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Emissions and Performance Benchmarking of a Prototype Dimethyl Ether-Fueled Heavy-Duty Truck

February 2014

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This benchmarking data was collected in cooperation with Volvo North America. The authors are grateful to Skip Yeakel and colleagues for making the prototype DME truck available at the Penn State University facility for testing so that benchmarking data could be collected. The authors are also grateful to Brian West, Ron Graves, and Robert Wagner at ORNL for their support and guidance on this project.

EXECUTIVE SUMMARY

In cooperation with Volvo, ORNL commissioned the benchmarking of the emissions and performance data from a heavy-duty truck with a prototype engine fueled with dimethyl ether (DME). The prototype engine is equipped with a 3 way catalyst, but is not equipped with a diesel particulate filter or lean NOx aftertreatment. The benchmarking took place at Penn State University's heavy duty chassis laboratory, which is equipped with a full-flow dilution tunnel. The benchmarking test consisted of duplicate tests of a 60 mph steady cruise and the cruise portion of the Heavy Heavy-Duty Diesel Truck (HHDDT) driving schedule, with complete details of the Penn State testing reported in Appendix A. The results from the DME truck are compared to the results from another Volvo truck with a conventional diesel engine collected at the same chassis laboratory facility in 2011.

The results show that the prototype DME truck performed well over the course of the testing with no significant failures or obstacles. The DME results were repeatable over the duplicate tests for both the 60 mph cruise and the cruise portion of the HHDDT driving schedule. The prototype DME truck was calibrated to meet the Euro V emission standards, and the emission measurements confirmed that NOx, PM, CO, and HC were below the expected level for vehicles meeting Euro V emissions. The PM emissions for DME were sufficiently low to approach the detection limit, and were a minimum of an order of magnitude below the 2010 U.S. emission standard without the use of a diesel particulate filter. In addition, while methane is not currently regulated for heavy-duty compression ignition vehicles in either the U.S. or Europe, the methane emissions were an order of magnitude below what is permissible for the heavy duty natural gas vehicles for the Euro V emission standard. The transient nature of the HHDDT driving scheduled produced high spikes in both unburned HC and CO emissions for the prototype DME truck. While these emissions spikes did not lead to emissions exceedances, they do illustrate that further reductions in emissions and possibly fuel economy could be realized with further hardware and controls development.

The fuel economy for the prototype DME truck was compared to that of a conventional, diesel truck and found to be similar on an energy-equivalent basis given the specification differences of the two vehicles. The prototype DME truck had an average diesel-equivalent fuel economy of 5.3 mpg, while the diesel truck had a fuel economy of 6.0 mpg. Given that the DME truck has two drive axles, it has a lower driveline efficiency than the single-drive axle diesel truck. In addition to the powertrain efficiency differences there are number of additional differences between the DME and diesel vehicles, such as the emission calibration and the engine displacement. As a result, it can be concluded that the engines produced a similar level of efficiency.

The tests demonstrate the near-term viability of DME in heavy-duty applications. The truck performed well under real-world driving conditions and emissions were within the targeted emission standards. The tests confirmed that no PM aftertreatment is necessary when using DME as the fuel. Further NOx emissions reductions are feasible with the use of NOx aftertreatment, a pathway which could also enable a higher efficiency combustion strategy.

1. BACKGROUND

Dimethyl ether (DME) is a fuel that is known to have a number of desirable fuel properties for compression ignition engines. The fuel properties of diesel fuel and DME are compared in Table 1, where the fuel property data is taken from Arcoumanis et al. [1].

Table 1. Fuel properties of DME and diesel fuel [1].

	DME	Diesel Fuel
Carbon content (mass %)	52.2	86
Hydrogen content (mass %)	13	14
Oxygen content (mass %)	34.8	0
Critical temperatrure (K)	400	708
Critical pressure (MPa)	5.37	3.00
Critical density (kg/m^3)	259	-
Liquid density (kg/m^3)	667	831
Cetane number	> 55	40-50
Auto-ignition temperature (K)	508	523
Stoichiometric air/fuel ratio	9.0	14.6
Boiling point at 1 atm (K)	248.1	450-643
Enthalpy of vaporization (kJ/kg)	467.13	300
Lower heating value (MJ/kg)	27.6	42.5
Gaseous specific heat capacity (kJ/kg-K)	2.99	1.7
Ignition limits (vol% in air)	3.4/18.6	0.6/6.5
Modulus of elasticity (N/m^2)	6.37E+08	14.86E+08
Kinematic viscosity of liquid (cSt)	<0.1	3
Surface tension (N/m)	0.012	0.027
Vapor pressure at 298K (kPa)	530	<<10

Of particular note is that the cetane number of DME is higher than that of diesel fuel, indicating that it has superior ignitibility in compression ignition engines. Also noteworthy is the high oxygen content of DME, 34.8%. While the high oxygen content reduces the lower heating value of the fuel (27.6 MJ/kg for DME compared to 42.6 MJ/kg for diesel fuel), the high oxygen content is also attributed to producing very low particulate matter and soot emission [2]. In fact, Miyamoto et al. showed that while the overall oxygen content is important, the ether functional group provides an additional advantage because the fuel has no carbon-carbon bonds [3].

Diesel engines traditionally have a tradeoff between NOx and particulate matter emissions, meaning that whatever in-cylinder measures are taken to reduce NOx emissions have the unintended effect of increasing particulate matter. Because DME does not produce particulate matter, such a tradeoff does not

1. Arcoumanis, C., Bae, C., Crookes, R., Kinoshita, E., "The Potential of Di-methyl Ether (DME) as an Alternative Fuel for Compression-Ignition Engines: A Review," Fuel, 87, pp. 1014-1030, 2008.

2. Ogawa, H., Miyamoto, N., Yagi, M., "Chemical-kinetic Analysis on PAH Formation Mechanisms of Oxygenated Fuels." SAE Technical Paper 2003-01-3190, 2003.

3. Miyamoto, H., Ogawa, H., Arima, T., Miyakawa, K., "Improvement of diesel combustion and emissions with various oxygenated fuel additives." SAE Technical Paper 962115, 1996.

exist and much more aggressive in-cylinder measures can be taken, particularly in regards to retarding combustion phasing and high levels of EGR, as in Salsing et al. [4].

While there are advantages of the high cetane number and high oxygen content, DME is a gas at atmospheric pressure and thus requires special fuel handling considerations. Primarily this means that the fuel tanks have to be pressurized to approximately 75 psi. The materials and amount of pressurization for DME weigh and cost less than the fuel tank systems required for compressed natural gas (CNG) and liquefied natural gas (LNG), but the pressurized fueling system does weigh and cost more than that of a conventional diesel truck [5, Appendix B].

DME is an isomer of ethanol, meaning that they both have the same molecular weight. As a result they have the same stoichiometric air/fuel ratio and similar energy content on a mass basis. However, they are produced from different feedstocks. Ethanol is primarily produced from fermentation of sugar and starch crops (primarily corn in the U.S.), with cellulosic processes expected to come online in the near future. DME is produced synthetically from methanol dehydration, and methanol is produced from syngas. While the source of the syn gas can be either renewable or fossil, the newly found abundance of natural gas in the U.S. makes it the most likely source material for DME on a widespread basis. Oberon Fuels is a company that is currently pursuing a concept of a small-scale plant to make DME from natural gas on-site to have a dispersed infrastructure for DME [6], thereby providing a possible path forward to the widespread use of DME.

The intent of this report is to provide a small amount of background information on DME rather than to provide a comprehensive literature review. For more in-depth literature reviews refer to Arcoumanis et al. [1].

Volvo has had significant development effort aimed at producing a DME engine, including a demonstration project in Europe that includes 10 trucks with a variety of duty cycles that have logged a combined 1.2 million kilometers [5]. In 2013 Volvo introduced 4 prototype DME trucks in the U.S. and announced plans to begin commercial offerings of DME trucks beginning in 2015 [7]. ORNL had the opportunity to benchmark the efficiency and performance of one of these 4 prototype DME trucks at the Pennsylvania State University's heavy-duty chassis laboratory facility on behalf of the U.S. Department of Energy. The results of the heavy-duty truck benchmarking are contained in the following sections.

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4. Salsing, H. and Denbratt, I., "Performance of a Heavy Duty DME Diesel Engine - an Experimental Study," SAE Technical Paper 2007-01-4167, 2007, doi:10.4271/2007-01-4167.

5. McLaughlin, S., "DME – Another Choice Alternative Fuel," SAE Presentation, 2013, also included as Appendix B.

6. Oberon Fuels Website, accessed January, 2014. http://www.oberonfuels.com/technology/oberon-process/

7. Volvo Press Release, Accessed January, 2014. http://www.volvogroup.com/group/global/en-gb/volvo%20group/worldwide/Volvo-Group-North-America/_layouts/CWP.Internet.VolvoCom/NewsItem.aspx?News.ItemId=143305&News.Language=en-gb

2. APPROACH

The Volvo truck with the prototype DME-fueled engine was tested at the Pennsylvania State University's heavy-duty chassis dynamometer laboratory during the week of August 12, 2013. The complete test report, including photographs of the testing and details about the facility and procedures, is included as Appendix A. The benchmarking consisted of duplicate runs of a steady 60 mph cruise and the cruise-phase of the HHDDT driving cycle. The truck performed well during the testing, and the benchmarking data was collected without any significant barriers.

The DME benchmarking data is compared to experimental data from a conventional diesel truck that was collected in 2011 at the same chassis laboratory facility. The specifications for the two engines are listed in Table 2. While there is both steady cruise and HHDDT driving cycle data available for the prototype DME truck, only HHDDT driving cycle data are available for the conventional diesel. Thus, emission and performance comparisons are only made for the HHDDT driving cycle data.

Table 2. Specifications of the prototype DME truck and the conventional diesel truck.

	Prototype DME Truck	Conventional Diesel Truck
Displacement [L]	13.0	11.0
Compression Ratio [-]	17:1	16.5:1
Max Torque [Nm]	2200	2050
Max Power [HP]	450	405
Fuel	DME	Diesel
Fueling	Common Rail Direct Injection	Unit injector
Max Rail Pressure [bar]	300	2400
Emissions Compliance	Euro V	U.S. 2010
Aftertreatment	DOC	DOC, DPF, Urea SCR

The same vehicle inputs were used for testing both the prototype DME truck and the conventional diesel truck. Namely, the inertia load on the truck was 30,000 lb (13,608 kg) and road load was applied in accordance to Equation 1, where V is the speed of the truck in miles per hour.

Equation 1. Road load (lb) = $0.02*V^2 + V + 200$

Neither the steady-cruise nor the cruise portion of the HHDDT driving cycle are representative of the emissions certification cycles for the U.S. or Europe, thus direct graphical comparisons are not made in this report. To provide a frame of reference for the emissions from the benchmarking tests, the relevant U.S. and European emissions are listed in Table 3. It is important to note that the methane emissions listed for the European standards are only for natural gas vehicles, while in the U.S. methane is not regulated for any heavy-duty engines. Finally, the emissions standards for both the U.S. and Europe are specified on the basis of the brake engine power. In this test, power was measured at the truck wheels. To convert wheel power to engine power, a total driveline efficiency of 94% is assumed for the baseline truck and 89% is assumed for the DME truck. The driveline efficiency difference is due to the difference in the two truck chassis; the DME truck happened to be equipped with two drive axles whereas the diesel truck was of the single drive axle design.

Table 3. European and U.S. regulated emissions for heavy duty engines [8].

	Euro IV	Euro V	U.S. 2010[1]
CO[g/kW-h]	1.5[2]	1.5[2]	20.79[4]
HC [g/kW-h]	0.46[2]	0.46[2]	-
NMHC [g/kW-h]	-	-	0.19[4]
CH_4 [g/kW-h]	1.1[3]	1.1[3]	-
NOx [g/kW-h]	3.5[2]	2.0[2]	0.27[4]
PM [g/kW-h]	0.02[2]	0.02[2]	0.013[4]

1. U.S. 2010 emission standards are converted from g/bhp-h
2. Diesel vehicles on the ESC/ELR test cycle
3. Natural gas vehicles on the ETC test cycle
4. Diesel vehicle on the EPA Transient Test Procedure

3. RESULTS

3.1 STEADY CRUISE RESULTS

The steady cruise results for the prototype DME truck are presented in Figure 1, showing the truck speed, power, and exhaust temperature across the duration of the 550 sec steady cruise test. It can be seen that the truck speed and power are held nearly constant throughout the duration of the test. The exhaust temperature plot shows that it takes approximately 3 minutes for the exhaust temperature to arrive at a steady state value for this condition. The slow approach to equilibrium may be, in part, an artifact of the rising engine compartment temperature while the truck was on the chassis dynamometer. Additionally, it shows that the exhaust temperature for the DME truck is very low (< 300°C) for an engine condition that exceeds 50% of the full load power for the engine. The low exhaust temperature can be attributed to the high EGR strategy that is employed by this prototype truck to reduce engine-out NOx emissions, and a higher exhaust temperature would be expected with a strategy that uses less EGR and urea-SCR to control NOx emissions.

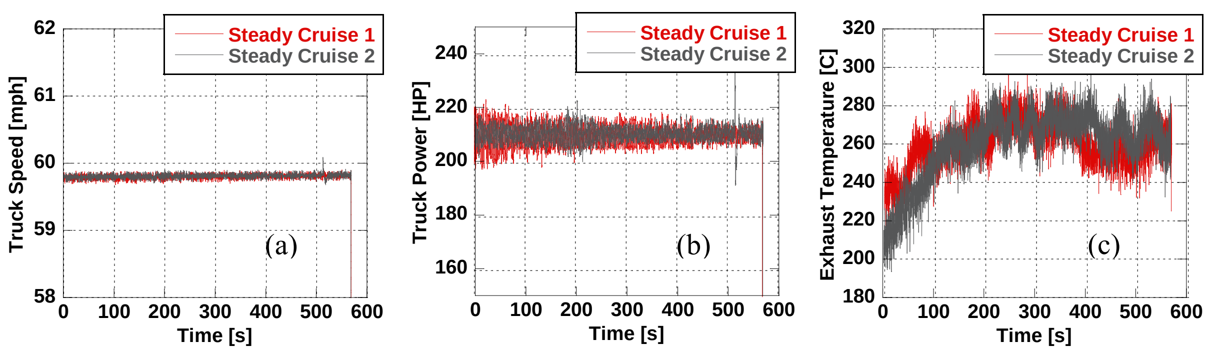

Figure 1. Speed, power, and exhaust temperature for the duplicate steady 60 mph cruise tests for the DME truck.

The NOx emissions are shown Figure 2 for the two repeats of the steady cruise condition. It is observed that the NOx emissions increase steadily over duration of the test, suggesting that the engine did not come

8. Delphi, "Worldwide Emissions Standards: Heavy Duty and Off-Highway Vehicles," 2013-2014, http://delphi.com/emissions-hd.

to a true thermal equilibrium. Although this steady cruise condition is not representative of the emissions certification driving cycle, the NOx emissions are below the emissions standards for Euro IV (3.5 g/kWh) and Euro V (2.0 g/kWh) without the use of any NOx aftertreatment devices. It is not surprising that the NOx emissions are higher than the U.S. 2010 standards given that the 0.27 g/kWh target is currently only being met with the use of lean NOx aftertreatment equipment (primarily urea SCR).

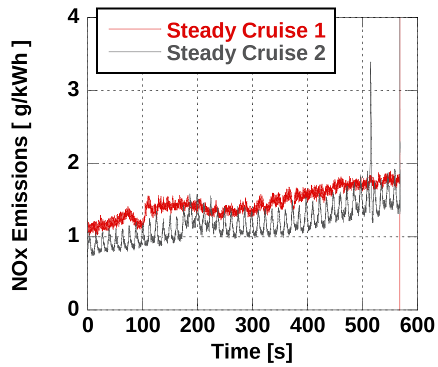

Figure 2. NOx emissions for the two repeats of a 60 mph cruise for the prototype DME truck. Note that these emissions have been adjusted to an engine brake power basis with the assumption of 89% total driveline efficiency.

The total unburned HC emissions are shown in Figure 3 for both steady cruise repeats for the DME truck. With the exception of an excursion of HC emissions near the end of each test, the HC emissions are very low, below 0.02 g/kWh. This level of total HC emissions are more than an order of magnitude below both the Euro IV and Euro V requirements (0.46g/kWh) and the U.S. emission standards (0.19 g/kWh). It should be noted that the HC emissions in Figure 3 includes methane, and the U.S. emission standard of 0.19 g/kWh is for non-methane hydrocarbons (NMHC). It is important to note that this HC measurement is performed using a flame ionization detector (FID), and while this is the industry-standard technique for engine emission testing, oxygenated species such as DME typically have response factors that are lower than that of the propane calibration gas. As a result, the unburned HC emissions are likely biased low by an unknown amount. The net result of this bias is undetermined.

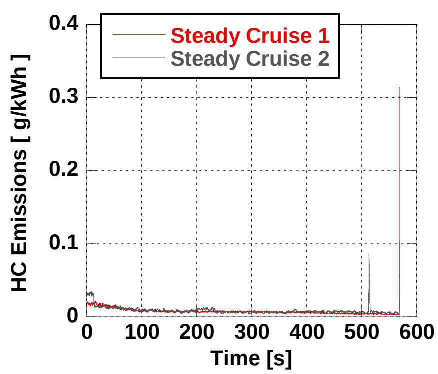

Figure 3. Unburned HC emissions for the two repeats of a 60 mph cruise for the prototype DME truck. Note that these emissions have been adjusted to an engine brake power basis with the assumption of 89% total driveline efficiency.

Methane emissions are shown in Figure 4 for the two repeats of the steady cruise for the DME truck. It is notable that while emissions of methane are low, less than 0.02 g/kWh, methane emissions do comprise the majority of HC emissions from the engine. Methane emissions are not regulated for compression ignition vehicles in either the U.S. or in Europe. There is a methane emission standard for heavy-duty natural gas engines under the Euro IV and Euro V standards of 1.1 g/kWh. Although this standard is not directly comparable, it is noteworthy that the methane emissions from the DME truck are nearly two orders of magnitude lower. Thus, while methane emissions are present, they are are insignificant compared to the emissions permitted from heavy-duty natural gas engines.

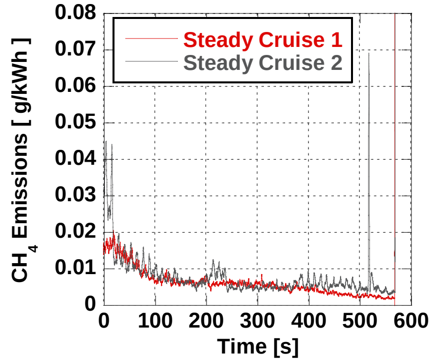

Figure 4. Methane emissions for the two repeats of a 60 mph cruise for the prototype DME truck. Note that these emissions have been adjusted to an engine brake power basis with the assumption of 89% total driveline efficiency.

Finally, the particle emissions for the prototype DME truck are extremely low, 0.0015 g/kWh without the use of a DPF. This result is nearly an order of magnitude lower than the current U.S. diesel emission standards of 0.01 g/HP-h (0.0134 g/kWh), a standard that is only being met in the U.S. with the use of DPF aftertreatment devices. Thus, this finding confirms that PM aftertreatment is not required when fueling with DME. It is also worth noting that the measured emissions of PM are approaching the detection limits of the instruments used.

3.2 HHDDT Cruise Phase Emissions and Performance

The Heavy Heavy-Duty Diesel Truck (HHDDT) Schedule is a driving cycle that was developed by the California Air Resources Board [9]. The schedule consists of an idle portion, a creep portion, a transient portion, and a high speed cruise. The prototype DME truck was tested only in the high speed cruise portion of the driving schedule. The speed-time trace from the two repeats of the prototype DME truck and the diesel truck are shown in Figure 5. Due to differences in the location of exhaust gas temperature probes on the two trucks, no comparisons of exhaust gas temperature can be made.

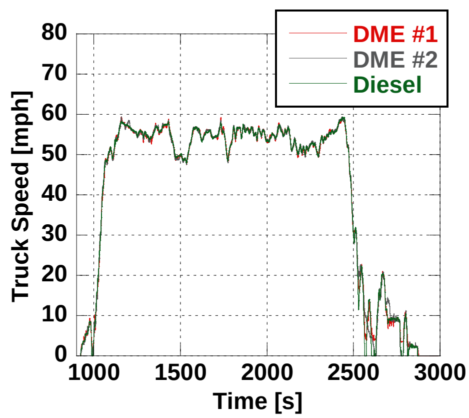

Figure 5. Speed-time trace for the cruise portion of the HHDDT schedule.

The NOx emissions for the prototype DME truck are shown as a function of time in Figure 6(a). There is a spike in NOx emissions for both of the DME repeats and for the diesel test that corresponds with the acceleration at 1000 seconds from a stop to more than 50 miles-per-hour. The spike in NOx emissions from the DME truck is higher than for the diesel truck. Once the initial acceleration is complete, NOx emissions for the DME truck fluctuate between about 30 and 100 mg/s. In contrast, the NOx emissions

9. Heavy Heavy-Duty Diesel Truck (HHDDT) chassis dynamometer schedule, accessed from DieselNet on December 11, 2013. http://www.dieselnet.com/standards/cycles/hhddt.php

from the diesel truck steadily decrease. The net result, which can be seen in the cumulative emissions in Figure 6(b), is that the NOx emissions are a factor of 3 higher for the prototype DME truck. A difference in NOx emissions was expected between these two vehicles because the prototype DME truck was calibrated to be compliant with Euro V NOx emissions whereas the diesel truck has urea SCR NOx aftertreatment and is compliant with the U.S. 2010 NOx emission standards. While the HHDDT driving cycle is not an emissions certification cycle, the emission measurements here compare favorably to the emission standards in Table 3.

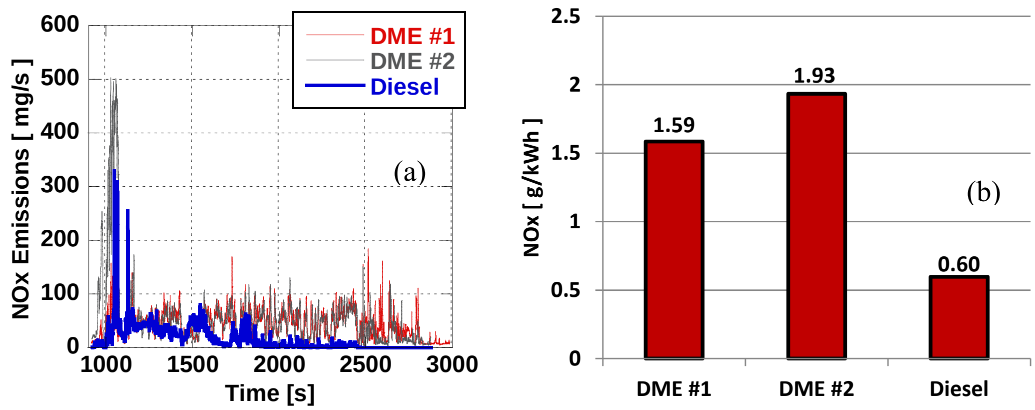

Figure 6. NOx emissions for the prototype DME truck and for the conventional diesel truck for (a) emissions as a function of time, and (b) cumulative emissions on an engine-specific basis corrected for a 89% total driveline efficiency in the DME truck and 94% driveline efficiency in the diesel truck.

The total unburned HC emissions are shown as a function of time in Figure 7(a), and for the cumulative driving schedule in Figure 7(b). For the prototype DME truck, the baseline level of HC emissions is low, but there are a number of short duration spikes that are in excess of an order of magnitude higher than the baseline level. While the cause of the unburned HC spikes has not been determined, it is noteworthy that this behavior was not observed for the steady cruise data in Figure 3. This prototype version of the DME truck does not contain fully developed transient engine maps, thus it is likely that this behavior would be negated by additional development of the engine controller, as it would be for a fully-developed, commercially-available engine or vehicle. Nonetheless, the cumulative emissions shown in Figure 7(b) are significantly below both the European and the U.S. emission limits for HC emissions, with the caveat that the HHDDT driving cycle is not an emission certification cycle.

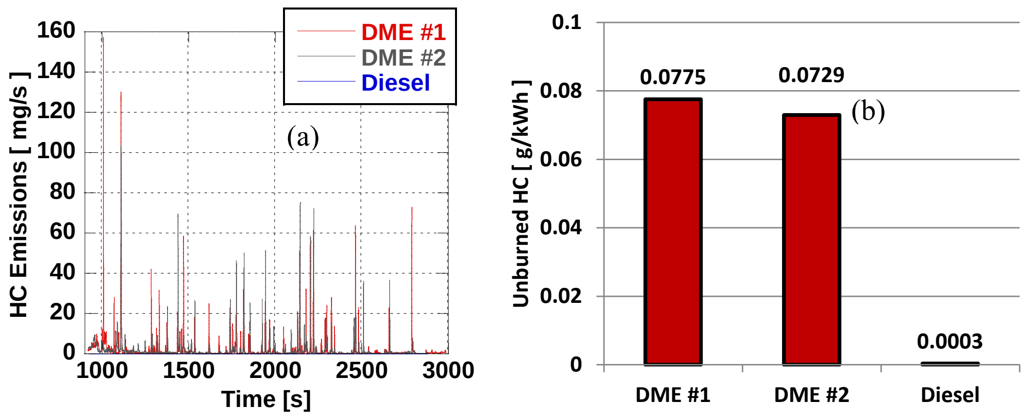

Figure 7. Unburned HC emissions for the prototype DME truck and for the conventional diesel truck for (a) emissions as a function of time, and (b) cumulative emissions on an engine-specific basis corrected for a 89% total driveline efficiency in the DME truck and 94% driveline efficiency in the diesel truck.

The CO emissions are shown as a function of time in Figure 8(a). Under the 60 mph steady-cruise conditions the CO emissions were below the detection limit, and are therefore not shown. However, during the cruise portion of the HHDDT driving schedule, there are numerous spikes of CO emissions in a similar manner to the HC emissions in Figure 7. The background level of CO emissions for the DME prototype is very low – below the detection limit for than analyzer and lower than for diesel, as can be seen in a smaller scale view in Figure 8(b). Ultimately, though, the high CO spikes resulted in higher CO emissions for the prototype DME truck than for the diesel truck over the cumulative driving cycle, as can be seen in Figure 8(c). Because of the very low CO emissions from DME during the steady cruise condition, it is reasonable to assume that with further development the transient CO emissions from the DME engine could be comparable to or lower than those from the diesel engine.

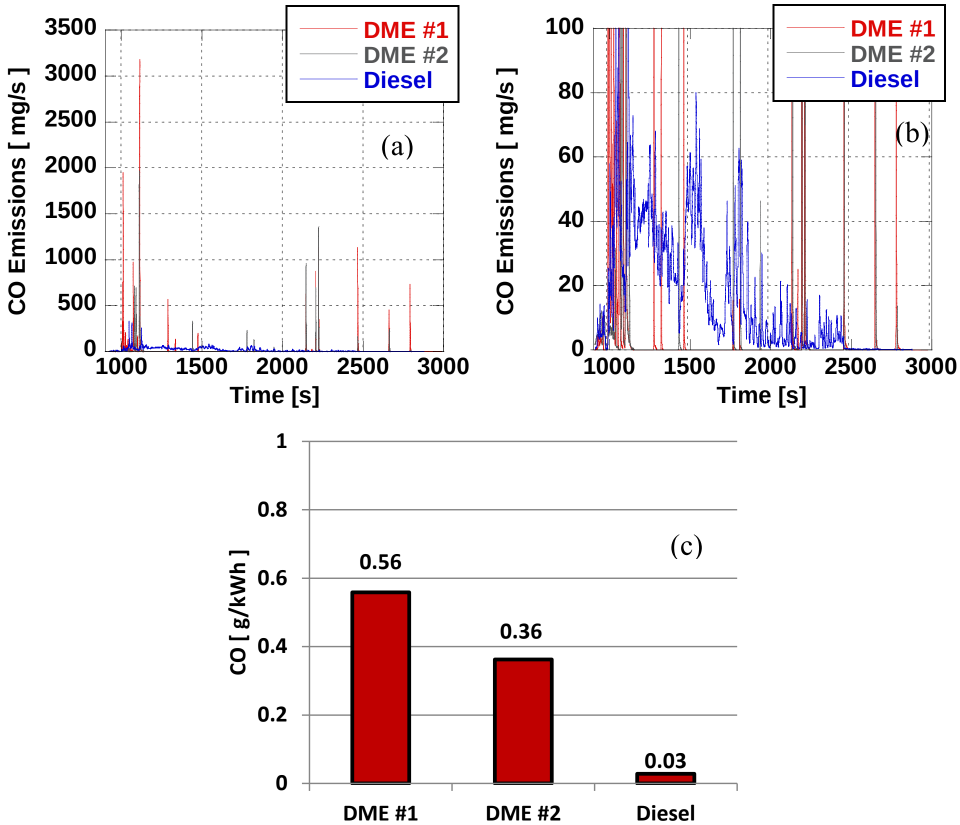

Figure 8. CO emissions for the prototype DME truck and for the conventional diesel truck for (a) and (b) emissions as a function of time (different scales), and (b) cumulative emissions on an engine-specific basis corrected for a 89% total driveline efficiency in the DME truck and 94% driveline efficiency in the diesel truck.

Figure 9 shows the particulate emissions for the DME truck and the diesel truck. As was discussed earlier, the diesel truck was equipped with a diesel particulate filter. Despite the lack of PM aftertreatment on the DME truck, the PM emissions were roughly half of that of the diesel truck. Both vehicles were substantially below the PM emissions levels required by the Euro V and the U.S. 2010 emission standards. It should be noted that the PM emissions are near-zero for all three cases, and quantification of PM at these levels approaches the detection limit of this PM measurement technique. This nonetheless confirms that PM emissions with DME are near-zero, and thus PM aftertreatment is not required with a DME engine.

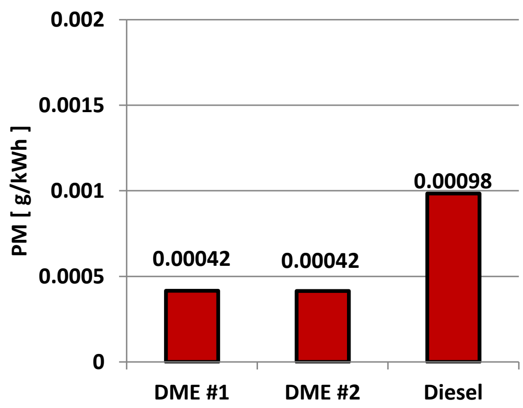

Figure 9. Particulate matter emissions for the prototype DME truck and for the conventional diesel truck on an engine-specific basis corrected for a 89% total driveline efficiency in the DME truck and 94% driveline efficiency in the diesel truck.

Finally, the fuel consumption of the prototype DME truck can be compared to the diesel truck. CO_2 emissions were measured directly from the dilution tunnel as part of the HHDDT driving cycle, but in order to convert this measurement into a miles-per-gallon fuel economy, fuel properties have to be assumed for both the diesel and DME. The properties listed in Table 1 were used for the fuel economy calculations, the results of which are presented in Figure 10. Figure 10(a) shows that the fuel economy of DME is less than half that of diesel fuel. Lower fuel economy is expected because of the reduced volumetric energy density for DME.

Figure 10(b) shows the diesel-equivalent fuel economy for the prototype DME truck and the diesel truck. Once corrected for the energy density, the fuel economy for the DME truck is nearly in-line with the fuel economy of the diesel truck. However, there is still a disadvantage for the DME fuel economy with a reduction from 6.02 mpg to an average of 5.30 mpg. This difference can be attributed to a number of factors, the first of which is that there are significant vehicle differences. The DME truck has a lower mechanical driveline efficiency than the diesel truck that it was compared to, thus biasing the fuel economy low due to the additional drive axle. Second, the properties of the diesel fuel from the diesel test were assumed, as no fuel analysis data was available. Next, the diesel engine and prototype DME engine were calibrated to meet different emission standards. Specifically, the prototype DME truck used a strategy of in-cylinder NOx control, which likely requires late combustion phasing and high levels of EGR, both of which can reduce engine efficiency. Finally, the spikes in HC and CO emission throughout the HHDDT suggest that there could be further development of the combustion and control strategy for the prototype DME truck, possibly resulting in an increase in fuel economy.

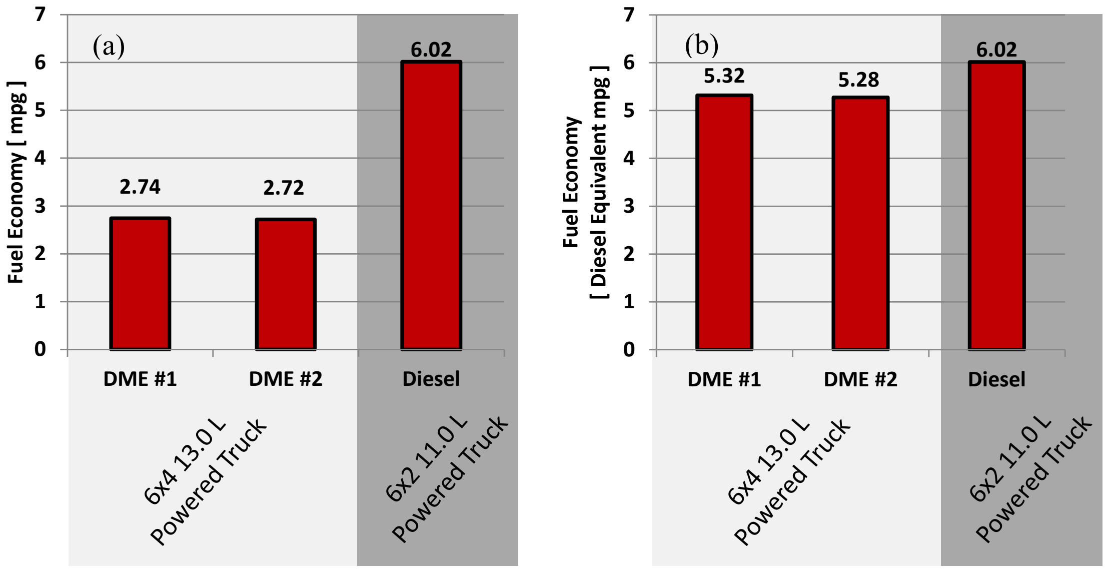

Figure 10. Fuel economy for the prototype DME truck and for the diesel truck. (a) raw fuel economy, (b) diesel equivalent fuel economy.

4. CONCLUSIONS

In partnership with Volvo and Penn State University, benchmarking of emissions and fuel economy of a prototype DME truck calibrated for Euro V emissions has been conducted on the Penn State heavy-duty vehicle dynamometer. Results for a U.S.-legal, 2010-compliant diesel truck tested under similar conditions at the same facility are available for comparison. Review of the available data leads to the following conclusions:

- NOx emissions were within the expected range for the prototype DME truck based on the emission standard for which the engine was calibrated (Euro V). This NOx emission level was met without the use of NOx aftertreatment. Further NOx reductions are feasible with the use of NOx aftertreatment to enable compliance with the U.S. 2010 emission standards.
- The prototype DME truck produces spikes of HC emissions throughout the HHDDT driving schedule. As a result, the HC emissions exceeded the conventional diesel truck by two orders of magnitude. Nonetheless, HC emissions were within the expected range for a truck compliant with the Euro V emission standard. Reductions of the HC spikes are feasible with additional calibration and hardware development.
    - While methane emissions are not currently regulated in either the U.S. or in Europe for compression ignition engines, the methane emissions were on average an order of magnitude below the Euro V standard for heavy duty natural gas engines.
- Under the steady-cruise conditions the CO emissions were below the detection limit. However, during the HHDDT driving schedule, there were frequent spikes in CO emission in a manner similar to the HC emissions. As a result, CO emissions for the DME truck were an order of magnitude higher for the DME truck than for the conventional diesel. Reductions of the CO spikes are feasible with additional calibration and hardware development.
- The diesel-equivalent fuel economy was measured to be approximately 12% lower for the two-drive axle DME vehicle than for the single-drive-axle diesel vehicle (5.3 mpg vs. 6.02 mpg). Given the numerous differences between the emissions level, engine and vehicle configurations whereby the DME mechanical efficiency has at least a 4% disadvantage, it can be concluded that the energy efficiency between the two engines is similar.

APPENDIX A.
Penn State Report on Testing of Volvo Prototype DME Truck

CHASSIS DYNAMOMETER BASED FUEL ECONOMY AND EMISSIONS TESTS ON A TRUCK FUELED BY DME

Project Sponsored by
Battelle - Oak Ridge National Laboratory
Oak Ridge, TN
Contact: James P. Szybist

Di-Methyl Ether Fueled Truck Sponsored by
Volvo Group Truck Technology
Hagerstown, PA
Contact: Samuel Mclaughlin

FINAL REPORT, September 16, 2013

Principal Investigator
Dr. Suresh Iyer

LTI Report Number 2014-02

PENNSTATE

1855

THE LARSON INSTITUTE

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Introduction

The Thomas D. Larson Pennsylvania Transportation Institute (LTI) of The Pennsylvania State University (Penn State) has prepared this report to describe the tasks performed and the results obtained from the chassis dynamometer-based fuel economy and emissions research tests using their large-roll chassis dynamometer on a truck supplied by Volvo Group Truck Technology (Volvo GTT) for Oak Ridge National Laboratory (ORNL). This truck, which was fueled by dimethyl ether (DME), was tested in accordance with the test standards and specifications set forth by the Volvo Group Truck Technology (Volvo GTT).

Test Vehicle

The test was conducted using an over-the-road Volvo tractor powered by a prototype heavy-duty engine with the following specifications:

- Displacement: 13 liters
- Engine type: Compression Ignition
- Fuel: Di-methyl ether (DME)
- Maximum Engine speed: 1800 RPM
- Maximum torque: 2200 Nm
- Transmission: Semi-automatic

Test Equipment

This investigation was carried out at the emissions testing facility inside the Vehicle Testing Laboratory of The Larson Institute of Penn State. This facility is equipped with a full-scale dilution tunnel with constant volume sampling (CVS), laboratory grade emission analyzers, and a heavy-duty chassis dynamometer. The chassis dynamometer is capable of absorbing and delivering power, thus enabling simulation of inertia during drive and coast modes of vehicle under test. In addition, it has the capability of simulating the road load (tractive effort) of the vehicle as a function of speed. It has large, 72-inch diameter rollers to reduce the effects of tire flexure and prevent tire slip. This dynamometer can absorb or deliver 300 HP, simulate up to 50,000 lbs inertia load electrically, and has a maximum speed of 80 mph.

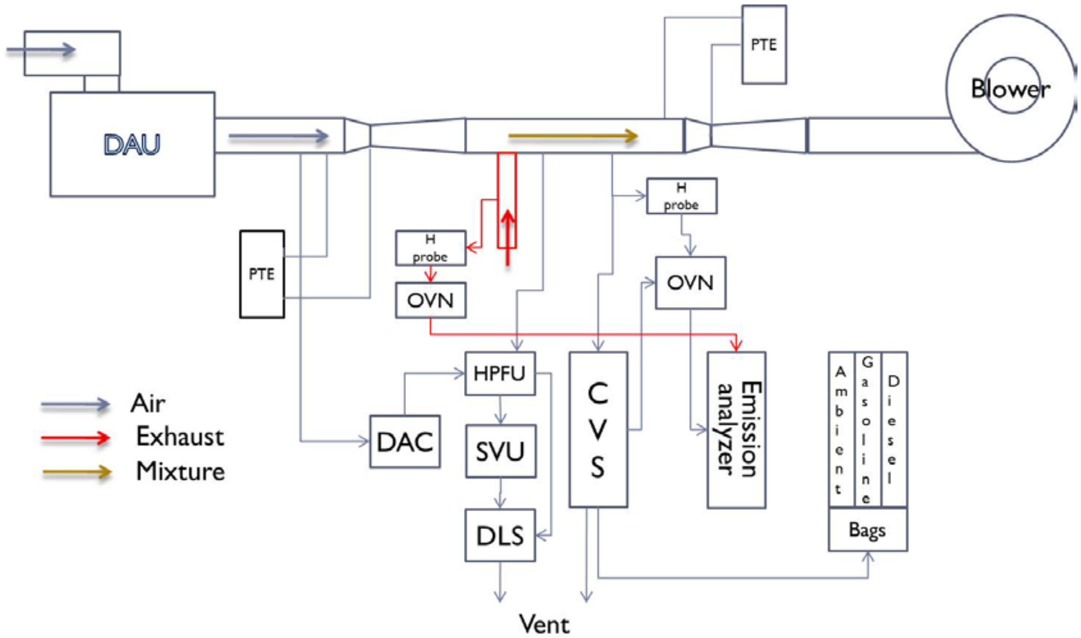


Figure 1. Schematic diagram of emission system.

The schematic diagram of the emissions measurement system is shown in the figure 1. It consists of a dilution air conditioning unit (DAU), which conditions the ambient air for temperature and humidity before it enters the dilution tunnel. The vehicle's tail pipe is plumbed into this tunnel so that all vehicle exhaust enters the tunnel and is diluted with the dilution air. The dilution tunnel is fitted with two sub-sonic venturi flow meters (smooth approach orifices, SAO); one measures the dilution air flow rate while the other measures the diluted exhaust flow rate; the difference between the two provides the exhaust flow rate from the tail pipe. Heated probes are used for sampling both raw exhaust before it enters the tunnel and the diluted exhaust in the tunnel. The sampled gas passes through two banks of heated oven analyzers (OVN) for NO_X, THC, and CH_4 measurements. Two additional banks of unheated analyzers measure concentrations of CO_2, CO, and NO. Thus, two independent sets of gas analyzers measure the concentrations of dilute and raw exhaust at a frequency of 10Hz. The analyzers are also used to measure the concentration of the sample collected continuously in the bags during the test (dilute bag measurement). The particulate sampling unit (PSU) is used to pass a fraction of diluted exhaust through pre-weighed 47 mm filters. The particulate sampling system is comprised of dilution air conditioning unit (DAC), heated particulate filter unit (HPFU), solenoid valve unit (SVU), and a dilution sampler (DLS). The test filters are post-weighed to determine the particulate emissions. At the end of a test, a computer program processes the data from the analyzers' flow sensors and particulate data and calculates the gaseous and particulate emissions in gm/mile for the test. The measurement principle and range of the instruments of different gas analyzers are shown in table 1. The range of the flow meters used in the system is given in table 2.

Table 1. Measurement principle and range for different gas analyzers.

Constituent	Principle	Dilute measurement	Raw measurement
CO_2	NDIR	0-5%	0-20%
CO	NDIR	0-500 ppm	0-2500 ppm
NO_X	CLD	0-50 ppm	0-500 ppm
NO	CLD	0-50 ppm	0-500 ppm
CH_4	HFID	0-100 ppm	0-1000 ppm
THC	HFID	0-500 ppm	0-2500 ppm

Table 2. Range of flow meters.

Flow Meter	Range
SAO (Dilution air)	0-4000 SCFM
SAO (Diluted Exhaust)	0-4000 SCFM
Particulate sample	0-50 LPM
Sampling probes (raw and dilute)	10 LPM

The accuracy specifications of different analyzers used in the measurements is shown in Table 3. The two venturi flow meters have a specified uncertainty of 0.3% of reading.

Table 3. Specification of different gas analyzers.

Constituent	Bias	Precision	
	Linearity	Noise	Repeatability
CO_2: Dilute /Raw	±1.0% FS or ±2.0% of readings	±1.0% FS	±0.5% FS
CO: Dilute /Raw	±1.0% FS or ±2.0% of readings	±1.0% FS	±0.5% FS
NO: Dilute /Raw	±1.0% FS or ±2.0% of readings	Less than 2.0 % FS	±0.5% FS
THC/CH_4: Dilute/Raw	±1.0% FS or ±2.0% of readings	Less than 1.0 % FS	±0.5% FS
NO_X: Dilute /Raw	±1.0% FS or ±2.0% of readings	Less than 2.0 %FS	±0.5% FS

Test Procedure

The test vehicle was mounted on the chassis dynamometer, as shown in Figures 2 and 3. Figures 4 and 5 are photographs of the screen displays for the data collection and test control software. Volvo's engineers were present during the tests. They inspected the test set up and switched the truck to 'dyno mode' to enable driving on the dynamometer. A thermocouple was installed before the muffler in the truck to measure the exhaust temperature. A high velocity fan was placed in front of the truck to simulate cooling by head wind. A jet of air was directed towards the fuel pipe under the hood to reduce heating and prevent vapor formation in the fuel lines at low fuel flow rates.

The simulated inertia load on the truck was 30,000 lbs. In addition, a simulated road load was also applied by the dynamometer according to the following equation:

$$\text{Road load (lb)} = 0.02*V^2 + 1*V + 200$$

where V is the speed of the tractor on the dynamometer in mph.

Figure 2: Volvo DME Tractor mounted on the chassis dynamometer at Penn State.

Figure 3: View of the test set up showing ballast weights on fifth wheel

Figure 4: Computers monitoring (from left) driver's trace, chassis dynamometer, and test control

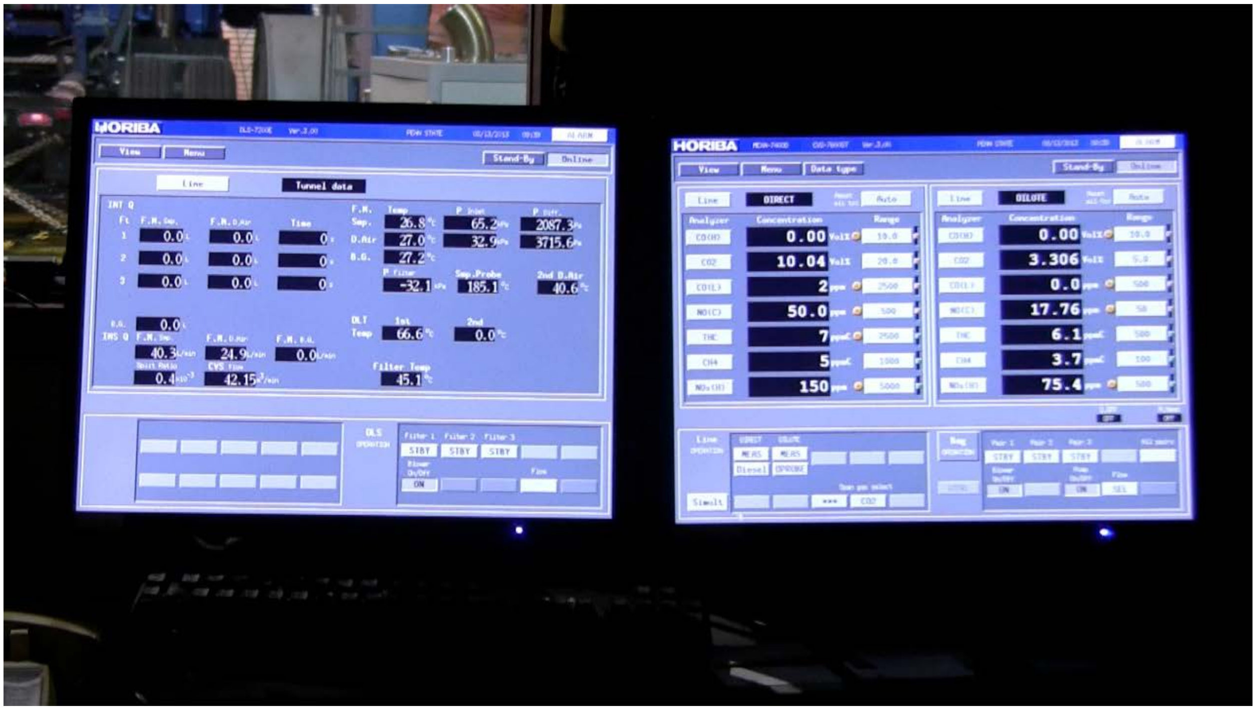


Figure 5: Data display from dilution tunnel (left) and emissions analyzers (right)

Test matrix

The test series consisted of two parts. In the first part, the truck was driven at constant speed (60 mph) for approximately 10 minutes and the data for gaseous emissions and particulates was collected. This measurement was repeated once, for a total of two times. In the second part of the test series, the truck was driven in accordance with the cruise phase of the HHDDT cycle. The HHDDT cycle has three phases namely, the idle (low speed, low load), the transient, and the cruise (high speed, high load) phase. Volvo GTT is interested in only one phase of the HHDDT cycle namely, the cruise phase. This phase is the high speed section of the cycle, and its time-speed trace is shown in Figure 6. This measurement was also repeated, for a total of two times.

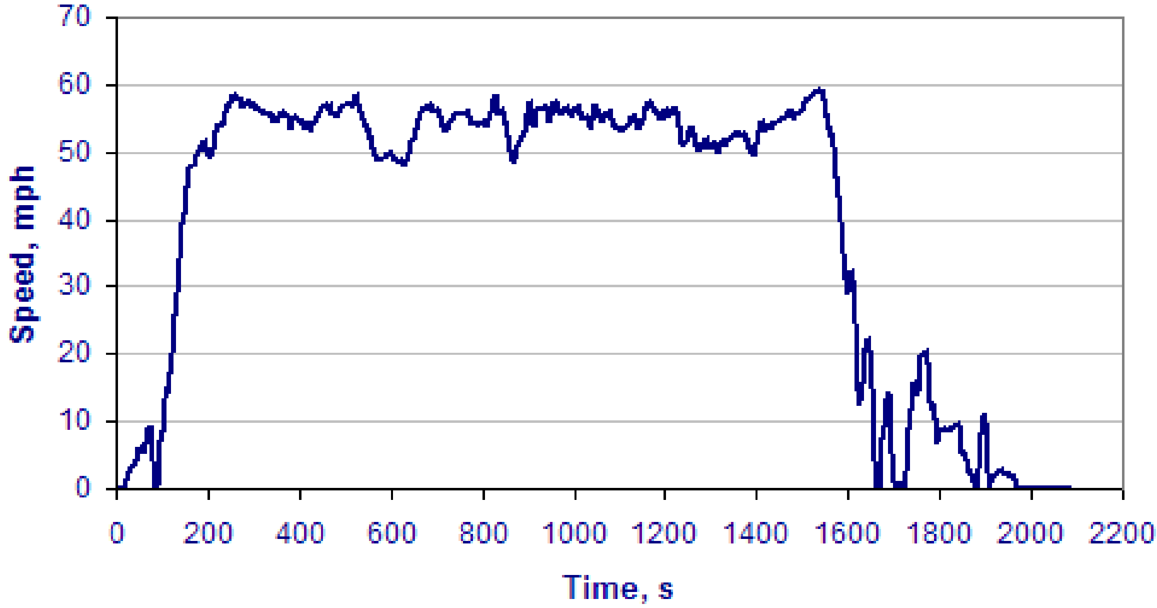


Figure 6: Cruise phase of the HHDDT cycle

Carbon balance

Fuel consumption was calculated by carbon balance, from CO_2 emission measurements. Volvo represented that the fuel was purchased from Dupont, and supplied to The Larson Institute with the Material Safety Data Sheet, wherein it is specified 100% DME. Therefore, the properties of pure DME are used in the calculations. It is assumed that all fuel is converted to CO_2 during combustion. This is a reasonable assumption given that the emissions of CO and THC are either zero or orders of magnitude lower than that of CO_2 (see Table 4).

Complete combustion of DME in air can be represented in molar form by:

$$C_2H_6O+3*(O_2+3.76)\ N2 \rightarrow 2CO_{2+}3H_2O+11.3N_2$$

Considering the molecular weights of DME and CO_2 as 46.07 and 44.01, respectively, the above equation yields:

Ratio of weight of fuel to weight of CO_2 = (46.07/2*44.01) = 0.5234

The liquid density of DME is 734.7 kg/m^3 at 1.013 bar and boiling point of -24.8^oC (encyclopedia.airliquide.com). Considering 264.172 gallons in 1 m^3 yields:

Volume of DME required to produce 1 gm of CO_2 = $1.882*10^{-4}$ gallon

A typical calculation is shown below for the 60 mph test:

Weight of CO_2 emission = 2000 gm/mile

Therefore, fuel economy = $2000*1.882*10^{-4}$ = 0.3764 gallon DME/ mile, or 2.66 mpg DME.

Results

The overall summary of fuel consumption and emission measurements is shown in Table 4. The emissions are shown in gms/mile, while fuel economy is shown in miles per gallon of DME.

Table 4. Emissions and fuel economy measurements.

Measured Parameter	Test Condition					
	60 mph			HHDDT cycle, cruise phase		
	1	2	Average	1	2	Average
CO_2, g/mi	2000	1994	1997	1792	1780	1786
CO, g/mi	0	0	0	0.88	1.35	1.16
NO_x, g/mi	4.32	3.52	3.92	4.74	3.88	4.31
THC, g/mi	0.02	0.03	0.03	0.19	0.19	0.19
NMHC, g/mi	0	0.01	0.01	0.06	0.04	0.05
PM, g/mi	0.004	0.004	0.004	0.001	0.001	0.001
Fuel, mpg-DME	2.66	2.66	2.66	2.97	2.99	2.98
Distance, miles	9.451	9.453	9.452	23.180	23.184	23.182
Test time, s	569.0	569.0	569.0	2084.1	2084.1	2084.1
Average Roller HP	210.2	210.5	210.4	--	--	--
Max. Roller HP	223.6	249.6	--	--	--	--
Max. Ex. Temp, C	302	304	--	329	330	--

Based on the above results, the roller horsepower specific emissions are calculated for the steady state (60 mph) condition. The average numbers are used in the calculation. The product of distance specific emissions multiplied by the distance gives the total emissions during the test. The product of average power and the duration of the test yields the work output during the test (hp-hr). Results are compared with the 2010 EPA mandate in Table 5. It is noted that a transmission efficiency of 75% is assumed for these calculations.

Table 5: Calculated roller horsepower specific emissions

	Results are for average data from Table 4 for 60 mph steady state condition				
	Calculated Parameters				2010 EPA mandate
	Total emissions, gms	Net work Hp-hr	Roller specific Emission, gm/hp-hr	Engine specific emissions* gm/hp-hr	Engine specific gm/hp-hr
NOx	37.05	33.25	1.11	0.83	0.20
NMHC	0.095	33.25	0.003	0.002	0.14
PM	0.038	33.25	0.001	0.0008	0.01

*These are based on a transmission efficiency of 75% between engine and driving wheels.

Discussion

It is important to note that the following discussion is based on one test condition—the constant speed test at 60 mph. It is seen from Table 5 that the calculated engine out emissions for NMHC and PM are well below the 2010 EPA mandate, while engine out NOx is about 4 times higher than the mandate. These results were anticipated, as Volvo GTT represented that the test truck was equipped with a diesel oxidation catalyst that accounts for the low NMHC numbers. In the absence of a DPF, the low PM numbers could have resulted from the nature of combustion of DME in a compression ignition engine and/or the presence of a diesel oxidation catalyst. While EGR was applied to this truck, there was no after treatment for NOx and that could explain the high NOx numbers. One area of potential research would be to investigate the effect of increasing EGR to mitigate NOx emissions. Reduction of NOx during after treatment might also be considered.

End of Report

APPENDIX B.
DME – Another Choice Alternative Fuel

DME – ANOTHER CHOICE ALTERNATIVE FUEL

Samuel McLaughlin
Volvo Group Trucks Technology

SAE INTERNATIONAL

VOLVO
Volvo Group

Contents
DME – Another Choice Alternative Fuel

Advancing Fuel Alternatives at Volvo Group

- The Volvo Group products are almost exclusively driven by fossil diesel fuel
- The Volvo Group has for many years tried to increase the use of renewable fuels in viable commercial applications. None of the existing alternative fuels are optimal for all applications and all situations.

  - ➢ Prioritize high energy efficiency and Greenhouse Gas (GHG) reduction based on a well to wheel perspective.
  - ➢ Relate energy consumption and GHG impact to the work done (g/ton-mile)
  - ➢ Formulate means and incentives with an international perspective
  - ➢ Clearly specify and standardize the properties of any fuel or fuel blend

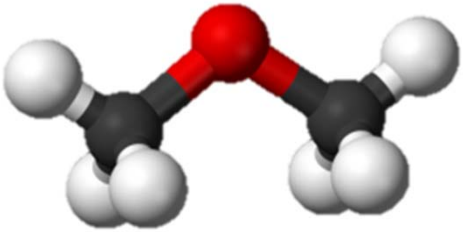
What is DME (dimethyl ether)

DME uses

- Household fuel (China)
- Propellant in aerosol canister
- Chemical feedstock

DME in diesel engine

- Near zero soot and controlled NOx



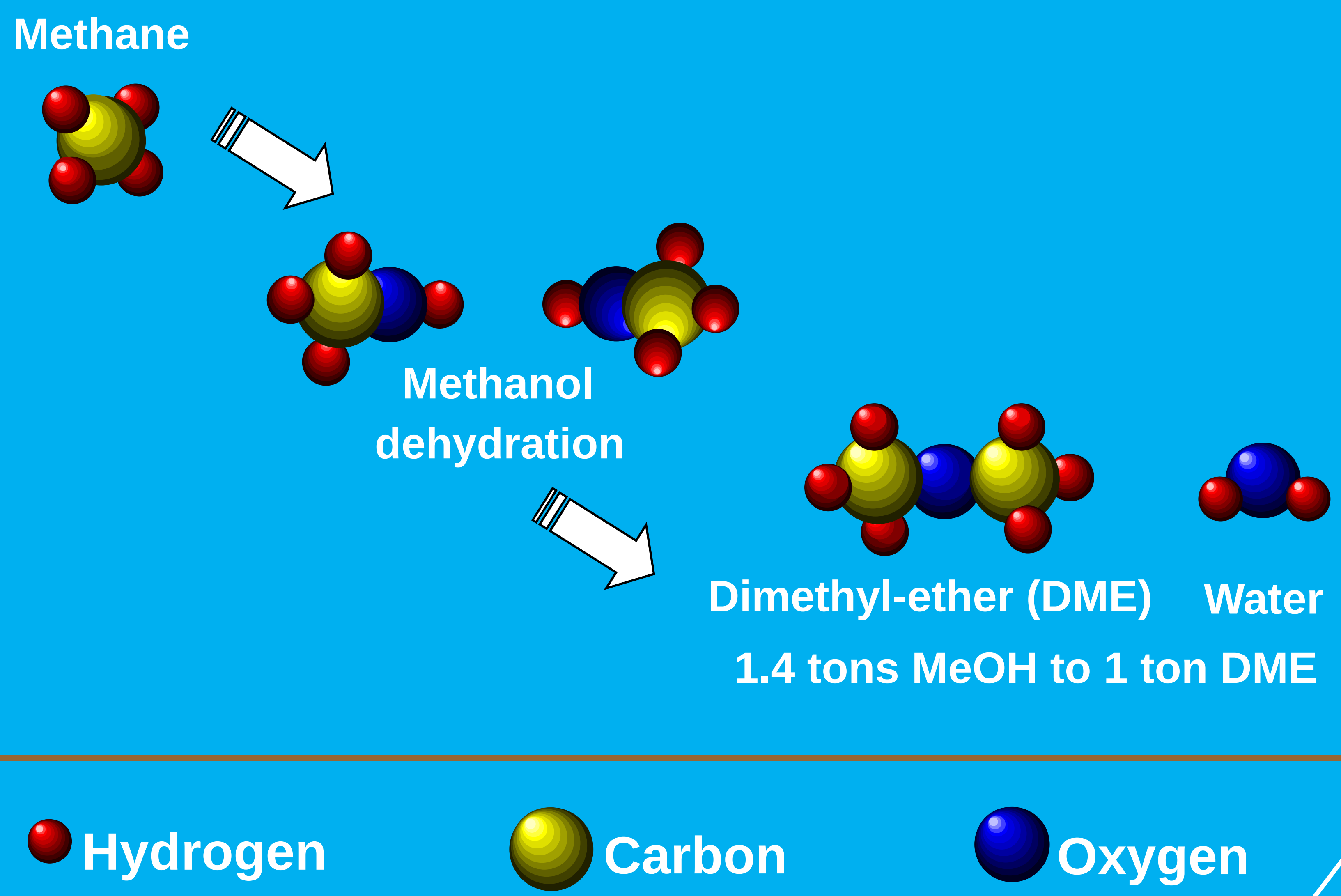
DME C_2H_6O

DME is non-toxic, non-carcinogenic, and not a greenhouse gas

Properties

- No sulfur
- Heavier than air (behaves like LPG)
- Boils at -11F
- Liquid at ambient temperature under 5 bar pressure

What is DME (dimethyl ether)



DME Fuel Properties

Physical Properties & Characteristics of DME					
Property	**DME**	**Diesel**	**Methane**	**Methanol**	**LPG**
Formula	CH3OCH3	-	CH4	CH3OH	C3H8
Boiling point, deg. C	-25	180 - 370	-162	65	-42
Liquid density, g/cm3	0.66	0.84	0.42	0.78	0.49
Viscosity, 40 deg C (cP)	0.18	2.3-3.3	-	-	0.1
Cetane Number	55 - 60	40 - 55	-	5	5
Auto Ignition temperature, deg.C	235	250	650	450	470
Lower Heating Value, MJ/kg	28.8	42.5	49.9	-	46

Why DME?

- **Excellent diesel cycle fuel (high cetane)**
- **Easy to store and transport (liquefies at low pressure)**
- **Not cryogenic, negligible fugitive emissions, no tank venting**
- **Clean, no soot combustion (no Particulate Filter required)**
- **Non-toxic**
- **10% carbon reduction in combustion balance compared to diesel**
- **Low global warming potential (**GWP = 0.3 @100 yr)
- **Synthesis from variety of bio-based feedstock**
  - **High well-to-wheel efficiency for GHG emission**
  - **Potential RINS opportunities**
- **Synthesis from natural gas provides opportunity for single fuel from NG/methanol pathway with diesel like efficiency**

Demo Project
10 Trucks, 1.2 Million km

Feedstock: Black liquor from paper mill **Output: 4 tons Bio-DME/day**

- **Local Delivery**
- **Regional and local hauling**
- **Heavy-haul transport**

DME Fuel Objectives and Challenges
Knowledge from Swedish Field Test

Objectives

- **Minimize CO_2 emissions, well to wheel**
- **Meet diesel engine efficiency**
- **Meet current diesel vehicle fuel economy**
- **Limit the cost of vehicle adaptation**

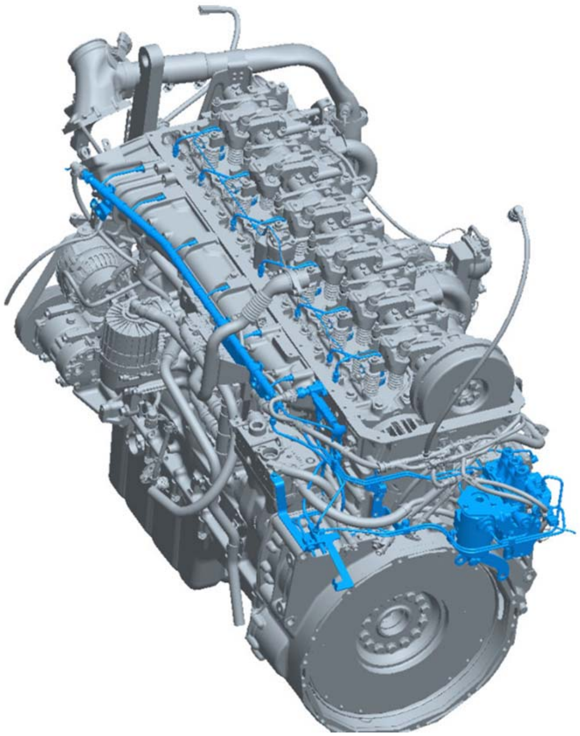
Challenges

- **High fuel compressibility**
- **Reduced energy content compared to diesel**
- **Low fuel viscosity and lubricity**
- **Seal and gasket material compatibility**
- **Combustion development**

A DME Engine is a Compression-ignition Engine

- **The modified engine components consist of:**
  - **High pressure fuel pump, common rail, and fuel injectors.**

- **Moderate proprietary changes due to DME properties:**
  - **Higher fuel flow needed due to 67% energy content of diesel.**
  - **DME fuel also includes:**
    Lubricity improver for low fuel viscosity
    Chemical properties → seal & gasket materials
  - **DPF can be removed, however an oxi-cat is used for CO and HC reduction.**
  - **EGR versus SCR is under investigation for NOx control.**



No DPF necessary

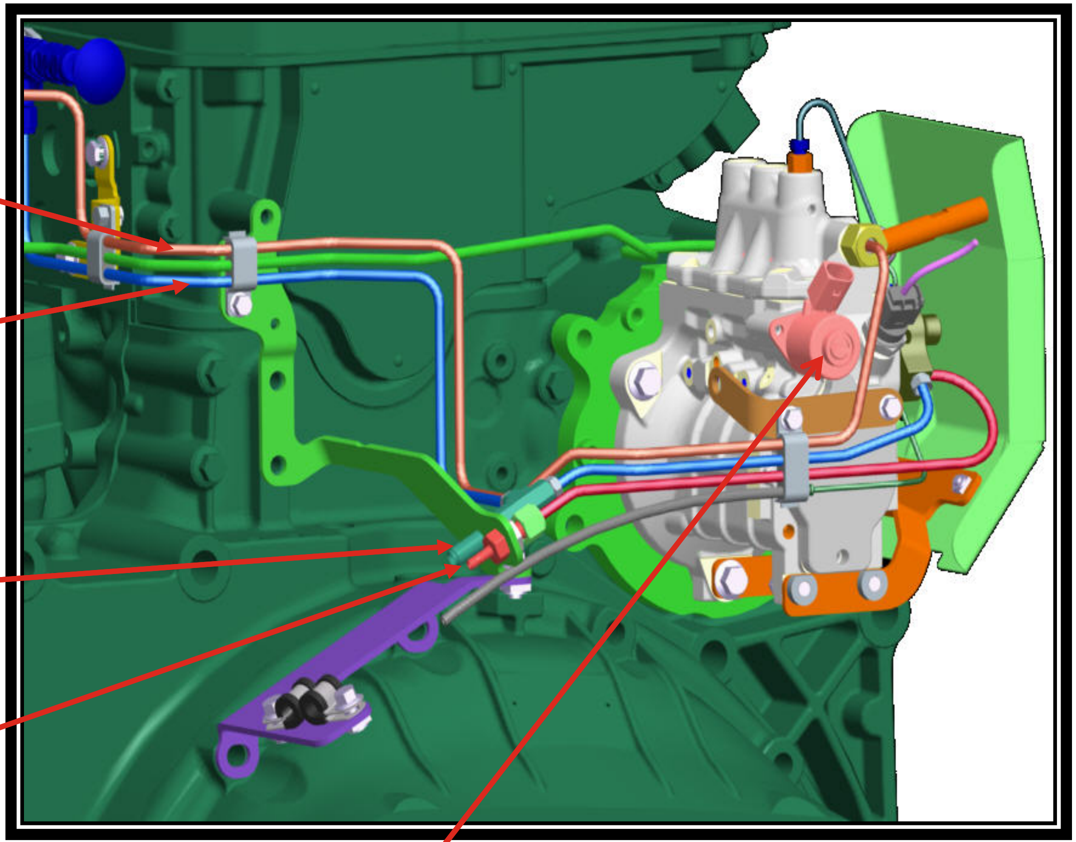
Engine Component Difference

High pressure feed line to rail

Injector return line

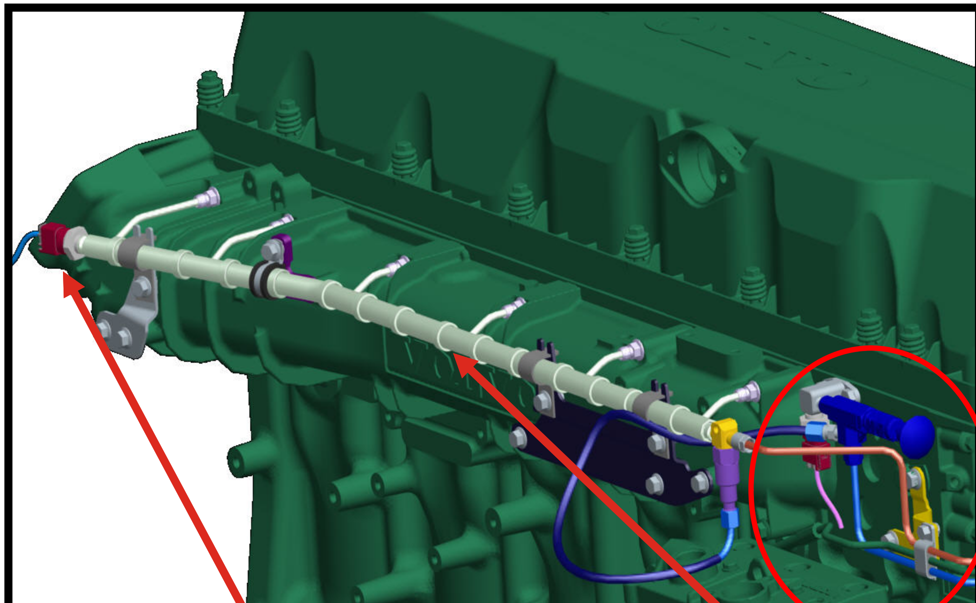
High pressure pump and injector return line to tanks

Supply line from tanks

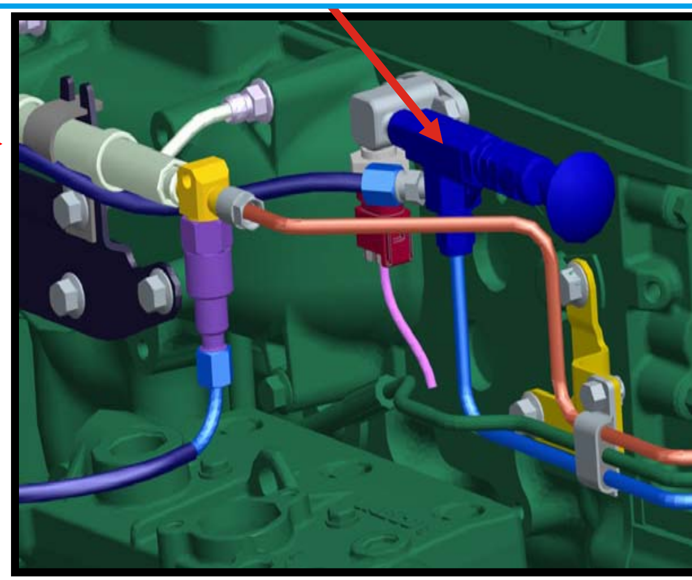


"RPCV" (Rail Pressure Control Valve) alternatively "IMV" – Inlet Metering Valve
Performs feedback-based control of common rail pressure by variation of HP pump's volumetric efficiency in real time

Engine Component Difference



LPRV (low pressure relief valve, injector return)
Sets correct backpressure level of the injectors

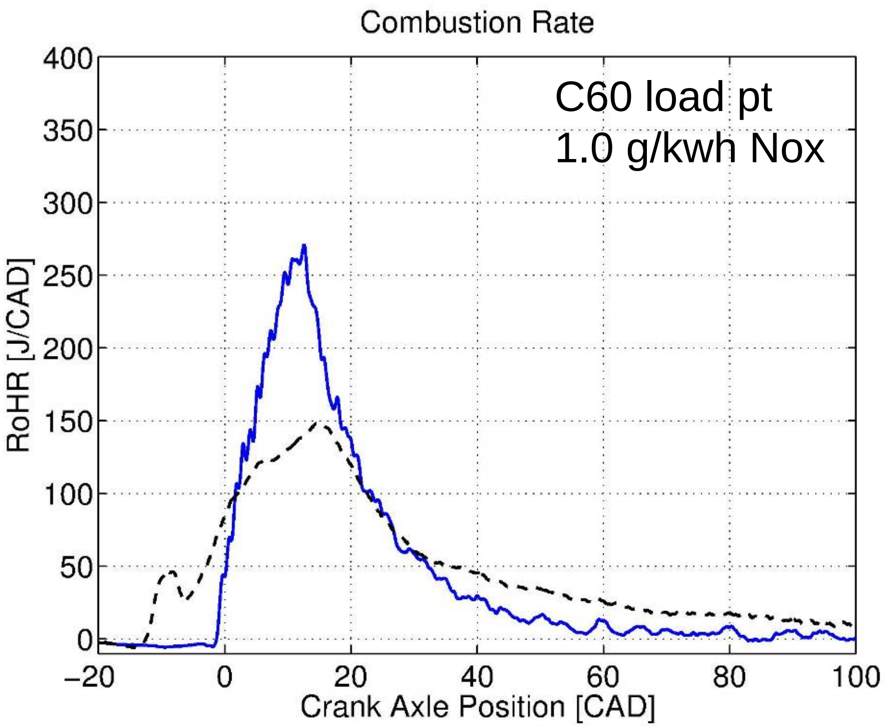


Rail pressure sensor
Gives rail pressure feedback to ECU

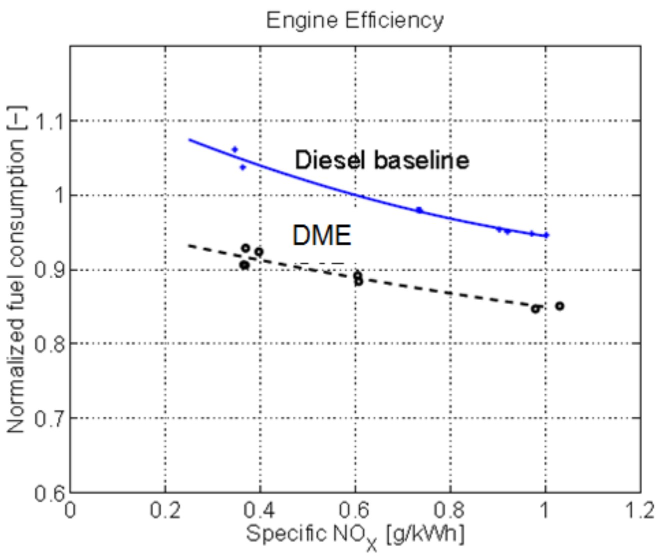
Common rail
Delivers fuel to injectors via paths in cylinderhead

DME Combustion

(DME Combustion in HD Diesel Engines, Dr. Salsing 2011, Chalmers University)

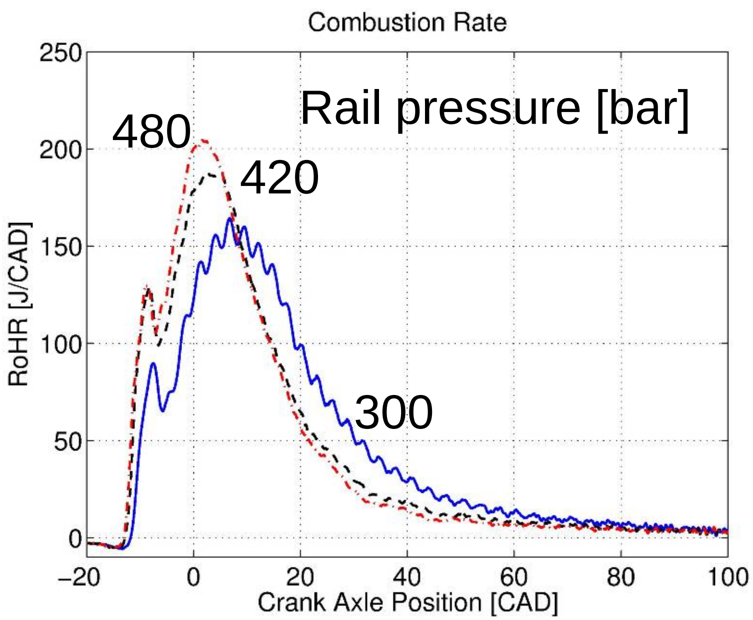


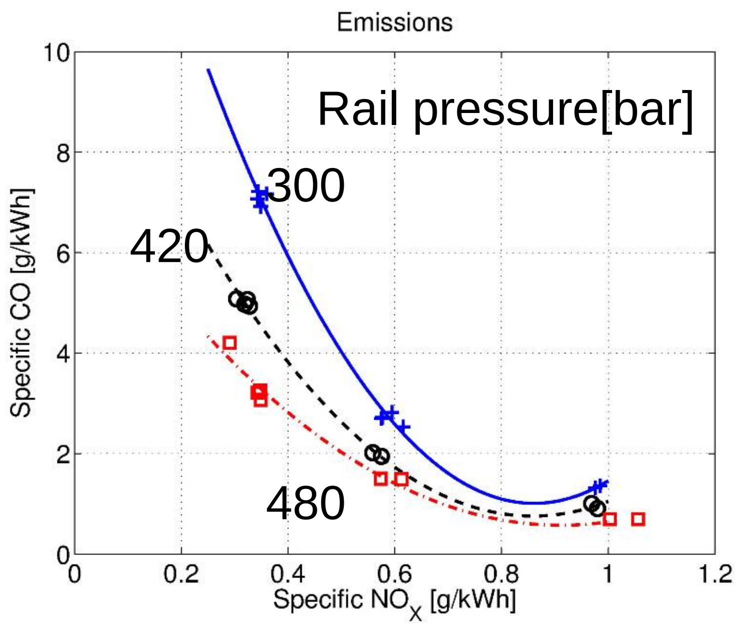
- Using same combustion chamber h/w, distinct combustion differences are found between diesel and DME process.
- Distinct pre-mix burn notable for DME. Added slowing of diffusion burn indicates that additional mixing is needed for DME case.
- Below indicates potential improvement!



DME Combustion Improvements

(DME Combustion in HD Diesel Engines, Dr.Salsing 2011, Chalmers University)





- Higher injection pressure results in:

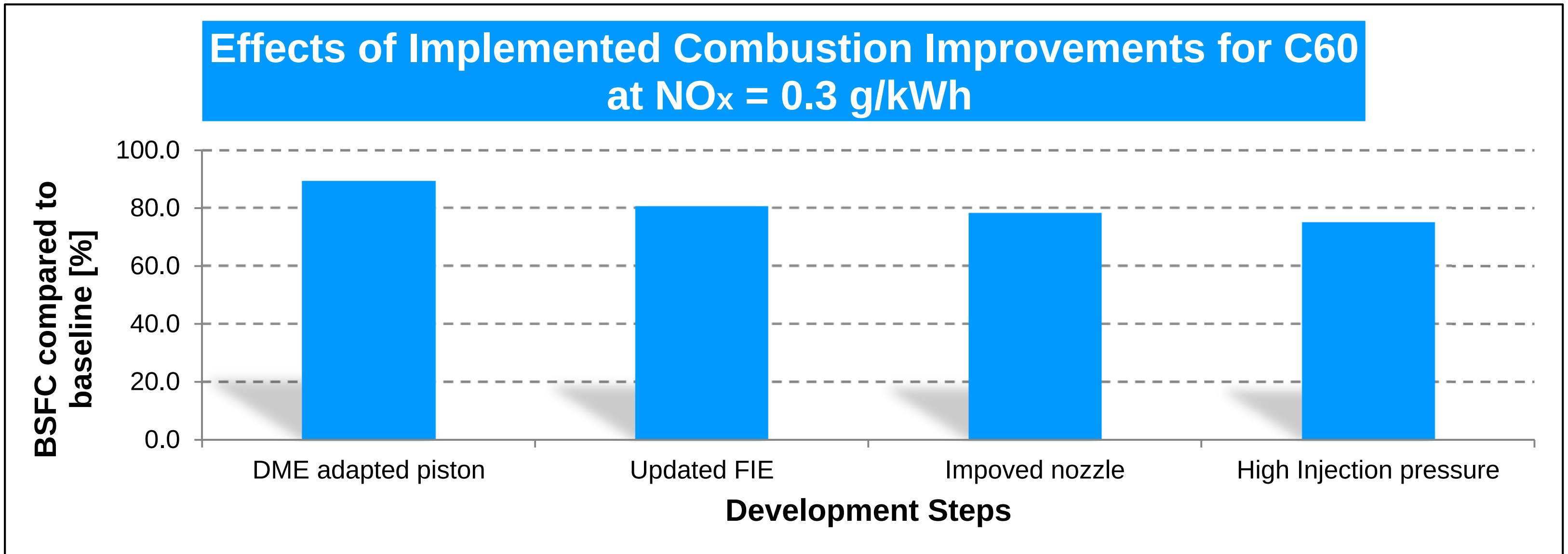
  -Faster combustion and lower CO emissions

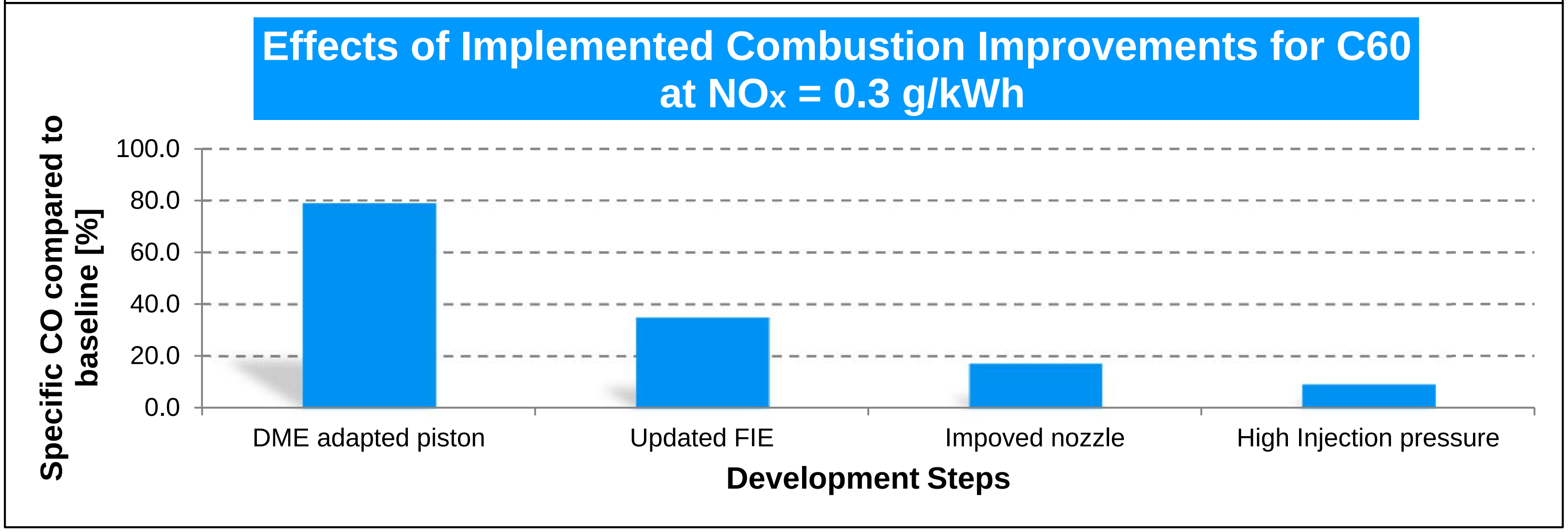
  -More rapid mixing entire combustion process

- Fundamental DME combustion improvement steps included piston bowl, injector sizing, and rail pressure.

Realized Fuel Efficiency Improvements

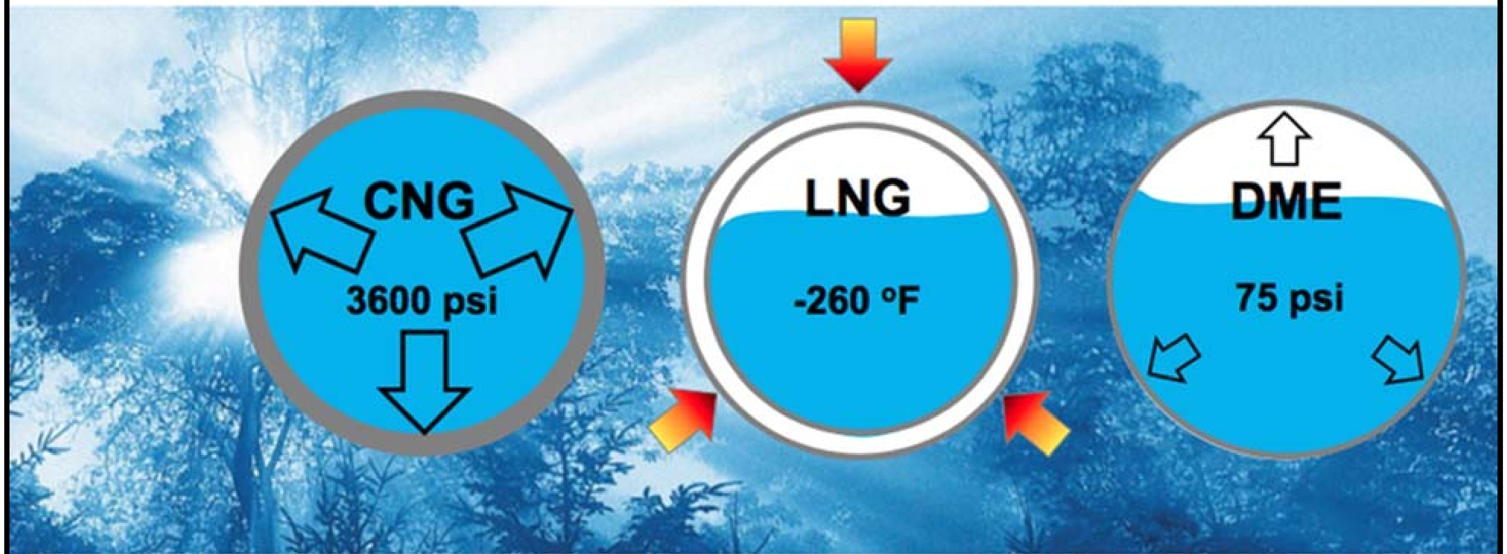
(DME Combustion in HD Diesel Engines, Dr.Salsing 2011, Chalmers University)





DME Vehicle Fuel Tanks

Fuel Tank Packaging



	CNG	LNG	DME
Material	carbon graphite	stainless steel	steel
Cost	$$$	$$$	$
Weight	~800 lbs. > DME	~700 lbs. > DME	----

DME Vehicle Fuel Tanks

- D= 26 inches (660mm)
- L= 62 inches (1570mm)
- V= 123 gallons (465L)

- Design temperature range:
- -20° C to 70° C
- Sealing material: Isolast and EPDM

DME Tank Install.

Diesel Tank Install.

US Field Test

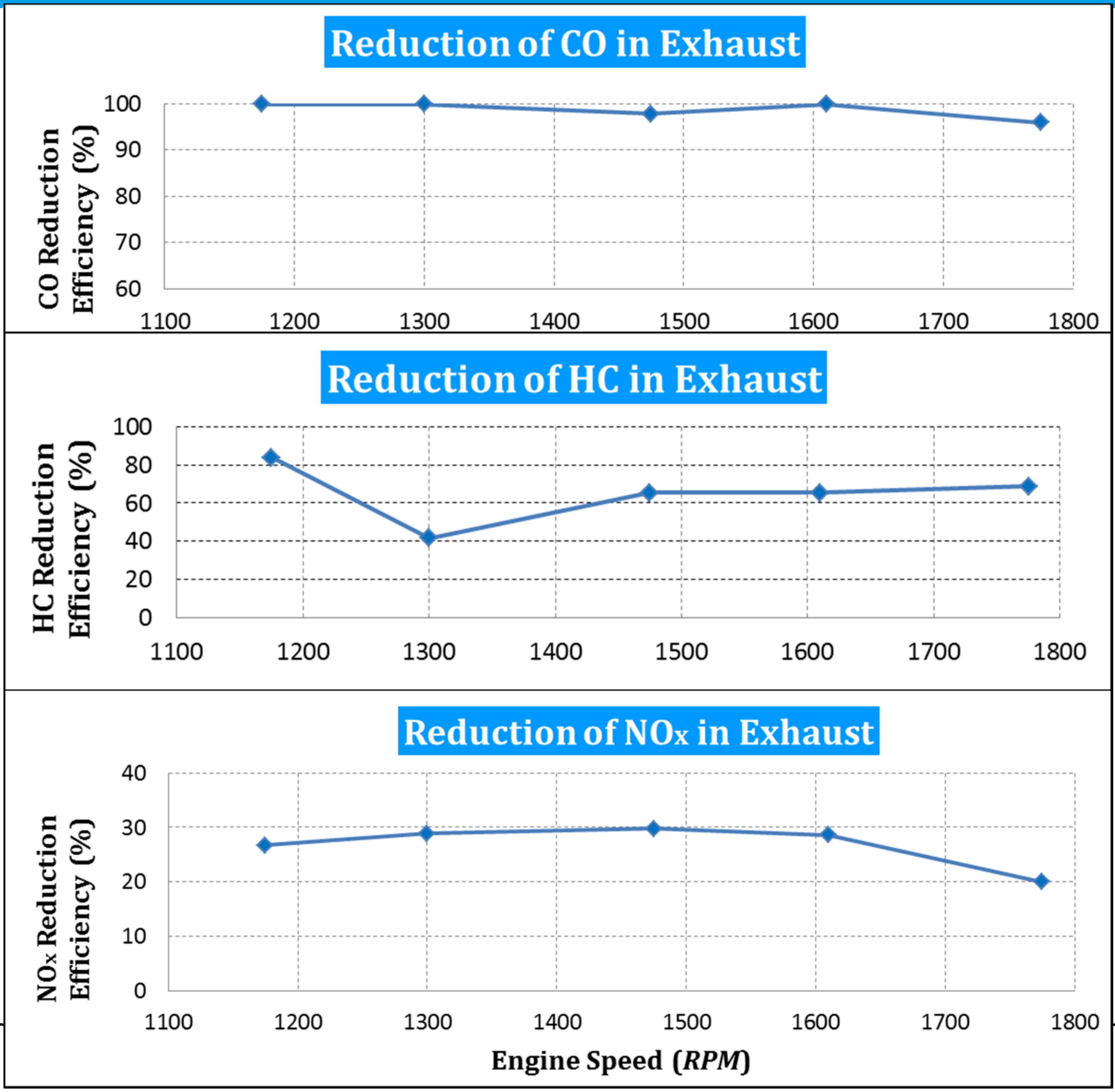
Announcement and Volvo DME truck display on steps of California state capitol

At an event in Sacramento, California, **Volvo Trucks announced that it will commercialize dimethyl ether powered commercial vehicles** in North America, with limited production beginning in 2015. Safeway Inc. will begin field testing two VNLs that use DME under a grant from California's San Joaquin Valley Air Pollution Control District.

"We look forward to further validating DME technology for the trucking industry with Safeway and Oberon," said Göran Nyberg, president of Volvo Trucks North American Sales & Marketing. "We believe the fuel shows great potential for the North American market, **and when produced from biomass, it can provide a 95 percent reduction in CO_2 compared to diesel."**

June, 2013

US Field Test Exhaust Emission Result



Reduction eff = $\frac{\text{g/kwh in} - \text{g/kwh out}}{\text{g/kwh in}}$

Chassis Vehicle Test at Penn State University

<u>Test Procedure:</u>

- VNL 6x4, I-shift
- Rated power, 450 hp@ 1800 rpm. EuV emission
- Fuel economy measurement with full tailpipe emissions.
- Constant 60 mph test and HHDDT cruise cycle test.

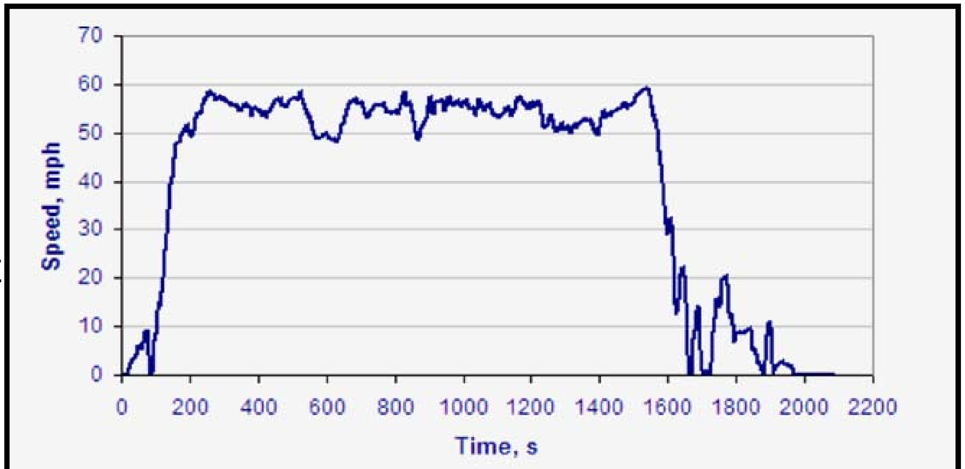


Figure 3. HHDDT Cruise Mode

Chassis Vehicle Test at Penn State University

Measured Parameter	Test Condition					
	60 mph			*HHDDT cruise phase*		
	1	2	Average	1	2	Average
CO_2, g/mi	2000	1994	1997	1792	1780	1786
CO, g/mi	0	0	0	0.88	1.35	1.16
NO_x, g/mi	4.32	3.52	3.92	4.74	3.88	4.31
THC, g/mi	0.02	0.03	0.03	0.19	0.19	0.19
PM, g/mi	0	0.01	0.01	0.06	0.04	0.05
Fuel, mpg-DME	2.66	2.66	2.66	2.97	2.99	2.98

5.5 DGE matches diesel baseline

Summary

- Excellent environmental properties
- Energy-efficient
- Cost-effective
- Global potential for diesel replacement in certain applications
- Technology is demonstrated
- Energy carrier for the future

Future Opportunities

- **Emission development and certification**
- **Component refinement and cost**
- **Reliability and durability demonstration**
- **Lube and fuel additive, continued development**
- **Combustion optimization towards 50% brake thermal efficiency**

Acknowledgements

- Dr. Henrik Salsing, 2011 PhD “DME Combustion in Heavy Duty Diesel Engines”, Chalmers University
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