much energy could be supplied relative to available acreage of farmland and the fact that biodiesel was produced from first tier agricultural products whereas biogas and methanol could be produced from second tier products via the gasification of organic wastes and byproducts (26).

The first part of the project comprised a survey of the most promising fuels which include LNG, CNG, LPG, Methanol, DME, and Hydrogen. Although hydrogen is not yet a fuel that that would be easily adapted to a commercial application it was included in the discussion in order to serve as a standard because it is the only fuel which does not release CO_2 as a product of its combustion.

In the course of the analysis, CNG was ruled out because of its low energy density and the difficulties associated with storing the fuel at pressures in excess of 250 bar. LPG was ruled out because it is the only fuel which is not synthesized from biomass and because it has a greater density than air at ambient conditions which entails greater difficulty in designing fuel systems, machinery space configurations, and arrangements for ventilation. Hydrogen was ruled out because of its low energy density, even as compared to the other alternative fuels, and because of the hazards associated with the handling of hydrogen, including its wide flammability range, the extremely low temperatures required for liquefaction, and an increased propensity for leakage due to its small molecular size.

The remaining fuels, including LNG, methanol, and DME, were selected for further consideration. The second part of the project comprised an extensive literature survey in which the feasibility of the application of the fuels was considered from the perspective of availability and functionality criteria which were discussed previously. In addition to having favorable handling characteristics relative to the other fuels considered, these fuels were selected for further consideration because they benefit from some notable synergies which improve the potential for near term availability of their respective technologies for the marine market in a scale that is commensurate with a typical pilot vessel.

In the case of LNG, the last ten years have seen a considerable and concerted effort towards the development of LNG fueled marine vessels. Although the majority of development has been directed towards larger scale projects such as passenger ferries and short haul shipping applications, these projects are nevertheless beneficial because they help to establish the demand, expertise, and infrastructure that is required to support the presence of LNG in a port environment. The marine industry has also been able to leverage off of years of experience in handling LNG as both cargo and as a fuel source aboard LNG tankers which is most evident in the classification standards and safety guidelines. On the other hand, there has also been significant progress towards the development of LNG fueled heavy duty road vehicles such as trucks, and there are a number of major manufacturers which currently produce LNG fueled road vehicles, including Volvo, IVECO, Cummins Westport, Caterpillar, and Freightliner. The power train and auxiliaries associated with these trucks is more similar in scale to pilot boats than most marine applications and includes many of the same components, including the fuel tank and fuel delivery system. In addition, LNG fueled road trucks have been available on the market for over 20 years which is a sufficiently long time scale to develop experience and correct deficiencies.

Relative to LNG and natural gas, there is significantly less literature available regarding the development of methanol and DME fueled engines and systems. The discussions within this paper reflect the imbalance of available sources of information. Nevertheless, there have been successful developments and test trials of both methanol and DME fueled engines, both in marine and road applications. Currently, DME fueled trucks have been brought to market by Volvo Trucks, and recently there has been considerable interest within the port of Gothenburg relative to the development of methanol and DME based infrastructure including test installations aboard vessels, such as in the case of the SPIRETH project.

While the experience bases with methanol and DME is considerably less than with LNG, all three fuels have nevertheless satisfied the criteria of having technology, including fuel systems that can be brought to market within a reasonable timeframe. Likewise, with the presence of LNG fueling facilities for road vehicles in multiple Swedish cities, and the interest in the development of methanol and DME facilities in the port of Gothenburg, the availability of the fuels in at least some Swedish ports is also considered feasible.

The combined availability of both the fuel and technology in Sweden presents a strong case for the further evaluation of this project. Although there are some negative aspects associated with the technology, for example increased fuel tank volumes and decreased engine power, these are disadvantages that can be addressed via the engineering and design of the installation. Likewise, the availability and infrastructure for alternate fuels in Sweden is favorable relative to many other ports in the world. While southern ports such as Gothenburg have the best access, fuels could be delivered to other ports as long as the costs associated with trucking fuel were not considered prohibitive. More importantly, Sweden also has a well-developed infrastructure for biofuels when compared to the rest of the world. Not only is biogas already being injected into the Swedish gas grid at several locations, but Sweden also boasts a functioning biomethanol production facility. As such, Sweden is the ideal location for the test of biofuel powered vehicles and watercraft.

The benefits derived from the reduction of port emissions from Swedish pilot boats are likewise tangible. Although pilot vessels are small craft relative to the other vessels and work boats that operate in a harbor, they are characterized by high power densities and, whether operating in winter or summer mode, by very high fuel consumption relative to their size. Because pilot vessels typically operate near populated centers, there is also a real benefit in reducing emissions and their associated health effects on nearby populations. Further advantage is gained from the fact that the different regions within the Swedish pilotage system are administered by the same agency. Because of this, and relative to geographically proximate ports that may be competing with each other in terms of port costs and fees, there is greater flexibility in the Swedish system which enables individual ports to better accommodate increased costs that are associated with the use of the alternate fuel. This is corroborated by the work of Homsombat et al. which demonstrates that the most effective reductions in pollutant emissions are achieved when competing ports cooperate with each other so that neither undercuts the costs of the other (87).

Despite the apparent benefits, a more comprehensive assessment was necessary to determine whether the proposed project is able to fulfill the ultimate goal, which is an alternate fueled pilot boat that is able to reliably and economically perform its function while in commercial service.

The basic functionality of a pilot boat is to deliver a pilot safely and in good condition to take charge of the transit of the vessel they have just boarded. Although the actual transfer of the pilot from the pilot boat to the larger vessel (or vice versa) represents only a short segment in the progression of events that are required to bring an unfamiliar ship safely into port, it is the step that is the most immediately hazardous to the actual pilot.

The task of transferring the pilot between two moving vessels via a rope ladder hanging off the side of the larger vessel is difficult to begin with, and is further complicated by the relative motions between the pilot boat and the larger ship. External forces such as waves and the wake from another vessel or even from the pilot vessel itself can cause unexpected motions. In heavy weather or in open water, swells can cause significant vertical relative motion between the pilot vessel which can make it extremely difficult to time the moment when the pilot needs to step off the ladder and onto the boat. And if not properly anticipated, hydrodynamic effects between the two vessels that cause a suction effect can result in dangerous heeling of the pilot vessel as it "walks" up the side of the larger ship. The danger associated with each of these types of erratic motion is loss of footing which can result in a man overboard situation. This is a situation that poses significant risks to the individual, including hypothermia and being struck by either the pilot boat's or the larger vessel's propellers, that can and do lead to loss of life.

These risks associated with pilot transfers are mitigated first and foremost via the skill and experience of the boat crew, the pilot, and especially the boat operator. However equally significant is the ability of the boat to reliably perform its function and the confidence of the crew therein. In practical terms, this means that the boat must not be underpowered, have good maneuvering characteristics, and must not unexpectedly lose power, especially in the course of a pilot transfer.

The function of the pilot boat must also be considered within the larger context of the port operations. Pilots play a crucial role in ensuring safe and incident free passage and trade of vessels within a port. Even a relatively minor incident such as an aborted passage due to problems arising from a pilot transfer can be expensive due to the costs and fees associated with delays, lost opportunities, and the remobilization of resources and personnel. In the event of a larger incident such as a collision or grounding, costs escalate quickly and there is potential for significant environmental impacts.

Also important to bear in mind are the less apparent factors that nevertheless contribute to marine incidents. One area to consider is the possible contribution of delays from non-functioning equipment on pilot fatigue. While it may be a stretch to establish the failure of a pilot boat as a contributory cause of a later accident, there is a well-documented relationship between marine accidents and loss of sleep or fatigue (88). The irregular work schedules of pilots are well acknowledged and any further delays can contribute to a decrease in the higher level cognitive functions upon which pilots rely to detect and anticipate situations before they become critical (88).

As such, one of the important questions that must be asked is whether the proposed design in a developmental stage will deliver adequate reliability so as not to become a factor which contributes to a possible incident. At the very least, this issue underscores the absolute importance of developing a complete, well thought out, and reliable design.

The concern regarding the reliability of the final design stem first and foremost from the physical and chemical handling characteristics of the fuel. As was discussed, LNG, methanol, and DME each handle very differently than standard marine fuels such as diesel. Some of the issues that are of particular concern include the necessity of storing LNG at -162 °C or lower, the challenges associated with limiting heat ingress into LNG tanks and controlling the consequent pressure that results, the fact that both methanol and DME vapors are heavier than air, the need for additional material considerations due to the low temperatures of LNG, the wider flammability ranges for all three fuels, but particularly methanol, and different combustion characteristics of the fuels.

It is the opinion of this paper that these challenges can individually and as a group be addressed through a thoughtful and thorough design process. However, the question must be considered and resolved is whether the accumulation of engineering controls that are required to safely handle the fuel and satisfy regulatory requirements is appropriate to the scale of the initial installation.

From the review of the draft IGF code, there is guidance available regarding the types of engineering controls that are considered appropriate for a marine environment. However these regulations have been developed as an extension of the design practices which were originally developed for LNG tankers utilizing cargo boil-off as a source of fuel. As such, the regulations are geared towards installations that frankly do not reflect the scale of a typical pilot boat. In practical terms, this means that regulations will require significant modifications to a typical pilot boat design, including the segregation of machinery and fuel spaces, the requirements for either ESD protected or intrinsically safe equipment, safety systems that include the installation of fire and gas detection systems, and requirements regarding ventilation, fuel isolation, and purging systems which include a minimum permissible vent mast height of 6 meters that, given the motions that can be expected when a pilot vessel comes alongside, is simply not feasible.

For a number of reasons, there is a good probability that some of these design requirements can be adjusted to an appropriate scale. One such reason is that since Swedish pilot boats are built to class but not actually classified, there is not an absolute requirement to comply with class rules. In addition to this, both classification society rules and the draft IGF codes specifically include provisions for alternate arrangements provided that an adequate or similar level of safety is achieved by the alternate design. In order to gain approval, the alternate design must be subjected to a thorough risk assessment in order to demonstrate that an equivalent standard of safety was achieved.

A template for a more straightforward design can be found in the many alternate fueled trucks which have been developed, including LNG and DME fueled versions that are currently available. One of the avenues that was explored in the early stages of this study was the possibility of exploiting and adapting this land-based technology to the marine market. Despite the similarity of scale, however, one of the major differences between the two applications was the fact that the LNG and DME fueled trucks are ventilated de facto in the course of their operations. Even if the pilot boat's fuel tanks were installed on the weather deck of the boat, the fuel lines would still need to be run through interior spaces and therefore many of the requirements listed in the IGF code would need to be considered and applied.

It should thus be noted that even a scaled down version of the requirements listed in the draft IGF code would still represent a marked increase in the complexity and sheer quantity of equipment that would be required compared with a conventional diesel fueled pilot boat.

A major concern that accompanies the additional requirements is whether the increased complexity of the design will adversely affect the long term reliability of the design. The concerns regarding the effect of increased complexity upon the reliability of the boat are separate from the reliability concerns associated with the growing pains that are typical to the test trials for new equipment designs. Instead, the long term reliability concerns relate to the concept of design fragility. The idea of design fragility presented by Colwell and summarized as follows: “Complexity breeds fragility. Fragility breeds surprises. Surprises are bad.” (89) Simply put, the more components that are included in a design, the greater the number of possible failure nodes, and the more interconnected the separate elements, the greater the chance that a single failure will adversely affect the operation of the system as a whole.

In the case of pilot boats, not only is there a significant increase in the number of systems and individual components relative to current pilot boat configurations, but because most of the new systems are related to the vessel’s safety system, there is increased probability that a failure in one of these systems could result in the shutdown of the propulsion engines. The latter is undesirable and possibly dangerous should the vessel happen to be in the midst of a pilot transfer.

The increased complexity is also problematic from a financial point of view because each additional system and piece of equipment that is installed represents an increase in the cost of building and maintaining the boat. While additional costs are to be expected in a developmental project such as this, the newbuild costs for pilot boats are low relative to the larger vessels to which alternate fuels are usually applied. As such, the relative increase in cost will be much higher for a pilot boat than for a larger vessel such as a passenger ferry or supply boat.

A detailed and conclusive economic analysis is difficult to achieve at this stage of the project. Because of the considerable ambiguity regarding the regulatory requirements to which the boat will have to be built, it is impossible to predict the capital costs of the project other than to note that any additional equipment will increase the cost of the project. Operating costs are likewise difficult to predict other than to say that the increased complexity of the systems and the use of specialized materials will contribute to increased maintenance costs but that the cleaner nature of the fuels should reduce the consumption of consumable parts that are related to the engines and fuel system.

Fuel cost estimates for the port of Gothenburg that were compiled for the EFFSHIP project in 2013 do suggest that methanol and LNG are competitive in cost relative to MGO. (See Figure 36.) However, these estimates did not account for the 20% fuel penalty that is associated with Otto cycle engines. When this penalty is applied, the fuel costs for LNG and methanol fueled vessels is expected to be comparable to those of conventional MGO fueled pilot boats. Estimates for the cost of DME were not presented, but the cost of DME was assumed to follow methanol prices. Since DME is burned in compression ignition engines, there is no need to apply a fuel penalty to engines burning DME.

In the longer term, fuel costs are also sensitive to such variables as transportation fees, the duty cycles of the pilot boats, and global and regional pricing trends. Market trends from the past couple of years have been extremely difficult to predict. As such, and given the long expected service lives of Swedish pilot boats, it is nearly impossible to anticipate the long term economic advantage of these boats.

This study was also envisioned to include an analysis of the duty cycles of Swedish pilot vessels in order to aid with the analysis of economic feasibility. However, given the magnitude of uncertainty relative to the costs associated with the project, and due to some fundamental reservations regarding the feasibility of the project, this portion of the project was omitted as it would not contribute significantly to the final conclusions of this project.

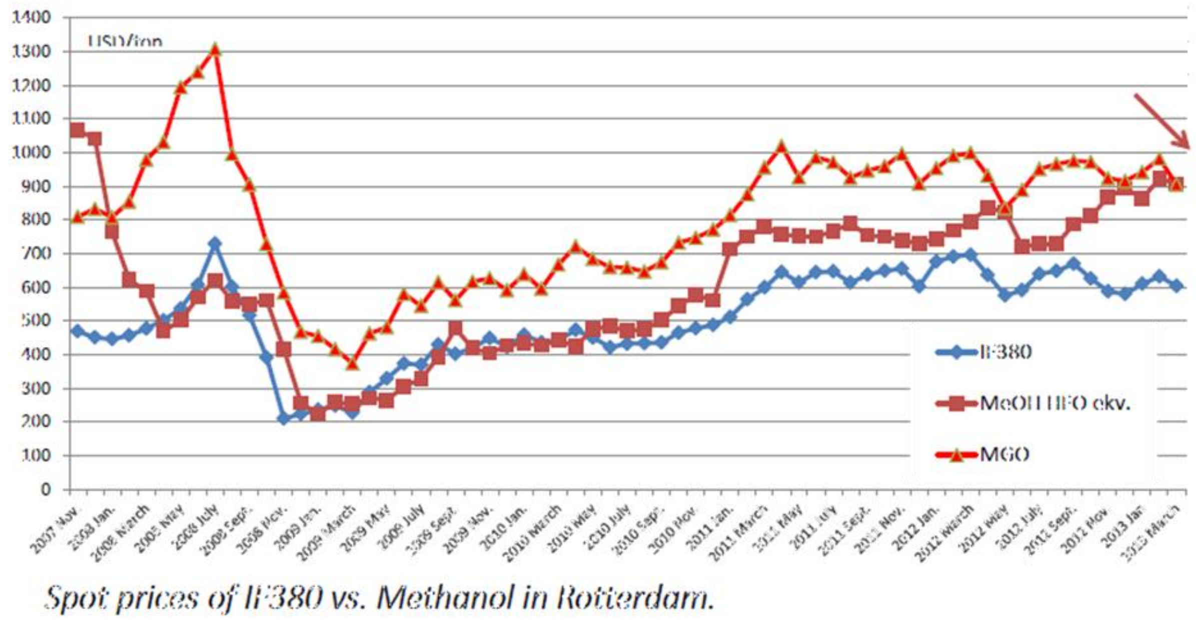


Figure 36 - Price comparison of Methanol, IF380, and MGO. (Adapted from 50.)

Finally, there are three handling issues which are considered to be extremely problematic if not prohibitive for the proposed application. The first relates to LNG and the fact that most LNG fuel systems require a means of periodic fuel consumption in order to limit tank pressure increases that are a result of heat ingress to the tank. This requirement makes LNG fueled pilot boats ill-suited for applications in ports with little traffic and those that require only occasional use of the pilot vessels. This is a significant concern because most Swedish ports maintain both winter and summer pilot vessels. The difference between the two types of boats is that the winter boats are designed to operate in waters with ice whereas the summer boats are designed to handle open water conditions. Because of the weather conditions in Sweden, it is probable that one or the other boat will be laid up for significant portions of the year. This cyclical duty cycle is ill matched to a fuel storage system which must be monitored regularly and fired up periodically in order to control fuel tank pressures so as to avoid venting.

Second, the relative density of methanol and DME are ill suited for a small application such as a pilot boat. The fact that methanol and DME are heavier than air means that any released gas or vapors will sink and collect in the low spots of confined spaces. On a small boat, this means that fumes or vapors have the potential to collect within bilges. Although it is possible to design ventilation systems such that they supply air or draw air from the lower regions of a space, the bilges are notorious for being geometrically complex spaces with intervening pipework, bilge wells, and machinery foundations. As such, complete ventilation is difficult to ensure.

Lastly, methane slip associated with LNG burning Otto cycle engines is a significant issue that cannot be ignored. Although methane burning engines are routinely touted as being environmentally friendly, the fact that the unburned methane that is released during the regular operation of the engine is 20 – 25 times worse a greenhouse gas than CO_2 is rarely mentioned. Depending on the goals of the project, LNG fueled engines may still be a feasible choice from the standpoint of having reduced NO_X, SO_X, CO_2, and particulate emissions. Nevertheless, the effect of unburned methane emissions must at least be accounted for and contended with.

12 CONCLUSIONS

A number of factors collectively present a strong case for the development and testing of alternate fueled pilot boats Sweden. These include the proximity and availability of technical resources, the advanced state of alternate fuel infrastructure, the positive benefits to population centers from the reduction of marine emissions, and the localized development and availability of non-fossil fuel feedstocks.

This study investigates the feasibility of operating Swedish pilot boats on a variety of simple fuels, including CNG, LNG, LPG, methanol, DME, and hydrogen. The intent of the study is to facilitate the development of technology that will allow small service craft such as pilot boats to operate on alternate fuels, with the eventual goal of the project is a full transition to fuels that are produce from biomass feedstock.

The first part of the study presents a discussion of the properties, handling characteristics, and sources of the various fuels. On the basis of this discussion LNG, methanol, and DME are selected as the most promising candidates for further investigation. Liquid fuels such as biodiesel and GTL fuels were considered briefly but were ruled out as being an inefficient use of resources. CNG and hydrogen were ruled out due to challenges associated with their handling characteristics and storage requirements and LPG did not fulfill the requirements of this project in that it does not present a ready path to synthesis from biomass.

The second part of the study focuses on LNG, methanol, and DME, and considers the application of these fuels from technical, operational, and environmental perspectives in order to ascertain whether the concept is feasible and suitable for further development.

From the technical review of engine concepts and fuel systems, it was concluded that the technology for both systems is mature. A possible synergy presented itself in the similarity of size and design of the prime movers for heavy duty road vehicles and pilot vessels. In addition, Sweden was found to have a well-developed infrastructure for alternate fuels, and, particularly in the southern ports of Sweden, the availability of LNG, methanol, or DME are not seen as a hindrance to the project.

The project was also found to have tangible environmental benefits in the form of emissions reductions. The potential for emissions reduction while using LNG, methanol, or DME has been well documented in literature. Pilot vessels are seen as good candidates for emissions reduction in that they are high powered craft with high fuel consumptions and because they operate in port areas which tend to be near to population centers. In addition, the organization of Swedish pilots is seen as a benefit in that the effect of any increased operating costs can be better distributed so as not to affect the competiveness of the port.

The final determination of feasibility must also account for a number of practical factors that include the availability of the fuels and related technology, the likelihood of the final concept to deliver reliable and economic performance while in commercial service, and the potential availability of the fuel as a product of biomass feedstock.

Although the initial assessment regarding the conversion of Swedish pilot boats to operating on alternate fuels was extremely promising, an in depth technical review concluded that pilot vessels are not a well suited platform for the development this technology.

Regardless of the final choice between LNG, methanol, and DME, a major disadvantage of the concept is the significant increase in the complexity that is required to implement the design. This is a problem because overall pilot boat reliability and adequate powering are considered to be of utmost importance due to the critical role that adequate maneuverability plays in ensuring the safety of the pilot during a pilot transfer.

Some of this added complexity is a result of the special handling requirements of the fuels, for example the insulation and material choice that would be required for an LNG tank. However, the majority of the complexity is a result of the fact that pilot boats, unlike their heavy-duty on-road cousins are not essentially self-ventilating. As such there is risk of gas or vapors being accumulated in confined spaces and additional safety systems are specified order to protect personnel and equipment in the event that there is a gas leak and possible source of ignition.

Additional systems which are likely to be required include double-walled fuel systems, venting and purging arrangements, gas and fire detection systems, and the provision for the safe operation or shutdown of equipment in the event of a gas or fuel leak. These systems are designed to protect personnel and maintain the essential functionality of the equipment. However because control functions are often nested, for example to prevent operation of the engines in the event that there is not sufficient inert gas pressure to adequately purge fuel lines, in reality each additional safety component becomes another source of a potential failure which will affect the overall reliability of the design.

A significant level of uncertainty is also introduced into the project on account of the fact that there is uncertainty regarding the extent to which the proposed pilot boat will have to comply with currently proposed regulations. Although both the IMO IGF code and various classification society rules include provisions for alternate designs, the current approach toward the design of vessels that utilize low flashpoint fuels, including LNG, methanol, and DME, is based upon approaches that were developed from the design of fuel systems for LNG carriers that burned boiled-off gas cargo as fuel. As such, and even when applied to larger applications such as passenger ferries, the regulatory requirements add considerable levels of complexity and some of the requirements, such as a 6 meter vent mast, are simply unfeasible for small vessels such as pilot boats.

Although Swedish pilot boats are not required to be classified by a Classification Society, they are generally built to Class rules and inspected by the Swedish Transportstyrelsen. It is therefore expected that a detailed risk assessment will be required in order to justify a design which deviates from currently proposed requirements and/or those that are already in force.

From an economic point of view, it is difficult to predict whether the final concept will be commercially viable. The pilot boat itself is expected to be more expensive to construct due to the additional systems, components, and special materials. Furthermore, an increased complexity will result in increased costs due to greater usage of spare parts, increased specialization in technicians, and special handling practices in the case of repairs to LNG fuel systems. Since pilot boats are relatively small vessels, it is expected that the increased costs associated with the additional systems will be proportionally greater than for a larger installation such as a ferry or supply vessel. Nevertheless, LNG and methanol are expected to be competitive with MGO fuel prices in the near future and could therefore make the concept economically viable. However, the stability of these prices on both a local and a global scale is anything but certain and therefore the ultimate economic advantage is impossible to predict.

Finally, there are certain handling concerns which are difficult to dismiss. In the case of LNG, the fact that many current engine designs release unburned methane in the form of methane slip is a severe impairment to the environmental performance of the concept. In the case of methanol and DME, the fact that the released gas is heavier than air raises concerns about the ability to safely ventilate spaces with complex bottom contours such as are typical of machinery spaces.

Upon completion of the technical review of the LNG, methanol, and DME fueled concepts, it is concluded that, given the availability and state of advancement of the technologies, a pilot vessel is not well suited to gaseous and low flashpoint fuels. It is suggested a fuel mixing program using conventional fuel and up to approximately 20% of biomass derived liquid fuels such as biodiesel or GTL fuels, become the topic of further study. This solution would provide for a fuel which could theoretically be burned in a pilot boat with conventional equipment and without the storage difficulties associated with low flashpoint fuels. Although this solution was originally excluded from the scope of the project based upon inefficiencies in the use of resources, the versatility of the blended fuel has the potential to effect a greater net emissions reduction relative to a limited implementation of the more complex LNG, methanol, or DME fueled concepts because the blended fuels could be expanded to include a larger portion of the Swedish pilot boat fleet.

13 RECOMMENDATIONS FOR FUTURE WORK

Depending on whether drawbacks associated with the concept of a low flashpoint fueled pilot boat are deemed to be acceptable, there are two possible paths forward.

If the low flashpoint fueled concept is considered suitable for further development, the next step of the project will involve a more detailed scoping of the design, including the availability of the fuel supply, in order to determine the economic and material feasibility of the project. Since all three options have demonstrated potential, a comparative approach should be utilized in order to determine which of the three options best fulfills the requirements of the project. An important early step in the process will involve engaging in discussions with an appropriate Classification Society and the Swedish Transportstyrelsen in order to obtain clarity regarding the permissivity of regulatory requirements.

An important point that will need to be resolved is the availability, pricing, and logistics of the fuel supply. This will involve approaching suppliers and obtaining proposals for pricing and delivery. Once the logistics and pricing of fuel have been evaluated, the next step will involve the scoping and pricing of various designs in order to enable estimation of the capital and operating expenditures associated with each option. This will necessitate the scoping of a rough design and obtaining quotes from suppliers regarding equipment, building, and maintenance costs. These will enable a more quantifiable and cogent comparison of the three fuel options and should identify any major obstacles or impediments. Once the initial design has been selected, it is expected that a detailed risk assessment will need to be completed in order to verify that the design is equivalent to or exceeds the safety requirements of the appropriate classification society.

If the low flashpoint fueled pilot boat concept is not considered feasible, then further work should investigate the feasibility of operating on blends of conventional diesel and biomass derived fuels such as biodiesel or biomass derived GTL fuels. B20 is a blend of 20% biodiesel and 80% conventional diesel which is commonly available and can be used in diesel engines with minimal modifications; B5 (5% biodiesel and 95% conventional diesel) is also available. These fuels are liquid fuels which handle like convention diesel and consequently require considerably less drastic modifications to the engines and boats as a whole. As such there is a greater potential for a more widespread and immediate implementation across the entire fleet and would therefore entail a much greater substitution of biofuels that a more limited and certainly more drastic implementation of a low flashpoint, though not necessarily biofueled design (65).

REFERENCES

1. Weigall, F. “Marine Pilot Transfers: A Preliminary Investigation of Options.” Australian Transportation Safety Bureau: Canberra City, Australia. Sept. 2006.
2. Daily Astorian. “Variety of Mishaps Led to Bar Pilot’s Death.” 05 April 2006.
3. Schomberg, J. “Hypothermia Prevention: Survival in Cold Water.” University of Minnesota: Sea Grant – Coastal Communities Department. 18 April 2012.
4. International Maritime Organization. “Second IMO GHG Study 2009.” International Maritime Organization: London, UK. 2009.
5. Wang, C. and Corbett, J. J. “The Costs and Benefits of Reducing SO_2 Emissions from Ships in the US West Coastal Waters.” Transportation Research Part D, Vol 12 2007 pages 577 – 588.
6. Corbett, J. J., Winebrake, J. J., Green, E. H., Kasibhatla, P., Eyring, V., and Lauer, A. “Mortality form Ship Emissions: A Global Assessment.” *Environmental Science and Technology*. American Chemical Society. Vol 41, No. 24, 2007 pages 8512 – 8518.
7. McArthur, D. P. and Osland, L. “Ships in a City Harbour: An Economic Evaluation of Atmoshperic Emissions.” Transportation Research Part D: Transport and Environment. Vol 21, June 2013, Pages 47-52.
8. Corbett, J. J., and Fishbeck, P. S. “Emissions from Waterborne Commerce Vessels in United States Continental and Inland Waterways,” *Environmental Science and Technology*, Vol. 34, No. 15, August 2000.
9. “IPCC, 2007: Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II, and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.” IPCC, Geneva, Switzerland, 104pp. Core writing team: Pachauri, R. K. and Reisinger, A.
10. Schenk, C., Hengeveld, J., and Aabo, K. “Wear Processes in Low Speed Diesel Engines: The Role of Temperature and Pressure in Wear Processes in Low Speed Diesel Engines,” *Schip en Werf de Zee*, pp. 14-19, Oct. 2003.
11. Turns, S. R., Introduction to Combustion: Concepts and Applications. Singapore : McGraw-Hill Higher Education, 2006
12. Verbiezen, K., A.J. Donkerbroek, R.J.H. Klein-Douwel, A.P. van Vliet,. “Diesel combustion: In-cylinder NO concentrations.” *Combustion and Flame*. Vol. 151, 2007.
13. “Development of a Hybrid Fuel Cell Ferry.” Summary Report to Water Transit Authority. JJMA: 21 Aug 2003.
14. “MARPOL Annex VI: Prevention of Air Pollution from Ships.” IMO: 2005.
15. Freudendahl, U. T. “Experiences from Norway on LNG as Ship Fuel.” PowerPoint Presentation. DNV. Helsinki: 18 Nov 2011.
16. Teo, T. and Bant, P. “LNG as a Fuel: What’s Curent & What’s New.” PowerPoint Presentation. DNV (Canada) Ltd. April 2012.
17. Stefenson, P. “End-User’s Perspective.” Stena Teknik: PowerPoint presentation made at EffShip Final Seminar. March 2013.
18. “First Hydrogen Fuel Cell Powered Ferry in UK Showcases Green Technology.” Renewable Energy Focus: 19 July 2013.
19. Giefer, J. “German Submarine Class U212A.” 2008 Fuel Cell Seminar & Exhibition: Phoenix, USA. 29 Oct 2008.
20. Tyler, D. A. “Battery-related fire damages famed hybrid tug, puts it out of service.” *Professional Mariner*, Navigator Publishing LLC: Portland, ME, USA. 08 Nov 2012.

21. Cameron, A. "Conventional Pilot Boats – The Way Ahead." CAMARC Design: Argyll, Scotland. UKHMA Spring Seminar 2007.
22. "Waterjets vs Propellers." Product brochure. CAMARC Design: Argyll, Scotland.
23. Kokarakis, J. E. and Taylor, R. K. "Hydrodynamic Interaction Analysis in Marine Accidents."
24. Yanchunas, D. "Pilot Escapes but boat operator is killed when pilot boat capsizes following transfer." Professional Mariner: 28 Mar 2007. (www.professionalmariner.com/March-2007/Pilot-escapes-but-boat-operator-is-killed-when-pilot-boat-capsizes-following-transfer/)
25. Deublein, D. and Steinhauser, A. Biogas from Waste and Renewable Resources: An Introduction. Wiley-VCH Verlag GmbH & Co. KGaA: Wienheim., Germany 2008.
26. Olah, G. A., Geoppert, A., and Surya Prakash, G.K. Beyond Oil and Gas: The Methanol Economy. Second Ed. Wiley-VCH Verlag GmbH & Co. KGaA: Wienheim, Germany. 2009.
27. Wang, M. and He, D. "Full Fuel-Cycle Greenhouse Gas Emission Impacts of Transportation Fuels Produced from Natural Gas." SAE International: Warrendale, PA, USA. 2000. (2000-01-1505)
28. Kavalov, B., Petrić, H., and Georgakaki, A. "Liquefied Natural Gas for Europe – Some Important Issues for Consieration." European Commission: Joint Research Centre – Institute for Energy. The Netherlands, 2009.
29. IGU World LNG Report 2011. International Gas Union: 25^{th} World Gas Conference: Kuala Lumpur, Malaysia. 2011.
30. "Biogas in Sweden." Energigas Sverige. March 2011.
31. Feist, M. D., Landau, M., and Harte, E. "The Effect of Fuel Consumption on Performance and Emissions of a Variety of Natural Gas Engines." SAE International: Warrendale, PA, USA. 2010.
32. Thipse, S. S., Kavathekar, K. P., and Chitnis, P. P. "Development of a Six Cylinger HCNG Engine Using an Optimized Lean Burn Concept." SAE International: Warrendale, PA, USA. 2009.
33. Bartunek, B. and Hilger, U. "Direct Induction Natural Gas (DING): A Diesel-Derived Combustion System for Low Emissions and High Fuel Economy." SAE International: Warrendale, PA, USA. Oct. 2000.
34. Boretti, A. and Grummisch, C. "100% LPG Long Haul Truck Conversion – Economy and Environmental Benefits." SAE International: Warrendale, PA, USA. 2012.
35. Boretti, A. A. and Watson, H. C. "Development of a Direct Injection High Flexibility CNG/LPG Spark Ignition Engine." SAE International: Warrendale, PA, USA. 2009.
36. Boretti, A. "Direct Injection and Spark Controlled Jet Ignition to Convert a Diesel Truck Engine to LPG." SAE International: Warrendale, PA, USA. 2010.
37. Wiens, J., Powars, C., and Pope, G. "LNG Vehicle Fuel Pressure Strategy Alternatives." SAE International: Warrendale, PA, USA. 2001.
38. Boylston, J. W. "LNG as a Fuel for Vessels – Some Design Notes." June 2011.
39. Newhouse, N. L. and Cederberg, C. A. "Enhanced All-Composite NGV Fuel Container Design and Qualification." SAE International: Warrendale, PA, USA. 2000.
40. Æsøy, V., Einang, P. M., Stenersen, D., Hennie, E., and Valberg, I. "LNG-Fuelled Engines and Fuel Systems for Medium-Speed Engines in Maritime Applications." SAE International: Warrendale, PA, USA. Society of Automotive Engineers of Japan, Inc.: Japan. 2011.
41. Nielsen, J. B. and Stenersen, D. "Emission factors for CH_4 , $N0_X$, particulates and black carbon for domestic shipping in Norway." MARINTEK, SINTEF: Trondheim, Norway. Nov. 2010.
42. He, D. and Wang, W. "Contribution Feedstock and Fuel Transportation to Total Fuel-Cycle Energy Use and Emissions." SAE International: Warrendale, PA, USA. 2000. (Reprinted from *Alternative Fuels* 2000.)

43. Dhaliwal, B. and Checkel, D. "Tailpipe Emissions Comparison Between Propane and Natural Gas Forklifts." SAE International: Warrendale, PA, USA. 2000.
44. Birch, B. J. and Jaeger, S. "LPG Refueling Technology." SAE International: Warrendale, PA, USA. 2002. (Reprinted from *Alternative Fuels* 2002.)
45. Khan, M. and Watson, H. "4 L Light Duty LPG Engine Evaluated for Heavy Duty Application." SAE International: Warrendale, PA, USA. 2010.
46. Wu, D-Y., Matthews, R.D, Popova, E.T., and Mock, C. "The Texas Project, Part 4 – Final Results: Emissions and Fuel Economy of CNG and LPG Conversions of Light-Duty Vehicles." SAE International: Warrendale, PA, USA. 1998. (Reprinted from *Alternative Fuels* 1998.)
47. Bromberg, L. and Cohn, D. "Alcohol Fueled Heavy Duty Vehicles Using Clean, High Efficiency Engines." SAE International: Warrendale, PA, USA. 2010.
48. Law, K., Rosenfeld, J., and Jackson, M. "Methanol as a Renewale Energy Resource." TIAX LLC: Cupertino, CA, USA. 16 Jan 2013.
49. Ellington, R. T., Meo, M., and El-Sayed, D. "The Net Greenhouse Warming Forcing of Methanol Produced from Biomass." *Biomass and Biometry*: UK. Vol 4, No. 6, pages 405-418, 1993.
50. Haraldson, L. "Future Fuels." Wärtsilä Corporation: PowerPoint presentation made at EffShip Final Seminar. March 2013.
51. Sato, Y., Nozaki, S., and Noda, T. "The Performace of a Diesel Engine for Light Duty Truck Using a Jerk Type In-Line DME Injection System." SAE International: Warrendale, PA, USA. 2004.
52. Saxman, E: "DME for Heavy Duty Trucking." Volvo Trucking. June 6, 2013.
53. Louis, J. J. J. "Well-to-Wheel Energy Use and Greenhouse Gas Emissions for Various Vehicle Technologies." SAE International: Warrendale, PA, USA. 2001. (Reprinted from *Fuel Cell Power for Transportation* 2001.)
54. Wallner, T., Matthias, N.S., and Scarcelli, R. "Influence of Injection Strategy in a High-Efficiency Hydrogen Direct Injection Engine." SAE International: Warrendale, PA, USA. 2011.
55. Cheenkachorn, K. Poompipatpong, C., and Ho, C. G. "Performance of a Heavy-Duty Diesel Engine Fuelled with Diesel and LNG (Liquid Natural Gas)." *Energy*, Vol 53, Pages 52 – 57, 01 May 2013.
56. Beroun, S. and Martins, J. "The Development of Gas (CNG, LPG, and H2) Engines for Buses and Trucks and Their Emission and Cycle Variability Characteristics." SAE International: Warrendale, PA, USA. 2001. (Reprinted from *New Developments in Alternative Fuels for CI Engines* 2001.)
57. Packman, K. "Lean-burn engine technology increases efficiency, reduces NO_X emissions." Cummins Power Generation: USA. 2007.
58. Norton, P., Frailey, M., Clark, N. N., Lyons, D. W., Gautam, M., Addy, J. M., and Back, N. J. "Chassis Dynamometer Emission Measurements from Trucks and Buses Using Dual-Fuel Natural Gas Engines." SAE International: Warrendale, PA, USA. 1999. (Reprinted from *Alternative Fuels* 1999.)
59. Weins, J., Addy, M., Leonard, J. H., Bogdanoff, M.A., and Frailey, M.R. "LNG Truck Demonstration." SAE International: Warrendale, PA, USA. 2002. (Reprinted from *Alternative Fuels* 2002.)
60. Richards, B. G. "Methanol-Fueled Caterpillar 3406 Engine Experience in On-Highway Trucks." SAE International: Warrendale, PA, USA. 1990. (Reprinted from *Methanol Fuel Formulations and In-Use Experiences* 1990.)
61. Lockridge, D. "Chart Improves LNG Truck Fuel System." *Fuel Smarts*: 08 April 2013.

62. "U.S. and Canada Natural Gas Vehicle Market Analysis: Liquefied Natural Gas Infrastructure." America's Natural Gas Alliance.
63. Bromberg, L. and Cheng, W.K. "Methanol as an Alternative Transportation Fuel in the US: Options for Sustainable and/or Energy-Secure Transportation." Massachusetts Institute of Technology: Cambridge, MA, USA. 2010.
64. Pui, P. K., Yuen, J. B., and Villaire, W. "Automotive Materials Engineering Challenges and Solutions for the Use of Ethanol and Methanol Blended Fuels." SAE International: Warrendale, PA, USA. 2010. (2010-01-0729)
65. Pearson, R.J., Turner, J. W. G., Eisaman, M. D., and Littau, K. A. "Extending the Supply of Alcohol Fuels for Energy Security and Carbon Reduction." SAE International: Warrendale, PA, USA. 2009.
66. Hansen, K. F., Nielsen, L., Hansen, J. B., Mikkelsen, S, Landälv, H., Ristola, T., and Vielwerth, K. "Demonstration of a DME Fuelled City Bus." SAE International: Warrendale, PA, USA. 2000. (Reprinted from *State of Alternative Fuel Technologies* 2000)
67. Oguma, M. and Goto, S. "Evaluation of Medium Duty DME Truck Performance – Field Test Results and PM Characteristics." SAE International: Warrendale, PA, USA. 2007.
68. http://www.todaystrucking.com/volvo-lays-out-plans-for-dme-powered-trucks-29934 Accessed, March 30, 2014.
69. Clark, N. N., Lyons, D. W., Rapp, B. L., Guatam, M., Wang, W., Norton, P., White, C., and Chandler, K. "Emissions from Trucks and Buses Powered by Cummins L-10 Natural Gas Engines." SAE International: Warrendale, PA, USA. 1998. (Reprinted from *State of Alternative Fuel Technologies* 1998.)
70. Pitblado, R. M., Baik, J., Hughes, G. J., Ferro, C., and Shaw, S. J. "Consequences of LNG Marine Incidents." DNV Consulting. CCPS Conference, Orlando, USA. 2004.
71. Jerve, T. "Experience from Practice: Stockholm LNG Terminal." The Linde Group: PowerPoint presentation for Deutsch-Norwegische Handelskammer. Hamburg 2012.
72. Astbury, G. R. "A Review of the Properties and Hazards of Some Alternative Fuels." *Process Safety and Environment Protection*. Vol. 86, pps 397 – 414. 2008.
73. Nedelka D., V. Sauter, J. Goavic, and R. Ohba. "Last Developments in Rapid Phase Transition Knowledge and Modeling Techniques." Offshore Conference 2003: OTC 15228.
74. "Safety in use of Dimethyl ether as an extraction solvent." European Food Safety Authority: Scientific Opinion of the Scientific Panel on Food Contact Materials, Enzymes, Flavourings, and Processing Aids (CEF): Question No.: EFSA-Q-2007-186. 2009.
75. Roberts, R. R. "Using Physical and Chemical Properties to Manage Flammable Liquid Hazards: Part Tow of a Three Part Series." Methanol Institute: *Methanol Safe Handling Technical Bulletin*. 2012.
76. Signet North America. "Methanol Fire and explosion-awesome.flv." Available on Youtube.com. Posted 17 July 2011.
77. "Chemicals in the Environment: Methanol (CAS NO. 67-56-1)." U.S. Environmental Protection Agency: Office of Pollution Prevention and Toxics. 2004.
78. Würsig, G. and Scholz, B. "MSC.285(86) and Code for gas-fuelled ships (IGF-Code) – technical challenges and perspective." Germanischer Lloyd: Gastech 2011. 2011.
79. Kurowski, Z. "Use of low flash point fuels on ships Assessment of Risk Based Designs vs SPIRETH project." Lloyd's Register Marine: Presentation to Effship Seminar. 21 March 2013.

80. Andreola, M. "The Use of LNG as Fuel for Propulsion Onboard Merchant Ships." Rolls-Royce: European Fuels Conference: Paris. 2011.
81. "The Safe Isolation of Plant and Equipment." Health and Safety Executive – Crown: U.K. 2006.
82. "World Energy Technology Outlook – *WETO* H_2." European Communities: Directorite-general for Reseach. 2006.
83. "Gas Medium-Term Market Report 2012: Market Trends and Projections to 2017." International Energy Agency (IEA): France. 2012.
84. Chandler, K., Norton, P., and Clark, N. "Raley's LNG Truck Fleet: Final Results." U.S. Dept. of Energy - Center for Transportation Technologies and Systems at the National Renewable Energy Laboratory. May 2000.
85. Addy, J., Bining, A., Norton, P., Peterson, E. et al., "Demonstration of Caterpillar C10 Dual Fuel Natural Gas Engines in Commuter Buses," SAE International: Warrendale, PA, USA. 2000. (SAE Technical Paper 2000-01-1386).
86. "Raley's LNG Truck Fleet: Start-up Experience." U.S. Dept. of Energy - Center for Transportation Technologies and Systems at the National Renewable Energy Laboratory. October 1997.
87. Homsombat, W., Yip, T. L., Yang, H., and Fu, X. "Regional Cooperation and Management of Port Pollution." Maritime Policy and Management, Vol. 40, Issue 5, 2013.
88. Phillips, R. "Sleep, Watchkeeping, and Accidents: a Content Analysis of Incident at Sea Reports." *Transportation Research Part F 3*: pps 229 – 240. 2000.
89. Colwell, B., "Design fragility," *Computer* , vol.37, no.1, pp.13,16, Jan. 2004.
90. Thiessen, F. J. and Dales, D. N. Diesel Fundamentals and Service. Fourth Ed. Prentice Hall, Inc.: Upper Saddle River, New Jersey, USA. 2000.
91. Speight, J. G. Handbook of Petroleum Analysis. John Wiley and Sons, Inc.: USA. 2001.
92. Drapcho, C. M., Nhuan, N. P., and Walker, T. H. Biofuels Engineering Process Technology. The McGraw-Hill Companies, Inc: USA. 2008.
93. Näslund, M. Energigasteknik. Second Ed. Svenskt Gastekniskt Center AB: Malmö, Sweden. 2004.
94. Schade, B. and Wiesenthal, T. "Comparison of Long-Term World Energy Studies: Assumptions and Results from Four World Energy Models." European Commission, Joint Research Center: Seville, Spain. 2007.
95. Liquid Carbonic, Inc. and Trucking Research Institute. "Using LNG as a Fuel in Heavy-Duty Tractors." Subcontractor Report to National Renewable Energy Laboratory - DOE: July 1999. NREL/SR-540-24146.
96. Lee, D., Goto, S., Kim, I., and Motohashi, M. "Spectroscopic Investigation of the Combustion Process in an LPG Lean-burn SI Engine." SAE International: Warrendale, PA, USA. 1999.
97. Varde, K. S. and Asar, G. M. M. "Burn Rates in Natural Gas Fueled Single Cylinder Spark Ignition Engine." SAE International: Warrendale, PA, USA. 2001.
98. Bo, Z., Weibiao, F., and Jingsong, G. "Study of Fuel Consumption when Introducing DME or Ethanol into Diesel Engine." *Fuel*, Vol. 85, Pages 778 – 782, 2006.
99. Boretti, A.A. and Watson, H. C. "The Lean Burn Direct Injection Jet Ignition Gas Engine." SAE International: Warrendale, PA, USA. 2009.
100. Allard, M. "Issues Associated with Widespread Utilization of Methanol." SAE International: Warrendale, PA, USA. 2000. (Reprinted from *Fuel Cell Power for Transportation* 2000.)
101. Berlowitz, P. J. and Darnell, C. P. "Fuel Choices for Fuel Cell Powered Vehicles." SAE International: Warrendale, PA, USA. 2000. (Reprinted from *Fuel Cell Power for Transportation* 2000.)

102. Sinor, J. E. "Comparison of CNG and LNG Technologies for Transportation Applications." National Renewable Energy Laboratory: Final Subcontract Report. 1992.
103. Raj, P. K. and Lemoff, T. C. "Fire Safety Analysis Manual for LP-Gas Storage Facilities." Propane Education & Research Council. 2011.
104. "International Safety Guide for Inland Navigation Tank-barges and Terminals." CCNR & OCIMF. 2010.
105. Seiffert, M., Rönsch, S., Schmersahl, R., Zeymer, M., Majer, S. Pätz, C., and Kaltscitt, M. "Bio-SNG – Demonstration of the production and utilization of synthetic natural gas (SNG) from solid biofuels: Specific Targeted Research or Innovation Project." European Commission: Sixth Framework Programme: TREN/05/FP6EN/S07.56632/019895. 2009.