ENHANCED EMISSION PERFORMANCE AND FUEL EFFICIENCY FOR HD METHANE ENGINES

FINAL REPORT

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INTERNATIONAL ENERGY AGENCY – ADVANCED MOTOR FUELS

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SUMMARY

This is the Final Report dealing with Annex 39 (***Enhanced Emission Performance and Fuel Efficiency for HD Methane Fuelled Engines***) within the framework of the International Energy Agency (IEA) and its Implementing Agreement Advanced Motor Fuels (AMF).

The purpose of Annex 39 is to investigate how far the level of the development of methane fuelled engines for heavy duty vehicles has reached as well as assessing the potential to reach high energy efficiency, sustainability and emission performance.

Annex 39 is split in two phases. The first phase is a literature study and to describe mainly engine and after-treatment technology for methane fuelled engines used in heavy duty vehicles. The result of the survey is presented in a technical report finalized May 2010 and can be found at the web site of AMF (www.iea-amf.org). The second phase of the project present testing carried out in Sweden, Finland and Canada and is presented in this report.

Tests of state-of-the-art technology for methane fuelled heavy duty vehicles have been carried out in Sweden, Finland and Canada based on a Task sharing agreement. Japan (LEVO and JGA), Germany and IEA Bioenergy (DG Energy) contributes to Annex 39 by Cost Sharing.

Measurement has been carried out on chassis dynamometers in laboratories under well specified conditions as well as on the road in real-life operation by the use of Portable Emission Measurement System (PEMS). On-road testing reflects the normal use of a vehicle, such as influence of ambient temperature, topography, vehicle/engine load and driving patterns. Vehicles tested has been spark ignited (SI) dedicated gas engines and vehicles equipped with compression ignited engines (CI) using a combination of methane gas and diesel, at various mixing ratios, as the fuel (diesel dual fuel, DDF/Methane diesel).

Testing in Sweden and Finland has been carried out on heavy duty vehicles using spark ignited engines (SI) as well as engines using diesel dual fuel technology/methane-diesel (DDF). Methane used as fuel has been compressed natural gas (CNG) sometimes mixed with bio gas. In some cases Liquefied Bio Gas (LBG) has been used. Diesel fuel used in Sweden for dual fuel technology has been commercial available environmental classified diesel (Mk1). Diesel fuel used in Finland has been commercial available diesel, meeting EN590 specification. However, in Finland test was also carried out with diesel fuel mixed with blends of bio-components.

Testing in Canada was carried out on a heavy duty vehicle equipped with a diesel dual fuel engine but with different technology. This technology, High Pressure Direct Injection (HPDI), where diesel is injected in the combustion chamber use a small amount of diesel just for igniting the mix of methane gas and diesel. Methane used as fuel is Liquefied Natural Gas (LNG). The diesel fuel meets the U.S. specification for Ultra Low Sulphur Diesel (ULSD).

The tested dedicated gas buses (SI technology) operates only on gas, while the tested dual fuel concepts in Sweden and in Finland could operate both in diesel mode, using only diesel fuel, and in dual fuel mode, using a variable mix of diesel and methane gas. The tested truck in Canada using HPDI-technology could only operate properly when both methane and diesel fuel is available. In case only diesel is available the engine will operate in “limp-home

mode". As reference, a corresponding vehicle with conventional diesel engine has also been tested.

Analyses and sampling of regulated exhaust emission pollutants has been carried out by the use of instruments and equipment meeting requirements specified by latest European and US Requirements. In addition, some measurement of unregulated pollutants has been performed.

Discussions with representative from Asia Pacific Natural Gas Vehicles Association (ANGVA), invited to join AMF ExCo meetings, made it possible to have updates of the general situation for gas fuelled vehicles in Asia. Of specific interest were emission requirements, conversion (retrofit) of vehicles in-use and the importance to reduce the operating cost of vehicles.

The report also contains contribution financed by the Swedish Gas Technology Centre (SGC). A summary of findings from the measurements of unregulated emissions pollutants on exhaust gases and the biological activity in the exhausts are presented. The actual measurements were carried out in Sweden simultaneously as the measurements of the regulated emission for the same vehicles.

Test result from testing heavy duty vehicles equipped with dedicated spark ignited (SI) methane fuelled gas engines show nice emission performance. Chassis dynamometer measurement in Sweden of energy efficiency of the dedicated gas engines is not in the same range as for the heavy duty vehicles when they operated in diesel mode (~ 18% vs. ~ 33%). Tests in Finland revealed results from the tested bus with SI engine well in line with Euro VI emission requirements and is considered as "best in class".

The results from testing heavy duty vehicles equipped with diesel dual fuel/methane diesel technology have shown that the expected theoretical diesel replacement capacity of 75-80% has been very difficult to achieve, particularly at low engine loads. In some odd cases a diesel replacement ratio of only 7% has been verified.

Further, to reach Euro V/EEV and Euro VI emission levels, especially for THC, it is obvious that advanced combustion control, thermal management and updated exhaust after-treatment systems must be a vital part of the emission control system. To manage such a challenge, the original equipment manufacturer (OEM) must be responsible and closely involved in proper design of DDF systems. It could be questioned whether dual fuel technology commercial available on the market today (Jan. 2014) can reach emission requirements for Euro V and later emission requirements.

New dual fuel technology (HPDI 2.0) expected to meet Euro VI and EPA 2014 emission requirement is under development. The plan is to introduce the second generation of HPDI technology as OEM applications late 2014 or beginning 2015. However, during the timeframe of this project there has been no possibility to validate the new system.

Additionally, a newly developed dual fuel systems using the "fumigation" technology meeting Euro IV and V emission requirements was presented February 2014. The new technology, Gas Enhanced Methane Diesel (GEMDi), is intended to OEM to offer fully integrated engine optimized for DDF operation. It is estimated that the average ratio for diesel replacement will be about 60%.

During the duration of the project (although not a part of the project) some concerns have also been given retrofit systems where older heavy duty vehicles (meeting Euro III emission requirements) have been converted to use DDF technology. Limited testing clearly shows that the emission performance will be dramatically negatively affected, except for particle emissions. However, a possible advantage might be to reduce operating costs for the vehicle.

When this project started it was not possible to obtain EU or ECE type approval certificate for heavy duty engines using two different fuels simultaneously (diesel and methane gas). Vehicles using this type of technology could only be accepted in EU Member States based on national exemptions (waiver). US emission regulations open up for this kind of technology and based on diesel/gas ratio, different approach will be applicable. In addition, requirements for emissions of methane are not implemented in US.

However, after pressure from EU member states and the industry work started within the frame of “World Forum for Harmonisation of Vehicle Regulation” (WP 29) by the Working Party on Pollution and Energy (GRPE). The actual work was carried out by the informal group Gaseous Fuelled Vehicles (GVF), with the main objective to modify the present ECE Regulation 49 (Emissions from Heavy Duty Engines) to also include approval procedure for dual fuel technology according to Euro VI emission requirements. The final result is found in the Commission Regulation No 133/2014 of 31 January 2014, amending Directive 2007/46/EC, Regulation (EC) No 595/2009 and Regulation (EU) No 582/2011.

As a summary of key findings for all tests, the following is high-lighted:

- Diesel dual fuel (Methane diesel) concepts:
    - Very difficult to meet mandatory emission standards (Euro V, Euro VI) with present available technology
    - Suitable technology only possible for OEM applications
    - Diesel replacement very much dependent upon load conditions and is not meeting expectations
    - Total emissions of GHG might be higher in dual fuel mode than vehicles operating on diesel fuel

- Dedicated spark ignited engines (SI)
    - No problem to meet Euro V/EEV emission requirements
    - Engine efficiency lower for SI applications compared to diesel especially for lean-mix applications (18% vs. 33%)
    - Lean-mix concept operating mostly on λ1

Some of the vehicles tested in Sweden and included in the test fleet were kindly supplied by Volvo Truck AB.

SVENSK SAMMANFATTNING

Detta är slutrapporten för Annex 39 (***Enhanced Emission Performance and Fuel Efficiency for HD Methane Fuelled Engines***) inom ramen för International Energy Agency (IEA) och dess Implementing Agreement Advanced Motor Fuels (AMF).

Arbetet inom Annex 39 har som syfte att utreda hur långt utvecklingen nått inom området metandrivna motorer för användning i tunga fordon samt undersöka potentialen för olika koncept med avseende på energieffektivitet, hållbarhet och emissionsprestanda.

Annex 39 är indelat i två olika faser. Den första fasen är en litteratur studie och behandlar i huvudsak den teknologi som används för metangas drivna motorer och efterbehandling av avgaserna för tunga fordon. Resultatet av studien är presenterad i en teknisk rapport från maj månad 2010 och finns på amf websida (www.iea-amf.org). Den andra fasen av projektet presenterar provningar som utförts i Sverige, Finland och Kanada och som redovisas i denna rapport.

Provning av senaste teknologi för motorer, helt eller delvis drivna med metangas, har utförts i Sverige, Finland och Kanada baserat på en överenskommelse om att samarbeta (Task share). Japan (LEVO och JGA), Tyskland och Implementing Agreement IEA Bioenergy har bidragit med finansiering av projektet (Cost share).

Mätningar har utförts dels på chassie dynamometer (rullande landsväg) i laboratorier under noga specificerade förhållanden och dels på väg med fordon i normal drift med hjälp av ett Portabelt Emissions Mät System (PEMS). Provning på väg återspeglar normal användning av ett fordon som påverkas av omgivningens temperatur, topografi, fordonets/motorns belastning och körmönster. Fordon som har provats har dels varit utrustade med gnist-tända motorer (SI) som drivs enbart med metangas och dels med kompressions-tända motorer (CI) som drivs med en varierande blandning av diesel och metangas (diesel dual fuel, DDF eller Metan diesel).

Provning i Sverige och Finland har utförts på tunga fordon med gnisttända motorer (SI) likväl som på motorer med dual fuel/metan diesel teknik (DDF). Metangas som används har varit naturgas (CNG) ibland uppblandad med biogas. I vissa fall har flytande biogas (LBG) används. Det dieselbränsle som har används vid provning av dual fuel teknologi i Sverige har varit kommersiellt tillgängligt miljöklassat bränsle (Mk1). Dieselbränsle som använts vid provning i Finland har varit kommersiellt tillgängligt bränsle som uppfyller specifikation EN590. I Finland har även proving utförts med detta bränsle blandat med biokomponenter.

Provning i Kanada har utförts på ett tungt fordon utrustad med en motor som arbetar enligt principen för dual fuel, dock med en annan teknologi. Denna teknologi, High Pressure Direct Injection (HPDI), sprutar in en liten mängd diesel i motorns förbränningsrum enbart med uppgift att tända blandningen av gas och diesel. Den metangas som har använts är flytande naturgas (LNG), och dieselbränslet uppfyller de amerikanska kraven för ULSD (Ultra Low Sulphur Diesel).

De provade gasbussarna med SI-motorer kan endast fungera när metangas finns tillgängligt som bränsle, medan de dual fuel koncept som provats i Sverige och Finland fungerar när en blandning av metangas och diesel finns tillgängligt (dual fuel mode), men kan dessutom fungera även med enbart diesel som bränsle (diesel mode). Den provade lastbilen i Kanada vars motor arbetar enligt HPDI principen kan endast fungera om både diesel och metangas finns tillgänligt. Med enbart diesel kan motorn endast arbeta i ”limp-home mode”. Som referens har ett motsvarande fordon utrustad med konventionell diesel motor också testats.

Analys och uppsamling av avgaskomponenter som är reglerade i lagstiftning har utförts med instrument och utrustning som uppfyller kraven i senaste Europeiska bestämmelserna och i Federala krav i USA (EPA). Dessutom har en del mätningar av oreglerade komponenter utförts.

Diskussioner med representant från Asia Pacific Natural Gas Vehicles Association (ANGVA), inbjuden att närvara vid AMF ExCo möten, har gjort det möjligt att få uppdatering av den övergripande situationen för metangas drivna fordon i Asien. Speciellt intresse ägnades åt emissionskrav, konvertering av fordon i bruk och betydelsen av att sänka rörliga kostnader.

Rapporten innehåller också bidrag från ett projekt finansierat av Svenskt Gastekniskt Center (SGC). Bidraget utgörs av en sammanfattning av resultat från mätningar av oreglerade komponenter samt den biologiska aktiviteten i avgaserna.Dessa mätningar utfördes i Sverige samtidigt som mätningar av de reglerade komponenterna gjordes och som redovisas i denna rapport.

Resultat från provningar av tunga fordon utrustade med metangas drivna SI-motorer uppvisar god överenstämmelse med fastlagda emissionskrav. Mätningar på chassie dynamometer i Sverige visar att energi effektiviteten för en metangas driven SI motor inte är i paritet med en dual fuel motor som arbetar i diesel mode (~ 18% vs, ~ 33%). Resultat från provning i Finland visar att den provade bussen med SI-motor har resultat nära avgaskraven för Euro VI och får anses som ”bäst i klassen”.

Provning av tunga fordon utrustade med motorer med diesel dual fuel teknologi har visat att den förväntade ersättningen av dieselbränsle på 75-80% är mycket svår att uppnå, särskilt vid låg belastning på motorn. I vissa fall har ersättning av diesel endast varit 7%.

För att nå emissionsnivåer för Euro V/EEV och Euro VI, speciellt för utsläpp av totalkolväten (THC), är det uppenbart att avancerade system för avgasrening och avgasefterbehandling måste användas. För att nå sådana mål måste därför den ursprungliga motortillverkaren (OEM) vara ansvarig för utveckling av systemet och nära inblandad i design av konceptet. Det kan också starkt ifrågasättas om det i dag (januari 2014) på marknaden kommersiellt tillgängliga DDF-system kan uppfylla emissionskrav för Euro V eller senare.

Ny DDF teknologi, (HPDI 2.0) som förväntas uppfylla emissionskraven gällande för Euro VI och EPA 2014 är under utveckling. Ambitionen är att lansera andra generationen av HPDI teknologi som OEM lösningar i slutet av 2014 eller början av 2015. Under tidsaxeln för detta projekt har det dock inte varit möjligt att praktiskt utvärdera detta nya system.

Dessutom har ett nytt dual fuel system som använder sig av “fumigation-teknik” och som påstås uppfylla avgaskraven för Euro IV och V presenterats i Februari 2014. Denna teknik, “Gas Enhanced Methane Diesel” (GEMDi), är avsedd för OEM för att kunna erbjuda ett fullt integrerat systems, optimerat för DDF. Målsättningen är att nå en genomsnittlig dieselersättning på ca 60%.

Under arbetet med projektet (dock inte som en del av projektet) har viss uppmärksamhet även ägnats åt system med ombyggnad av äldre motorer som uppfyller kraven för Euro III till att använda en kombination av diesel och gas som bränsle (retrofit). Begränsad provning har dock visat att emissions prestanda har påverkats i negativ riktning, förutom utsläpp av partiklar. Dock kan viss reduktion av rörliga kostnader konstateras då priset för gas i regel är lägre än för diesel.

När detta projekt påbörjades var det inte möjligt att erhålla typgodkännande enligt EU eller ECE kraven för motorer som använder två olika bränslen samtidigt (diesel och gas). Fordon som använder denna teknologi kunde endast bli accepterade i EU medlems stater baserade på nationella dispenser. Utformning av avgaskraven i USA gör det dock möjligt att godkänna denna teknologi dels beroende på graden av dieselersättning och dels att olika principer för gränsvärdesättning tillämpas. Dessutom saknas krav för utsläpp av metan i USA.

Efter påtryckningar från vissa EU medlemstater och industrin påbörjades ett arbete inom ramen för "World Forum for Harmonisation of Vehicle Regulation" (WP 29) genom arbetsgruppen "Working Party on Pollution and Energy" (GRPE). Arbetet har utförts inom den informella gruppen "Gaseous Fuelled Vehicles" (GVF). Resultatet av arbetet resulterade i en modifiering av nuvarande ECE bestämmelse (ECE Regulation 49, Emissions from Heavy Duty Engines) till att också inkludera en process för att kunna godkänna teknologi för DDF enligt kraven för Euro VI. Slutresultatet återfinns i Kommissionens förordning nr 133/2014 av den 31 januari 2014, om ändring av direktiv 2007/46/EG, förordning (EG) nr 595/2009 och förordning (EU) nr 582/2011 för att anpassa dessa till den tekniska utvecklingen avseende utsläppsgränser.

Samanfattning av provning utförd inom projektet:

- Diesel dual fuel (Metan-diesel) koncept
    - Mycket svårt att uppfylla obligatoriska emissionskrav (Euro V, Euro VI) med nuvarand teknologi
    - Teknologi som krävs endast möjlig för tillverkare av motorer (OEM)
    - Diesel ersättning varierar starkt beroende på olika körförhållanden och motsvarar inte ställda förväntningar
    - Totala utsläppen av GHG kan vara högre för "dual-fuel mode" än för motsvarande fordon vid dieseldrift

- Gasmotorer med gnisttändning, tändstift (SI)
    - Inga problem med att uppfylla emissions krav enligt Euro V/EEV
    - Energieffektivitet lägre för SI motorer jämfört med diesel särskilt för lean-mix konsept (18% vs. 33%)
    - Lean-mix konsept arbetar merparten av tiden med $\lambda 1$

Slutligen, en del av fordonen som provades i Sverige och som ingår i provflottan, ställdes välvilligt till förfogande av Volvo Lastvagnar AB.

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2. BACKGROUND

Availability to energy resources is a key to economic growth and hence the welfare state. Due to the rapidly increasing levels of Green House Gases (GHG) in the atmosphere and to secure energy, the quest for sustainable alternatives to fossil fuels is of great immediate importance. Besides from cost effective manufacturing the ideal candidate fuel should be compatible to present engine technologies without impairment of emission performance. This is of particular importance for countries where the fleet of vehicles is rather old and where the prospect of implementing new advanced vehicle technologies in the near future seems farfetched. Methane is a good candidate fuel, but emissions to the atmosphere must be strictly avoided since it is a strong GHG. Latest revision of the Global Warming Potential (GWP) is estimated to 86 on a time horizon of 20 years, and 34 on a time horizon of 100 years, going from 72 respectively 25 estimated in year 2007, and 62 respectively 23 estimated in year 2001. (Intergovernmental Panel on Climate Change, IPCC, *Climate Change 2013, the physical science basis,* http://www.ipcc.ch/report/ar5/wg1/).

Some of the existing technologies using methane as fuel suffer from problems with methane slipping through the combustion process (methane slip) and the exhaust after-treatment system if no special devices are installed. Furthermore, vehicles fuelled with liquid methane (LNG/LBG) suffer, under various conditions, from leakage of methane from the fuel storage system to the atmosphere (boil-off). Tests to verify the amount of boil-off has not been further investigated within this project. Important, however, is to recognize that European emission regulation do not include limit values for methane leaking to the atmosphere. Methane has a great potential as alternative fuel but nonetheless the gas engine technology still need some improvements.

Methane is commercially available in the forms of bio gas and natural gas. Bio gas is produced by anaerobic processing of organic waste products. Unlike bio gas, natural gas is extracted from the ground which means that it is a fossil fuel and could not be classified as a sustainable source of energy. However, natural gas still has an advantage over petrol- and diesel fuel since it is usually found in connection with extraction of crude oil in the ground as a bi-product. Therefore it is better to use the methane as fuel rather than releasing it directly to the atmosphere or burning it (flaring). Other arguments for changing over to natural gas from petrol and diesel are a potential to cleaner exhaust gas (no emissions of particulates) and that natural gas could be more economically beneficial.

Effort has been made to assess the emission performance and fuel efficiency for Heavy Duty methane engines within Annex 39 of the implementing agreement for a programme on research and demonstration on Advanced Motor Fuels (AMF). AMF functions within the framework of the International Energy Agency (IEA).

3. INTRODUCTION

The contribution to this Annex by the participating Member Countries consist of either cost sharing (financing) or task sharing activities (results delivered at the latest in March 2014, as reports on testing)

Sweden (via Swedish Transport Administration) acts as the Operating Agent (OA) and thereby responsible for the project.

Cost sharing partners for phase 2 of the project are:

- ***Japan*** (Organization for the promotion of low emission vehicles, LEVO and Japan Gas Association, JGA)
- ***Germany*** and,
- ***DG Energy*** via IEA Bioenergy

Member States or organizations participating on a task sharing basis for phase 2 of the project in form of providing information or test results from national programs, are:

- ***Asia Pacific Natural Gas Vehicles Association***, ***ANGVA***;
  - Providing information about natural gas vehicles in Asia and statistics on CNG consumption in Asia.
- ***Canada and Finland***
  - Providing test results of methane fuelled HD vehicles participating in national program.

Financing of the project by cost sharing Member States and organization has made it possible to carry out sophisticated testing of state-of-the-art methane fuelled heavy duty vehicles on chassis dynamometer in controlled laboratory conditions as well as during real operation under various driving conditions such as ambient and engine temperatures, vehicle load, driving pattern etc. In overview, testing has been conducted with the following engine technologies:

	Tested in
• Diesel dual fuel – (Westport, HPDI); LNG, OEM	Canada
• Diesel, as reference – Conventional	Canada
• Diesel dual fuel – (Hardstaff); CNG, Retrofit	Finland
• Dedicated methane (SI) – Stoichiometric combustion, CNG, OEM	Finland
• Diesel dual fuel – (Hardstaff); CNG, Retrofit	Sweden
• Diesel dual fuel – (Clean Air Power); LBG, Retrofit/OEM	Sweden
• Diesel dual fuel – (Clean Air Power); LNG, OEM	Sweden
• Dedicated methane (SI) – lean-mix combustion, CNG, OEM	Sweden
• Dedicated methane (SI) – lean-burn combustion, CNG, OEM	Sweden

Overview of test program in Sweden

The results from tests carried out in Sweden by AVL MTC, presents measurements on five different vehicles equipped with engines entirely or partly fuelled with methane gas (Four of the vehicles are tested within the scope of the project). Two of the vehicles were equipped with spark ignited dedicated gas engines. The three remaining vehicles were all equipped with compression ignited diesel dual fuel (DDF) engines (methane-diesel) which were fuelled with diesel and blends of methane gas at various mixing ratios.

Further, test results from one additional vehicle with DDF technology from NGV Motori, Italy representing a "pure" retrofit application has been included in the report, despite that the actual testing was not a part of the project.

From a parallel project, financed by Swedish Gas Technology Center (SGC), a summary of measurements of unregulated pollutants is included in the report.

Overview of contribution and test program in Finland

The contribution to this report from Finland is based on testing at VTT Technical Research Center of Finland. The report including result from testing is presented in Annex 2.

Two vehicles equipped with compression ignited diesel dual fuel (DDF) engines fuelled with blends of diesel and methane gas at various mixing ratios were tested. The tested vehicles used identical technology (Hardstaff, "DDF2") as the vehicles tested in Sweden.

One dedicated CNG (SI) bus approved according to European EEV (Enhanced Environmental Vehicle) emission requirements was tested on chassis dynamometer.

Further, as a task sharing contribution to Annex 39, Finland and VTT agreed to make its bus database available, including the measurements carried out for AMF Annex 37. This contribution is attached in Appendix 1 of the report describing the tests carried out in Finland. This excellent data base makes it possible to compare emission performance and energy consumption from heavy duty vehicles operating on different fuels from Euro I to Euro V/EEV engine technology.

Overview of test program in Canada

The contribution to this report from Canada is based on testing at Environment Canada. The report/result from testing is presented in Annex 3.

Two similar heavy duty vehicles were tested on chassis dynamometer according to various driving cycles. One of the vehicles was equipped with an engine using diesel dual fuel technology (HPDI). However, this technology is not yet approved according to EU/ECE emission regulation, but approved for use on the North American market. For reference, a heavy duty truck with conventional diesel engine from the same manufacturer, model year and similar engine was also tested. Except for pollutants specified in (U.S.) Regulations also nitrous oxide (N_2O) was analyzed.

4. RATIONALE

The main objectives with the testing were to verify real life emissions and compare the results with results from testing on chassis dynamometer and to validate the potential of methane fuelled heavy duty vehicles.

The purpose of the project and the test program, was to evaluate the performance of methane fuelled heavy duty vehicles considering the following points:

1. Energy efficiency
2. Emissions
3. Fields of application

Energy efficiency was calculated by comparing the energy content of the fuel consumed during the test with the actual work executed during the test. The energy efficiency is a strong indicator of fuel economy but also, to some extent, an indicator of climate effects. The climate is affected by emissions of green-house gases, GHG e.g. carbon dioxide (CO_2) “hence energy efficiency” and methane (CH_4) and particles. The most well-known transport related air pollutants, from diesel fuelled engines, impairing air quality are oxides of nitrogen (NO_x) and particulate matter (PM). However, there are several other groups of unregulated chemical compounds in exhaust gases that impacts human health e.g. polycyclic aromatic hydrocarbons (PAH), aromatic compounds and carbonyl compounds.

In order to gain more knowledge about emissions of these pollutants from methane fuelled vehicles, Swedish Gas Technology Centre (SGC) financed measurements of unregulated compounds, mentioned above. The results from SGC measurement program are presented in the report as a summary and the full report (SGC Report 2013:289) can be found at the website of SGC (http://www.sgc.se/ckfinder/userfiles/files/SGC289.pdf).

Similar measurements on unregulated compounds were previously carried out on diesel engines in Sweden by AVL MTC. The project was financed by the Swedish Transport Administration (STA). The main objective with the project was to verify the difference in emission performance when using European specification (EN590) for diesel fuel compared to Swedish environmental classified diesel, Mk1 on modern heavy duty diesel engines. These data on unregulated emissions can serve as reference to the results of unregulated emissions obtained from measurement on gas fuelled engines within Annex 39. The report is available at the web site of Swedish Transport Administration.
http://www.trafikverket.se/PageFiles/65300/delrapport_emissionsmatning_tunga_fordon.pdf

The different concepts of gas fuelled engines have different weaknesses and strengths which would complicate decision maker’s efforts to choose the most suitable technology for any given field of application. In this report, recommendations regarding fields of application for the different tested concepts are mentioned.

The test program was designed to mimic real world usage of heavy duty vehicles. To achieve real world conditions the tests were performed on-road using a Portable Emission Measurement System (PEMS) and on a chassis dynamometer. The tests on the chassis dynamometer were carried out according to the World Harmonized Vehicle drive Cycle (WHVC) (http://www.dieselnet.com/standards/cycles/whvc.php) and the FIGE drive cycle (for reference, see below). The WHVC is the chassis dynamometer version of the World Harmonized Transient Cycle (WHTC) (http://www.dieselnet.com/standards/cycles/whtc.php) .

In a similar way FIGE is an almost identical version of the European Transient Cycle (ETC) (http://www.dieselnet.com/standards/cycles/etc.php) but intended for testing on chassis dynamometers. Further information of test cycles can be found in Paragraph 6.3, Test cycles.

5. VEHICLES TESTED IN SWEDEN

5.1 Vehicle specifications

Table 1 below present an overview of the vehicles included in the Swedish test program. In addition, one extra vehicle is included in the figure (DDF3) as a typical representative vehicle subjected to retrofit program. Such buses have been in normal operation for several years and the intention is either to improve the emission performance or simply reduce operating cost for the vehicle.

The two dedicated gas buses represent state-of-the-art technology and are offered on the market as new buses (OEM) by manufacturers in Europe. As input from task sharing members of Annex 39 there is a wish for adding more test results and experience for vehicles using dedicated gas engines.

The two trucks named DDF1 and DDF2 is offered as new vehicles (OEM) by a manufacturer in Europe. The working principal for those two engines are dual fuel technology and at the time for testing such technology could not be approved in Europe. The vehicles are therefore accepted on the road based on a national waiver. This system is commonly used in Europe for field testing of technology not mature enough for the commercial market. As input from task sharing members of Annex 39 there is a wish for adding test results and experience for DDF concepts not yet available on the European market as well as tests results from DDF vehicles that have been in normal operation for longer time.

Table 1. Specifications of vehicles tested in Sweden.

	DDF1	**DDF2**	**DDF3**	**SI-lean burn**	**SI-lean/mix-burn**
Model year	2011	2010	2003	2010	2010
CD Test weight (tons)	~20	-	18.8	14.1	13.8
PEMS Test weight (tons)	~20 and~40	9.1	-	14.1	13.8
Retrofit/OEM	Retrofit/OEM	Retrofit	Retrofit	OEM	OEM
Gas system	Clean Air Power (CAP)	Hardstaff	NGV Motori	Dedicated SI	Dedicated SI
Cylinder volume (dm^3)	13	7	12	9	13
Max power (kW)	345	181	250	199	228
After-treatment	DOC, SCR	SCR	CRT	DOC, SCR	TWC
Fuel	Diesel/LBG	Diesel/CNG	Diesel/LNG	CNG	CNG
Emission class	Euro V	Euro V	Euro III	EEV	EEV
Chassis	Tractor	Truck	Intercity Bus	City bus	City bus
Odometer (km)	- - -	22 500	n.a.	15 500	85 793
Note	Test on-road at +5°C	Test only on-road	Test only on chassis dyno	Test on-road at -2°C	Test on-road at +10°C

Vehicles tested in the special program promoted by Swedish Gas Technology Centre (SGC) as well as the measurements of unregulated compounds were the following three vehicles:

1. Dedicated CNG bus with SI-lean/mix combustion, a technology alternating between stoichiometric and lean combustion. During the test program the CNG was supplied from the tank on the vehicle and was filled with gas from a commercial filling station.
2. A long haul truck using dual fuel technology. Modification of the engine and fuelling system was carried out in close cooperation with the manufacturer of the vehicle. The vehicle/engine was also modified to use liquefied biogas (LBG) as fuel. Both the bio gas and the diesel were supplied by the manufacturer of the vehicle.
3. Dedicated CNG bus with lean-burn combustion, a technology with air excess. During the test program the CNG was supplied from the tank on the vehicle and was filled with gas from a commercial filling station.

6. CLARIFICATION OF TESTS CARRIED OUT

The results from testing in Sweden of five different vehicles with methane fuelled engines are included in this report.

Two of the vehicles were equipped with dedicated spark ignited (SI) methane fuelled engines, one with lean-burn technology and one with lean/mix-burn technology. The lean/mix-burn engine operated at lambda (λ) between 1 (stoichiometric) and 1.65 (lean). However, the lean mode (ƛ = 1.65) was only active during the first minutes after cold start and subsequently the engine switched to stoichiometric combustion almost immediately.

The three DDF vehicles were all operating according to the same fuel injection strategy, port injection for gaseous fuel and direct injected diesel. All the three DDF vehicles suffered from high methane (CH_4) emissions under the DDF mode.

The thermal efficiency of a combustion engine is associated with the compression ratio. This could explain the difference in energy efficiency between the DDF and dedicated gas engines where the dedicated gas engines (lean-burn and lean/mix-burn) showed lower energy efficiency than the DDF engines. In general the compression ratio of compression ignited (CI) DDF engines is significantly higher than for SI-engines, hence the difference in energy efficiency between the tested concepts. The energy efficiency of the lean-burn engine ranges between the lean/mix and the DDF engines. This could be explained by the fact that lean-burn engines are less throttled than lean/mix and stoichiometric engines, especially at low loads.

Furthermore, the on-road measurements generated higher energy efficiencies than tests performed on the chassis dynamometer. The energy efficiency calculated from the chassis dynamometer is based on the energy transferred from the engine crankshaft via the transmission and further to the wheels and to the driving rollers of the dynamometer. The calculations of the energy efficiency when the vehicle is tested on the road are based on the calculated torque signal from the electronic control unit (ECU) of the vehicle and should represent the energy delivered by the crankshaft. These different approaches to calculate energy efficiency could explain the differences between the on-road tests using the PEMS and the tests on chassis dynamometer (CD). This is further elaborated in European Euro VI emission requirements were more focus is given the torque signal from the vehicle ECU.

To give a brief overview about the performed type of tests carried out on the different test vehicles, Table 2 can serve as a guide. Test cycles named WHVC and FIGE is carried out on chassis dynamometer under controlled test conditions in a laboratory. Both types of tests is related to certification/approval of engines intended for use in heavy duty vehicles, but are adopted to be used on a chassis dynamometer instead on an engine test bed needed for the formal approval of an HD engine.

Ambient temperature during the chassis dynamometer tests is in the range of 21-24°C, but some testing has been started with a warmed up engine were the temperature of the cooling liquid has been raised to the same temperature as when driving on the road (70-85°C). This was achieved by driving the vehicle on the chassis dynamometer for some time, (conditioning). Experience clearly shows different emission behavior depending upon temperature. It is further verified that temperature of the exhaust gases will have a significant influence on the performance of exhaust after-treatment devices. In most cases the tests has been repeated two or three times for accuracy.

Measurements have been carried out on the road according to a route called “PEMS route”. This test route has been used as the normal route with vehicles in normal operation and during various driving conditions. The ambient temperature is fluctuating depending upon time of the year and tests have been carried out even below freezing point. Vehicles have been tested at different loads, ranging from curb weight to gross vehicle weight for the tested vehicle combinations. Further, vehicles have also been tested using more or less demanding drive routes (uphill-downhill-acceleration). Most tests on road have been repeated several times, as identical as possible, for accuracy.

Additional explanation about on road testing will follow in Paragraph 6, Measurements

Table 2. Test matrix for vehicles tested in Sweden.

Test	mode	Vehicle				
		CI	CI	CI	SI	SI
		DDF 1	DDF 2	DDF 3	lean/mix-burn	Lean burn
WHVC_cold	Diesel	X				
WHVC_cold	Gas				X	X
WHVC_cold	DDF	X				
WHVC_hot	Diesel	X				
WHVC_hot	Gas				X	X
WHVC_hot	DDF	X				
FIGE	Diesel	X		X		
FIGE	Gas				X	X
FIGE	DDF	X		X		
PEMS route_Sthlm	Diesel	X	X			
PEMS route_Sthlm	Gas				X	X
PEMS route_Sthlm	DDF		X			
PEMS route_Gbg	Diesel	X				
PEMS route_Gbg	DDF	X				
PEMS bus route_hot	Gas				X	X

As can be seen from the table above, most attention was given the test program for vehicle DDF 1 since this concept was considered to be the closest one to series production at the time for the tests.

7. MEASUREMENTS

7.1 PEMS – Portable Emission Measurement System

For on-road measurement, two different units of PEMS have been used. One unit is Semtech-DS, developed by Sensors Inc. USA and one unit is M.O.V.E (Mobile on-board Vehicle Equipment), developed by AVL List GmbH, Austria.

Both devices are developed for testing all classes of light as well as heavy duty vehicles under real-world operating conditions. The instruments consists of on-board emissions analyzers which enables tailpipe emissions to be measured and recorded simultaneously while the vehicle is in operation. Sampling of data and measurements is carried out on a second-by-second basis.

The following measurement subsystems are included in the emission analyzers of both instruments:

- Heated Flame Ionization Detector (HFID) for total hydrocarbon (THC) measurement.
- Non-Dispersive Ultraviolet (NDUV) analyzer for nitric oxide (NO) and nitrogen dioxide (NO_2) measurement.
- Non-Dispersive Infrared (NDIR) analyzer for carbon monoxide (CO) and carbon dioxide (CO_2) measurement.
- Electrochemical sensor for oxygen (O_2) measurement.

The Semtech-DS instrument uses the flow data together with exhaust component concentrations to calculate instantaneous and total mass emissions. The two instruments are operated in combination with identical electronic vehicle exhaust flow meter, Semtech EFM. The flow meter is available in different sizes depending on engine size. All tests in the project were carried out with a 4” flow meter, which was suitable for the engine sizes of the tested vehicles.

In addition to the gas analyzing instrument (Semtech-DS) an AVL 483 Micro Soot Sensor was used to measure the soot emissions. The AVL 483 Micro Soot Sensor works on a photo-acoustic principle (PASS) and the cell design chosen (called the "resonant measuring cell") allows a detection limit of ≤10 µg/m^3, (typically ~ 5 µg/m^3).

The AVL MOVE PM PEMS combines the AVL photo-acoustic soot measurement principle with a gravimetric PM measurement which operates with a gravimetric filter. The time-resolved particulate emissions are calculated by weighing the loaded gravimetric filter after the end of the tests and additionally using the time resolved soot signal and the exhaust mass flow as inputs. The complete system consists of two 19” enclosures for the Micro Soot Sensor Measuring Unit (MSS), the Gravimetric Filter Module (GFM) and an external heated dilution cell and transfer line.

The program for calculation of emissions (EMROAD) from the PEMS instruments is developed by JRC (Joint Research Center of European Commission).This program is also used for verification of compliance for heavy duty vehicles in accordance with Euro VI emission requirements for in service conformity.

The on-road testing and calculation has for all vehicles been performed in accordance with the PEMS Pilot protocol. According to the PEMS Pilot protocol the measurements should be carried out during a normal working day representative for the vehicle type and if possible include hill climbs, segments with cruising at constant speed and segments that is highly transient in their character as well as different altitudes. The PEMS Pilot protocol is now further developed and is a part (Annex II) of the Euro VI emission requirements (http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2011:167:0001:0168:EN:PDF)

7.2 Chassis Dynamometer

The heavy duty chassis dynamometer is a cradle dynamometer with 515 mm roller diameters. The maximum permitted axle load is 13 000 kg. Vehicle inertia is simulated by flywheels in steps of 226 kg from 2 500 kg to 20 354 kg. The maximum speed is 120 km/h without flywheels and 100 km/h with flywheels.

Two DC motors, each 200 kW maximum load, and separate control system serves as power absorption units. The DC motors and their computer-controlled software enable an excellent road load simulation capability. The software sets the desired road load curve through an iterative coast down procedure with test vehicle on the dynamometer.

An AVL PUMA computer system is used as a superior test cell computer for engine monitoring and also for the measurement and collection of all data emanating from the vehicle, emission measurement system and test cell.

The sampling- and analysing equipment are based on full flow dilution systems, i.e. the total exhaust is diluted using the CVS (Constant Volume Sampling) concept. The total volume of the mixture of exhaust and dilution air is measured by a CFV (Critical Flow Venturi) system. For the subsequent collection of particulates, a sample of the diluted exhaust is passed to the particulate sampling system. The sample is here diluted once more in the secondary dilution tunnel, a system referred to as full flow double dilution.

According to the regulations for steady state tests, the raw exhaust gases are sampled for further gaseous analysis before the dilution in the tunnel occurs. For transient tests the diluted exhaust gases are both bag-sampled and sampled on-line. Through the CVS system a proportional sampling is guaranteed.

The equipment used for analysing the gaseous regulated emissions consist of double Horiba 9400D systems. Hereby exists the possibility to measure both diluted and raw exhaust emissions on-line simultaneously. The sampling system fulfils the requirements of European emission regulations and also the U.S. Federal Register in terms of sampling probes and heated lines etc.

The following measurement subsystems are included in the emission analyzers of both instruments:

- Heated Flame Ionization Detector (HFID) for total hydrocarbon (THC) and methane (CH_4) measurement.
- Chemiluminescence (CL) analyzer for nitrogen oxides (NO_x) measurement.
- Non-Dispersive Infrared (NDIR) analyzer for carbon monoxide (CO) and carbon dioxide (CO_2) measurement.
- Carbon balance of HC, CO and CO_2 for calculation of fuel consumption (Fc)
- Measurement by PLU for liquid fuel flow meter

The total fuel consumption (Fc) was calculated using the carbon balance method. The diesel consumption was also measured with a PLU (fuel mass flow meter measuring device). The deviation between the PLU and the carbon balance results shall ideally be equal to zero when running on diesel only. In dual fuel mode the PLU measures the diesel consumption and the carbon balance will show the total carbon consumption. The difference between the two will equal the gas consumption.

The particulate emissions were measured gravimetrically by the use of glass fibre filters. The diluted exhausts were sampled on the filters according to standard procedures. Two filters were used, mounted in series.

In the specification of the fuel, the fuel energy content is normally specified. The energy consumption can thereby be calculated by multiplying the energy content of the fuel with the proportion of each of the fuels. In this case there have been no fuel specifications available for the test result calculations. Instead have the lower heating values 43 MJ/kg for diesel and 45.48 MJ/kg for gas been used.

An Electrical Low Pressure Impactor (ELPI) was used for particle size distribution. The instrument is manufactured by Dekati Ltd. in Finland. The principle of the ELPI instrument is described below.

Before entering the ELPI instrument, the exhaust gases are diluted in order to reduce their concentration. In this case, sampling was carried out from the full flow primary dilution tunnel. The diluted exhaust is drawn through the instrument using a vacuum pump. In an impactor, the particles are classified according to their aerodynamic diameter. The ELPI impactor is equipped with a filter stage, and measures particle size distribution in 12 stages in the size range of 7nm to 10um. Before entering the first impactor stage the particles are charged using a unipolar charger. The particles are collected on a specific impactor stage and produce an electrical current that is recorded in real time using a multichannel electrometer.

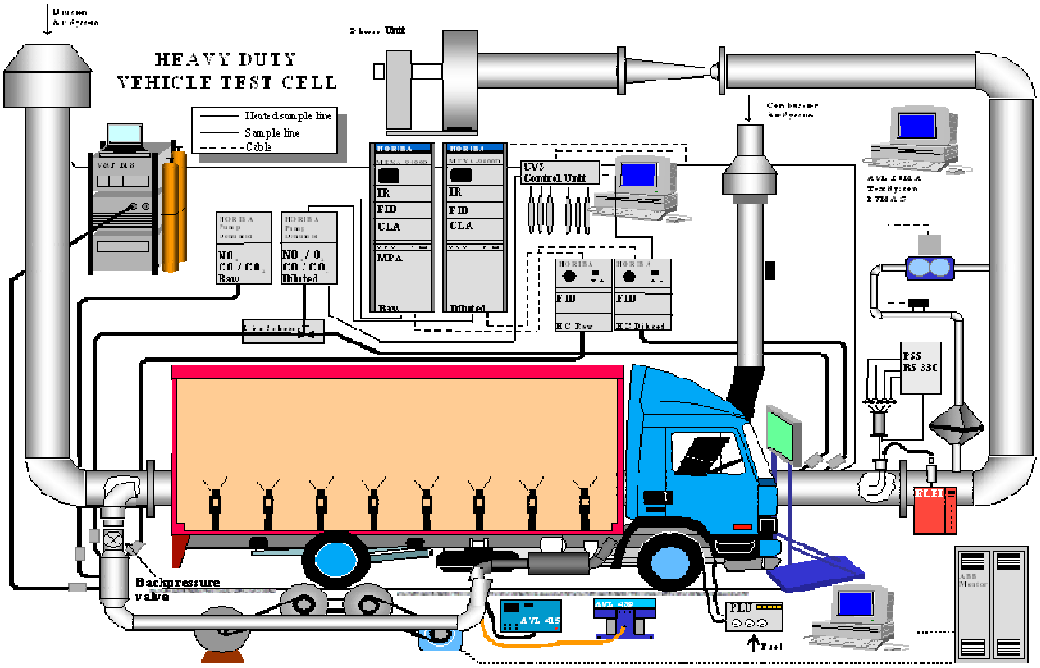


Figure 1. Typical lay-out of heavy duty chassis dynamometer.

7.3 Test cycles

7.3.1 WHVC driving cycle on chassis dynamometer

The WHTC (World Harmonized Transient Cycle) test cycle will become the future test cycle (probably to be introduced for later version of Euro VI emission requirements) for certification of engines intended for use in heavy duty vehicles. The formal EU approval procedure consists of testing of a stand-alone engine on an engine test bed in accordance with the test cycle specified as WHTC. The engine, including necessary exhaust after-treatment device, is tested on its own merits i.e. without gearbox, drive train and any auxiliaries for proper operation in a vehicle. The test cycle is well specified and should reflect normal operation of heavy duty vehicle as well as the procedure to condition the engine before the actual test starts. However, not all modes of operation, especially low loads, are reflected by the test cycle.

To verify emission performance of engines used in heavy duty vehicles is a time consuming and expensive task. The engine has to be removed from the vehicle and tested in an engine test cell and after tests are completed, the engine has to be reinstalled in the vehicle again. Therefore, huge efforts have been made to transform test cycles and procedures used in engine test cells to instead be used on chassis dynamometers for testing the whole vehicle.

In the case of WHVC (World Harmonized Vehicle Cycle), the test cycle was developed by sampling of information about actual driving pattern form heavy duty vehicles in normal operation. This test cycle was then further developed to be used for engine testing (WHTC).

The WHVC is fully not identical to the WHTC since it was only an intermediate step from data collection to engine test bench cycle. Especially, grade of accelerations have to be considered as well as the use of gearbox. The bottom line is however, that the WHVC driving cycle is accepted by the industry to give a rough estimate about the emission performance of an engine installed in a heavy duty vehicle. The emission results can be presented either in g/km but also possible to convert to g/kWh using estimations of executed work during the transient test cycle.

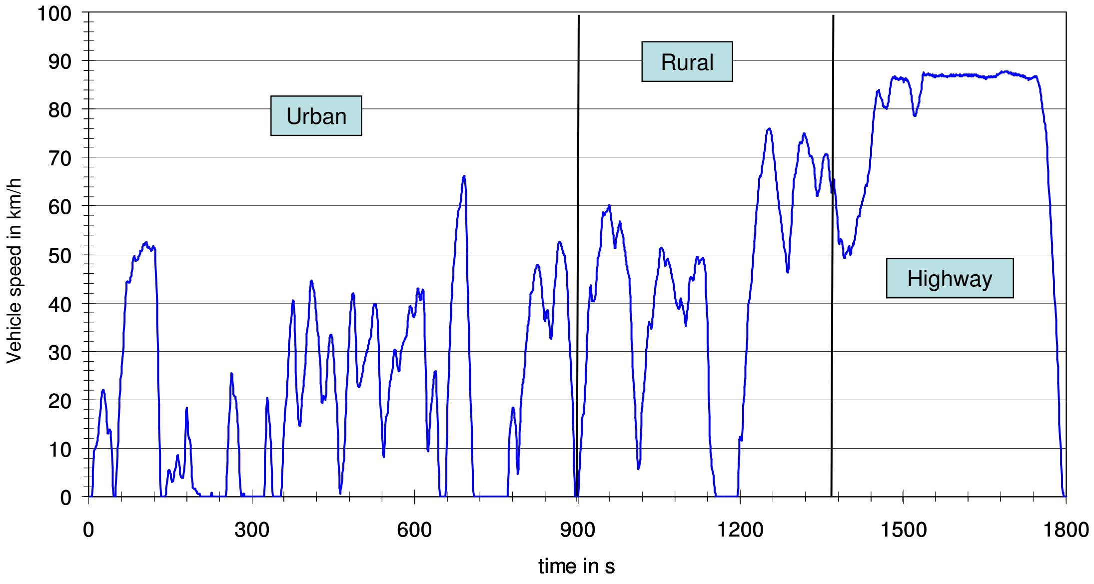


Figure 2. Characteristics of the WHVC driving cycle

During the test program carried out in Sweden the transient driving cycle WHVC was used.

Different driving conditions are represented by the three parts, urban, rural and highway driving. Before the actual test was started, the vehicle was pre-conditioned on the chassis dynamometer by driving the vehicle on the dynamometer with a steady speed for a specific time either to reach stabilization of the coolant temperature (70-85℃) or stabilization of exhausts temperature.

The duration of the entire WHVC cycle is 1800 sec. The main properties of the test cycle are:

- The first 900 seconds represents urban driving, average speed of 21 km/h and maximum speed of 66 km/h. This part includes frequent starts, stops and idling.
- The following 468 seconds represents rural driving, average speed of 43 km/h and maximum speed of 76 km/h.
- The last 432 seconds are defined as highway driving, average speed of 76 km/h.

7.3.2 FIGE driving cycle on chassis dynamometer

A test cycle for verification of emission performance from heavy duty vehicles has been developed by the FIGE Institute of Germany. The test cycle is called the FIGE test cycle and is based on measurement from real road driving of heavy duty vehicles. FIGE Institute developed the cycle in two variants, one for chassis dynamometer testing and one for engine dynamometer test. The engine dynamometer version is a shortened and slightly modified version of the test and is used for certification purposes of engines intended for heavy duty vehicles and called ETC cycle (European Transient Cycle).

The duration of the entire cycle is 1800 sec. The duration of each part is 600 sec.

- Part one represents urban driving, maximum speed of 50 km/h, frequent starts, stops, and idling.
- Part two is rural driving starting with a steep acceleration segment. The average speed is about 72 km/h
- Part three is motorway driving, average speed of about 88 km/h.

During the test program carried out in Sweden the transient driving cycle FIGE was used.

Different driving conditions are represented by the three parts urban, rural and highway driving. Before the actual test was started, the vehicle was pre-conditioned on the chassis dynamometer by driving the vehicle on the dynamometer with a steady speed for a specific time either to reach stabilization of the coolant temperature (70-85℃) or stabilization of exhausts temperature.

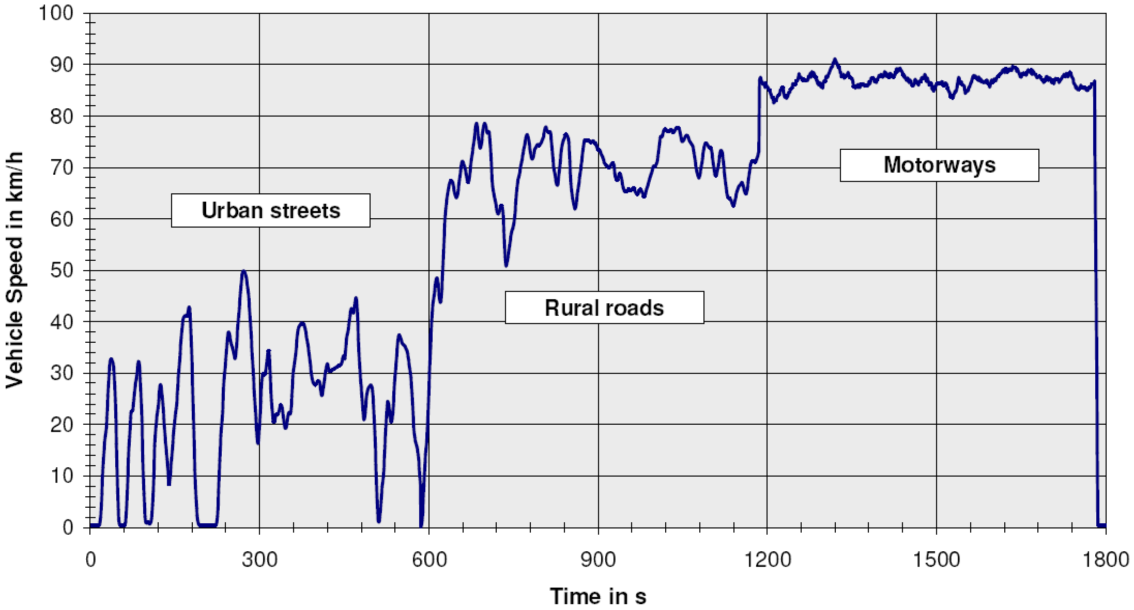


Figure 3. Characteristics of the FIGE driving cycle

7.3.3 PEMS route

During the past years, measurement of emission performance on road with vehicles in normal operation has been more of interest, partly because experience shows big differences in exhaust emissions performance when an engine is tested in well-controlled laboratory environment according to the set requirements and when the same engine is installed in a vehicle operating on the road under normal operating conditions. Further, questions have been raised why the ambient air quality not has been improved in the same manner as emission limits are becoming more stringent. Measurement of vehicles in use by PEMS (Portable Emissions Measurement System) has therefore become more important to verify real-life emissions.

Around year 2000, efforts started by JRC to develop a method to measure emissions from vehicles in normal operation using a portable measurement system. Together with the measuring method, JRC also started to develop a method for calculation of the measured emission (EMROAD). The work has been carried out together with industry and interested Member States. The result is a method now mandated in European legislation and fully implemented for Euro VI emission regulations as a mean to verify emission compliance on heavy duty vehicles in use.

The on-road tests of vehicles in this project have been carried out in accordance with the requirements (PEMS protocol). Calculation has been carried out according to the EMROAD method. The design of the actual test routes meeting the requirements of the protocol can further be split into different types such as “the vehicle in normal operation” or a specific route designed to include urban, rural and highway driving.

There are two different methods for calculation of emitted exhaust emissions. One method is to verify whether engines mounted in heavy duty vehicles meet set emission requirements for European type approval. The other method is to calculate total emissions when a vehicle is moving from a point A to a point B. The first method for calculation only account for those measuring points (area) in the engine map (rpm/torque) that corresponds to those measuring points (area) subjected to the engine tests for European type approval. The purpose of this approach is that the engine should be tested as identical as possible for type approval as for in service conformity. The other method for calculation is to include all measurements during the trip including all transient conditions, low load and periods of idle (called “all events”). During most of the tests in Sweden the “all events” method has been used to present “real-life emissions”.

Although the requirements are set, there are still possibilities to interpret the requirement in different ways. During the testing another test route have also been used, by purpose, reflecting more aggressive driving, especially since we have noticed that “diesel replacement” for the tested dual fuel technology vehicles will vary depending upon engine load and payload.

Figure 4 below, represent a test route used mainly for references. The route has the following main data:

- Approximate trip duration: 5 000 seconds
- Average trip distance: 77 km
- Average speed: 55 km/h (of course dependant on traffic situation)
- Trip composition:
    - Urban driving: 43%
    - Rural driving: 17%
    - Highway driving: 40%
    - Acceleration: 18%
    - Deceleration: 18%
    - Cruising: 57%
    - Idle: 7%

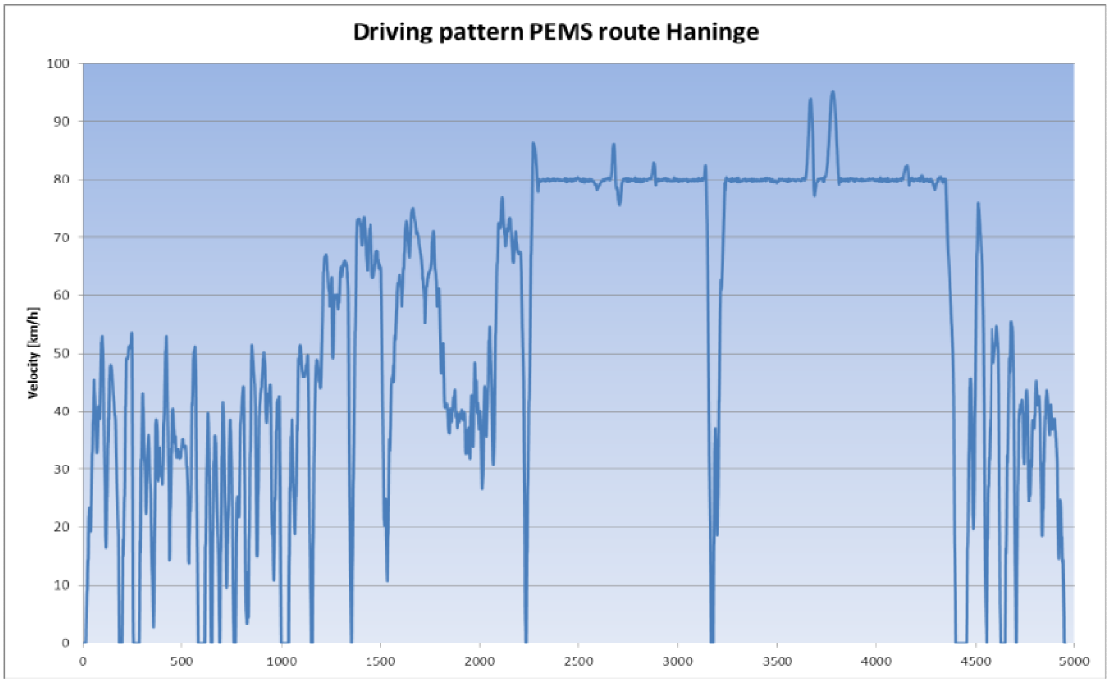


Figure 4. PEMS Test route in the Stockholm area

Another test route, in the Gothenburg area, has also been used for testing. This test route (PEMS Test Route Gbg, Figure 5) is more aggressive (uphill and downhill) but still meeting the same criteria as the one mentioned above, but with complete different characteristics. The results from test using different routes will of course differ.

- Approximate trip duration:	14 800 seconds
- Average trip distance:	220 km
- Average speed:	54 km/h (of course dependant on traffic situation)
- Trip composition:	
o Urban driving:	38%
o Rural driving:	22%
o Highway driving:	40%
o Acceleration:	15%
o Deceleration:	12%
o Cruising:	60%
o Idle:	13%

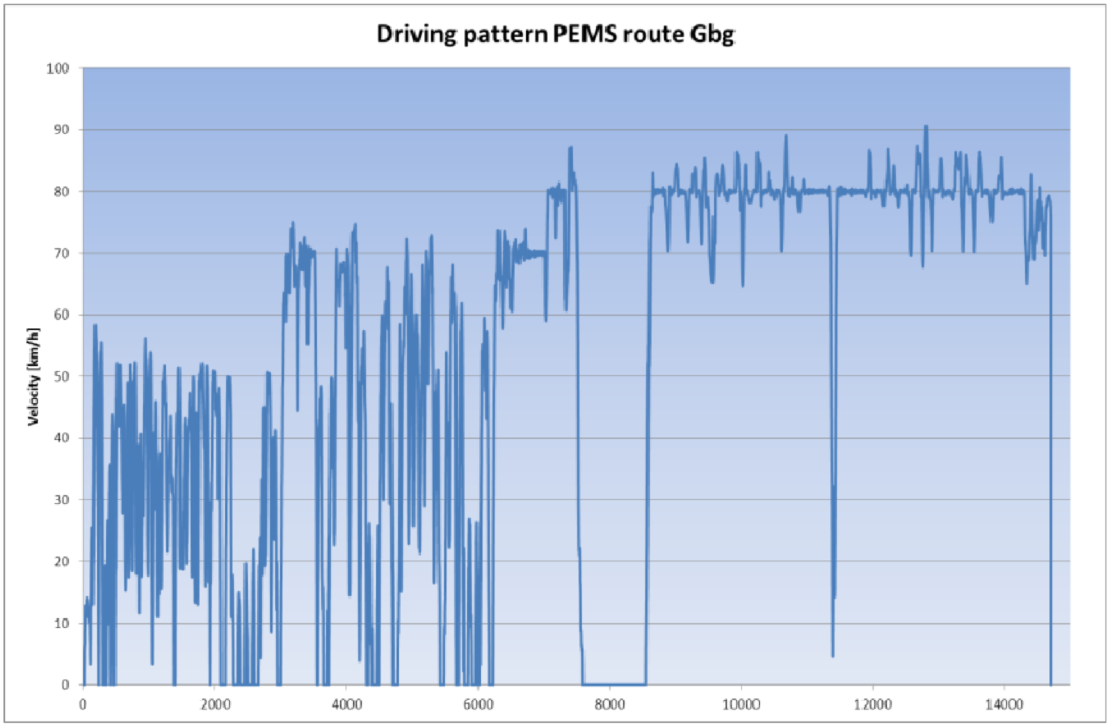


Figure 5. PEMS Test route in the Gothenburg area

When looking at the speed/time trace the routes look almost the same, but please note the different time lines.

7.3.3.1 Bus route (PEMS)

Especially when testing city buses on the road during normal operation to verify real life emission performance under different driving conditions, it is obvious that another test route (a bus route) with high portion of low load and low speed is needed. Therefore, a real bus line is used as the test route for verification. The route is located in the suburban of

Stockholm and can be considered as typical. To simulate passengers going on and off the bus, the bus was stopped at every second stop for 30 seconds.

The bus route is not meeting the set requirements for a test route according to Euro VI emission requirements, but is good enough for validation of low speed/load emission performance for city buses using a technology implying conventional diesel engine in combination with Selective Catalytic Reaction (SCR) as after-treatment device.

The results from the measurement can be found in paragraph 8, below.

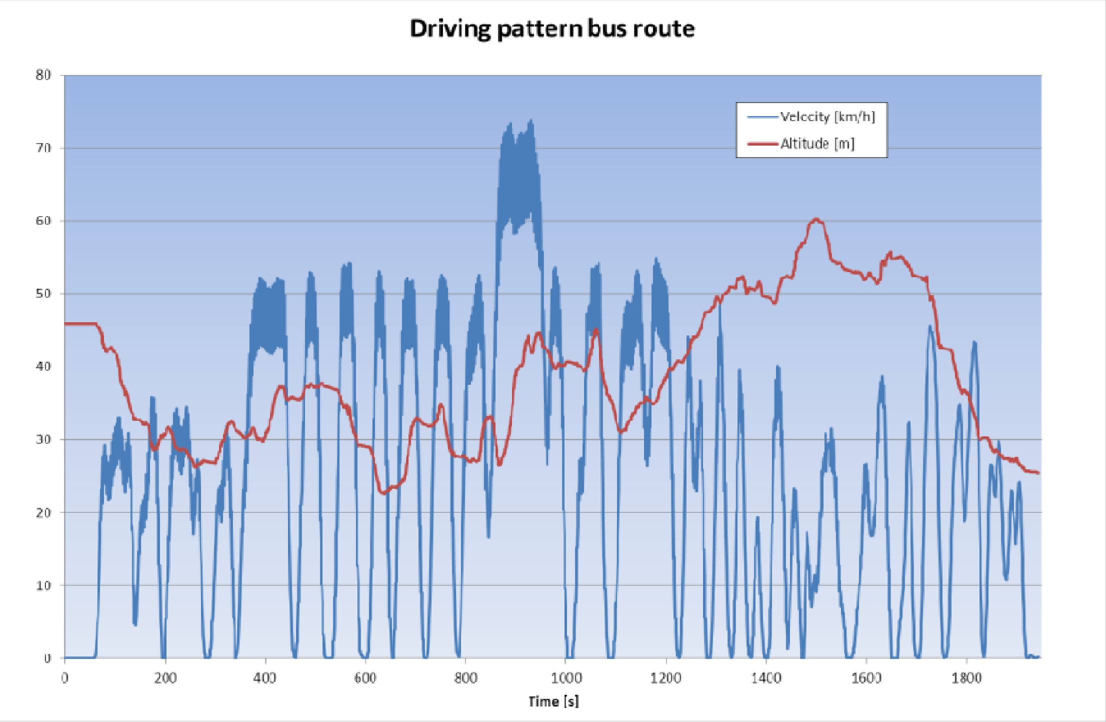


Figure 6. Bus line 835 in Stockholm, used as the PEMS bus line route

The bus route has the following main characteristics:

- Approximate trip duration: 1 900 seconds
- Average trip distance: 13.5 km
- Average speed: 26 km/h (of course dependant on traffic situation)
- Trip composition:
  - Urban driving: 90%
  - Rural driving: 10%
  - Highway driving: 0%
  - Acceleration: 37%
  - Deceleration: 40%
  - Cruising: 11%
  - Idle: 10%

8. EMISSION TEST RESULTS

Emissions of methane (CH_4) could not be measured separately by the PEMS instrument used. For the chassis dynamometer tests, the THC is calculated as $NMHC+CH_4$.

□PEMS: Test with Portable Emissions Measurement System

PEMS: Test with Portable Emissions Measurement System

CD: Test on chassis dynamometer

8.1 Dedicated SI lean/mix gas engine

Table 2. Test results dedicated SI lean/mix gas engine

	CO		THC		CH_4		NO_x		CO_2		PM		PN		Energy efficiency
	g/km	g/kWh	g/km	g/kWh	g/km	g/kWh	g/km	g/kWh	g/km	g/kWh	g/km	g/kWh	$\#\times10^{11}$/km	$\#\times10^{11}$/kWh	%
PEMS, Haninge, cold start	4.87	n.m.	0.38	n.m.	n.m.	n.m.	1.14	n.m.	973	n.m.	n.m.	n.m.	n.m.	n.m.	-
PEMS, Haninge, warm start	1.58	n.m.	0.28	n.m.	n.m.	n.m.	1.06	n.m.	1025	n.m.	n.m.	n.m.	n.m.	n.m.	-
PEMS, Bus line Haninge, warm start	3.34	n.m.	0.16	n.m.	n.m.	n.m.	1.56	n.m.	1365	n.m.	n.m.	n.m.	n.m.	n.m.	-
CD, Average WHVC cold start	5.96	6.67	0.80	0.90	0.72	0.81	0.92	1.03	1024	1145	0.007	0.008	315	353	18
CD, Average WHVC warm start	1.14	1.28	0.20	0.22	0.17	0.20	0.65	0.73	974	1086	0.004	0.005	126	141	19
CD, FIGE	0.75	0.86	0.44	0.50	0.39	0.46	0.80	0.93	952	1102	0.005	0.006	n.m.	n.m.	19

8.2 Dedicated SI lean-burn gas engine

Table 3. Test results dedicated SI lean-burn gas engine

	CO		THC		CH_4		NO_x		CO_2		PM		PN		Energy efficiency
	g/km	g/kWh	g/km	g/kWh	g/km	g/kWh	g/km	g/kWh	g/km	g/kWh	g/km	g/kWh	$\#\times10^{11}$/km	$\#\times10^{11}$/kWh	%
PEMS, Haninge, warm start	0.20	0.19	0.28	0.26	n.m.	n.m.	1.64	1.54	588	553	n.m.	n.m.	n.m.	n.m.	44
PEMS, Bus line Haninge, warm start	0.17	0.11	1.98	1.34	n.m.	n.m.	6.11	4.13	862	583	n.m.	n.m.	n.m.	n.m.	41
CD, Average WHVC cold start	0.45	0.50	1.80	2.01	1.65	1.83	1.84	2.04	843	939	0.003	0.003	6.75	7.52	26
CD, Average WHVC warm start	0.06	0.07	0.42	0.47	0.37	0.41	1.46	1.62	795	881	0.002	0.003	2.80	3.10	27
CD, FIGE	0.03	0.03	0.53	0.63	0.48	0.56	0.99	1.17	660	779	0.004	0.004	n.m.	n.m.	31

8.3 Diesel Dual Fuel Vehicle – DDF1 CAP (OEM/Retrofit)

Table 4. Test results Diesel Dual Fuel Vehicle, OEM/CAP

	CO		THC		CH_4		NOx		NO_2		CO_2		PM		PN		Energy efficiency	GER
	g/km	g/kWh	g/km	g/kWh	g/km	g/kWh	g/km	g/kWh	g/km	g/kWh	g/km	g/kWh	g/km	g/kWh	$\#\times10^{11}$/km	$\#\times10^{11}$/kWh	%	%
PEMS, Gbg, 40 ton, DDF	0.05	0.03	11.70	7.15	n.m.	n.m.	2.48	1.52	0.26	0.16	809	494	0.042	0.025	n.m.	n.m.	41	61
PEMS, Gbg, 40 ton, Diesel	0.11	0.08	0.00	0.00	n.m.	n.m.	5.51	3.82	1.36	0.94	900	623	0.026	0.018	n.m.	n.m.	42	-
PEMS, Gbg, 20 ton, Diesel	0.17	0.15	0.00	0.00	n.m.	n.m.	5.63	5.17	1.56	1.43	714	655	0.027	0.024	n.m.	n.m.	41	-
PEMS, Haninge, 20 ton, DDF	0.07	-	14.29	-	n.m.	n.m.	4.29	-	0.51	-	838	-	0.039	-	n.m.	n.m.	-	-
PEMS, Sthlm, 20 ton, Diesel	0.33	0.34	0.05	0.05	n.m.	n.m.	5.73	5.86	1.32	1.36	783	802	0.030	0.030	n.m.	n.m.	35	-
CD, WHVC cold DDF	0.03	0.03	6.75	7.20	6.12	6.53	5.42	5.79	1.46	1.56	733	783	0.006	0.006	1056	1128	29	38
CD, WHVC cold Diesel	0.03	0.03	n.d.	n.d.	n.d.	n.d.	5.36	5.76	1.62	1.74	771	829	0.006	0.007	940	1010	30	-
CD, WHVC warm DDF Average	0.06	0.07	9.29	9.91	8.60	9.17	4.11	4.47	0.80	0.87	612	666	0.042	0.046	752	818	32	51
CD, WHVC warm Diesel Average	0.18	0.20	0.03	0.03	n.d.	n.d.	5.33	5.88	1.53	1.68	718	792	0.051	0.057	847	933	32	-
CD, FIGE DDF Average	0.06	0.08	7.37	9.08	7.02	8.66	3.20	3.95	0.72	0.89	497	612	0.025	0.031	n.m.	n.m.	41	45
CD, FIGE Diesel Average	0.04	0.05	n.d.	n.d.	n.d.	n.d.	4.25	5.15	1.48	1.80	578	699	0.037	0.044	n.m.	n.m.	35	-

8.3.1 Diesel Replacement

A lot of test results can be found in Table 4 and as mentioned in paragraph 6, the priority was given to the test program for vehicle DDF 1, since this concept was considered to be the closest one to series production at the time for testing.

It has been verified that the actual amount of diesel fuel replaced by methane is dependent upon engine/vehicle load, Figure 7. The figure present the ratio of replacement when the vehicle, with a test weight of about 20 ton, is tested on the chassis dynamometer using different driving cycles WHVC (Figure 2) respectively FIGE (Figure 3). The driving cycles have slightly different characteristics.

The bar to the right (PEMS, 40 ton, Gbg) represents the diesel replacement of ~60% when the vehicle combination (truck + trailer), with a test weight of 40 ton, is tested on the road according to Figure 5. When this bar is further divided to represent urban-rural-highway, the diesel replacement is 50% - 58% - 63% respectively, well below the figures given in sales literature, up to 80%.

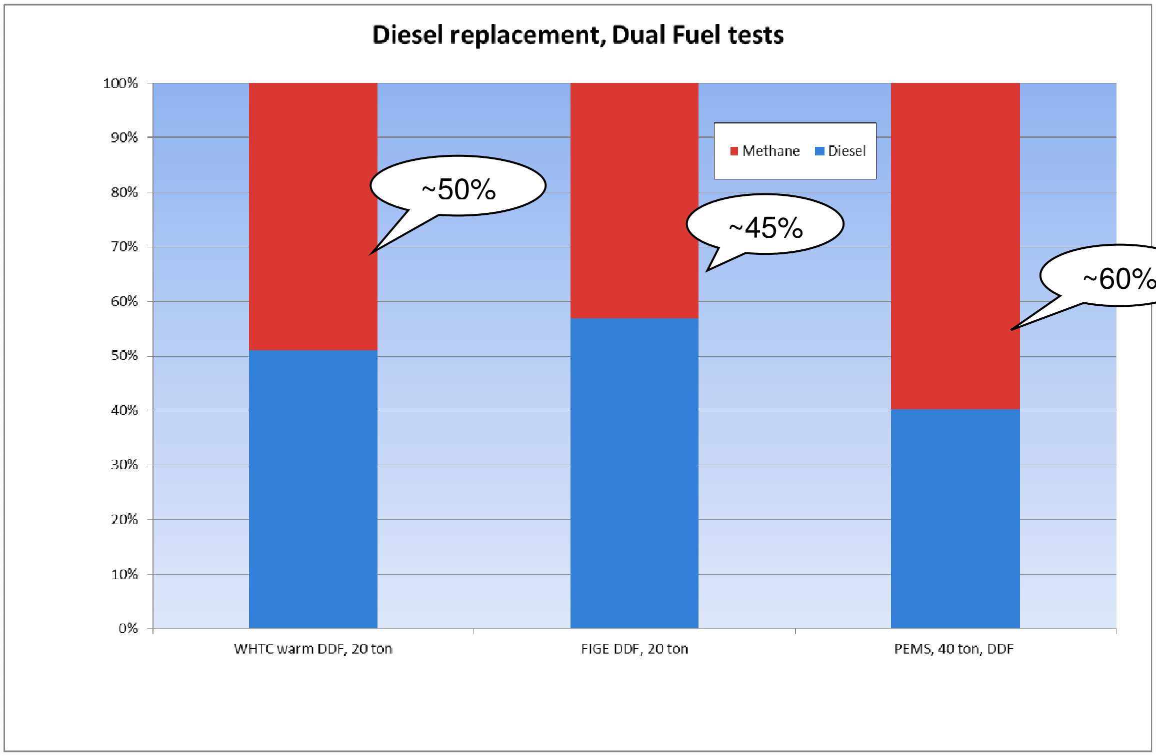


Figure 7. Diesel replacement with different drive cycles and load

8.3.2 CO_2 and CO_2 equivalent emissions

A common opinion when changing the fuel in the transport sector going from conventional fuel to methane gas is a decrease of CO_2, and thereby also GHG emissions, by 20%. Figure 8 show that this is not always the case.

The results in the figure present measurement of different combustion strategies on a chassis dynamometer using the WHVC driving cycle. All tests have been carried out with a warmed up engine. The blue bars represents tail-pipe emissions of CO_2 and the red bars represents the CO_2 equivalent emissions comprising the tail-pipe CO_2 plus the emissions of CH_4 multiplied by the factor (34) for global warming potential. From the figure, it is easy to see that in all cases the lowest CO_2 emissions are found when a dual fuel engine is operating in diesel mode. Further, tail-pipe CO_2 emissions are higher for the two dedicated SI-engine methane fuelled buses than for the dual fuel engines operating in diesel mode. This is mainly because the energy efficiency for engines using diesel technology is higher than for engines operating according to spark ignited technology.

When adding the emissions of CH_4 to the CO_2 emissions for a total picture of GHG, it is easy to see that the equivalent CO_2 emissions for dual fuel engines operating in dual fuel mode will increase.

The overall experience from the test program is that emissions of CH_4 will increase when the diesel replacement is increased. In reality, higher rate of diesel replacement with gas will result in higher total greenhouse gas emissions of. This is in fact a serious dilemma for technology of today.

For the dedicated SI-engine methane fuelled vehicles the contribution of CH_4 to the CO_2 equivalent emissions is far better than for the dual fuel concepts simply because the dedicated SI-engines have to emit less CH_4 in order to be approved according to the European emission regulations.

The conclusion from the figure could be summarised as: the tail-pipe greenhouse gas emission benefit from replacing diesel fuel with methane gas as a fuel is marginal based on measurements of tested technologies. On a full life cycle assessment, the source of the methane (i.e. conventional natural gas, shale gas or biogas) may affect this conclusion.

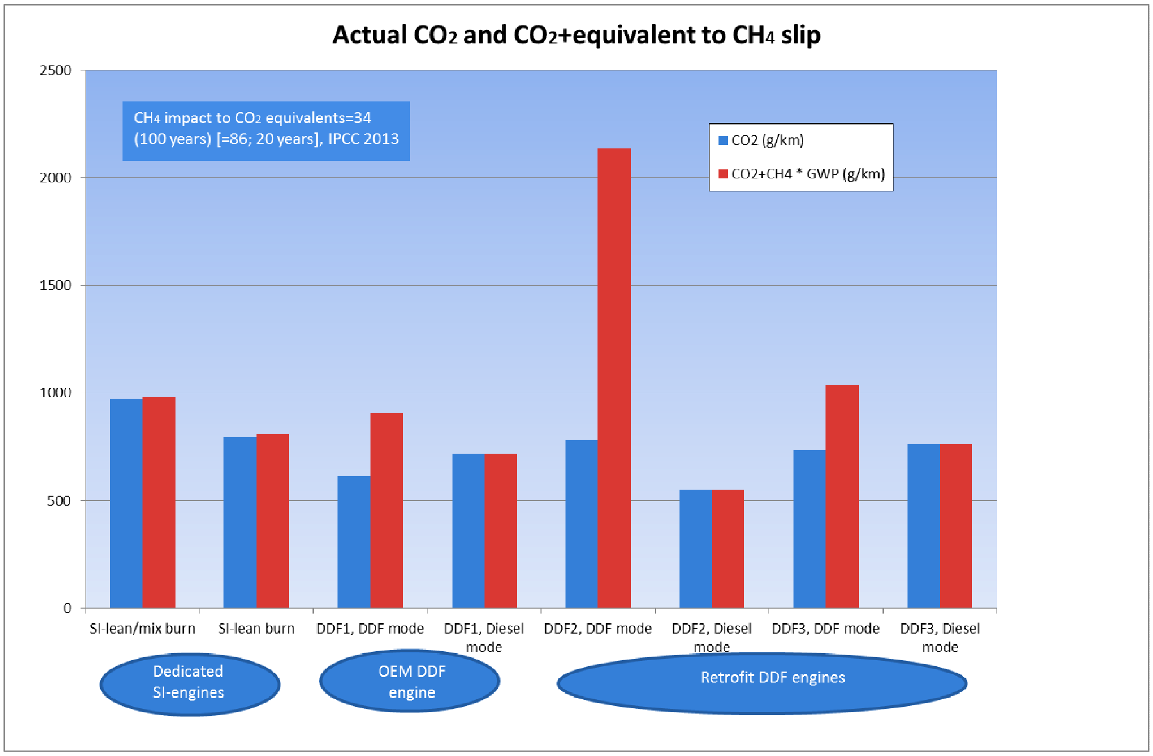


Figure 8. Equivalent CO2 emissions from different concepts

8.3.3 Result from testing vs. emission limits

An attempt to compare test results with Euro V emission limit values is presented in Figure 9. The test results are calculated in g/kWh, the same metrics as for the limit values.

The results from chassis dynamometer tests according to FIGE driving cycles can be directly compared with the limits since the FIGE driving cycle is a “transformation” of the ETC test cycle, used for certification of stand-alone engines. The results from the bars representing “PEMS 40 ton” can only be used as a reference since the drive cycle (on the road) and load of the vehicle (40 ton for the full vehicle combination) do not fully agree with requirements for test parameters during certification.

It is obvious from Figure 9 that the regulated limit value for CH_4 is significantly exceeded (with a factor of about 8) when the vehicle is operated in DDF mode. The difference between CH_4 in diesel mode compared with DDF mode is even larger since the emissions of THC/CH_4 are below detection limits (n.d.) for the analysers. In addition, the emissions of NO_x, measured according to the FIGE driving cycle, with the engine operating in both diesel and DDF mode exceeds the emission limit values for Euro V with a factor of around 2. It is interesting to note that the emissions of NO_x are lower in DDF mode than in diesel mode.

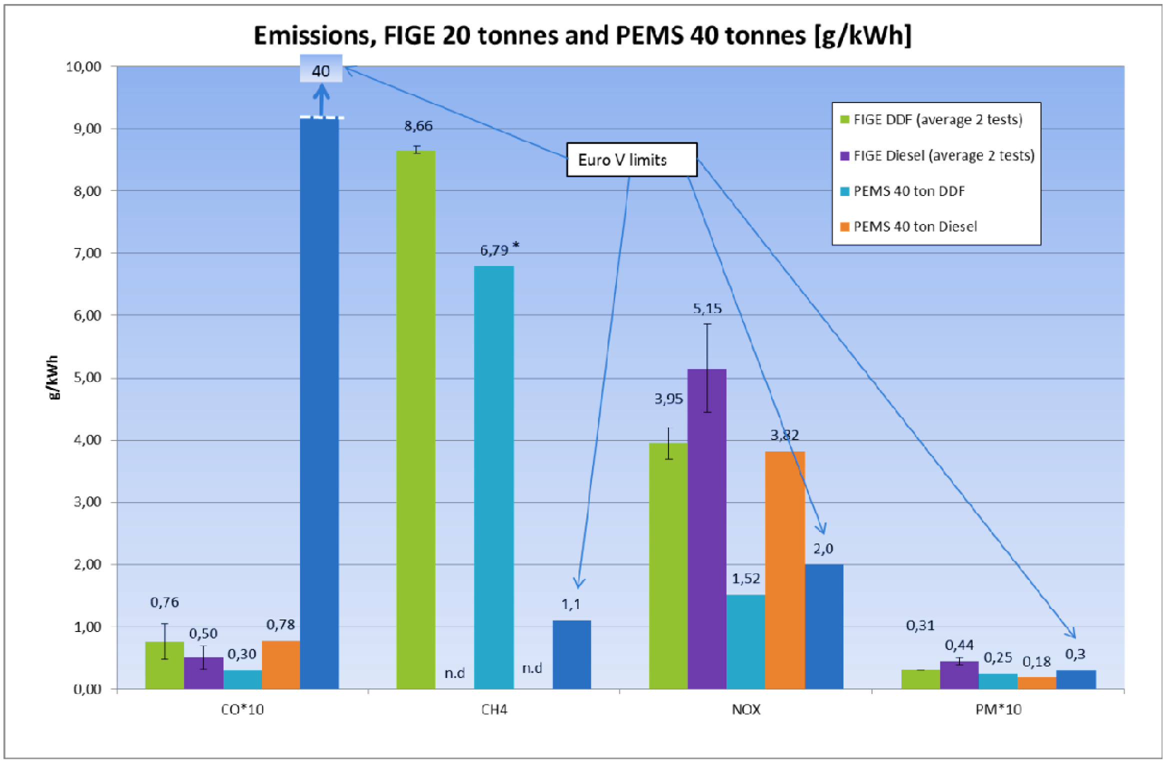


Figure 9. Test results vs. limit values (CH_4 for PEMS measurement calculated as 0.95 x THC)*

8.4 Diesel Dual Fuel Vehicle – DDF2 Hardstaff (Retrofit)

Table 5. Test results DDF vehicle, Hardstaff retrofit

PEMS testing	CO	THC	NOx	CO_2	Soot
	g/km	g/km	g/km	g/km	g/km
PEMS, Haninge, diesel	0.50	0.01	5.7	550	1.2
PEMS, Haninge, DDF	1.50	39.9*	10.0	780	7.0

* No tests on chassis dynamometer were carried out on this vehicle since it was considered to be “non-representative” due to extreme high emissions of total hydrocarbons.

8.5 Diesel Dual Fuel Vehicle – DDF3 NGV Motori (Retrofit)

The result from measurement of this vehicle is only included in the report as example of an older vehicle in use subjected to a retrofit program i.e. the engine of the vehicle is modified from a conventional diesel fuelled engine to an engine operating on a variable mix of diesel fuel and methane gas (diesel dual fuel). The original diesel engine is approved according to Euro III emission requirements. Unfortunately after conversion to dual fuel technology the emission performance is not even close to Euro III. Intentions from fleet operators to modify engines might be to verify whether engines have a potential to meet Euro V emission requirements. Measurement of emissions on road in real world operation was not a part of the project.

Table 6. Test results DDF vehicle, NGV Motori retrofit

	CO		THC		NO$_x$		CO$_2$		PM		Energy efficiency	GER
	g/km	g/kWh	g/km	g/kWh	g/km	g/kWh	g/km	g/kWh	g/km	g/kWh	%	(%)
CD, FIGE Diesel	0.11	0.12	0.00	0.00	7.02	7.34	762	796	0.005	0.005	33	-
CD, FIGE DDF	0.07	0.08	8.94	9.28	5.50	5.71	731	759	0.003	0.004	30	46

8.6 Further observations

A Swedish project "Clean Truck" (http://www.stockholm.se/cleantruck the site unfortunately only in Swedish language) with the main objective to promote and demonstrate "clean trucks" including different renewable fuels for heavy duty vehicles and improved infrastructure was initiated in year 2010 and will be finalized 2014. Participating vehicles are, among others, also vehicles using dual fuel technology. No verification of performance for exhaust emissions has been carried out during the fleet trial. The general experiences from the field test when the vehicles have been in operation, is that the ratio for diesel replacement is lower than expected. When vehicles are operating in city centres (as distribution trucks or garbage trucks), the diesel replacement is around 20% and when the vehicles are transporting goods between cities the diesel replacement is in best cases 60%. Before start of the project, the estimated diesel replacement was around 70%.

Further, during the field test it has been observed that the specification of diesel fuel including any blend of FAME, HVO or other bio-components is crucial for best performance as well as the content of methane for the methane gas used (CNG/LBG). The composition of the fuel is recommended to be further investigated.

A fleet operator in Sweden managing around 30 vehicles has been using trucks with dual fuel technology for the last 4 years. Today the fleet consist of four DDF vehicles whereof three is using LNG/ LBG as the fuel. The annual distance driven per vehicle is up to 210 000 km. All vehicles are operating between cities 24/7 with only a few short stops for loading or unloading. The weight of the vehicle combination varies between 45 to 52 ton, fully loaded.

Due to the driving pattern comprising high amount of highway driving and high payload combined with limited driving in city centres, the diesel replacement is in best cases about 75% for the LNG/LBG vehicles and about 70% for the CNG vehicle. Those figures are estimated by the consumption of the different fuels and not really calculated. No verification of emission performance and whether the vehicles meeting set emission standards has been carried out.

During the years the vehicles have been working properly and only regular maintenance has been carried out. However, the time needed for service is double the time for corresponding service of a conventional diesel truck because the new technology needs some extra attention. In addition, the cost for the service is about 200 Euro extra than for a diesel truck.

The new technology vehicles have been well received by the drivers. However, it is obvious that training have to be carried out for new drivers, especially how to fill the gas tank. The gas is liquefied and has a very low temperature. When the fuel tank is almost empty it has been observed that the time for filling a big LNG/LBG tank is sufficient for nozzles and hoses to freeze, causing unexpected problems to end the filling of gas and to remove the nozzle.

Further, it seems very important to know what type of gas that is filled in the tank. When going from LNG to LBG and vice versa, the driveability of the vehicles will be affected, and from driver´s perspective, the vehicle will not behave in an acceptable way and the driveability will be affected. The reason for this inconvenience might depend upon different energy content due to presence of other hydrocarbons in LNG compared to LBG. As a quick fix, the workshop recalibrates the ECU depending upon the type of gas used and in accordance with manufacturer´s instructions. Whether such recalibration has any influence of emission performance is not validated.

Testing of a retrofit dual fuel truck in normal operation on the road has been carried out in the Netherlands by TNO. The results are presented in the report "***The Netherlands In-Service Testing Programme for Heavy-Duty Vehicle Emissions 2012: summary report***" (TNO 2013 R10960). Various trips were driven with different payloads and repeated in diesel mode and in dual fuel mode. The following conclusions were then high-lighted:

- The vehicle emits a lot of methane
- The total CO_2 equivalent emissions are 15-40% higher than in diesel mode, taking account of the GWP for methane.
- The NO_x emissions is somewhat lower than in diesel mode

The result from tests carried out in the Netherlands and experiences from field tests in Sweden corresponds very well with findings presented in this report.

9. SUMMARY OF EMISSION TEST RESULT (FROM “SGC PROJECT)

On behalf of Swedish Gas Technology Centre SGC, AVL MTC has measured unregulated emissions from three methane fuelled heavy duty vehicles tested on chassis dynamometer. Two of the engines were dedicated methane fuelled engines while one used the diesel dual fuel technology. For reference, also result from a reference vehicle, with a conventional diesel engine using Swedish environment class 1 (Mk1) diesel fuel is presented.

The measurement of unregulated pollutants was carried out simultaneously as measurement of the regulated compounds. The tests were performed with engine cold and warm start conditions for all vehicles according to WHVC. The unregulated compounds analyzed were aldehydes, polycyclic aromatic hydrocarbons (PAH) and particulate matter size distribution. Ames´ salmonella tests were also performed on the PAH extracts.

Measurement of particulates

For all vehicles and for all particle sizes, it can be concluded that starting the tests with a cold engine generates slightly more particulates than after warm start tests.

Distribution of particle size and number of particles did not vary significantly between the two driving modes, diesel and dual fuel, for the vehicles with dual fuel technology.

The dedicated (SI) methane fuelled vehicle with lean-burn technology generated the lowest amount of particles. Both the dedicated methane fuelled vehicles generated fewer particles than the vehicle using dual fuel technology as well as a reference vehicle using Swedish environment class 1 (Mk1) diesel fuel.

Measurement of aldehydes

For the acetaldehyde levels, no clear trend depending on start temperature could be seen.

For all vehicles, formaldehyde and acetaldehyde was the dominated pollutant of the aldehydes measured. The sum of the other aldehydes varied between 3% and 17% of the total aldehydes. The amount of aldehydes appears to be reflected in the amount of THC/CH_4.

For the methane fuelled vehicle using DDF technology and operated in dual fuel mode, the levels of formaldehyde were considerable higher compared to the diesel mode tests and the other vehicle technologies.

The dedicated methane fuelled vehicles emitted significantly more formaldehyde during the cold start test compared to the warm start test. For the methane fuelled vehicle using dual fuel technology the situation was reversed, significantly more formaldehyde during warm start test compared to the cold start.

Measurement of NO_2/NO_x

For the vehicle using dual fuel technology, measurements with FTIR were performed. The NO_2/NO_x ratio was, regardless of start temperature and drive cycle, slightly higher when the engine was operating in diesel mode than in dual fuel mode. One of many reasons for this might be that high NO_2/NO_X ratios are favoured at low exhaust temperatures and the temperature of diesel combustion exhaust is lower than of methane combustion exhaust.

When the engine was operating in diesel mode, slightly lower levels of N_2O compared to dual fuel mode could be observed.

No emissions of NH_3 were detected in any test.

Measurement of Polycyclic Aromatic Hydrocarbons, PAH

The higher level of Polycyclic Aromatic Hydrocarbons (PAH) in diesel fuel compared to the level in methane gas was reflected in the amount of particulate PAH contained in the diesel exhaust which was significantly higher than in the methane exhaust.

The highest amount of volatile PAH was found in the exhaust from the dedicated methane engine using lean-mix technology. This might depend upon the fact that the engine most of the time, except during the first minutes after cold start, was operating in stoichiometric conditions.

The higher levels of volatile PAH and genotoxicity for the lean-mix technology methane fuelled engine might have been caused by the consumption of engine oil, which generally is higher for methane fuelled engines. Further, the quality of the oil might also have influenced the result. In addition, the mileage of this vehicle was considerable higher compared to the other vehicles and also that the after-treatment system was of a different type.

Biological activity in the exhaust

For the engine using dual fuel technology and operating in diesel mode and for the reference vehicle using Mk1 diesel fuel, the results indicate that the exhaust components need to be metabolically activated in order to induce mutations.

In Ames' test, the number of mutants increased compared to the blank sample for all analyzed samples, but in some samples was the increase not significant. The highest level of mutagenicity response was in the cold start test of the dedicated methane fuelled engine using lean-mix technology.

The engines using diesel dual fuel technology, shows an increase of mutations when operating in dual fuel mode, compared to the blank test.

10. CONCLUSIONS

The exhaust emissions from dedicated methane fuelled engines (SI) could be considered as meeting the requirements for Euro V/EEV emission regulations. The tested dedicated methane fuelled bus in Finland show results close to Euro VI emission levels, using the stoichiometric technology in combination of EGR-system and three-way catalyst as after-treatment devices. Within the time schedule of the project no vehicle certified/approved according to Euro VI emission requirements have been tested.

Past experience show that attention must be given to the performance of the catalytic converts after mileage accumulation due to degradation. For late technology gas engines, design of exhaust after-treatment systems might however have been improved.

Engine efficiency for the dedicated gas engines (SI) are decreased compared to conventional diesel engines, especially for the tested lean-mix concept. This might be because the lean mode was only active during the first minutes after cold start and subsequently the engine then switched to operation at $\lambda 1$, stoichiometric mode.

For the tested dual fuel concepts, the expected diesel replacement was not achieved even during high load operation. The maximum diesel replacement during highway cruising with a vehicle combination weight of 40 tons was “only” 63%, well below estimations.

From testing in Finland it was observed that the energy share of methane drops with increasing load and other test parameters identical (63% to 51%). The reason might be to avoid knocking and therefore the amount of gas is reduced as a safety measure when the engine power is approaching maximum output. Please also see Table 5 in the report from VTT.

Experience from Sweden and Finland verifies decreased emission levels (but still above applicable emission standards) for the DDF concepts when vehicles are tested with a brand new catalyst installed immediately before start of the test. However, when same vehicles are re-tested after mileage accumulation the concepts are drastically deteriorated. Whether this is due to degradation of the catalyst or the emission control system is unclear.

In theory, the potential to reduce emissions and discharge of GHGs by implementation of the DDF technology is high. Results from testing, although limited to only a few vehicles, so far do not fully agree with this statement even if biogas is used as gas. Testing in Finland verified an increase in energy consumption in the range of 5-9% when the engine was operated in dual fuel mode compared to diesel mode.

For the tested vehicles, using dual fuel technology with the possibility to operate both in diesel mode as well as in dual fuel mode, the tail-pipe emissions of CO_2 is lower in dual fuel mode than in diesel mode. However, due to high level of CH_4 emissions, with high GWP, the total CO_2 equivalent emission, are higher in dual fuel mode.

Testing in Canada of a vehicle using HPDI technology for dual fuel operation, show a significant improvement of the emission performance, but it is still unclear whether the tested technology will meet the European Euro V emission standards. Dependent upon drive cycle, the energy efficiency of the truck using HPDI technology was 26-36% whereas the diesel truck, used as reference, was in the range of 36-42%.

Test results so far show that the DDF technology is in need of further development to improve diesel replacement and reduce methane slip. New development are ongoing both in Europe and USA to develop improved concepts meeting strict emission requirements, high rate of diesel replacement and acceptable durability performance to a reasonable cost.

Discussions with representative from ANGVA made it clear that the priorities for heavy duty CNG fuelled vehicles in Asian countries are to decrease the cost for fuel and to some extent also to reduce the emissions of particulates. The interest to introduce dedicated CNG fuelled vehicles in normal operations is limited, while the interest to convert diesel fuelled vehicles (mainly buses) already in-use to operate on methane gas as fuel is significant higher. This type of conversion implies that the engine technology is modified from diesel combustion (CI) to spark ignited combustions (SI). However, during the last couple of years also conversion to diesel dual fuel has become more common, since the engine technology not need to be modified. Probably, this kind of conversion also is cheaper.

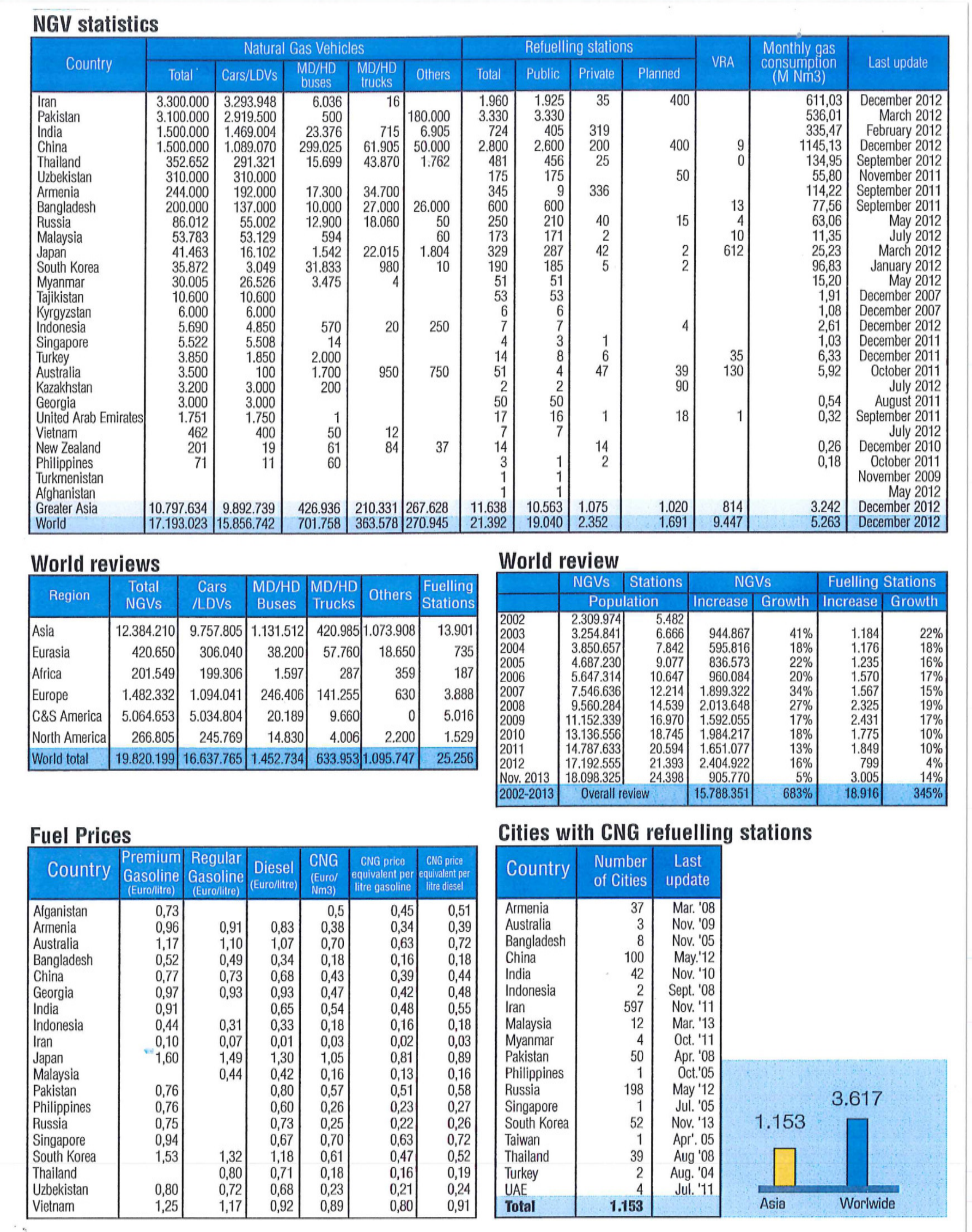
Worth mentioning is also the fact that this kind of conversion is in most cases accepted by the regulatory system, since the emission requirements for heavy duty vehicles subjected to mandatory vehicle inspection programs only deals with smoke emissions from vehicles in-use. Converted vehicles can therefore be introduced on the market without any problem since they normally will pass the limit values for smoke emissions and the basic engine is approved in accordance with the type certificate at the time when the vehicle for the first time is introduced on the market.

11. LIST OF ABBREVATIONS

AMF	Advanced Motor Fuels
ANGVA	Asia Pacific Natural Gas Vehicles Association
BTU	British Thermal Units
CAP	Clean Air Power
CD	Chassis Dynamometer
CFV	Critical Flow Venturi
CH_4	Methane
CI	Compression Ignited
CL	Chemiluminiescence
Class 8	U.S. HD Vehicle Classification (Gross weight above 14 969 kg)
CNG	Compressed Natural Gas
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CRT	Continuously Regenerating Trap
CVS	Constant Volume Sampling
DC	Direct Current
DEFC	Diesel Equivalent Fuel Consumption
DEFE	Diesel Equivalent Fuel Economy
DF	Dual Fuel
DDF	Diesel Dual Fuel – Methane Diesel
DG Energy	Directorate-General for Energy (within European Commission)
DOC	Diesel Oxidation Catalyst
DPF	Diesel Particulate Filter
ECE	United Nations Economic Commission for Europe
ECU	Electronic Control Unit
EEV	Enhanced Environmental Vehicle (Heavy Duty)
EGR	Exhaust Gas Recirculation
ELPI	Electric Low pressure Impactor
EMROAD	Software Package to Process PEMS data (developed by JRC)
EN(590)	European Norm
EPA	Environmental Protection Agency (in USA)
ERMS	Emission Research and Measurement Section
ETC	European Transient Test
EU	European Union
FAME	Fatty-acid Methyl Ester
Fc	Fuel Consumption
FE	Fuel Economy
FIGE	FIGE Institute (Germany)
FTIR	Fourier Transform Infrared Spectroscopy
GEM	Gravimetric Filter Module
GER	Gas Energy Ratio
GHG	Green House Gases

GRPE	Working Party on Pollution and Energy
GVF	Gas Fuelled Vehicles
GWP	Global Warming Potential
HC, THC	Hydrocarbons, Total Hydrocarbons
HD	Heavy Duty
HFID	Heated Flame Ionization Detector
HPDI	High Pressure Direct Injection
HVO	Hydro-treated Vegetable Oil
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
JGA	Japan Gas Association
JRC	Joint Research Centre of European Commission
LBG	Liquefied Bio Gas
LEVO	Organisation for the promotion of low emission vehicles, Japan
LNG	Liquefied Natural Gas
Mk1	Environmental class 1 (Miljöklass 1)
MOVE	Mobile On-road Vehicle Equipment
MSS	Micro Soot Sensor
NDUV	Non-Dispersive Ultraviolet Analyser
NDIR	Non-Dispersive Infrared Analyser
NHV	Net Heating Value
NMHC	Non-Methane Hydrocarbons
NO	Nitric Oxide
N_2O	Nitrous Oxide
NO_X	Oxides of Nitrogen
NO_2	Nitrogen Dioxide
O_2	Oxygen
OEM	Original Equipment Manufacturer
PAH	Polycyclic Aromatic Hydrocarbons
PASS	Photo Acoustic Soot Sensor
PEMS	Portable Emission Measurement System
PLU	Instrument for Measurement of Fuel Consumption
PM	Particulate Matter (when used for emissions)
SCR	Selective Catalytic Reduction
SGC	Swedish Gas Technology Centre
SI	Spark Ignited
STA	Swedish Transport Administration
TPM	Total Particulate matter
TWC	Three Way Catalyst
UDDS	Urban Dynamometer Driving Schedule (for Heavy-duty vehicles)
ULSD	Ultra Low Sulphur Diesel
UNFCCC	United Nation Framework Convention on Climate Change
WHTC	World Harmonized Transient Cycle
WHVC	World Harmonized Vehicle Cycle
WP 29	World Forum for Harmonisation of Vehicle Regulations

12. ANNEX 1, ASIAN NGV STATISTICS (JAN. 2014)



NGV statistics

Country	Natural Gas Vehicles					Refuelling stations				VRA	Monthly gas consumption (M Nm3)	Last update
	Total	Cars/LDVs	MD/HD buses	MD/HD trucks	Others	Total	Public	Private	Planned			
Iran	3.300.000	3.293.948	6.036	16		1.960	1.925	35	400		611,03	December 2012
Pakistan	3.100.000	2.919.500	500		180.000	3.330	3.330				536,01	March 2012
India	1.500.000	1.469.004	23.376	715	6.905	724	405	319			335,47	February 2012
China	1.500.000	1.089.070	299.025	61.905	50.000	2.800	2.600	200	400	9	1145,13	December 2012
Thailand	352.652	291.321	15.699	43.870	1.762	481	456	25		0	134,95	September 2012
Uzbekistan	310.000	310.000				175	175		50		55,80	November 2011
Armenia	244.000	192.000	17.300	34.700		345	9	336			114,22	September 2011
Bangladesh	200.000	137.000	10.000	27.000	26.000	600	600			13	77,56	September 2011
Russia	86.012	55.002	12.900	18.060	50	250	210	40	15	4	63,06	May 2012
Malaysia	53.783	53.129	594		60	173	171	2		10	11,35	July 2012
Japan	41.463	16.102	1.542	22.015	1.804	329	287	42	2	612	25,23	March 2012
South Korea	35.872	3.049	31.833	980	10	190	185	5	2		96,83	January 2012
Myanmar	30.005	26.526	3.475	4		51	51				15,20	May 2012
Tajikistan	10.600	10.600				53	53				1,91	December 2007
Kyrgyzstan	6.000	6.000				6	6				1,08	December 2007
Indonesia	5.690	4.850	570	20	250	7	7		4		2,61	December 2012
Singapore	5.522	5.508	14			4	3	1			1,03	December 2011
Turkey	3.850	1.850	2.000			14	8	6		35	6,33	December 2011
Australia	3.500	100	1.700	950	750	51	4	47	39	130	5,92	October 2011
Kazakhstan	3.200	3.000	200			2	2		90			July 2012
Georgia	3.000	3.000				50	50				0,54	August 2011
United Arab Emirates	1.751	1.750	1			17	16	1	18	1	0,32	September 2011
Vietnam	462	400	50	12		7	7					July 2012
New Zealand	201	19	61	84	37	14		14			0,26	December 2010
Philippines	71	11	60			3	1	2			0,18	October 2011
Turkmenistan						1	1					November 2009
Afghanistan						1	1					May 2012
Greater Asia	10.797.634	9.892.739	426.936	210.331	267.628	11.638	10.563	1.075	1.020	814	3.242	December 2012
World	17.193.023	15.856.742	701.758	363.578	270.945	21.392	19.040	2.352	1.691	9.447	5.263	December 2012

World reviews

Region	Total NGVs	Cars /LDVs	MD/HD Buses	MD/HD Trucks	Others	Fuelling Stations
Asia	12.384.210	9.757.805	1.131.512	420.985	1.073.908	13.901
Eurasia	420.650	306.040	38.200	57.760	18.650	735
Africa	201.549	199.306	1.597	287	359	187
Europe	1.482.332	1.094.041	246.406	141.255	630	3.888
C&S America	5.064.653	5.034.804	20.189	9.660	0	5.016
North America	266.805	245.769	14.830	4.006	2.200	1.529
World total	19.820.199	16.637.765	1.452.734	633.953	1.095.747	25.256

World review

	NGVs	Stations	NGVs		Fuelling Stations	
	Population		Increase	Growth	Increase	Growth
2002	2.309.974	5.482				
2003	3.254.841	6.666	944.867	41%	1.184	22%
2004	3.850.657	7.842	595.816	18%	1.176	18%
2005	4.687.230	9.077	836.573	22%	1.235	16%
2006	5.647.314	10.647	960.084	20%	1.570	17%
2007	7.546.636	12.214	1.899.322	34%	1.567	15%
2008	9.560.284	14.539	2.013.648	27%	2.325	19%
2009	11.152.339	16.970	1.592.055	17%	2.431	17%
2010	13.136.556	18.745	1.984.217	18%	1.775	10%
2011	14.787.633	20.594	1.651.077	13%	1.849	10%
2012	17.192.555	21.393	2.404.922	16%	799	4%
Nov. 2013	18.098.325	24.398	905.770	5%	3.005	14%
2002-2013	Overall review		15.788.351	683%	18.916	345%

Fuel Prices

Country	Premium Gasoline (Euro/litre)	Regular Gasoline (Euro/litre)	Diesel (Euro/litre)	CNG (Euro/ Nm3)	CNG price equivalent per litre gasoline	CNG price equivalent per litre diesel
Afganistan	0,73			0,5	0,45	0,51
Armenia	0,96	0,91	0,83	0,38	0,34	0,39
Australia	1,17	1,10	1,07	0,70	0,63	0,72
Bangladesh	0,52	0,49	0,34	0,18	0,16	0,18
China	0,77	0,73	0,68	0,43	0,39	0,44
Georgia	0,97	0,93	0,93	0,47	0,42	0,48
India	0,91		0,65	0,54	0,48	0,55
Indonesia	0,44	0,31	0,33	0,18	0,16	0,18
Iran	0,10	0,07	0,01	0,03	0,02	0,03
Japan	1,60	1,49	1,30	1,05	0,81	0,89
Malaysia		0,44	0,42	0,16	0,13	0,16
Pakistan	0,76		0,80	0,57	0,51	0,58
Philippines	0,76		0,60	0,26	0,23	0,27
Russia	0,75		0,73	0,25	0,22	0,26
Singapore	0,94		0,67	0,70	0,63	0,72
South Korea	1,53	1,32	1,18	0,61	0,47	0,52
Thailand		0,80	0,71	0,18	0,16	0,19
Uzbekistan	0,80	0,72	0,68	0,23	0,21	0,24
Vietnam	1,25	1,17	0,92	0,89	0,80	0,91

Cities with CNG refuelling stations

Country	Number of Cities	Last update
Armenia	37	Mar. '08
Australia	3	Nov. '09
Bangladesh	8	Nov. '05
China	100	May.'12
India	42	Nov. '10
Indonesia	2	Sept. '08
Iran	597	Nov. '11
Malaysia	12	Mar. '13
Myanmar	4	Oct. '11
Pakistan	50	Apr. '08
Philippines	1	Oct.'05
Russia	198	May '12
Singapore	1	Jul. '05
South Korea	52	Nov. '13
Taiwan	1	Apr'. 05
Thailand	39	Aug '08
Turkey	2	Aug. '04
UAE	4	Jul. '11
Total	**1.153**	

13. ANNEX 2, TASK SHARING CONTRIBUTION FROM VTT, FINLAND (COPIED FROM ORIGINAL REPORT)

Background

VTT Technical Research Centre of Finland has been running a heavy-duty vehicle test facility since 2002. Over the years, some 400 different HD vehicles have been tested, and a comprehensive data base on HD vehicle performance has been built up. The work has involved, among other things, research on energy efficiency, exhaust gas after-treatment and alternative fuels.

As for buses, VTT works in cooperation with Helsinki Region Transport to determine the true performance of various buses and to refine the tendering system for procuring bus services. VTT was also responsible for IEA Advanced Motor Fuels Annex 37/Bioenergy Task 41: “Fuel and technology alternatives for buses: Overall energy efficiency and emission performance” (http://www.iea-amf.org/app/webroot/files/file/Annex%20Reports/AMF_Annex_37.pdf).

Currently VTT is coordinating a national research programme looking for HD vehicle substitute fuels. The work programme includes field testing of various concepts (tall oil based renewable diesel, additive treated ethanol for diesel engines and diesel dual fuel methane engines). In addition, VTT works on test methods for alternative fuels, e.g. special exhaust emissions analytics.

As a task sharing contribution to Annex 39, Finland and VTT agreed to make its bus database available, including the measurements carried out for AMF Annex 37. In addition, VTT agreed to perform measurements on one additional methane fuelled bus, namely a bus equipped with the stoichiometric Cummins ISLG gas engine. The expectation was that this engine would deliver very low regulated exhaust emissions.

Within the project on substitute fuels for HD vehicles, three operators in Metropolitan Helsinki are operating altogether five diesel dual fuel methane trucks. VTT’s tasks include monitoring the field testing, but also extensive chassis dynamometer testing to establish, e.g., the effects of driving cycle, load and also type of pilot fuel on vehicle performance.

In the case of the diesel dual fuel trucks, Finland and VTT agreed to make some of the data of the preliminary chassis dynamometer measurements available to Annex 39.

Methods and devices for chassis dynamometer testing

Chassis dynamometer:

The exhaust emission and fuel consumption tests were conducted on heavy-duty chassis dynamometer capable of simulating the inertia weight and road loads that buses and trucks are subjected to during normal on-road operation.

For measurements of heavy-duty vehicles, VTT uses a single-roller, 2.5 meter diameter chassis dynamometer with electric inertia simulation. The system has the capability of testing vehicles from 2,500 to 60,000 kilograms. Maximum power absorbed power (continuous) is 300 kW. ***Figure 1*** presents the schematic of VTT test facility.

VTT has developed its own in-house method based covering both emission and fuel consumption measurements, partly based on SAE J2711. In June 2003, FINAS, the Finnish Accreditation Service, granted accreditation for the method of VTT (T259, In-house method, VTT code MK02E).

CVS and analytical systems:

For emission measurements VTT uses full-flow CVS dilution system. The analytical equipment (Pierburg CVS-120-WT CVS and analyzer set Pierburg AMA 4000) is compliant with Directive 1999/96/EC.

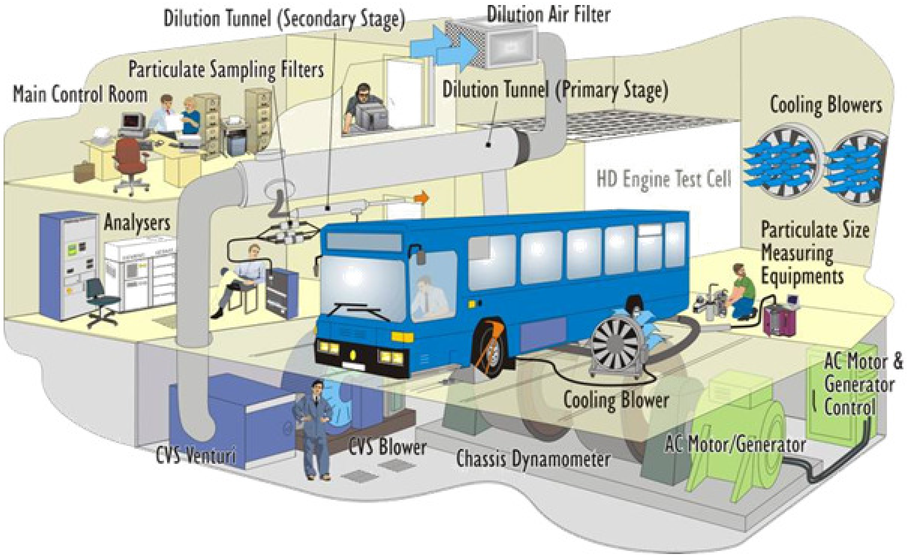


Figure 1: Schematic of VTT's heavy-duty test facility.

The total exhaust stream produced by the vehicle is collected and diluted using the CVS dilution system. The raw exhaust is then diluted with filtrated laboratory background air and the mixture drawn through a critical flow venturi. During the exhaust emissions tests, continuously proportioned samples of the dilute exhaust mixture and the dilution air are collected and stored in sample bags for analysis. *Table 1* presents a summary of sample collection and analysis devices.

Table 1: Summary of sample collection and analysis

Compound	Analysis method	Sample collection
Regulated components		
Carbon dioxide (CO_2)	NDIR	bag
Carbon monoxide (CO)	NDIR	bag
Oxides of nitrogen (NO_x)	CLD	bag
Total hydrocarbons (THC)	FID	Continuous collection
Particulate mass (PM)	Gravimetric	70 mm filter
Unregulated components		
Methane (CH_4)	FID splitter	bag
Nitric oxide (NO)/ Nitrogen dioxide (NO_2) balance	CLD	Continuous collection

CLD: Chemiluminescence Detection (heated)
FID: Flame Ionization Detection (heated)
NDIR: Non-Dispersive Infrared Detection

<u>Fuel consumption:</u>

VTT measures fuel consumption gravimetrically. The liquid fuel container is placed on a scale and the container is connected to the vehicle with external fuel lines. A similar method is used for urea in the case of SCR equipped vehicles.

With CNG vehicles, a special gas meter calibration system, consisting of a compressed natural gas (CNG) cylinder and a special scale is used to measure the fuel consumption.

<u>Dynamometer settings:</u>

VTT uses a road-load model based on coast-down measurements on the road. To determine the dynamometer settings (F0, F1, F2), the rolling resistances of the rear tires and the rear axle are deducted from the total resistance values, a common practice in setting up the chassis dynamometer. When testing vehicles on the chassis dynamometer, VTT used special sets of tires with longitudinal grooves only to normalize the effects of tires. Normally these kinds of tires are used only on non-driving steering axles.

VTT has built up a library of road load values for different types of heavy-duty vehicles. In the case of the measurements for Annex 39, it was not possible to carry out on-road measurements, so road load values for corresponding vehicles were used.

For a vehicle running a transient drive cycle, the mass of the vehicle is decisive for driving resistances. Vehicle mass affects inertia as well as rolling resistance. Emission tests with buses are usually run with inertia that corresponds half load counted from the buses unladen and maximum weight. For heavy-duty trucks test load depend on the type and purpose of use of the truck. It was decided to test the diesel dual fuel trucks with two different loads to provide information of the effect of load on diesel replacement ratio of methane, energy efficiency, fuel consumption and emissions. Road load values for tested vehicles are presented in *Table 2*.

Table 2: Dynamometer set up values for tested vehicles

Vehicle	Load	Inertia (kg)	F0	F1	F2
Solaris Urbino 15 CNG	Half load	18 880	446	5.85	0.1459
Volvo FE 340 DDF 6x2	Half load	18 100	74	4.471	0.2676
Volvo FE 340 DDF 6x2	Full load	26 000	464	3.923	0.2889

<u>Vehicle conditioning:</u>

Before running tests, vehicles are first warmed up for 15 – 30 minutes on the chassis dynamometer by running at constant speed of some 80 km/h. Then the test cycle is driven three times, and the final results are calculated as an average of the two last cycles.

Methane fuel:

The gas is refuelled from stations connected to the Finnish natural gas network. However, as there is feeding-in of biogas into the natural gas grid, the vehicles are considered to run on biogas. In practise the gas quality corresponds to Russian natural gas with high methane content, typically >98 %.

Solaris Urbino 15 CNG Emission Test Results

<u>Introduction:</u>

VTT measures emissions and fuel consumption from all new bus models that are entering Finnish bus market and carries out follow-up measurements to create a view of city buses emission through its lifecycle. The latest update of city bus emission database is presented in Appendix 1. The data base includes data for various CNG buses For Annex 39, the test vehicle, a Solaris Urbino 15 CNG, was rented from Veolia Sweden and transported to Finland for measurements.

<u>Test vehicle & settings:</u>

Solaris Urbino 15 CNG is a CNG powered version of 15 meter long 3-axle Solaris city/regional bus. The bus was equipped with Cummins ISLG 8.9 l 239 kW CNG engine with stoichiometric fuel system, EGR, three-way catalyst and automatic transmission from ZF. The bus had been driven for approximately 160 000 kilometers before the emission tests.

Tests were run with three different duty-cycles that describe different kind of urban bus routes. The test cycles selected were Braunschweig, ADEME, and UDDS, since there is fair amount of reference data available for these cycles. ADEME simulates driving in an European mega city, Braunschweig in a middle sized city and UDDS simulates driving in suburban lines. These cycles have also been used in IEA report on Fuel and technology alternatives for buses (Nylund, Koponen 2012).

Test results:

Emission results for the bus were really good. Regulated gaseous emissions and particulate matter were really low. Fuel consumption was in the same range with other 3-axle CNG buses, some 55 kg/100 km for Braunschweig. To make comparison with normal 2-axle city buses easier, the results were scaled to represent a normal 2-axle city bus. Scaling was done by comparing actual cumulative work throughout the cycle to average value for 2-axle city buses. Emission measurement and fuel consumption results are presented in *Table 3*.

Table 3: Emissions and fuel consumption of Solaris Urbino 15 CNG (three first rows actual data without scaling)

Test cycle	Load	Make	CO g/km	HC g/km	CH4 g/km	NO2 g/km	NOx g/km	CO2 g/km	CO2 eqv. g/km	PM g/km	NMHC g/km	Fuel consump. kg/100km	Energy Consump.	
													MJ/km	MJ/kWh
ADEME	Half load	Solaris Urbino 15	5.73	1.49	1.35	0.35	2.30	2090	2121	0.01	0.14	76.86	37.82	24.75
UDDS	Half load	Solaris Urbino 15	1.56	0.57	0.52	0.21	1.72	1038	1050	0.01	0.05	38.44	18.91	18.69
Braunschweig	Half load	Solaris Urbino 15	3.19	0.63	0.56	0.20	0.83	1457	1470	0.00	0.07	53.32	26.3	18.1
Braunschweig	Scaled results for 2-axle bus		2.37	0.47	0.42	0.15	0.62	1083	1093	0.00	0.05	39.63	19.55	13.45

Conclusions:

Emission results were extremely low for NO_x and particulate matter. *Figure 2* presents particulate matter and NO_x results from several CNG buses in the Braunschweig cycle. Included in the figure are boxes approximating Euro limits. The engine of a 2-axle city bus performs some 1.8 kWh of work per kilometer in Braunschweig cycle. The “boxes” have been created by multiplying the limit values for the different Euro classes (g/kWh for engine testing) by a factor of 1.8, thus converting the limit values into approximate distance based (g/km) values. As can be seen from the figure, the tested bus in practice reached the Euro VI emission levels for 2-axle city bus, although it is significantly heavier than a 2-axle bus. The conclusion must be that the vehicle clearly fulfils NO_x and PM requirements of the Euro VI emission standards. The same conclusion can be drawn from the scaled results in table 3. Solaris Urbino 15 CNG is by this far the cleanest bus measured in VTT. The vehicle also fulfils the Euro VI requirement for methane emissions (limit 0.5 g/kWh, measured value (unscaled) 0.42 g/km). Appendix 1 presents data for the other vehicles in greater detail.

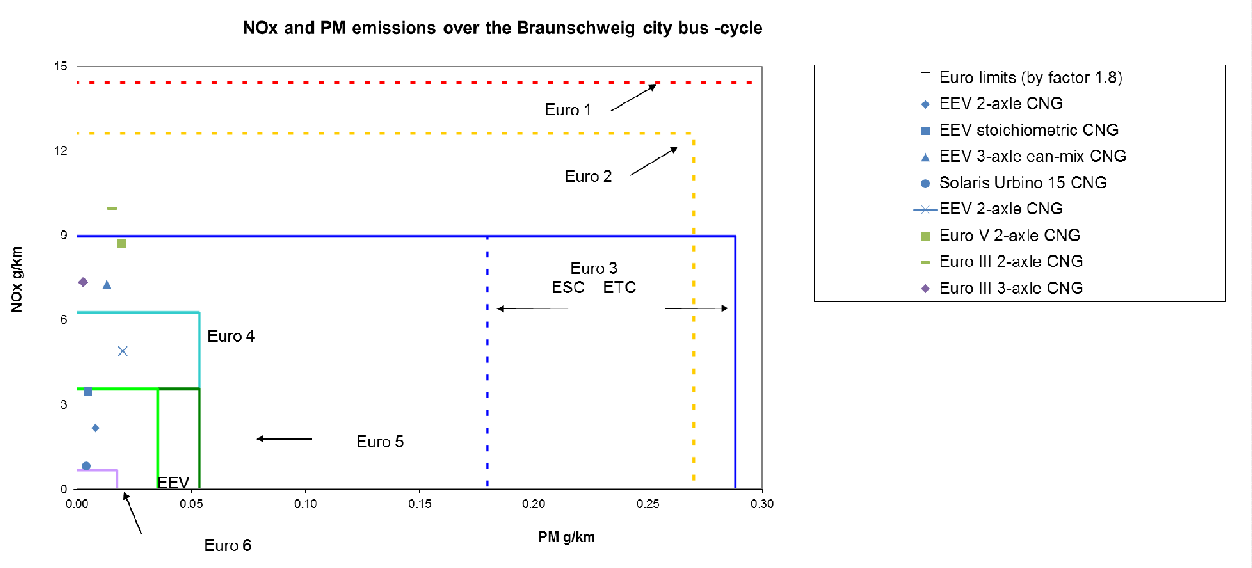


Figure 2: Emission results of CNG buses (Emission database for city buses, Fuel and technology alternatives for buses)

Diesel dual fuel truck project

Introduction:

The diesel dual fuel truck project follows the performance of diesel dual fuel trucks by putting five of these vehicles in a field test. The goal is to study how this new technology works both on the road and in laboratory conditions. In the field test the trucks are operating with premium diesel (Worldwide Fuel Charter 2013 Category 5 diesel fuel including a component of hydrotreated vegetable oil HVO) fuel and methane.
There are indications of high emissions of unburned methane for diesel dual fuel technology. One side-track in the project is to evaluate how the use of high quality diesel fuel as pilot fuel affects emissions and energy consumption (Cetane number of 100 % HVO is some 80 or even more).

The five diesel dual fuel trucks are operated by three Finnish truck operators. Two of the operators have two trucks and one smaller operator has one. The fuel use and driving routes of all vehicles is monitored and two of the trucks are also used for exhaust gas follow up measurements.

The vehicles:

The trucks are manufactured by Volvo, and the gas injection system has been installed by Hardstaff. The trucks use 7.2 litre six cylinder diesel engines that have been modified slightly for methane use. The main difference is the intake manifold that has 2 gas injection nozzles for each intake runner.

The diesel dual fuel engines are equipped with methane catalysts to lower the methane emissions. The engine's SCR system with urea injection is also controlled by the gas injection controls system. The amount of urea injection is lower than normal when the gas is used. If needed, the vehicles can operate on 100 % diesel, as the original fuel injection system has not been modified.

Two of the trucks are 26 ton Volvo FE series models with 250 kW engine and the rest are 18 ton FL models with 176 kW engines. The FE models are equipped with an automatic transmission and they are mainly used for road maintenance duties and construction work. FL models are with manual transmission and they are used for delivery work. One of the FE models is shown in *Figure 3*.

Figure 3: Volvo FE on VTT's heavy chassis dynamometer

Calculation of fuel consumption

In the tables presented hereafter, methane has been converted to diesel equivalent, so that in the case of diesel dual fuel operation the aggregated g/kWh or kg/100 values are compensated for heating value and depict equivalent diesel consumption.

The emission measurements:

According to the original project plan, two of the vehicles were supposed to undergo four emission measurements each under a period of three years, an initial measurement and then annual measurements. The plan was to carry out the first measurements once the vehicles had accumulated couple of thousands of kilometres. The first measurement session was planned to include a wide variety of tests, and the latter ones will be simple follow-up measurements. One FE and FL truck were selected to be measured.

The first measurements were planned to include several driving cycles, two different road loads and 6 different fuel combinations. The fuels will include different blends of regular diesel, FAME and HVO components. Also testing on diesel only is included.

Among a wide variety of test cycles it was decided to carry out the tests using two internationally used test cycles (FIGE and WHVC) and a highway cycle by VTT. The highway cycle was used because it provides comparison basis to VTT's previous tests as the highway cycle has been used in over 400 chassis dynamometer tests. The highway cycle is described in the VTT report "Fuel Savings for Heavy-Duty Vehicle, HD Energy, Summary report 2003-2005" (http://www.motiva.fi/files/1027/2006_HDEnergy_summaryreport_eng_final.pdf).

The first exhaust emission measurement test session on VTT's heavy chassis dynamometer with a FE-type vehicle took place in September 2013. After couple of tests it became apparent the methane emissions of the tested truck were significantly higher than were expected. It was decided to postpone the tests and try to solve the problem with gas system provider.

The truck was retested in November 2013 with a Hardstaff maintenance technician present. The methane emissions were still high, but no faulty components could be found. The gas system programming was updated to the newest version, but the methane emissions remained high.

Although not originally planned, also the second FE truck was tested to see if the methane emission problem only was limited to the first tested vehicle, but the second vehicle produced even worse methane emissions. It was apparent the problem was common for both FE trucks. The testing was again postponed until the real reason for the emission problems could be found. The results from the first tests using the dynamic FIGE cycle are presented in *Figure 4*.

Besides the FIGE tests also constant load tests were conducted. It could be seen that the methane emission was reduced when the vehicle was driven on constant load for a while. Increasing load lowered methane emissions significantly. This suggested that the catalyst was performing poorly in the temperature range occurring when running the FIGE cycle, with an average power of some 50 kW. Only some parts of the cycle require full power accelerations. The results from the constant load tests are shown in *Table 5* and *Figure 4*.

Table 4: *Preliminary test data showing high methane emissions*

Vehicle	Cycle	Inertia [kg]	CH4 [g/km]	NOx [g/km]	CO2 [g/km]	PM [g/km]
Malfunctioning truck	FIGE	18100	5.71	1.47	683	0.05
Malfunctioning truck 2nd test session	FIGE	18100	5.07	3.32	685	0.00
Malfunctioning truck, new firmware	FIGE	18100	3.56	2.97	705	0.05
2nd malfunctioning truck	FIGE	18100	6.15	2.05	684	

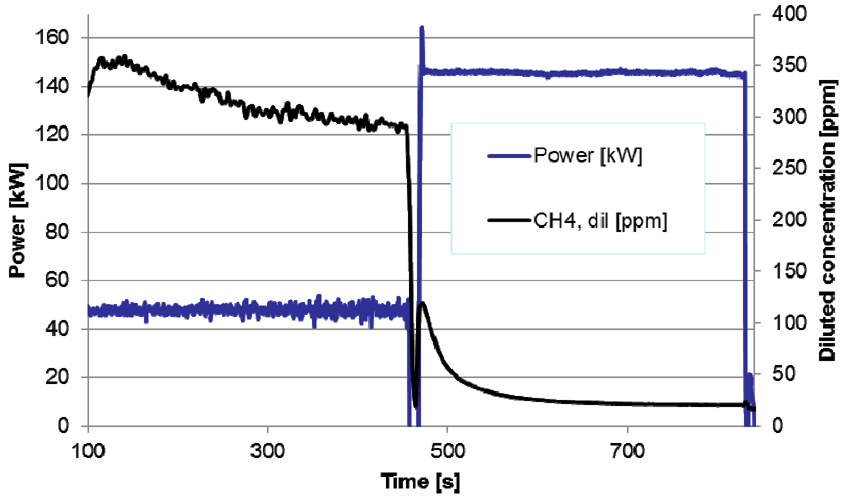


Figure 4: *Methane emissions under constant load*

Table 5: *Results from constant load tests*

Fuel	**Speed**	**Power***	**Diesel**	**CNG (diesel eq.)**	**SFC (diesel eq.)**	**Energy cons.**	**Energy share**	**CH4**	**NOx**	**CO2 tailpipe**	**CO2 eq.**
	[km/h]	**[kW]**	**[kg/100km]**	**[kg/100km]**	**[g/kWh]**	**[MJ/kWh]**	**of CNG, [%]**	**[g/km]**	**[g/km]**	**[g/km]**	**[g/km]**
Diesel	80	48	20.6	-	345	14.9	0	0	0.6	627	627
Diesel	80	152	47.8	-	252	10.9	0	0	3.9	1492	1492
Diesel+CNG	80	48	8.5	14.6	387	16.7	63	10.6	1.2	577	799
Diesel+CNG	80	146	23.1	24.3	260	11.2	51	0.50	2.1	1287	1298

*Drive wheel power

It was noted that the diesel replacement ratio of methane drops with increasing load. To avoid knocking, the amount of gas is reduced as a safety measure when the engine power is approaching the maximum output. Maximum diesel replacement ratio of methane was some 65 %.

In December 2013 it was decided to replace the methane catalysts, and the catalysts on the FE vehicles were replaced in January 2014. The original catalysts were sent to the manufacturer for inspection. The preliminary analysis revealed poisoning by sulphur, the reason of which is still unknown.

In February one FE truck was again tested, and now the methane emissions had improved substantially. In was then decided to go ahead with the full measurement programme.

Results:

Preliminary results are shown in *Table 6* and *Table 7*. The presented results are averaged results from two consecutive tests. The tables show results for three dynamic cycles. The results for the WHVC cycle are given for two weights, 18 t and 26 t. It should be emphasized that these results are preliminary, and that the testing will continue.

The tests were carried out with two different pilot fuels, regular EN590 diesel fuel without biocomponent (denoted B0) and the premium diesel fuel with a biocomponent (denoted WWFC 5).

The main result was than methane emissions were now in the range of 0.25 – 1.3 g/km. In the case of the FIGE cycle, this means a reduction of some 90 % compared to the first measurements.

The NO_x emissions are first and foremost controlled by the SCR system, and no unambiguous effect of feeding in methane can be seen. Surprisingly, the feed in of methane tends to increase particle emissions, and this trend is consistent for all test cycles.

As for the effect of pilot fuel, based on the results it’s not possible to draw any firm conclusions on differences between B0 and WWFC 5. The use of 100 % HVO as pilot fuel might bring about differences.

Diesel dual fuel operation increases energy consumption 5 – 9 % depending on the driving cycle.

Table 6: *Emission results with new catalyst*

Cycle	Fuel	Inertia	CO	HC	CH4	NMHC	NOx	PM
		[kg]	[g/km]	[g/km]	[g/km]	[g/km]	[g/km]	[g/km]
Highway	EN590, B0	18100	0.066	0.00	0.00	0.00	0.91	0.012
Highway	EN590, B0 + CNG	18100	0.046	0.27	0.25	0.02	1.28	0.043
Highway	WWFC 5 + CNG	18100	0.048	0.37	0.40	0.00	1.00	0.055
FIGE	EN590, B0	18100	0.064	0.00	0.00	0.00	1.46	0.022
FIGE	EN590, B0 + CNG	18100	0.093	0.67	0.61	0.05	1.19	0.053
FIGE	WWFC 5 + CNG	18100	0.041	0.62	0.56	0.06	1.31	0.045
WHVC	EN590, B0	18100	0.053	0.00	0.00	0.00	2.14	0.028
WHVC	EN590, B0 + CNG	18100	0.069	0.42	0.39	0.04	2.11	0.038
WHVC	WWFC 5 + CNG	18100	0.056	0.41	0.37	0.04	2.00	0.044
WHVC	EN590, B0 + CNG	26000	0.123	1.43	1.33	0.10	1.37	0.084
WHVC	WWFC 5 + CNG	26000	0.077	1.08	0.98	0.10	1.64	0.067

Table 7: Fuel consumption and performance values new catalyst

Cycle	Fuel	Inertia	Diesel	CNG (diesel eq.)	Fuel, total	Urea	Energy share of CNG	SFC (diesel eq.)	Speed, avg	Dist	Work pos.
		[kg]	[kg/100km]	[kg/100km]	[kg/100km]	[kg/100km]	[%]	[g/kWh]	[km/h]	[km]	[kWh]
Highway	EN590, B0	18100	22.01		22.01	1.94	0.0 %	317.5	80.1	28.740	19.9
Highway	EN590, B0 + CNG	18100	9.59	14.46	24.05	0.96	60.3 %	345.4	79.8	28.627	20.0
Highway	WWFC 5 + CNG	18100	10.09	14.10	24.19	0.95	58.3 %	345.5	80.1	28.710	20.1
FIGE	EN590, B0	18100	23.90		23.90	1.81	0.0 %	326.4	59.5	29.560	21.6
FIGE	EN590, B0 + CNG	18100	13.71	12.15	25.86	1.06	47.2 %	351.3	59.4	29.502	21.8
FIGE	WWFC 5 + CNG	18100	13.28	12.67	25.94	0.95	48.8 %	356.9	59.4	29.520	21.5
WHVC	EN590, B0	18100	27.97		27.97	1.76	0.0 %	330.8	40.4	20.170	17.1
WHVC	EN590, B0 + CNG	18100	20.70	8.49	29.19	1.42	29.2 %	343.6	40.4	20.179	17.2
WHVC	WWFC 5 + CNG	18100	20.77	8.77	29.54	1.35	29.7 %	350.1	40.2	20.090	17.0
WHVC	EN590, B0 + CNG	26000	20.62	16.21	36.83	1.86	44.2 %	321.9	40.2	20.058	23.0
WHVC	WWFC 5 + CNG	26000	22.43	13.64	36.07	1.78	37.8 %	315.7	40.2	20.078	22.9

Conclusions:

As delivered, the two measured FE trucks had unacceptably high methane emissions due to faulty catalysts. Replacing the catalysts lowered methane emissions to acceptable levels. Diesel dual fuel operation had negligible effect on NO_x emissions, but quite unexpected, increased PM emissions. The field testing will show how stable emissions will remain over time.

Diesel replacement ratio of methane was in the range of 30 – 60 %, depending on load and duty cycle. Energy consumption increases 5 – 9 % in diesel dual fuel operation compared to diesel operation. The results so far indicate a need to further refine the diesel dual fuel technology for higher diesel substitution, better efficiency and at least partly also better emission control.

Appendix 1 : City bus emission database

Braunschweig	*Count n*	*Mileage Min*	*Mileage Max*	*CO g/km*	*HC g/km*	*CH_4* g/km*	*NOx g/km*	*PM g/km*	*CO_2 g/km*	*CO_2 eqv** g/km*	*FC kg/100km*	*FC MJ/km*
2 - axle												
Diesel Euro I	2	555025	672700	1.39	0.32		15.59	0.436	1220	1220	38.6	16.6
Diesel Euro II	13	160500	1125674	1.60	0.21		12.86	0.213	1286	1286	40.7	17.5
Diesel Euro III	14	15934	786164	0.85	0.12		8.48	0.209	1213	1213	38.4	16.6
Diesel Euro IV	8	6105	474152	2.96	0.10		8.36	0.112	1207	1207	38.2	16.5
Diesel Euro V***				2.96	0.10		7.51	0.089	1207	1207	38.2	16.5
Diesel EEV	23	1020	696931	1.07	0.04		6.38	0.080	1167	1167	36.9	15.9
Ethanol EEV	1	98032	98032		0.43		5.58	0.037	1150	1150	65.3	16.5
Diesel Hyb, EEV	4	2602	44620	0.98	0.02		5.70	0.039	844	844	26.7	11.5
CNG Euro II	2	211000	672946	4.32	7.12	6.76	16.92	0.009	1068	1224	42.1	20.7
CNG Euro III	2	37600	237189	0.05	2.64	2.51	9.44	0.019	1111	1168	43.7	21.5
CNG EEV	8	1824	640252	2.78	1.28	1.21	3.17	0.008	1196	1224	47.1	23.2
2 - axle, lightweight												
Diesel****	4	993	26436	0.88	0.03		6.70	0.047	953	953	30.17	13.0
3 - axle												
Diesel Euro V	4	1400	232494	6.68	0.03		3.16	0.089	1414	1414	44.8	19.3
Diesel EEV	6	5444	94910	1.41	0.04		5.50	0.077	1461	1462	46.2	19.9
CNG EEV	5	121773	651529	10.96	1.69	1.61	6.37	0.010	1319	1356	51.9	25.5

*For CNG vehicles CH_4 = THC * 0.95, For diesels CH_4 = 0

** CO_2 eqv = CO_2 + 23 * CH_4

*** Euro V results are interpolated from Euro IV and EEV results

**** Includes results from emission classes Euro III, Euro IV ja EEV

Braunschweig														
Make	**Emission class**	**Fuel**	**Type**	**Exht.**	**CO [g/km]**	**HC [g/km]**	**CH4 [g/km]**	**NOx [g/km]**	**PM [g/km]**	**CO2 [g/km]**	**CO2 eqv.**	**FC [kg/100 km]**	**FC [MJ/km]**	**UC [kg/100 km]**
Volvo	Euro I	Diesel	2 - axle		0.06	0.12		19.47	0.248	1352	1352	42.8	18.4	
Scania	Euro I	Diesel	2 - axle		2.71	0.52		11.71	0.624	1087	1087	34.4	14.8	
Volvo	Euro II	Diesel	2 - axle		1.16	0.14		12.35	0.157	1343	1343	42.5	18.3	
MB	Euro II	Diesel	2 - axle		1.26	0.31		12.43	0.248	1236	1236	39.1	16.9	
Scania	Euro II	Diesel	2 - axle		0.98	0.24		8.77	0.176	1267	1267	40.1	17.3	
Kabus	Euro II	Diesel	2 - axle		4.31	0.15		16.54	0.398	1368	1368	43.3	18.7	
Renault	Euro II	Diesel	2 - axle		2.40	0.26		15.22	0.257	1155	1155	36.5	15.7	
Volvo	Euro II	CNG	2 - axle		2.87	8.96	8.51	17.58	0.007	1171	1367	43.2	21.3	
Volvo	Euro II	Diesel	2 - axle	PDPF	0.07	0.03		12.34	0.075	1267	1267	40.1	17.3	
Volvo	Euro II	Diesel	2 - axle	CRT	0.04	0.10		11.75	0.407	1589	1589	50.3	21.7	
Volvo	Euro II	Diesel	2 - axle	SCRT	0.12	0.01		1.54	0.010	1314	1314	41.6	17.9	
Volvo	Euro III	Diesel	2 - axle		1.31	0.02		8.81	0.308	1244	1244	39.4	17.0	
Scania	Euro III	Diesel	2 - axle		0.60	0.17		8.30	0.154	1195	1195	37.8	16.3	
Volvo	Euro III	CNG	2 - axle		0.05	2.64	2.51	9.44	0.019	1185	1243	43.7	21.5	
Scania	Euro III	Diesel	2 - axle	PDPF	0.13	0.03		7.37	0.093	1141	1141	36.1	15.6	
Scania	Euro III	Diesel	2 - axle	SCR + DPF	0.06	0.00		2.51	0.007	1194	1194	37.8	16.3	1.40
Volvo	Euro III	Diesel	2 - axle	CRT	1.17	0.10		9.70	0.042	1103	1103	34.9	15.0	
Volvo	Euro IV	Diesel	2 - axle	SCR	6.71	0.02		11.44	0.083	1119	1119	35.4	15.3	0.55
MB	Euro IV	Diesel	2 - axle	SCR	1.41	0.04		2.57	0.058	1130	1130	35.8	15.4	
Scania	Euro IV	Diesel	2 - axle	EGR	1.78	0.14		8.29	0.134	1258	1258	39.8	17.2	
Iveco	EEV	Diesel	2 - axle	SCRT	0.16	0.00		6.65	0.013	1093	1093	34.6	14.9	2.40
Iveco	EEV	Diesel	2 - axle	SCR	5.03	0.04		6.56	0.154	1208	1208	38.2	16.5	N/A
Volvo	EEV	Diesel	2 - axle	SCR	3.18	0.04		6.09	0.072	1120	1120	35.5	15.3	2.20
Scania	EEV	Diesel	2 - axle	EGR	0.41	0.06		6.43	0.107	1228	1228	38.9	16.7	
VDL	EEV	Diesel	2 - axle	SCRT	0.58	0.01	0.00	5.66	0.011	1217	1217	38.5	16.6	N/A
Volvo	EEV	Diesel	2 - axle	SCRT	0.04	0.01		6.96	0.031	1107	1107	35.0	15.1	1.75
VDL	EEV	Diesel	lt. 2 - axle	SCR	0.55	0.01	0.00	5.47	0.036	919	919	29.1	12.5	N/A
Scania	EEV	Ethanol	2 - axle			0.43		5.58	0.037	1150	1150	65.3	16.5	
MB	EEV	CNG	2 - axle		0.14	2.53	2.40	4.89	0.016	1583	1639	58.4	28.7	
MAN	EEV	CNG	2 - axle		3.86	0.80	0.76	2.69	0.004	1201	1218	44.3	21.8	
Iveco	EEV	CNG	2 - axle		2.62	1.17	1.11	2.16	0.008	1038	1063	38.3	18.8	
Scania	Euro III	Diesel	3 - axle	SCR + DPF	0.08	0.01		0.47	0.016	1443	1443	45.6	19.7	
Scania	Euro IV	Diesel	3 - axle	EGR	0.98	0.05		9.75	0.162	1501	1501	47.5	20.5	
Volvo	Euro V	Diesel	3 - axle	SCR	6.68	0.03		3.16	0.089	1414	1414	44.8	19.3	2.94
Volvo	EEV	Diesel	3 - axle	SCR	1.33	0.07		4.76	0.082	1483	1483	46.9	20.2	2.70
Scania	EEV	Diesel	3 - axle	EGR	0.13	0.01		9.53	0.082	1395	1395	44.2	19.0	
Golden Dragon	EEV	Diesel	3 - axle	SCR	0.35	0.02		2.97	0.042	1407	1407	44.5	19.2	4.10
VDL	EEV	Diesel	3 - axle	SCRT	3.96	0.02	0.00	6.19	0.093	1518	1518	48.0	20.7	1.7
MAN	EEV	CNG	3 - axle	EGR	12.90	1.96	1.77	7.75	0.011	1398	1439	51.6	25.4	
Solaris	EEV	CNG	3 - axle	SEGR	3.19	0.63	0.56	0.83	0.004	1445	1458	53.3	26.2	

14. ANNEX 3, TASK SHARING CONTRIBUTION FROM ENVIRONMENT CANADA, CANADA (COPIED FROM ORIGINAL REPORT)

Emissions Characterization of a Diesel and a Liquefied Natural Gas Heavy Duty Truck

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ERMS Report 13-16

Eric Meloche, Greg Rideout, Debbie Rosenblatt, Christine Morgan
Emissions Research and Measurement Section
Environment Canada

Environment Canada Environnement Canada

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Funding for this research was provided under the Government of Canada's ecoENERGY Innovation Initiative.

EXECUTIVE SUMMARY

This study compares the fuel consumption, energy efficiency, and emissions rates of a Liquefied Natural Gas (LNG) fuelled Class 8 truck to a conventional diesel truck. Both trucks were model year 2013, with 15 Liter engines equipped with advanced emission control systems. The LNG truck utilized a high pressure direct injection (HPDI) fuel system with diesel pilot ignition.

Both vehicles were tested over the Heavy-Duty Urban Driving Dynamometer Schedule (HD UDDS), the World Harmonized Vehicle Cycle (WHVC) and two steady-state speed cycles of 89 and 95 kilometers per hour (kph).

Along with fuel consumption, diesel equivalent fuel consumption, and energy efficiency, the emission rates are provided for the following compounds: carbon monoxide (CO), oxides of nitrogen (NO_x), total hydrocarbons (THC), non-methane hydrocarbons (NMHC), particulate matter (PM), carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O).

The percent difference between the diesel equivalent fuel consumption from the diesel and LNG trucks ranged from 11 to 27 percent higher for the LNG, depending on drive cycle, with slower average speeds, and increased idling leading to the higher diesel equivalent consumption. It should also be noted here that the diesel truck was certified to a higher NOx emission level which may have also contributed to the fuel consumption differences.

Methane was emitted at an average rate of 1.17 g/km to 1.95 g/km from the LNG truck but was not emitted from the diesel truck. Both CH_4 and N_2O were accounted for in the CO_2 equivalency rates (CO_2e), which were mostly lower for the LNG truck than for the diesel truck. However, the UDDS results showed 8% higher CO_2e rates for the LNG truck over the diesel truck, and this variation was statistically significant. The LNG truck had significantly lower emission rates of NO_X however the engines were certified to different NOx levels while particulate mass was also lower for the LNG truck.

For both trucks, the impacts of driving cycle on emissions and fuel consumption were noted. Generally, the steady-state driving cycles resulted in better fuel consumption, and lower emissions when compared to transient driving with varying acceleration and deceleration rates, while even a modest difference of 6 kph in the steady-state tests translated into a 7% and 6% change in fuel consumption for the LNG and diesel truck, respectively.

Increasing the vehicle test load from 24,000 kg to 33,000 kg on the diesel truck resulted in a 12% to 31% increase in fuel consumption combined with an averaged 3% reduction in energy efficiency. This higher weight test configuration also produced higher energy efficiency over the steady-state cycles than over the transient operation cycles.

Comparing emission results of the increased test load to the baseline load on the diesel truck: CO_2 emission rates were increased by 15% to 31%; CO_2 equivalent emission rates were increased by 17% to 36%; NO_x emission rates were decreased by 9% to 44%; and TPM emission rates changes were varied as two of the four test cycles did not show any statistically significant differences while a 123% increase and a 72% decrease were observed over the HD UDDS and SS 95 kph test cycles, respectively.

Over the course of this program, the diesel truck was observed to have relatively high NO_x emissions in the range of 1.2 g/km for steady-state driving conditions to 5.6 g/km for transient driving conditions. This was in contrast to similar tests conducted by the ERMS on other SCR equipped engines/trucks[1,2] where aftermarket SCR systems produced steady-state (89 kph) emission rates as low as 0.04 g/km and 2.24 g/km for transient operation, while a Class 7 truck had NO_x emission rates of 0.5 g/km and 1.2 g/km across the same steady-state and transient cycles.

Since these NO_x emission levels were of concern, an investigation of various signals from the engine control module of the vehicle was undertaken which did not provide an indication of any operational issues with the vehicle. Review of the ECU data and discussions with Cummins Engine Company suggested that the test cycles and vehicle loadings that were used in this study resulted in relatively low exhaust temperatures and consequently the SCR catalyst was not operating under optimal conditions. Results of the increased test load configuration supported this observation, as an extra 9,000 kg of simulated inertia weight contributed to an averaged 21°C increase in exhaust temperature and NO_x emissions were lowered on average by 17%. However, further testing would be required to determine if more factors could have been a contributor to the elevated NO_x emissions observed with this vehicle, or if these values are within normal range for this type of duty cycle.

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[1] Anthony El-Behery, Greg Rideout, Svetlana Iretskaya, Eric Meloche, Ted Tadrous, Deborah Rosenblatt, Kevin Brown, Development and Field Performance Validation of a Retrofit SCR System for On-Road Heavy-Duty Application SAE Technical Paper 2010-01-1186

[2] Aaron Loiselle-Lapointe, Evaluation of a Class 4 Heavy-Duty Diesel Electric Hybrid Kenworth Intra-City Delivery Truck for Fuel Efficiency, GHG and Regulated Exhaust Emissions Report A: Conventional vs. Hybrid Mode, ERMS Report No 10-35

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1.0 Introduction

This ecoENERGY Innovation Initiative (ecoEII) project was developed to support the advancement of energy efficient technologies for on-road vehicles by gathering fundamental knowledge of the air pollutants, greenhouse gas (GHG) emissions and fuel consumption reductions that can be attributed to emerging transportation technologies operated under Canadian conditions. This knowledge base will enable improved analysis of the energy and environmental potential of these systems, as well as support the development of future policies, incentives, and regulations that may be needed to further their broad deployment. The knowledge transfer to industry and raised awareness with the consumer could lead to accelerated deployment and uptake of these emerging technologies, thereby increasing the rate at which the Canadian legacy vehicle fleet is replaced with clean sustainable transportation technologies.

The project was designed to generate this baseline knowledge by conducting chassis dynamometer testing of state-of-the-art vehicles at Environment Canada's Emissions Research and Measurement Section (ERMS) test facility. The experimental design is based upon a test matrix organized into three vehicle categories; light-duty passenger vehicles, medium-duty trucks (Class 2-3) and heavy-duty trucks (Class 7-8). The finalized test matrix included a variety of driving cycles and ambient temperatures in order to give real world and application specific data. This is a unique approach as many studies focused on standardized certification type cycles and temperatures and, therefore, may have underestimated possible benefits or potential issues. These off-cycle conditions were considered crucial for broadening the knowledge of these technologies, as vehicles tend to be optimized to the certification requirements.

The heavy-duty vehicle portion of the study looks at the overall vehicle system and where gains may have been made in terms of lowering emissions along with fuel consumption in the near term, for both the new vehicles entering the fleet and for the older legacy vehicles that may remain on the road for several years to come. The systems approach considers technologies such as idle reduction systems, low rolling resistance tires and improved aerodynamics, while the final test matrix may also include alternative fuels, advanced engines, hybrids – electric and hydraulic, advanced transmissions, and the impacts of exhaust emission control technologies such as active diesel particulate filters, selective catalytic reduction and other oxides of nitrogen controls.

In support of the ecoENERGY Innovation Initiative and the Advanced Motor Fuels Implementing Agreement of the International Energy Agency (Annex 39), gaseous and particulate emissions measurements were conducted on an in-use 2013 diesel transport truck and one equipped with a high pressure direct injection system that uses liquefied natural gas as the primary fuel along with a small amount of diesel as a pilot ignition source. The vehicles were provided by Robert Transport, a Canadian transport company, and Excellence-Peterbilt.

Fuel consumption, energy efficiency, and emission rates of carbon monoxide (CO), oxides of nitrogen (NO_x), total hydrocarbons (THC), non-methane hydrocarbons (NMHC), particulate matter (PM), carbon dioxide (CO_2), methane (CH_4) nitrous oxide (N_2O) and speciated carbonyls, were determined over four drive cycles. The cycles reported herein were the Heavy-Duty Urban Driving Dynamometer Schedule (HD UDDS), the World Harmonized Vehicle Cycle (WHVC), an 89 kilometer per hour (kph) steady-state (SS) cycle and a SS 95 kph cycle.

The tests were performed under controlled laboratory conditions on a heavy-duty chassis dynamometer capable of simulating the inertia weight and road load that highway trucks are subjected to during normal on-road operation.

2.0 Facility and Equipment Description

2.1 Exhaust Emissions Measurement and Analytical Techniques

The total exhaust stream produced by the truck was collected and diluted using a constant volume sampling (CVS) system with a total dilute exhaust flow rate of approximately 45 m^3/minute (1600 scfm). The dilution air was conditioned by removal of particulate matter using HEPA filtration. The total volume of raw exhaust was transferred from the truck exhaust to the CVS through a flexible stainless steel pipe. The raw exhaust was then diluted with HEPA filtered ambient air and the mixture was drawn through a dilution tunnel and critical flow venturi (CFV). During the exhaust emissions tests, continuously proportioned samples of the dilute exhaust mixture and the dilution air were collected and stored in Kynar^{TM} sample bags for analysis while continuous sampling was also undertaken through heated pump, filter and sample line systems for NO_x and THC. From a separate probe in the dilution tunnel, sample bags were collected for the per-phase analysis of N_2O as well as CH_4 and other light hydrocarbons (C_1 to C_3 hydrocarbons). The averaged THC emission rates of the LNG truck, as shown in Table 6 of this report, are the sum of CH_4 and NMHC results from the gas-chromatography flame-ionisation detector (GC-FID) bag analysis of light hydrocarbons. Over the course of the study it was observed that the total hydrocarbons reported from the continuous measurements conducted in the test cell were, on average, 94% of the speciated hydrocarbon emissions with that vehicle.

The determination of particulate matter (PM) was performed as per Title 40 Part 1065 of the Code of Federal Regulations (CFR). This method excludes vapour phase particulate matter from collection on the filter. As per Part 1065, the ERMS balance room conforms to an “as-built” Class 6 clean room specification according to ISO 14644-1. Prior to the test, 47 mm Teflon membrane filters were stored in a desiccator where the conditions were maintained at 40±5% humidity and 22±3°C. After stabilization, the filters were weighed on a Mettler Toledo XP2U ultra-microbalance. After the test, the filters were re-stabilized in the desiccator for 8 to 80 hours and re-weighed to determine the net mass of diesel particulate emissions. Table 1 provides a summary of the sample collection and analysis media and the analytical methods used to measure each compound.

Table 1: Summary of sample collection and analysis methods

Compound	Analysis Method	Sample Collection
Carbon Monoxide (CO)	Non-Dispersive Infrared Detection (NDIR)	Kynar™ Bag
Carbon Dioxide (CO_2)	Non-Dispersive Infrared Detection (NDIR)	Kynar™ Bag
Oxides of Nitrogen (NO_X)	Heated Chemiluminescence Detection	Continuous Collection
Total Hydrocarbons (THC)	Heated Flame Ionization Detection (FID)	Continuous Collection
Particulate Matter (CFR1065 PM)	Gravimetric Procedure	47mm Filters
Nitrous Oxide (N_2O)	Gas Chromatography with Electron Capture Detection (GC-ECD)	Kynar™ Bag
Methane (CH_4)	Gas Chromatography with Flame Ionization Detection (GC-FID)	Kynar™ Bag

2.2 Emissions Calculations

Exhaust Emissions

The exhaust emission rates were calculated in accordance with the U.S. EPA Code of Federal Regulation, Schedule 40, Part 1065 or Part 86, Subpart N, where applicable. The final reported exhaust emission test results were calculated using the equations described in 40 CFR 1065.650 or CFR Title 40 Part 86.144.90, 86.144.94, and 86.145.82.

Fuel Consumption Calculation for LNG Truck with Diesel Pilot Injection

The calculated fuel consumption for the LNG truck was based on the following equation to produce a diesel equivalent fuel economy:

$$\text{DEFE [mpg]} = \frac{\text{BTU / U.S. Gallon diesel}}{(\text{FFC}*(CH_4+\text{NMHC}) + 0.429*\text{CO} + 0.273*CO_2) * ((1/\text{FFC})*\text{NHV}_{\text{fuel}})} \qquad [1]$$

$$\text{DEFC [L/100km]} = 235.215 / \text{DEFE [mpg]} \qquad [2]$$

DEFE = diesel equivalent fuel economy
DEFC = diesel equivalent fuel consumption
FFC = fuel fraction carbon
BTU = British thermal units
NHV_{fuel} = neat heating value of fuel in BTU per grams
CH_4, NMHC, CO, CO_2 in grams per mile

Equivalent CO_2 emissions Calculation

As certain gases can contribute to the 'greenhouse effect' more than CO_2, the equivalent amount of CO_2 that was emitted was calculated using the following equation:

$$CO_2eq = CO_2 + 25*CH_4 + 298*N_2O \qquad [3]$$

NMHC Calculation

$$NMHC_{ppmC} = THC_{ppmC} - (R_{CH4} * CH_{4\,ppmC}) \qquad [4]$$

R_{CH4} = analyzer response factor to methane (unit less)

Energy Efficiency

The energy efficiency for each test was determined following the procedures outlined in SAE Recommended Practice J2951 NOV2011 'Drive Quality Evaluation for Chassis Dynamometer Testing'. The procedure described the calculations for determining the net energy a vehicle must provide in order to drive a test cycle on a chassis dynamometer. The cycle energy, divided by the fuel energy from each test is reported as energy efficiency.

2.3 Chassis Dynamometer Description

The heavy-duty dual axle dynamometer system consists of two sets of rolls, one per axle (dual axle vehicles), which have a diameter of 60 cm. The distance between the centers of these rolls can be adjusted from 122 to 183 centimetres. The inertia weight and road load are simulated during testing using two 295 kilowatt direct current motors, one per axle. The motors transfer power to and from the electrical grid using fully regenerative power converters. The system has the capability of testing vehicles from 7,700 to 35,000 kilograms, simulating both road load and the inertia of the vehicle at all vehicle speeds.

The rotating speed of the dynamometer rolls during a vehicle emissions test is measured by a pulse counter that communicates this information to a microprocessor controller. The controller translates the pulses into the linear speed of the vehicle and it is displayed on a video screen as a cursor. The vehicle driver then uses the cursor to follow a selected speed versus time trace. In this way, the vehicle can be operated over a selected transient operation or driving cycle.

The chassis dynamometer testing procedures followed for this type of emissions testing are outlined in a U.S. EPA report entitled "Recommended Practice for Determining Exhaust Emissions from Heavy-Duty Vehicles under Transient Conditions"[3]. The electronic programming feature of the dynamometer controller allows for a speed-power curve[4] for each test vehicle.

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[3] France, C., Clemmens W., Wysor T., Recommended Practice for Determining Exhaust Emissions from Heavy-Duty Vehicles under Transient Conditions USEPA Report SDSB-79-08.

[4] Urban c., Dynamometer Simulation of Truck and Bus Road Horsepower for Transient Emissions Evaluation SAE 840349

The vehicles were tested using target coefficients derived from a similar truck that was track tested by the Vehicle Performance & Engineering Analysis at Peterbilt Motors Company in Denton, Texas. The data was adjusted for rolling resistance and aerodynamic differences to produce a road load force curve. Target coefficients were derived using the SAE J2263 coast down technique. Based on these target coefficients, dynamometer set coefficients were obtained by performing a chassis dynamometer coast down procedure according to SAE J2264. Using the method detailed in SAE J1263, the A and C values were adjusted for the two test weights. The total set value of both vehicles is slightly different, which may be attributed to differences in the drivetrain of each vehicle. The LNG truck had an automated manual transmission while the diesel truck had a 13-speed manual transmission. Target and set coefficients of both test vehicles are provided in Table 2.

Table 2: Road load coefficients

Vehicle	Test Weight	Coefficients (HP @ 50 mph)	A	B	C	Total
LNG	**24,132 kg**	**Target**	34.12	26.78	42.35	103.25
		Set	24.59	17.82	42.23	84.64
Diesel	**24,132 kg**	**Target**	34.12	26.78	42.35	103.25
		Set	20.80	16.91	37.07	74.78
	33,200 kg	**Target**	50.81	26.78	42.67	120.26
		Set	37.49	16.91	37.39	91.79

2.4 Vehicle Description

Specifications for the test vehicles are listed in Table 3 while trucks are shown in Figures 1 and 2.

Table 3: Test vehicles specifications

VEHICLE TYPE	Class 8 / Peterbilt 386 LNG 6x4	Class 8 / Peterbilt 587 6x4
NUMBER OF AXLES	3 (1 Front, 2 Rear)	3 (1 Front, 2 Rear)
VEHICLE MODEL YEAR	2013	2013
Tare Weight*	9,140 kg	9,470 kg
GVWR	24,132 kg	24,132 kg
STARTING ODOMETER	225,650 km	243,649 km
ENGINE	Westport / HD 15L GX 475	Cummins / ISX
ENGINE DISPLACEMENT	15 L	15 L
INJECTION	High Pressure Direct Injection (HPDI)	Direct Injection XPI fuel system
TRANSMISSION	Automated manual	13-speed Manual
ADVERTISED HP (kW)	475 (330) @ 1750 RPM	425 (317) @ 1800 RPM
TORQUE FT-LB (Nm)	1750 (2370) @ 1200 RPM	1550-1750 (2100-2370) @ 1100 RPM
IDLE SPEED (RPM)	600-800	600-800
EMISSION CONTROLS	DPF, SCR, Cooled EGR	DPF, SCR, Cooled EGR
CERTIFICATION	EPA 2010	EPA 2010
NO_x Certification (g/bhp-hr)	0.135	0.35
FUEL DESCRIPTION	LNG + Diesel Pilot Injection	Diesel
TEST WEIGHT	24,132 kg	24,132 kg & 33,200 Kg
TEST ROAD LOAD	77kW @ 80kph	77kW @ 80 kph & 90kW @ 80 kph

*As indicated on tractor label

Figure 1: Class 8 LNG test vehicle

Figure 2: Class 8 Diesel test vehicle

2.5 Test Fuel

The test fuels were liquefied natural gas (LNG), and US EPA certification diesel. The properties of each fuel are listed in Table 4. During the LNG truck testing the ratio of diesel to natural gas that is injected into the engine varies depending upon the demands of the vehicle operation. Westport, the manufacturer of the high pressure direct injection system utilized in the LNG engine evaluated the driving cycles used in the study, and were provided with data recorded from the engine control unit. With this information Westport provided an engineering estimate of the average diesel pilot injection rate over the tests[5]; 15.1% over the World Harmonized Cycle, 18.0% over the Heavy Duty UDDS, and finally 15.7% and 12.1% over the 89 and 95 kilometer per hour steady states respectively.

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[5] Communication from James Saunders, Life Cycle Emissions Analyst, Westport

Table 4: Fuel specifications

Fuel Property	LNG[6]	ULSD[7]
Density (kg/L)	0.700	0.854
Carbon Fuel Fraction (mass %)	73.3	86.7
Sulphur (ppm)	-	8 ppm
Net Heating Value (MJ/kg)	49.8	43.2

2.6 Driving Cycles

Four driving cycles were used in this project: two transient cycles and two steady-state cycles. The UDDS and WHVC are similar in that they are transient cycles with similar maximum speeds, distances and test time. Differences between the driving cycles include a lower average speed, higher acceleration/deceleration rates and increased idle time for the UDDS and the WHVC has a dedicated highway driving phase. The steady-state speed of 89kph (55mph) was chosen as it is one of the cycles being used in North America in support of the Heavy-Duty Vehicle Greenhouse Gas Emissions and Fuel Efficiency Rules. According to the truck operator, however, the LNG trucks were operated along a specific highway corridor at a maximum speed of 95kph. Therefore, in order to provide fuel consumption and emissions rates of the truck simulating it's in-use operating conditions, the second steady-state speed of 95kph, although close to 89kph, was also selected for testing purposes.

The characteristics of each driving cycle are shown in Table 5 and speed versus time plots of the cycles are provided in Figures 3-5. The vehicles were preconditioned with a warm-up cycle prior to the start of testing and after any pause in testing longer than 20 minutes.

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[6] Communication from Gaz Metro

[7] Fuel analysis results from Alberta Innovates

Table 5: Driving cycle characteristics

Cycle	Avg. Speed (kph)	Max Speed (kph)	Max Accel. (kph/s)	Max Decel. (kph/s)	Total Time (s)	Idle Time (s)	Total Dist. (km)
HD UDDS x 2	30	93	6.8	-7.2	2120	706	17.9
WHVC	40	88	5.8	-6.3	1800	239	19.9
89 kph Steady-State	76	89	0.8	-1.4	700	50	14.7
95 kph Steady-State	80	95	1.1	-1.6	700	50	14.8

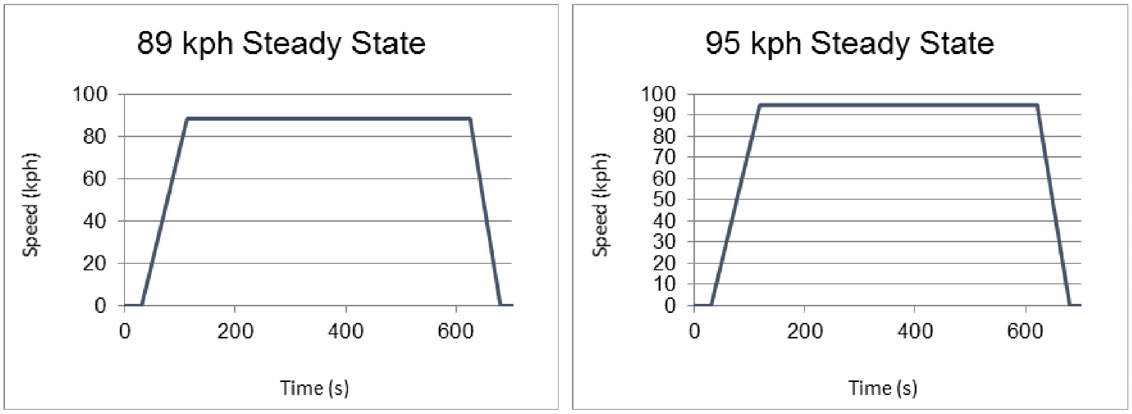

Figure 3: Steady-State Speed vs. Time Schedule, 89 KPH and 95 KPH

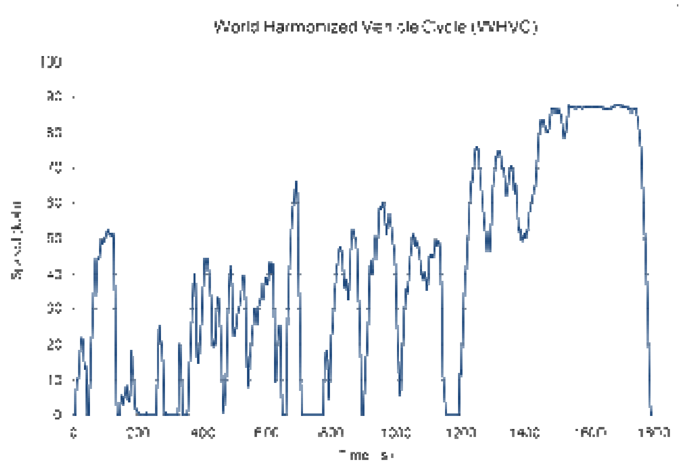

Figure 4: WHVC Speed vs. Time Schedule

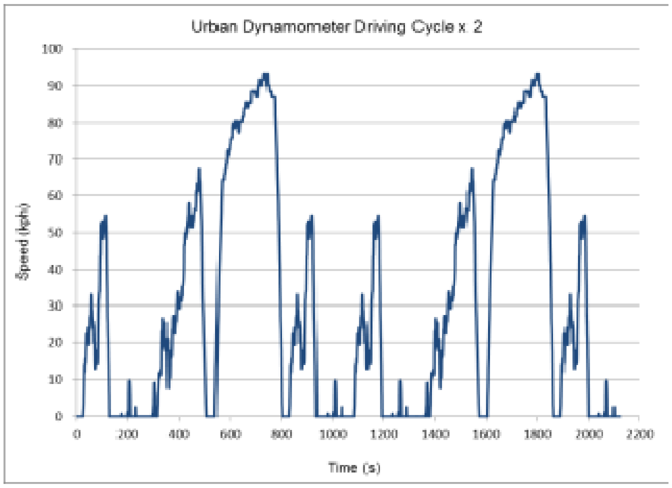

Figure 5: HD UDDS x 2 Speed vs. Time Schedule

3.0 Results and Discussion

The average mass emission rates results of CO, NO_x, THC, NMHC, PM, CO_2, CH_4, N_2O and total carbonyls along with calculated fuel consumption / diesel equivalent fuel consumption and energy efficiency are summarized in Table 6. The average and the standard deviation of the data sets are presented in Figure 10, 11 and 12 in Sections 3.2, 3.3 and 3.4 while individual test results are presented in the Appendix.

Table 6: Emissions and Fuel Consumption Results

Test Parameters		Regulated Emissions and FC							GHG Emissions			
		CO	NO_x	THC	NMHC	TPM	FC / DEFC	Energy Efficiency	CO_2	CH_4	N_2O	$CO2_e$
		g/km	g/km	g/km	g/km	mg/km	L/100 km	%	g/km	g/km	mg/km	g/km
386 LNG 24000 kg	HD UDDS	0.01	0.90	2.05	0.10	0.4	59.4	26	1253	1.95	92.1	1329
	WHVC	0.01	1.11	1.48	0.07	0.3	46.8	29	995	1.41	48.4	1045
	SS 95 kph	0.00	0.12	1.23	0.07	0.3	33.4	35	699	1.17	182.9	783
	SS 89 kph	0.00	0.10	1.32	0.07	0.4	30.9	36	653	1.26	123.2	722
587 Diesel 24000 kg	HD UDDS	0.00	5.62	0.00	0.00	0.4	46.8	37	1219	0.00	51.2	1234
	WHVC	0.00	4.55	0.00	0.00	1.2	40.5	36	1054	0.00	38.9	1066
	SS 95 kph	0.00	1.22	0.00	-	1.5	29.7	41	772	0.00	83.5	797
	SS 89 kph	0.00	1.38	0.00	0.00	0.9	28.0	42	728	0.00	77.9	752
587 Diesel 33000 kg	HD UDDS	0.00	5.09	0.00	-	0.8	55.3	30	1484	0.00	117.5	1519
	WHVC	0.00	3.61	0.00	-	1.2	53.2	40	1386	0.00	207.9	1448
	SS 95 kph	0.00	1.16	0.00	-	0.4	33.1	43	889	0.00	135.5	929
	SS 89 kph	0.00	0.77	0.00	-	0.5	31.3	45	838	0.00	266.0	918
LNG vs. Diesel		++	-84	++	++	-	27	-30	3	++	80	8
Diesel 33T vs. 24T		-	-9	-	-	123	18	-	22	-	130	23
LNG vs. Diesel		-	-76	++	++	-	16	-17	-6	++	24	-
Diesel 33T vs. 24T		-	-21	-	-	-	31	-	31	-	434	36
LNG vs. Diesel		-	-90	++	++	-81	13	-15	-10	++	119	-
Diesel 33T vs. 24T		-	-	-	-	-72	12	-	15	-	62	17
LNG vs. Diesel		-	-93	++	++	-	11	-15	-10	++	-	-
Diesel 33T vs. 24T		-	-44	-	-	-	12	-	15	-	241	22

++ Large difference / comparison with value below detection limits or assumed to be 0
- No value / No statistical differences

3.1 Diesel Emissions of NO_x

Over the course of conducting the tests on the diesel truck the emission rates that were being observed for NO_x were of concern given their comparison to previous ERMS experience with SCR equipped heavy duty engine and vehicle testing, and real world test results that are now being reported[8,9].

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[8] Gary A. Bishop, Brent G. Schuchmann and Donald H. Stedman, Heavy-Duty Truck Emissions in the South Coast Air Basin of California, dx.doi.org/10.1021/es401487b | Environ. Sci. Technol. 2013, 47, 9523

[9] Chandan Misra, John F. Collins , Jorn D. Herner , Todd Sax , Mohan Krishnamurthy , Wayne Sobieralski , Mark Burntizki , and Don Chernich, In-Use NOx Emissions from Model Year 2010 and 2011 Heavy-Duty Diesel Engines Equipped with Aftertreatment Devices, Environ. Sci. Technol., 2013, 47 (14), pp 7892–7898

During the testing program, selected outputs from the engine control system had been monitored using either the Cummins INSITE OBD tool or a PEMS OBD tool. An example of this is presented in Figure 6, which indicates various exhaust temperatures and also NO_x concentrations recorded before and after the SCR catalyst. From the NO_x concentration data recorded pre and post the SCR control system it appeared that the SCR system was lowering the levels of NO_x in the exhaust.

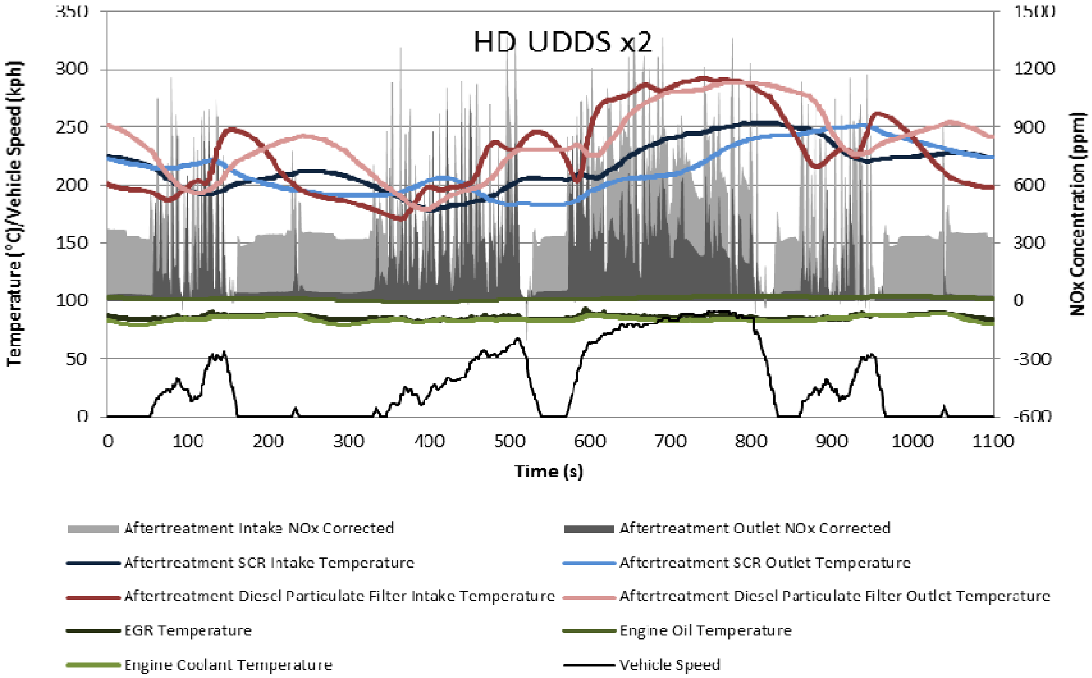

Figure 6: Engine OBD Outputs during a HD UDDS Test, First Test Round (Feb 18)

Near the conclusion of the tests that were being conducted separately to consider biodiesel and added vehicle weight, the check engine light became illuminated (amber) and subsequent investigation of the engine control unit indicated that the issue was related to the SCR system with the following fault code information suggesting a loose electrical circuit:

- 3429 – Aftertreatment Diesel Exhaust Fluid Line Heater 4 Circuit – Current below normal or open circuit
- 2976 – Aftertreatment 1 Diesel Exhaust Fluid Dosing Unit Temperature – Data erratic, intermittent or incorrect
- 3561 – Aftertreatment 1 Diesel Exhaust Fluid Dosing Unit – Current below normal or open circuit
- 3579 – Aftertreatment Diesel Exhaust Fluid Return Valve – Current below normal or open circuit
- 3578 – Aftertreatment Diesel Exhaust Fluid Return Valve – Voltage below normal or shorted to low source
- 3572 – Aftertreatment 1 Diesel Exhaust Fluid Pressure Sensor – Voltage Below Normal, or shorted to low source
- 3557 – Aftertreatment Diesel Exhaust Fluid Controller – Data erratic, intermittent or incorrect
- 3559 – Aftertreatment 1 Diesel Exhaust Fluid Dosing Unit – Voltage below normal or shorted to low source

After the check engine light was illuminated, the vehicle was returned to Excellence-Peterbilt for service and then brought back to the Environment Canada facility for further tests to confirm the data collected during the initial test series. Figure 7 is from the second round of testing and indicates the same level of NO_x control.

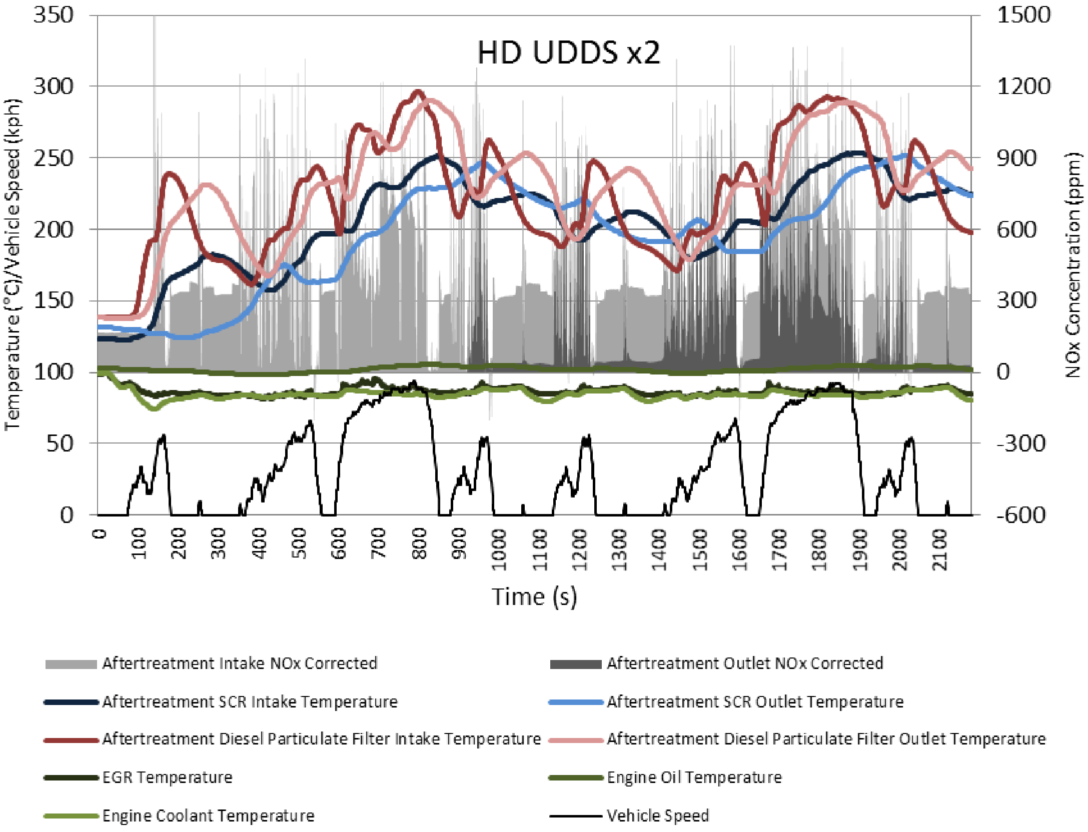

Figure 7: Engine OBD Outputs during a HD UDDS Test, Second Test Round (Mar 12)

Table 7 provides the averaged emission results from the two rounds of testing and, while there is some variability, the data is considered to be consistent between the two rounds of testing. Based upon the consistency from one test round to the other, the final data presented in this report combines the results from both rounds of diesel truck tests.

Diesel Phase 1	**Regulated Emissions and Fuel Consumption**						**GHG Emissions**			
	CO g/km	**NO_x g/km**	**THC g/km**	**NMHC g/km**	**PM mg/km**	**FC L/100km**	**CO_2 g/km**	**CH_4 g/km**	**N_2O g/km**	**CO_2e g/km**
HD UDDS	0.001	5.75	0.00	0.00	0.8	46.7	1245	0.00	0.044	1258
WHVC	0.000	4.56	0.00	0.00	1.9	40.4	1053	0.00	0.041	1065
SS 89 kph	0.000	1.30	0.00	0.00	1.1	28.2	735	0.00	0.090	762
Diesel Phase 2	**CO g/km**	**NO_x g/km**	**THC g/km**	**NMHC g/km**	**PM mg/km**	**FC L/100km**	**CO_2 g/km**	**CH_4 g/km**	**N_2O g/km**	**CO_2e g/km**
HD UDDS	0.000	5.66	0.00	0.00	1.3	47.0	1224	0.00	0.063	1242
WHVC	0.007	4.55	0.00	0.00	0.8	40.5	1056	0.00	0.037	1067
SS 89 kph	0.000	1.49	0.007	0.00	0.6	27.7	720	0.00	0.062	739

Table 8: Regulated Emission and Fuel Consumption, Diesel Truck Phases 1 & 2

The distance based NO_x emissions reported over these test cycles during the second phase of testing have been converted in the following Table to fuel based emissions, as well as brake specific using the energy measured at the chassis dynamometer. Included in the Table are driving cycle and exhaust parameters that may help to partially explain the elevated NO_x emissions observed. It should be noted that the brake-specific emission rates are not directly comparable to the engine emission standards due to the difference in test cycle as well as the inclusion of the vehicle drivetrain which is not part of the engine emissions certification procedure.

Table 8: NO_x Emission Rates and Driving Cycle Effect

Cycle	**NO_x**	**NO_x**	**NO_x**	**Average Speed**	**Idle Time**	**Average T° SCR Inlet**	**Time Under 200 °C**	**Time Over 250 °C**
	g/km	**g/bhp-hr**	**g/kg Fuel**	**kph**	**%**	**°C**	**%**	**%**
WHVC 2-1	4.41	2.21	12.52	41	16	203	39	0
WHVC 2-2	4.63	2.32	13.02	40	15	204	39	0
WHVC 2-3	4.60	2.30	13.83	42	13	198	41	0
HD UDDS 2-2	5.55	2.36	13.67	30	35	215	25	4
HD UDDS 2-3	5.77	2.45	14.51	30	34	206	39	1
SS 89 kph 2-1	1.65	1.01	7.02	76	7	234	17	43
SS 89 kph 2-2	1.55	0.95	6.74	76	6	242	12	53
SS 89 kph 2-3	1.26	0.77	5.15	76	6	245	11	60

The SCR systems used in North America typically use zeolite based catalysts as the material is better suited than vanadium for the high exhaust temperatures that are created during the regeneration of diesel particulate filters. Copper-Zeolites catalysts have the best low temperature performance with NO_x reduction starting as low as 150°C, with maximum NO_x conversion occurring between 225°C to 500°C [10,11]. The two transient cycles used in this study have a relatively low average speed, significant idle times, and resulting average exhaust temperatures that are just above the 200°C operating point that is generally referenced[12] as the starting NO_x conversion temperature for SCR systems. The exhaust temperatures observed over the two transient cycles were almost never above 250 ºC, while engine dynamometer testing at the ERMS of a Cummins 15L ISX engine over the Federal Test Procedure produced an average temperature at the DPF inlet of 286°C with a minimum temperature of 204°C.

From the above, the two transient cycles used in this study may have represented a worst case scenario for SCR performance in terms of their relatively low average exhaust temperature, with large portions of the test at idle, while the steady-state tests did produce exhaust temperatures that may have been more conducive to SCR performance. The NO_x emission rates over the steady-states were much lower than those from the transient tests, but were still above the respective emission standard of 0.2 g/bhp-hr and the engine specific Family Emission Limit (FEL) of 0.35 g/bhp-hr. The following illustrates the NO_x emissions over three consecutive steady-state tests that were separated by a 3 minute soak time. As can be seen from the plots, there is a rapid rise in the NO_x mass emissions during the acceleration but over time the emission rate declines to a much lower rate. If the duration of the test cycle was extended, the contribution from initial acceleration to the total mass of NO_x would be minimized to where the average NO_x emission rate would be more in-line with what could be expected from the emission standard. The averaged stabilized emission rate of 0.011 g/second that was measured

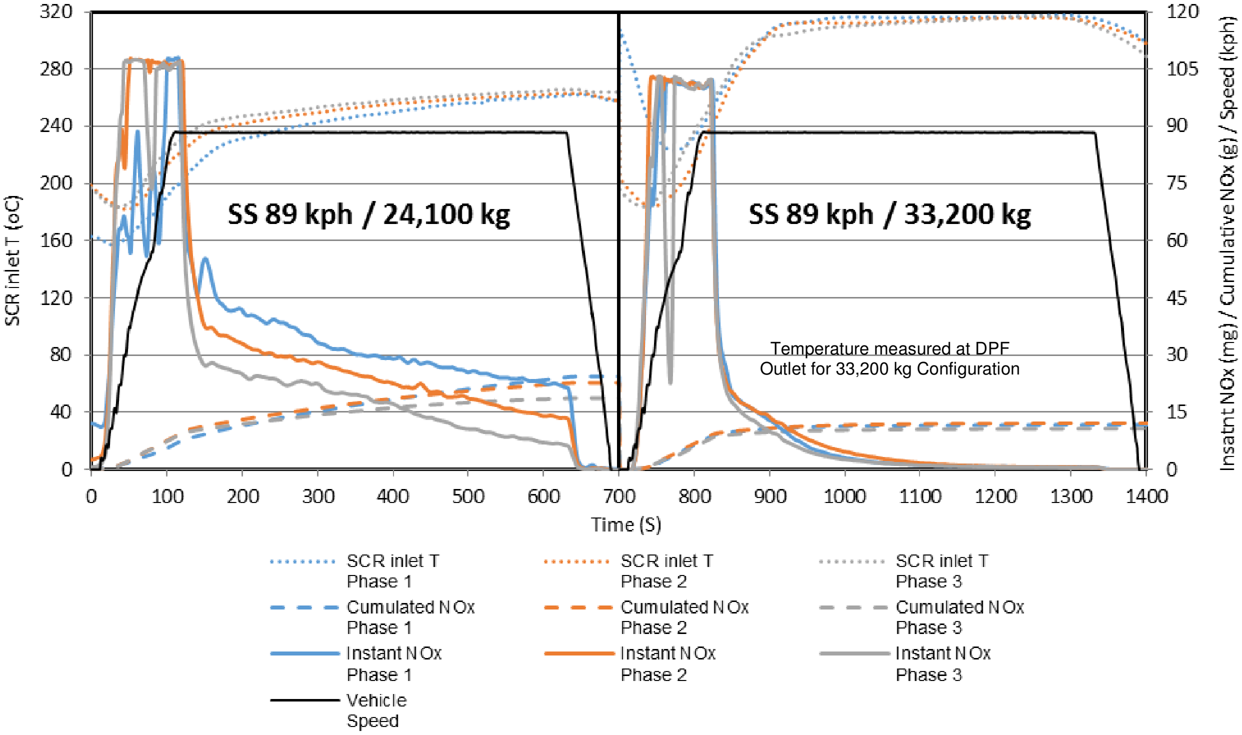

Figure 8: NO_x Emissions Rates over 3 consecutive SS 89 kph Cycles

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[10] Johnson, T., Vehicular Emissions in Review, SAE Technical Paper 2009-01-0121, Society of Automotive Engineers

[11] Johnson, T. Review of Diesel Emissions and Control, SAE Technical Paper 2010-01-0301, Society of Automotive Engineers

[12] Lowell, D., Kamatake, F. Urban Off-Cycle NOx Emissions from Euro IV/V Trucks and Buses. White Paper Number 18, The International Council on Clean Transportation.

toward the end of the short steady-state cycle translates to 0.32 g/bhp-hr or 2.2 g/kg Fuel, which is below the FEL of this engine. Looking at the information available from the engine control unit indicates that during the cruise portion of the steady-state the engine is operating at 1360 rpm and just below 30% load. This would place the engine just below the lower zone[13] of the Not-To-Exceed[14] requirements of the in-use testing required of the engine manufacturers.

For the same 89 kph steady-state speed additional tests were conducted at an increased inertia weight of 33,200 kg and an adjusted road load curve to reflect the added weight. On these tests the average engine speed and percent load were 1360 rpm and 41%, respectively, with an exhaust temperature at the DPF outlet closer to ~300°C. The NO_x emissions were lowered to 0.77 g/km, but over the well stabilized portion of the cycle the average emission rate was 0.25 g/km or the equivalent of 0.17 g/bhp-hr or 1.11 g/kg Fuel. The beneficial incidence of higher exhaust temperatures on NO_x emissions observed over these specific tests is further discussed in section 3.4 of this report.

As with the diesel truck, selected diagnostic data from the LNG truck was also collected. As an example, a display of engine oil temperature, coolant temperature and DPF outlet temperature over the HD UDDS x2 for the LNG truck is provided at the top of Figure 9 below. A second graph at the bottom shows the diagnostic data for a steady-state test. It is important to note that the average exhaust temperature downstream of the DPF was 269°C with a maximum of 344°C, representing adequate exhaust temperature for effective SCR performance. Another note worth of mention is that the LNG engine FEL for NO_x was set at 0.135 g/bhp-hr, which is below the 0.2 g/bhp-hr standard and more stringent than that of the diesel truck as previously mentioned.

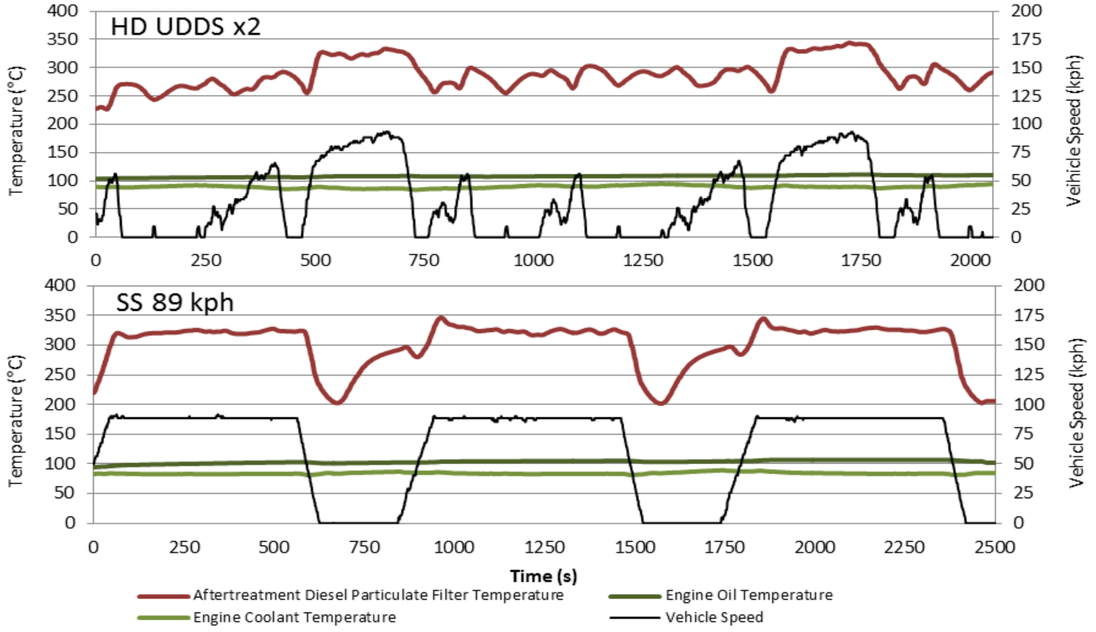

Figure 9: LNG Truck Engine Control Module Data

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[13] http://www.dieselnet.com/standards/cycles/nte.php
[14] http://www.epa.gov/otaq/inusetesting.htm

3.2 Comparison of LNG and Diesel Truck Results

The LNG truck was tested between July 24 and 26, 2013 and the diesel truck was tested over two periods, from February 12 to 20 and from March 11 to 14, 2014. A comparison of the emissions and fuel consumption is presented in the Figures below.

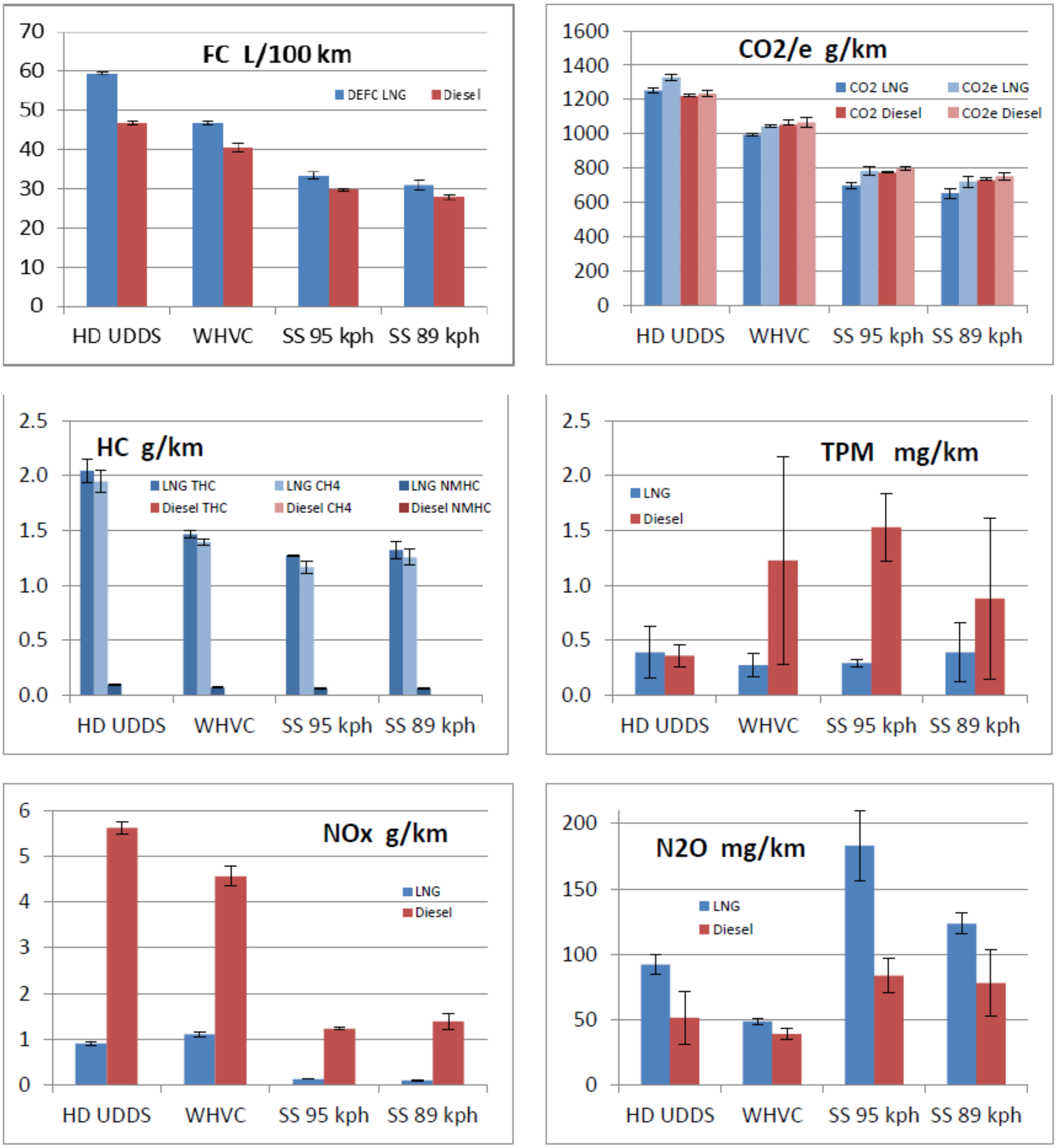

Figure 10: LNG vs. Diesel Fuel consumption and emission rates ± 1 standard deviation

As stated in Section 2.5, the diesel pilot injection rate (DPI) was not measured for this program but values were estimated by Westport based upon an analysis of the driving cycle and data logged from the engine control unit. Diesel equivalent fuel consumption (DEFC) was calculated using the average diesel pilot injection depending on the test cycle. The DEFC for the LNG truck ranged from 30.9 L/100km on the 89 kph steady-state cycle to 59.4 L/100km on the HD UDDS cycle demonstrating the strong impact of driving patterns on fuel consumption. The largest difference in fuel consumption between the LNG and diesel trucks was noted over the UDDS cycle which has a lower average speed coupled with hard accelerations and decelerations compared to the WHVC cycle, while the smallest difference was observed over the steady-state modes which resulted in the best overall fuel consumption.

Tailpipe CO_2 emission rates from the LNG truck were up to 10% lower than those of the diesel truck except for the HD UDDS cycle where they were 3% higher. Methane was emitted at average rates of 1.17 g/km to 1.95 g/km from the LNG truck but was not emitted from the diesel truck. N_2O emissions of the LNG truck were from 24% to 119% higher than those observed on the diesel truck. Both CH_4 and N_2O were accounted for in the CO_2 equivalency rates (CO_2e), which were mostly lower for the LNG truck than for the diesel truck but only the HD UDDS results, which showed 8% higher CO_2e rates for the LNG truck than for the diesel truck, were statistically significant.

The THC emissions were higher from the LNG truck than the diesel truck and were largely comprised of methane which is not readily oxidized by the exhaust catalyst. The diesel vehicle emissions of THC were essentially zero. The LNG truck NMHC emissions rates, although relatively small compared to THC results, were also higher than those of the diesel truck, reflecting the presence of other C2-C3 hydrocarbons in addition to CH_4 in the fuel.

NO_x emissions of the diesel truck were from 4 to 14 times higher than those of the LNG truck, depending on which test cycle was used. However, this may be partially attributable to the lower exhaust temperatures observed with this truck as seen in Figures 6, 7 and 9, and that the diesel engine was certified to a higher NOx level. Particulate mass emissions were also higher with the diesel truck than with the LNG truck, although overall TPM values were quite low ranging from 1 mg/km for the diesel truck to 0.3 mg/km for the LNG truck. The standard deviation for the PM results was relatively high compared to the average and reflects the limitations of gravimetric measurements at low mass levels

The rationale for the selection of two steady-state speeds that were only 6 kph apart was provided in Section 2.6. The 95 kph cycle provided an indication of the real world emissions from normal in-service operation. As expected, the 95 kph and 89 kph cycles provided similar emission rate results. Driving at steady-state speeds was more efficient than the transient cycles and produced lower emissions of CO_2, NO_X, hydrocarbons, and CO, however both steady-state speeds produced emissions of N_2O that were increased from the transient tests. The fuel consumption at 95 kph was at least 2 L/100km higher than the resulting fuel consumption at 89 kph. More specifically; for the diesel truck, fuel consumption was 28 L/100km at 89 kph and 29.7 L/100km at 95 kph; and for the LNG truck, 33.4 L/100km for the 95 kph and 30.9 L/100km for the 89 kph. The LNG fleet operator reported in-use equivalent fuel usage at approximately 40 L/100Km which may reflect heavier average truck-trailer loads than what was simulated in this study.

3.3 Effects of Increased Test Weight on Diesel Results

The diesel truck was tested at two different truck loadings to assess the impact of increased weight, such as would be experienced with a fully loaded trailer, on emissions and fuel consumption. The results are compared in the following graphs.

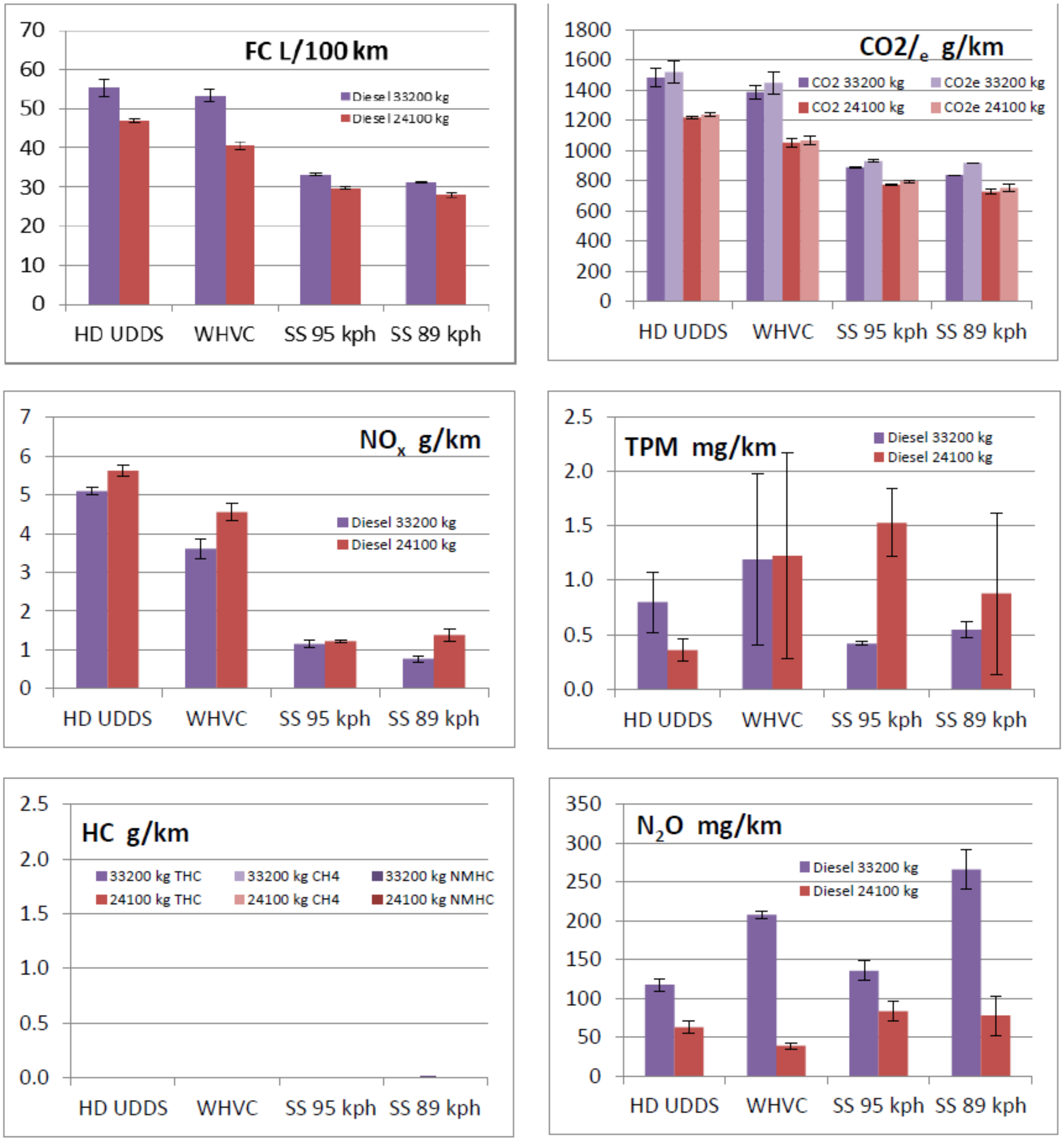

Figure 11: Fuel consumption and regulated emission rates ± 1 standard deviation

The test results showed that the percent difference in fuel consumption was increased from 12% to 31% for 3 of the 4 test cycles when the simulated inertia weight was increased from 24,000 kg to 33,000 kg. Results of the SS 95 kph cycle only showed 2% increase in fuel consumption for the heavier load but this was not statistically significant. The transient cycles which are characterised by urban-like driving patterns with extended idling period, multiple stops, steep accelerations and hard braking were shown to have higher impact on fuel consumption results than the steady-state cycles. The HD UDDS was the most demanding of the 2 transient cycles used for this evaluation with harder accelerations, decelerations and a higher top speed. However, in this case it was the WHVC cycle that resulted in the highest fuel consumption rate increase due to heavy loading with 31% as opposed to 18% over the HD UDDS cycle. A contributing factor to this could be that the WHVC includes more stops than the HD UDDS with ten compared to seven. With both the 24,000 kg and 33,000 kg loads, steady-state driving conditions demonstrated energy efficiency improvements between 4% and 9% in contrast to transient driving conditions.

Tailpipe CO_2 emission rates were increased between 15% and 31% when the simulated inertia weight was increased, while the CO_2 equivalent emissions rates, which take methane and N_2O into account were increased between 17% and 36% under the same conditions. Variations in tailpipe CO_2 and CO_2e emissions rates due to vehicle loading were less noticeable over the steady-state cycle than over the transient cycles. Increasing the inertia weight resulted in increased greenhouse gas emissions and while CO_2e emissions rates were comprised of 97% to 99% of CO_2 at the 24,000 kg inertia weight, they were only comprised of 91% to 98% of CO_2 at the 33,000 kg inertia weight. Elevated levels of N_2O at the heavier test weight configuration, which were up to 4 times the levels of the 24,000 kg test weight configuration, made up for this difference.

Despite the increased fuel consumption and overall tailpipe emissions observed under the 33,000 kg simulated test weight condition, emission rates of THC, NMHC, CH_4 and CO were also shown to be below instrumentation detection limits just as it was the case with the other test configurations.

The 33,000 kg inertia weight test results showed that increasing vehicle load actually resulted in reduced NO_x emissions. This may seem counterintuitive as higher emission rates would normally be expected since higher loads on the vehicle normally translate to higher load on the engine. However, statistically significant NO_x emission reductions in the magnitude of 9% to 44% were observed for 3 of the 4 test conditions. The most important reduction was observed over the 89 kph steady-state cycle while the 95 kph steady-state cycle result also followed the same trend but was not statistically significant. This phenomenon may be related to the exhaust temperatures differences observed between the test configurations. Elevated NO_x emissions are usually a result of high peak combustion temperatures which in turn correlate to high exhaust temperatures. In this case, as effective NO_x reduction occurs above a given exhaust temperature threshold, the higher temperatures encountered under heavy loading operation resulted in reducing NO_x emissions more efficiently at 33,000 kg than at 24,000 kg. During this program, as illustrated in the Appendix E, exhaust temperatures were about 15 °C to 30 °C higher at the high load configuration than at the baseline configuration. Misra et al. also established that NO_x

emissions can be elevated for SCR equipped trucks operating under cold starts and low load/slow speed driving conditions; mainly because of non-functional EGR during the first ten minutes of engine operation as well as non-functional SCR during exhaust temperature below the 200 °C threshold.[15]

The effects of increased test weight on TPM emissions were varied. Results of two of the four test cycles did not show any statistically significant results while a 123% increase and a 72% decrease were observed over the HD UDDS and SS 95 kph test cycles, respectively, when comparing the 33,000 kg results to the 24,000 kg results. Once more, it should be noted that overall values were quite low ranging from 0.4mg/km to 1.5 mg/km and that the standard deviation were relatively high.

4.0 Conclusion

The exhaust emissions from two Class 8 trucks were measured by Environment Canada using a chassis dynamometer. The primary objective of the study was to compare the emissions from an LNG truck with a High Pressure Direct Injection fuel system to those from a conventional diesel truck.

The vehicles were operated over different drive cycles including two transient cycles and two steady-state cycles. For both trucks the impacts of driving cycle on emissions rates, fuel consumption and energy efficiency were evaluated. The steady speed operation produced the best fuel consumption results with the lowest emissions, with the exception of TPM and N_2O, compared to the transient cycles.

When comparing the LNG truck to the diesel truck emission/efficiency rates, the following were noted:

- The LNG truck had 11 to 27% higher diesel equivalent fuel consumption depending upon driving cycle, while it should be noted that the diesel engine had been certified to a higher NOx standard and some engine parameters may have been optimized to trade off the higher NOx emissions for lower fuel consumption;
- CH_4 emissions from the LNG truck were higher compared to the diesel, which essentially had a methane emission rate of zero;
- N_2O emissions were also higher from the LNG truck operation;
- CO_2 tailpipe emissions from the LNG truck were lower than those from the diesel truck over the WHVC and steady-state cycles, but higher over the UDDS cycle;
- Likewise, the same trend was noted for the CO_2 equivalent emissions. Although CO_2e for the LNG truck was increased at a higher percentage compared to the CO_2e for the diesel truck;
- Emission rates of both NO_X and particulate were lower for the LNG truck; and

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[15] Misra C., Collins J. F., Herner J. D., Sax T., Sobieralski W., Burntzki M., Chernich D.: *In-Use NOx Emissions from Model Year 2010 and 2011 Heavy-Duty Diesel Engines with Aftertreatment Devices*, Environmental Science and Technology Article, 2013.

When comparing the 33,000 kg configuration to the baseline configuration of the diesel truck, the following were noted with the increased loading of the truck:

- Fuel consumption was increased from 12% to 31% for 3 of the 4 test cycles when the simulated inertia weight was increased from 24,000 kg to 33,000 kg;
- For most cycles, the energy efficiency decreased by an average 3% with the heavier simulated load;
- With both the baseline and the heavier loads, steady-state driving conditions demonstrated energy efficiency improvements between 4% and 9% in contrast to transient driving conditions;
- CO_2 emissions rates were increased between 15% and 31% with the heavier load while the CO_2 equivalent emissions were increased between 17% and 36%;
- NO_x emission reductions of 9% to 44% were observed with the heavier load for 3 out of the 4 tests cycles coinciding with rises in exhaust temperatures of 13°C to 27°C ;
- The impacts of increased inertia weight on particulate emissions were varied. Results of two of the four test cycles did not show any statistically significant results while a 123% increase and a 72% decrease were observed over the HD UDDS and SS 95 kph test cycles, respectively, however the actual emission rates were very low.

List of Abbreviations

BTU: British Thermal Units
CH_4: methane
CO: carbon monoxide
CO_2: carbon dioxide
DEFC: diesel equivalent fuel consumption
DEFE: diesel equivalent fuel economy
DPF: diesel particulate filter
EGR: exhaust gas recirculation
EPA: Environmental Protection Agency
ERMS: Emissions Research and Measurement Section
FC: fuel consumption
FE: fuel economy
GHG: greenhouse gas
GVWR: gross vehicle weight rating
HD UDDS: heavy-duty urban dynamometer driving schedule
LNG: liquefied natural gas
MY: model year
n.a.: not available
N_2O: nitrous oxide
NHV: net heating value
NO_X: nitrogen oxides
OBD: On-board diagnostics
PM: total particulate matter
SCFM: standard cubic feet per minute
SCR: selective catalytic reduction
THC: total hydrocarbon

Appendix A – LNG Truck Individual Test Results – 24100 kg – g/km

Peterbilt 386 LNG 24100 kg	**Regulated Emissions and FC**							**GHG Emissions**			
	CO	**NOx**	**THC**	**NMHC**	**TPM**	**DEFC**	**Energy Efficiency**	**CO2**	**CH4**	**N2O**	**CO2e**
	g/km	**g/km**	**g/km**	**g/km**	**mg/km**	**L/100 km**	**%**	**g/km**	**g/km**	**mg/km**	**g/km**
WHVC	0.01	1.04	1.49	0.07	0.4	47.2	29	1004	1.42	-	-
WHVC	0.01	1.16	1.51	0.08	0.2	46.7	30	994	1.44	46.5	1043
WHVC	0.00	1.11	1.45	0.07	0.2	46.4	29	988	1.38	50.2	1038
Average	0.01	1.11	1.48	0.07	0.3	46.8	29	995	1.41	48.4	1045
St. Deviation	0.00	0.06	0.03	0.01	0.1	0.4	0	8	0.03	2.6	9
HD UDDS	0.01	0.92	2.16	0.10	0.3	59.1	26	1248	2.06	100.3	1329
HD UDDS	0.01	0.93	1.96	0.09	0.2	59.9	26	1266	1.87	88.7	1339
HD UDDS	0.01	0.85	2.03	0.10	0.7	59.0	26	1245	1.93	87.2	1319
Average	0.01	0.90	2.05	0.10	0.4	59.4	26	1253	1.95	92.1	1329
St. Deviation	0.00	0.04	0.10	0.01	0.2	0.5	0	11	0.10	7.2	16
SS 89 kph	0.00	0.11	1.38	0.07	0.2	31.9	35	673	1.31	128.8	744
SS 89 kph	0.00	0.09	1.27	0.06	0.6	30.0	37	634	1.21	117.5	699
Average	0.00	0.10	1.32	0.07	0.4	30.9	36	653	1.26	123.2	722
St. Deviation	0.00	0.01	0.08	0.00	0.3	1.3	1	27	0.07	8.0	32
SS 95 kph	0.00	0.12	1.27	0.07	0.3	34.0	35	711	1.20	201.7	802
SS 95 kph	0.00	0.12	1.19	0.06	0.3	32.8	36	687	1.13	164.1	764
Average	0.00	0.12	1.23	0.07	0.290	33.4	35	699	1.17	182.9	783
St. Deviation	0.00	0.00	0.06	0.00	0.032	0.8	1	17	0.05	26.6	27

Appendix A – LNG Truck Individual Test Results – 53100 lbs – g/mile

Peterbilt 386 LNG 53100 lbs	Regulated Emissions and FC							GHG Emissions			
	CO	NOx	THC	NMHC	TPM	DEFC	Energy Efficiency	CO2	CH4	N2O	CO2e
	g/mile	g/mile	g/mile	g/mile	mg/mile	L/100 km	%	g/mile	g/mile	mg/mile	g/mile
WHVC	0.01	1.68	2.39	0.12	0.6	47.2	29	1615	2.28	-	-
WHVC	0.01	1.86	2.44	0.13	0.4	46.7	30	1599	2.31	74.9	1679
WHVC	0.01	1.79	2.33	0.11	0.3	46.4	29	1590	2.22	80.8	1670
Average	0.01	1.78	2.39	0.12	0.4	46.8	29	1601	2.27	77.8	1681
St. Deviation	0.00	0.09	0.05	0.01	0.2	0.4	0	13	0.05	4.2	15
HD UDDS	0.02	1.48	3.48	0.17	0.4	59.1	26	2008	3.31	161.5	2139
HD UDDS	0.02	1.49	3.15	0.15	0.4	59.9	26	2037	3.01	142.8	2154
HD UDDS	0.02	1.37	3.26	0.16	1.1	59.0	26	2004	3.11	140.2	2123
Average	0.02	1.45	3.30	0.16	0.6	59.4	26	2016	3.14	148.2	2139
St. Deviation	0.00	0.07	0.16	0.01	0.4	0.5	0	18	0.15	11.6	25
SS 89 kph	0.01	0.17	2.22	0.11	0.3	31.9	35	1083	2.11	207.3	1197
SS 89 kph	0.01	0.15	2.04	0.10	0.9	30.0	37	1020	1.94	189.1	1125
Average	0.01	0.16	2.13	0.11	0.6	30.9	36	1052	2.03	198.2	1161
St. Deviation	0.00	0.02	0.12	0.00	0.4	1.3	1	44	0.12	12.9	51
SS 95 kph	0.00	0.20	2.05	0.11	0.4	34.0	35	1145	1.94	324.6	1290
SS 95 kph	0.00	0.20	1.92	0.10	0.5	32.8	36	1105	1.82	264.1	1229
Average	0.00	0.20	1.98	0.11	0.5	33.4	35	1125	1.88	294.4	1260
St. Deviation	0.00	0.00	0.09	0.01	0.1	0.8	1	28	0.09	42.8	43

Appendix B – Diesel Truck Individual Test Results – 24100 kg / DIESEL – g/km

Peterbilt 587 Diesel 24100 kg	**Regulated Emissions and FC**							**GHG Emissions**			
	CO	**NOx**	**THC**	**NMHC**	**TPM**	**FC**	**Energy Efficiency**	**CO2**	**CH4**	**N2O**	**CO2e**
	g/km	**g/km**	**g/km**	**g/km**	**mg/km**	**L/100 km**	**%**	**g/km**	**g/km**	**mg/km**	**g/km**
WHVC-1	0.00	4.19	0.00	0.00	-	39.9	-	1040	0.00	46.7	1054
WHVC-1	0.00	4.74	0.00	0.00	0.8	39.8	-	1037	0.00	38.5	1048
WHVC-1	0.00	4.76	0.00	0.00	2.9	41.5	-	1081	0.00	36.6	1092
WHVC-2	0.00	4.41	0.00	0.00	0.8	41.2	35	1073	0.00	38.2	1084
WHVC-2	0.00	4.63	0.00	0.00	0.7	41.6	35	1082	0.00	39.5	1094
WHVC-2	0.02	4.60	0.00	0.00	0.9	38.9	37	1012	0.00	34.1	1023
Average	0.00	4.55	0.00	0.00	1.2	40.5	36	1054	0.00	38.9	1066
St. Deviation	0.01	0.22	0.00	0.00	0.9	1.1	1	29	0.00	4.3	30
HD UDDS-1	0.00	5.53	0.00	0.00	-	46.7	37	1216	-	-	-
HD UDDS-1	0.00	-	0.00	-	0.4	46.7	37	1216	-	-	-
HD UDDS-1	0.00	-	0.00	-	0.2	46.7	37	1216	0.00	28.4	1224
HD UDDS-2	0.00	5.55	0.00	0.00	-	47.5	36	1236	0.00	68.1	1256
HD UDDS-2	0.00	5.77	0.00	0.00	0.4	46.5	37	1211	0.00	57.0	1228
Average	0.00	5.62	0.00	0.00	0.4	46.8	37	1219	0.00	51.2	1234
St. Deviation	0.00	0.13	0.00	0.00	0.1	0.4	0	10	0.00	20.5	16
SS 89 kph-1	0.00	1.25	0.00	-	0.5	28.3	42	738	0.00	100.2	768
SS 89 kph-1	0.00	1.21	0.00	-	2.3	28.0	42	730	0.00	101.1	760
SS 89 kph-1	0.00	1.44	0.00	-	0.5	28.4	42	740	0.00	74.7	763
SS 89 kph-1	0.00	1.31	0.00	-	-	28.1	42	730	0.00	84.0	755
SS 89 kph-2	0.00	1.65	0.01	0.00	1.2	27.5	43	717	0.00	35.5	728
SS 89 kph-2	0.00	1.55	0.01	0.00	0.3	26.9	44	699	0.00	53.0	715
SS 89 kph-2	0.00	1.26	0.01	0.00	0.5	28.6	41	744	0.00	97.1	773
Average	0.00	1.38	0.00	0.00	0.9	28.0	42	728	0.00	77.9	752
St. Deviation	0.00	0.17	0.00	0.00	0.7	0.6	1	16	0.00	25.4	23
SS 95 kph	0.00	1.24	0.00	-	-	29.8	41	776	0.00	92.4	804
SS 95 kph	0.00	1.18	0.00	-	-	29.7	41	773	0.00	87.9	799
SS 95 kph	0.00	1.24	0.00	-	1.7	29.4	42	766	0.00	89.4	792
SS 95 kph	0.00	1.24	0.00	-	1.3	29.8	41	775	0.00	64.4	794
Average	0.00	1.22	0.00	-	1.5	29.7	41	772	0.00	83.5	797
St. Deviation	0.00	0.03	0.00	-	0.3	0.2	1	5	0.00	12.9	9

Appendix B – Diesel Truck Individual Test Results – 53100 lbs / DIESEL – g/mile

Peterbilt 587 Diesel 53100 lbs	**Regulated Emissions and FC**							**GHG Emissions**			
	CO	**NOx**	**THC**	**NMHC**	**TPM**	**FC**	**Energy Efficiency**	**CO2**	**CH4**	**N2O**	**CO2e**
	g/mile	**g/mile**	**g/mile**	**g/mile**	**mg/mile**	**L/100 km**	**%**	**g/mile**	**g/mile**	**mg/mile**	**g/mile**
WHVC-1	0.00	6.75	0.00	0.01	-	39.9	-	1673	0.00	75.2	1695
WHVC-1	0.00	7.63	0.00	0.00	1.3	39.8	-	1668	0.00	61.9	1687
WHVC-1	0.00	7.66	0.00	0.00	4.7	41.5	-	1740	0.00	58.8	1758
WHVC-2	0.00	7.09	0.00	0.00	1.3	41.2	35	1726	0.00	61.4	1744
WHVC-2	0.00	7.45	0.00	0.00	1.2	41.6	35	1741	0.00	63.5	1760
WHVC-2	0.03	7.40	0.00	0.00	1.4	38.9	37	1629	0.00	54.9	1646
Average	0.01	7.33	0.00	0.00	2.0	40.5	36	1696	0.00	62.6	1715
St. Deviation	0.01	0.35	0.00	0.00	1.5	1.1	1	46	0.00	6.9	48
HD UDDS-1	0.00	8.90	0.00	0.01	-	46.7	37	1957	-	-	-
HD UDDS-1	0.00	-	0.00	-	0.6	46.7	37	1958	-	-	-
HD UDDS-1	0.00	-	0.00	-	0.4	46.7	37	1956	0.00	45.7	1970
HD UDDS-2	0.00	8.94	0.00	0.00	-	47.5	36	1989	0.00	109.6	2022
HD UDDS-2	0.00	9.29	0.00	0.00	0.7	46.5	37	1949	0.00	91.8	1977
Average	0.00	9.04	0.00	0.00	0.6	46.8	37	1962	0.00	83.4	1987
St. Deviation	0.00	0.22	0.00	0.00	0.2	0.4	0	16	0.00	27.0	24
SS 89 kph-1	0.00	2.01	0.00	-	0.9	28.3	42	1188	0.00	161.2	1236
SS 89 kph-1	0.00	1.94	0.00	-	3.6	28.0	42	1175	0.00	162.7	1224
SS 89 kph-1	0.00	2.32	0.00	-	0.9	28.4	42	1192	0.00	120.1	1227
SS 89 kph-1	0.00	2.10	0.00	-	-	28.1	42	1175	0.00	135.2	1216
SS 89 kph-2	0.00	2.66	0.01	0.00	1.9	27.5	43	1154	0.00	57.1	1171
SS 89 kph-2	0.00	2.50	0.01	0.00	0.4	26.9	44	1125	0.00	85.3	1151
SS 89 kph-2	0.00	2.03	0.01	0.00	0.8	28.6	41	1197	0.00	156.2	1244
Average	0.00	2.22	0.00	0.00	1.4	28.0	42	1172	0.00	125.4	1210
St. Deviation	0.00	0.27	0.01	0.00	1.2	0.6	1	25	0.00	40.9	37
SS 95 kph	0.00	1.99	0.00	-	-	29.8	41	1249	0.00	148.8	1294
SS 95 kph	0.00	1.90	0.00	-	-	29.7	41	1244	0.00	141.5	1286
SS 95 kph	0.00	1.99	0.00	-	2.8	29.4	42	1232	0.00	143.8	1275
SS 95 kph	0.00	1.99	0.00	-	2.1	29.8	41	1247	0.00	103.6	1278
Average	0.00	1.97	0.00	-	2.5	29.7	41	1243	0.00	134.4	1283
St. Deviation	0.00	0.04	0.00	-	0.5	0.2	1	8	0.00	20.8	14

Appendix C – Diesel Truck Individual Test Results – 33200 kg / DIESEL – g/km

Peterbilt 587 Diesel 33200 kg	**Regulated Emissions and FC**							**GHG Emissions**			
	CO	**NOx**	**THC**	**NMHC**	**TPM**	**FC**	**Energy Efficiency**	**CO2**	**CH4**	**N2O**	**CO2e**
	g/km	**g/km**	**g/km**	**g/km**	**mg/km**	**L/100 km**	**%**	**g/km**	**g/km**	**mg/km**	**g/km**
WHVC-1	0.00	3.78	0.00	-	1.8	52.1	36	1356	0.00	276.6	1439
WHVC-1	0.00	3.44	0.00	-	0.6	54.4	34	1415	0.00	139.2	1457
Average	0.00	3.61	0.00	-	1.2	53.2	35	1386	0.00	207.9	1448
St. Deviation	0.00	0.24	0.00	-	0.8	1.6	1	42	0.00	97.1	71
HD UDDS-1	0.00	5.17	0.00	-	1.0	56.9	39	1527	0.00	141.0	1569
HD UDDS-1	0.00	5.02*	0.00	-	0.6	53.7	41	1441	0.00	94.1	1469
Average	0.00	5.09	0.00	-	0.8	55.3	40	1484	0.00	117.5	1519
St. Deviation	0.00	0.10	0.00	-	0.3	2.3	1	61	0.00	33.2	71
SS 89 kph-1	0.00	0.82	0.00	-	0.6	31.3	45	839	0.00	271.5	920
SS 89 kph-1	0.00	0.72	0.00	-	0.5	31.2	45	838	0.00	260.6	916
Average	0.00	0.77	0.00	-	0.5	31.3	45	838	0.00	266.0	918
St. Deviation	0.00	0.07	0.00	-	0.1	0.0	0	1	0.00	7.7	3
SS 95 kph	0.00	1.10	0.00	-	0.4	33.0	44	885	0.00	138.3	926
SS 95 kph	0.00	1.22	0.00	-	0.4	33.3	43	893	0.00	132.7	933
Average	0.00	1.16	0.00	-	0.4	33.1	43	889	0.00	135.5	929
St. Deviation	0.00	0.09	0.00	-	0.0	0.2	1	6	0.00	3.9	7

* Due to issues experienced with modal data for this test the value was taken from the Kynar bag result and was adjusted as bags results were found to be 18.2% higher on average than modal results for the 33200 kg dataset.

Appendix C – Diesel Truck Individual Test Results – 73100 lbs / DIESEL – g/mile

Peterbilt 587 Diesel 73100 lbs	**Regulated Emissions and FC**							**GHG Emissions**			
	CO	**NOx**	**THC**	**NMHC**	**TPM**	**FC**	**Energy Efficiency**	**CO2**	**CH4**	**N2O**	**CO2e**
	g/mile	**g/mile**	**g/mile**	**g/mile**	**mg/mile**	**L/100 km**	**%**	**g/mile**	**g/mile**	**mg/mile**	**g/mile**
WHVC-1	0.00	6.08	0.00	-	2.8	52.1	36	2183	0.00	445.0	2315
WHVC-1	0.00	5.53	0.00	-	1.0	54.4	34	2278	0.00	224.1	2344
Average	0.00	5.81	0.00	-	1.9	53.2	35	2230	0.00	334.6	2330
St. Deviation	0.00	0.39	0.00	-	1.3	1.6	1	67	0.00	156.2	114
HD UDDS-1	0.00	8.32	0.00	-	1.6	56.9	39	2457	0.00	226.9	2525
HD UDDS-1	0.00	8.08*	0.00	-	1.0	53.7	41	2319	0.00	151.4	2364
Average	0.00	8.20	0.00	-	1.3	55.3	40	2388	0.00	189.2	2445
St. Deviation	0.00	0.17	0.00	-	0.4	2.3	1	98	0.00	53.4	114
SS 89 kph-1	0.00	1.33	0.00	-	1.0	31.3	45	1350	0.00	436.9	1480
SS 89 kph-1	0.00	1.16	0.00	-	0.8	31.2	45	1348	0.00	419.4	1473
Average	0.00	1.24	0.00	-	0.9	31.3	45	1349	0.00	428.1	1477
St. Deviation	0.00	0.12	0.00	-	0.1	0.0	0	1	0.00	12.4	5
SS 95 kph-1	0.00	1.76	0.00	-	0.7	33.0	44	1424	0.00	222.6	1490
SS 95 kph-1	0.00	1.96	0.00	-	0.7	33.3	43	1437	0.00	213.6	1501
Average	0.00	1.86	0.00	-	0.7	33.1	43	1431	0.00	218.1	1496
St. Deviation	0.00	0.14	0.00	-	0.0	0.2	1	9	0.00	6.3	11

* Due to issues experienced with modal data for this test the value was taken from the Kynar bag result and was adjusted as bags results were found to be 18.2% higher on average than modal results for the 73000 lbs dataset.

Appendix E – DPF$_{outlet}$ Temperature and EGR Mass Flow Summary – Phase 1

Test Cycle	**24 T / Cert D**		**33 T / Cert D**	
	AVG	**Min/Max**	**AVG**	**Min/Max**
UDDS-1	219	131 284	242	119 301
UDDS-2	220	132 284		
UDDS-3	230	136 296		
UDDS-4	226	128 291		
UDDS-5	225	131 275		
UDDS-6	228	135 279		
WHVC-1	230	123 291	257	150 312
WHVC-2	223	131 284	249	137 312
SS 95 kph	265	171 302	286	184 318
SS 89kph-1	272	170 303	285	182 312
SS 89kph-2	264	134 299		