Annex 57

A Report from the
Advanced Motor Fuels Technology Collaboration Programme

Technology Collaboration Programme on
Advanced Motor Fuels




Heavy-Duty Vehicles Performance Evaluation

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Technology Collaboration Programme
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ADVANCED MOTOR FUELS
IEA-AMF
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Advanced Motor Fuels

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Abstract

The project “HDV Performance Evaluation” within IEA Advanced Motor Fuels Technology Collaboration Programme was set up to provide a snapshot of the performance of contemporary heavy-duty vehicles as well as to make projections of possible developments towards 2030.

The activities within the project combined chassis dynamometer measurements, on-road measurements and simulations. Projections towards 2030 were carried out in cooperation with the Hybrid and Electric Vehicle Technology Collaboration Programme.

All in all, the partners of the project tested 17 medium- and heavy-duty trucks. Vehicle testing was carried out in Canada, Chile, Finland and Sweden. Simulations were done in Finland and Korea, and in addition, within the Advanced Motor fuels and Hybrid and Electric Vehicle cooperation.

All in all, the best contemporary heavy-duty vehicles are energy efficient, and pollutant emission levels are close to zero in warmed-up operations. Renewable fuels can be introduced in several ways, either as drop-in fuels in ordinary diesel engines, or in engines specifically designed for certain fuels (e.g., ED95). In gas engines, biomethane constitutes a drop-in alternative for fossil natural gas.

However, in order to keep vehicles with internal combustion engines running on renewable fuels on the roads in the future, some adjustments to vehicle CO_2 regulations are needed. Electrification is progressing rapidly, but there are challenges related to heavy-duty long-haul trucks due to high energy consumption and additional mass of battery (resulting in, i.e., reduced payload). Thus they might not be the optimum target for electrification.

Summary and key findings

Over the years, the IEA Advanced Motor Fuels (AMF) Technology Collaboration Programme (TCP) has several projects related to commercial vehicles. Annex 57, HDV Performance Evaluation, is a continuation of AMF's activities to generate solid performance data for commercial vehicles. Annex 57, with a focus on energy efficiency of heavy-duty trucks, for the first time combines chassis dynamometer measurements, on-road measurements and simulations, with the aim to present a snapshot of the performance of contemporary vehicles as well as to present projections of performance up to the year 2030. The projections towards 2030 were done in cooperation with the Hybrid and Electric Vehicles (HEV) TCP. The report of Annex 57 encompasses a comprehensive survey of vehicle CO_2 and pollutant emission regulations and technical measures for CO_2 emission reductions.

The results of vehicle testing indicate that bigger vehicles in general are more energy efficient than smaller ones, expressed in energy use per ton-km. Currently, the engines of the best heavy-duty diesel tractors reach an efficiency of about 45% on the engine crankshaft, measured over cycles typical for long-haul operations. Today there are several heavy-duty engines available for alternative fuels. The alternatives include biodiesel blends, drop-in type renewable diesel fuel, different types of gas (methane) engines and additive treated ethanol (ED95). The newest addition to the spectrum of engine technologies is high pressure direct injection (HPDI) diesel/methane dual-fuel.

All of these options were evaluated within Annex 57. Independent of fuel, the concepts based on compression ignition (diesel proves), including HPDI dual-fuel, deliver rather high efficiency. Spark-ignited methane engines, on an average, have close to 30% higher energy consumption compared to compression ignition engines of the same size and power.

Tailpipe carbon dioxide (CO_2) emissions, which are the basis for vehicle regulations, are determined by energy consumption and specific CO_2 intensity (g CO_2/MJ) of the combustion of the fuel. This is the tank-to-wheel approach (TTW, current vehicle and engine regulations), which does not treat all energy carriers equally. The well-to-wheel (WTW) or even life cycle analysis (LCA) approach would be more objective.

Based on the testing within the project, the only technology that really lowers tailpipe (TTW) CO_2 emissions is HPDI dual-fuel, which on an average delivers close to 20% lower emissions than diesel. This stems from chemistry of the main fuel (methane) and an engine efficiency only moderately lower compared to conventional diesel engines. However, renewable diesel and ED95 reduce tailpipe CO_2 emissions about 5% compared to fossil diesel. This stems from small differences in fuel hydrogen/carbon ratio. Spark-ignition (SI) methane engines deliver tailpipe CO_2 emissions equivalent to those of diesel engines. In this case, the low engine efficiency nullified the advantage of fuel chemistry.

When evaluating the climate impact of exhaust emissions, also methane (CH_4) and nitrous oxide (N_2O) should be accounted for. All tested methane engines (stoichiometric SI and HPDI dual-fuel) had relatively low CH_4 emissions, especially in comparison with older lean-burn engines and port-injected dual-fuel engines. However, the testing revealed that N_2O emissions, with a very high CO_2 equivalence factor, can be a problem for vehicles equipped with specific selective catalytic reduction (SCR) systems, depending on chemistry. Parallel testing of Euro VI Step C and Step D vehicles confirmed that the problem can be controlled.

Looking at tailpipe CO_2 emissions only (i.e. combustion originated) is a quite narrow approach, as this methodology does not in any way take into account the use of renewable fuels, and always rates electric and fuel cell vehicles zero emission vehicles. To illustrate the statement above, projections towards 2030 were carried out on TTW and WTW basis using the EU CO_2 reduction targets for heavy-duty vehicles, -15% by 2025 and -30% by 2030, relative to reference level defined in 2019 – 2020 (average relative targets for individual manufacturers).

The only pure ICE powertrain alternative that has the potential to achieve the 2025 target with a margin and no modifications to the vehicle itself is HPDI dual-fuel. This is a consequence of diesel-like efficiency and the favorable specific CO_2 emission of methane. Hybridization alone can also meet the 2025 target with a margin.

The 2030 target of -30% will be challenging. The simulations indicate that improved diesel and spark-ignited engines, will not be able to provide the required reduction, probably not even combined with improvements on the vehicle level. As only a few advanced internal combustion engine (ICE) based powertrains can meet this target, this could lead to reduced offering of ICE vehicles and more electric vehicles. In the heaviest vehicle segment, especially battery electric trucks could be impaired by limitations in range and load restrictions, and the need for high power recharging infrastructure. Most probably there would also be cost implications to the transport industry.

When the CO_2 assessment is carried out on a well-to-wheel basis, taking into account both the upstream phase (well-to-tank (WTT)) and end-use phase (tailpipe, tank-to-wheel (TTW)), the picture is totally different. All renewable fuel alternatives, as well as battery electric vehicles (BEV) using anticipated 2030 EU power generation (regulated by the emission trading scheme) mix (carbon intensity 268 g CO_2/kWh) all surpass the reduction target of -30%.

Using a wider WTW approach instead of a pure tailpipe CO_2 based regulation system probably would increase flexibility for truck manufacturers as well as truck operators. In the way CO_2 regulations are set up currently, they are in principle mandates for certain technologies. The ideal situation would be that regulations define the targets in a smart and technology neutral way, letting the markets respond to the targets in the most functional and cost effective ways. However, if renewable fuels were to be taken into account in vehicle CO_2 regulations, some kind of credit or ticket system assuring that renewable fuels are really used in the field, has to be put in place.

In efforts to reduce CO_2 emissions from trucking operations, the impacts of vehicle size and relative loading are often dismissed. In Europe, Finland and Sweden are forerunners in allowing heavy combinations, 76 tons in Finland and 74 tons in Sweden. In pilot projects, high capacity transport (HCT) combinations with weights up to 100 tons have been tested. The simulations carried out within Annex 57 demonstrated that increasing gross vehicle weight rating (GVWR) from some 60 up to 90 tons could reduce CO_2 emissions per ton-kilometer of cargo by up to 40%.

All in all, the specific CO_2 emissions of trucks, relative to the carried load, depend on engine efficiency, the carbon intensity of the fuel used, the configuration of the powertrain and the vehicle itself and last but not least, the size and the effective payload of the vehicle. In addition, road and weather conditions and how the truck is driven affect fuel consumption and thereby CO_2 emissions.

Some vehicles were tested for pollutant emissions both in laboratory conditions (chassis dynamometer) and on-road using in service compliance (ISC) methodology. With only a few exceptions, the results are very good, well below ISC limits and in many cases, also well below levels corresponding to the actual certification limit values. VTT tested several Euro VI level vehicles in parallel, diesel, SI methane, HPDI methane and ED95. As all vehicles are equipped with sophisticated exhaust after-treatment (EAT) systems, no major differences in pollutant emissions can be pointed out, especially not for hot operation, typical for long-haul services.

All in all, the best contemporary heavy-duty vehicles are energy efficient, and pollutant emission levels are close to zero in warmed-up operations. Renewable fuels (now biofuels and later on possible also electrofuels) can be introduced in several ways, either as drop-in fuels in ordinary diesel engines, or in engines specifically designed for certain fuels (e.g., ED95). In gas engines, biomethane constitutes a drop-in alternative for fossil natural gas.

However, in order to keep ICE vehicles running on renewable fuels on the road also in the future, some adjustments to vehicle CO_2 regulations are needed, and likely also some mandates for renewable fuels. Electrification is progressing rapidly, but heavy-duty long-haul trucks are not the optimum target for electrification.

Abbreviations

BTE	Break Thermal Efficiency
CARB	California Air Resources Board
CBG	Compressed Bio Gas
CFS	Clean Fuel Standards
CI	Compression Ignition
CNG	Compressed Natural Gas
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CPC	Condensed Particle Counter
CTI	Cleaner Trucks Initiative
DDF	Dual-Fuel Systems
DME	Dimethyl Ether
DOE	(US) Department of Energy
ECCC	Environment and Climate Change Canada
EGR	Exhaust Gas Recirculation
EPA	(US) Environmental Protection Agency
EU	European Union
FAME	Fatty Acid Methyl Ester
FTP	Federal Test Procedure
GHG	Green House Gas
GVW	Gross Vehicle Weight
GVMR	Gross Vehicle Mass Rating
HC	Hydrocarbons
HCCI	Homogenous Charge Compression Ignition
HDV	Heavy-Duty Vehicle
HES	Heavy-duty vehicle Emission Simulator
HEV	Hybrid Electric Vehicle
HPDI	High Pressure Direct Injection
HVO	Hydrotreated Vegetable Oil
ICE	Internal Combustion Engines
ISC	In-Service Conformity
LNG	Liquefied Natural Gas

MN	Methane Number
MY	Model Year
NO_x	Nitrous Oxides
NTE	Not-to-Exceed
NHTSA	National Highway Traffic Safety Administration
OCE	Off-Cycle Emission testing
OEM	Original Equipment Manufacturer
PCCI	Partially Premixed Charge Compression Ignition
PM	Particulate Matter (mass)
PN	Particle Number
RCCI	Reactivity Controlled Compression Ignition
SCR	Selective Catalytic Reduction
SI	Spark-Ignited
THC	Total Hydrocarbons
TTW	Tank To Wheel
TWC	Three Way Catalyst
US EPA	US Environmental Protection Agency
VECTO	**V**ehicle **E**nergy **C**onsumption calculation **To**ol
WHR	Waste Heat Recovery
WHSC	World Harmonized Steady-State Test Cycle
WHTC	Word Harmonized Transient Cycle
WHVC	World Harmonized Vehicle Cycle
WTT	Well To Tank
WTW	Well To Wheel

Content

Introduction

Over the years, the IEA Advanced Motor Fuels Technology Collaboration Programme (TCP) has conducted several projects to assess the performance of heavy-duty vehicles. Heavy-duty vehicles, whether buses or trucks, provide vital services to the society. Included in the list of projects are, e.g.[1]:

- Annex 37: Fuel and Technology Alternatives for Buses
- Annex 38: Environmental Impact of Biodiesel Vehicles
- Annex 39: Enhanced Emission Performance and Fuel Efficiency for HD Methane Engines
- Annex 46: Alcohol Application in CI Engines
- Annex 49: "COMVEC" - Fuel and Technology Alternatives for Commercial Vehicles
- Annex 53: Sustainable Bus Systems

One of AMF's strengths is its ability to generate first-hand experimental data on the true performance of new vehicles and fuels. This data has been used to formulate national and regional policies, and has also served as input for various IEA analysis.

The "COMVEC" project, planned in 2012 and active in 2013 – 2016, assessed all categories of commercial vehicles, from vans to heavy-duty tractors for trailers. All in all, the eight partners of the project tested 35 different vehicles, with emission certification starting from Euro III up to Euro VI and US 2010.

However, technology as well as the regulatory framework progress rapidly, especially regulations related to carbon dioxide (CO_2) emissions and fuel efficiency of heavy-duty vehicles[2]. Therefore, in 2018, a number of the

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[1] https://www.iea-amf.org/content/projects/completed_projects

[2] A summary of CO_2 and fuel efficiency regulations is presented later on in

IEA AMF Executive Committee participants decided to start a new activity on heavy-duty vehicles. Compared to COMVEC, emphasis is slightly different as the new activity focuses on energy efficiency of contemporary conventional and alternative fuel vehicles in the heavier vehicle segment. Additional features compared to “COMVEC” are simulations and projections into the future. As for regulated emissions, measurements were now done both in the chassis dynamometer and on the road.

The study at hand can be seen as a natural continuation to the series of activities comparing various powertrain and fuel options for heavy-duty vehicles within AMF. The “COMVEC” project, which also covered older technology, forms an excellent reference to fall back on.

The project will thus cover three time dimensions:

- legacy vehicles and a reference backwards through completed AMF Annexes
- a snapshot of the performance of the current best-available-technology heavy-duty vehicles using conventional and alternative fuels (focal point of this activity)
- a projection into the future of how energy efficiency and emissions can develop

As in the case of “COMVEC”, also this new project was carried out in cooperation between several vehicle testing laboratories.

For the projection into the future a joint activity by AMF and Hybrid and Electric Vehicle TCP estimating performance of conventional and electrified powertrains was introduced in the work program.

Background

General

The trucking industry is a key enabler to modern society and global economic activity. Trucks transport a multitude of goods including; construction and raw materials, fuels and refuse and commodities from their points of production, to processing locations or to their final point of sale.

Many types of road vehicles deliver goods, however, globally, heavy freight trucks carry out about two thirds of the on-land freight activity, measured in ton-kilometers (tkm). These heavy freight trucks are articulated or have a rigid body with a gross vehicle weight (GVW) of greater than 15 tons (IEA, 2017). In the European Union (EU) in 2017, road vehicles carried out 73 % of the transport work within the member countries (European Union, 2019a). Similarly, in the United States, trucks accounted for 66 % of the tonnage within the country in 2015 (U.S. Department of transportation, 2016). Internationally, transport accounts for 29 % of the final energy use by sector (Figure 1).

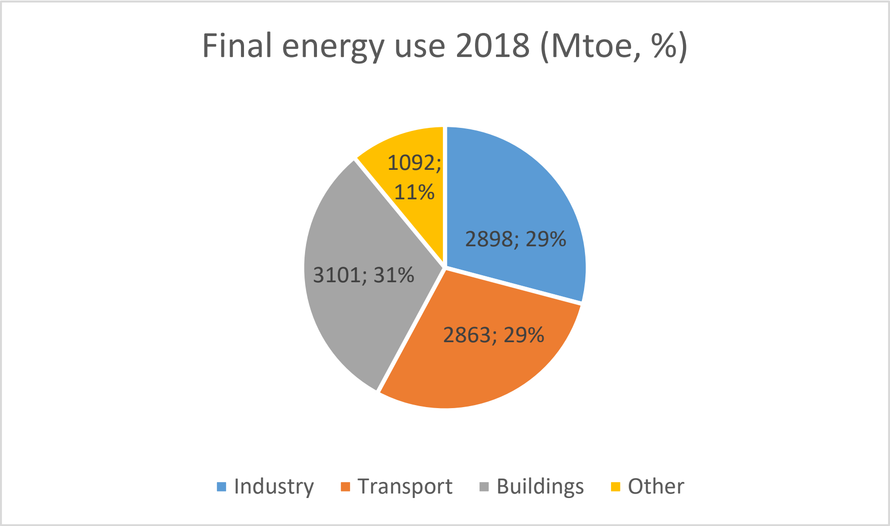


Figure 1: Final energy use by sector. Data from IEA World Energy Outlook 2019. (IEA, 2019)

Figure 2 below shows the breakdown of transport energy use by mode for selected IEA countries. Road vehicles dominate (88 %) of energy use by mode, with passenger cars and freight road together representing about 86 %, and road freight alone at 27 %. Air (domestic) accounts for 8 %, water (domestic) and rail transport account together for roughly 4 % (IEA Energy Efficiency Indicators 2020 (IEA, 2020)).

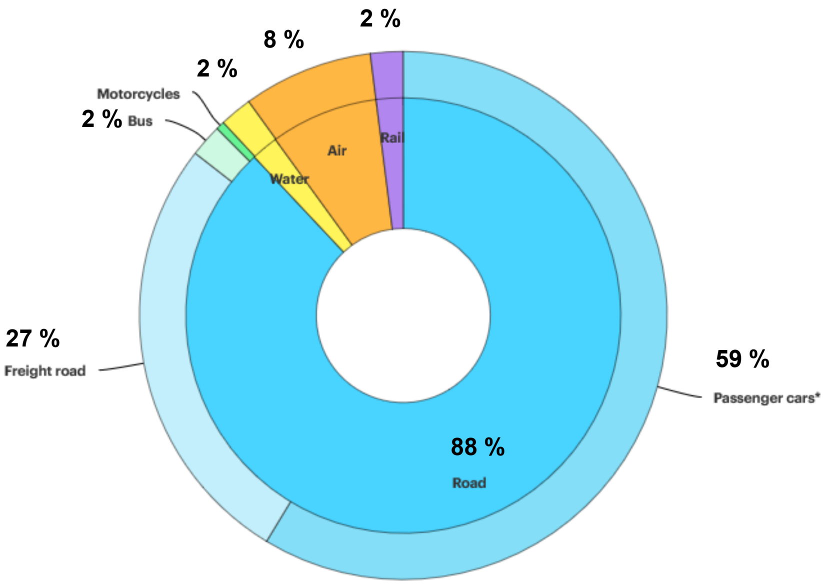


Figure 2: Breakdown of transport energy use by mode for selected IEA countries (IEA, 2020).

The 2017 IEA report "The Future of Trucks: Implications for energy and the environment" (IEA, 2017) states that road freight transport makes up 32 % of the total transport-related energy demand. In addition, the report found that road freight transport primarily uses petroleum-derived fuels, which accounts for more than 97 % of the sectoral final energy usage.

Road freight is a major contributor of carbon dioxide (CO_2) with its total share of some 30 % of transport energy and it's almost 100 % dependency on fossil fuels on a global scale. Figure 3 illustrates the top ten CO_2 sources in IEA countries and shows that road freight is one of the top three contributors of CO_2, bigger than, e.g., residential space heating. Furthermore, passenger cars and road freight together make up almost a third of the final energy-related CO_2 emissions.

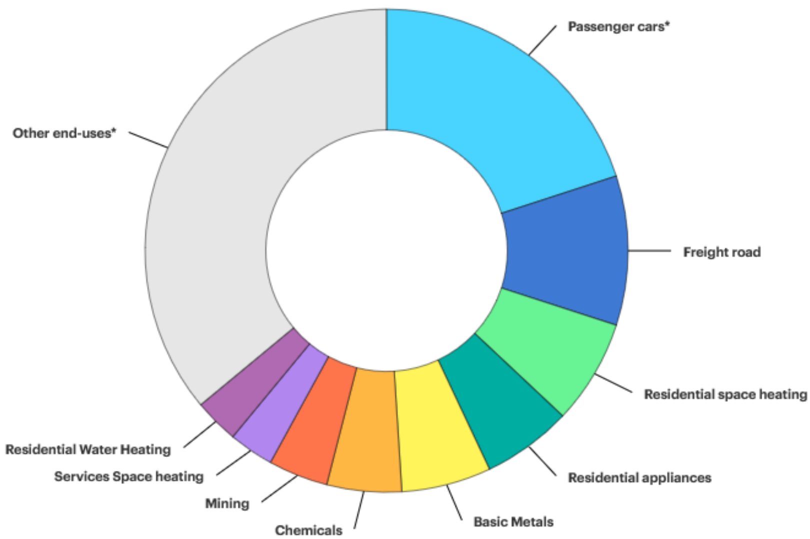


Figure 3: Top ten CO_2 emitting end uses in selected IEA countries in 2017 (IEA, 2020).

Heavy-duty trucks and all categories of freight vehicles in Europe are almost exclusively fueled by diesel. In Canada, the United States, and Asia there are also some lighter freight vehicles that use petrol. Currently, on the world level, the share of biocomponents in diesel is estimated to be less than 5 %. The use of methane (natural gas & biomethane) is still rather marginal as well.

Vehicle categories

Road freight vehicles basically fall into three main categories:

- light-duty commercial vehicles (van-type vehicles)
- medium-duty commercial vehicles (up to 12…15 tons)
- heavy-duty commercial vehicles (typically above 15 tons, with or without trailers)

Definitions of road freight vehicles vary by region. Table 1 presents truck classification schemes in the United States (and Canada), European Union, China and Japan.

Table 1: Truck classification schemes in the United States (and Canada), European Union, China and Japan (IEA, 2017).

United States		European Union				China		Japan			
Vehicle Category	Weight (t)**	Vehicle Category	Weight (t)*	Trailers & semitrailers	Weight (t)	Trucks Weight (t)	Tractors Weight (t)	Trucks Category	Weight (t)	Tractors Category	Weight (t)
		N1	< 3.5							1	< 20
2b	3.86 - 4.54	N2	3.5 - 12	O1	< 0.75	3.5 - 4.5	3.5 - 18	1-4	3.5 - 7.5		
3	4.54 - 6.35					4.5 - 5.5					
4	6.35 - 7.26			O2	0.75 - 3.5	5.5 - 7					
5	7.26 - 8.85					7 - 8.5		5	7.5 - 8		
6	8.85 - 11.79					8.5 - 10.5		6	8 - 10		
7	11.79 - 14.97			O3	3.5 - 10	10.5 - 12.5		7	10 - 12		
8a	14.97 - 27.22	N3	> 12			12.5 - 16		8	12 - 14		
						16 - 20	18 - 27	9	14 - 16		
						20 - 25		10	16 - 20		
8b	> 27.22			O4	> 10	25 - 31	27 - 35	11	> 20	2	> 20
						> 31	35 - 40				
							40 - 43				
							43 - 46				
							46 - 49				
							> 49				

The IEA Advanced Motor Fuels 2016 report "COMVEC: Fuel and technology alternatives for commercial vehicles (IEA AMF, 2016a)" covered all categories of commercial vehicles, from light to heavy, with different fuels. In the experimental work, the report at hand focused on the heaviest commercial vehicle segment (i.e., US Class 8 and European category N3).

The results of the COMVEC project clearly demonstrated that specific energy consumption decreases with increasing vehicle size (Figure 4).

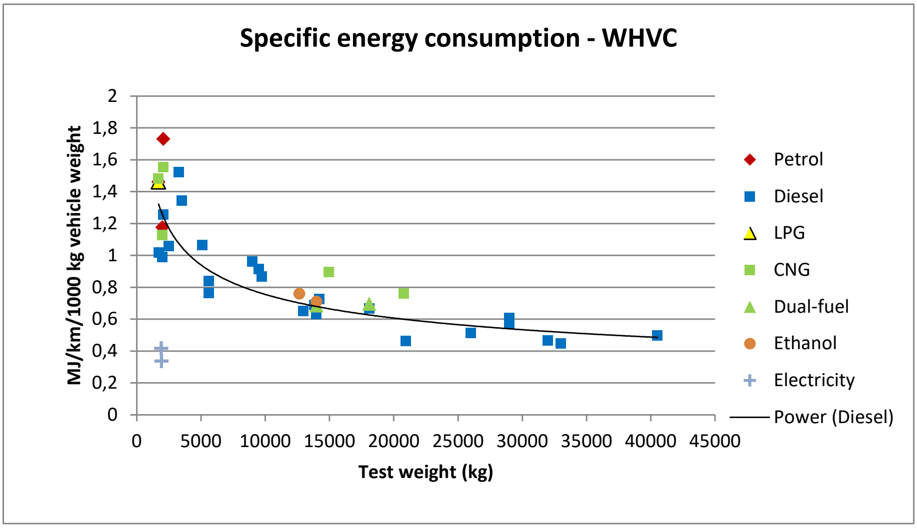


Figure 4: Specific energy consumption expressed in MJ per km per 1000 kg of vehicle weight (IEA AMF, 2016a).

In Europe, a typical long haul truck is a semi-trailer combination with a maximum weight of 44 tons. Finland and Sweden are forerunners in the adoption of heavier freight vehicles which deliver better efficiency than the typical European truck.

As of October 2013, Finland allowed full trailer combinations with a length of 25.25 m and a maximum weight of 76 tons. As of January 2019, Finland allows so-called High Capacity Transport combinations, with a maximum length of 34.5 m on its roads (Regulation 31/2019 (Valtioneuvosto, 2019)). Various combinations of semi-trailers and full trailers are possible. Maximum weight was kept at 76 tons, as higher weights would have required strengthening of some parts of the main road network. This conclusion on weight was drawn from piloting activities with maximum weight exceeding 100 tons. The increase in length alone (25.25 -> 34.5 m) is estimated to reduce the fuel use in heavy road transports by 5 to 15 % (fever vehicles on the roads) (Finnish Ministry of Transport and Communication, 2019).

Figure 5 shows a 34.5 m long vehicle combination. In Sweden, the maximum vehicle combination weight is 74 tons, and maximum length 25.25 m (Sweden Transport Styrelsen, 2020). Outside Europe, Australia is well known for its huge road trains.

Figure 5: A 34.5 m long HCT vehicle combination (Lahti, 2019).

Legislation insight (GHG and pollutants related)

General

As alluded to above, the rules and regulations concerning road vehicles vary greatly on a global scale. Additional vehicle regulations include; safety, exhaust emissions (regulated emissions), CO_2 emissions and fuel efficiency. Furthermore, fuel is regulated to ensure the operability and compatibility aligns with sophisticated engine and exhaust after-treatment technology. Examples of fuel regulations are the Canadian Clean Fuel Standard (Environment and Climate Change Canada, 2019) and the European Fuel Quality Directive (European Union, 2009)·

Fuel efficiency and CO_2 emissions

Fuel efficiency can be regulated either directly through fuel or energy consumption or indirectly by regulating CO_2 emissions. There are valid reasons to strive for both energy efficiency and low CO_2 emissions.

Current vehicle CO_2 regulations look at tailpipe-CO_2 emissions only. It should be noted that fuel/energy consumption and overall CO_2 emissions do not necessarily correlate. As long as mainly fossil petrol and diesel were used, tailpipe CO_2 emissions were a fair indicator of vehicle efficiency. Natural gas (methane) has a lower specific CO_2 emission than petrol or diesel (some 55 compared with some 73 g CO_2/MJ), giving an advantage for methane fueled vehicles.

However, with the introduction of alternative energies and renewable fuels, overall CO_2 emissions and vehicle efficiency are decoupled. Using a good renewable fuel in an internal engine equipped vehicle can deliver very low overall CO_2. Currently the vehicle manufacturers in practice get no credit for producing vehicles optimized for renewable fuels, and thereby the ever-tightening CO_2 limits are a strong incentive for the manufacturers to move towards electrification. In vehicle legislation, electric vehicles are calculated as zero emissions vehicles, even though in some markets they will mostly be powered by coal-generated electricity.

The concept of well-to-wheel CO_2 emissions will be discussed later on in this report.

CO_2 limits for passenger cars have been established for quite some time, for example, the United States was the first country to implement fuel economy standards almost 40 years ago. Currently, standards to improve the fuel economy of passenger vehicles cover more than 80 % of global passenger vehicle sales (IEA, 2017). Passenger cars and light-duty commercial vehicles are certified by running the vehicles on a chassis dynamometer with the tests producing actual measured figures for the entire vehicle, regulated emissions, CO_2 emissions and as well as fuel consumption.

Japan was the first country to enact fuel efficiency standards for heavy-duty vehicles in 2005 (TransportPolicy, 2019). Since then, a number of countries and regions have followed; China in 2012, Canada and the US in 2014 and Europe in 2019 (IEA, 2017)(DieselNet, 2020)(European Union, 2019). The way to report fuel economy or CO_2 emissions vary; km/liter (Japan), liters/100 km (China), g CO_2/ton-mile, g CO_2/bhp-hr and gallons/1,000 ton-mile (Canada and the US), g CO_2/ton-km (EU).

Many heavy-duty trucks are customized or tailored with variations in engine, transmission, chassis, tires and bodywork. Therefore, homologation of complete vehicles in a chassis dynamometer is not feasible. Instead, heavy-duty CO_2 certification procedures are a combination of actual testing of the engine and some other key components along with the simulation of the vehicle. Typically, a number of vehicle types are defined, and all classes of heavy-duty vehicles are not necessarily covered. Figure 6 the schematics of the European VECTO (**V**ehicle **E**nergy **C**onsumption calculation **To**ol) simulation tool.

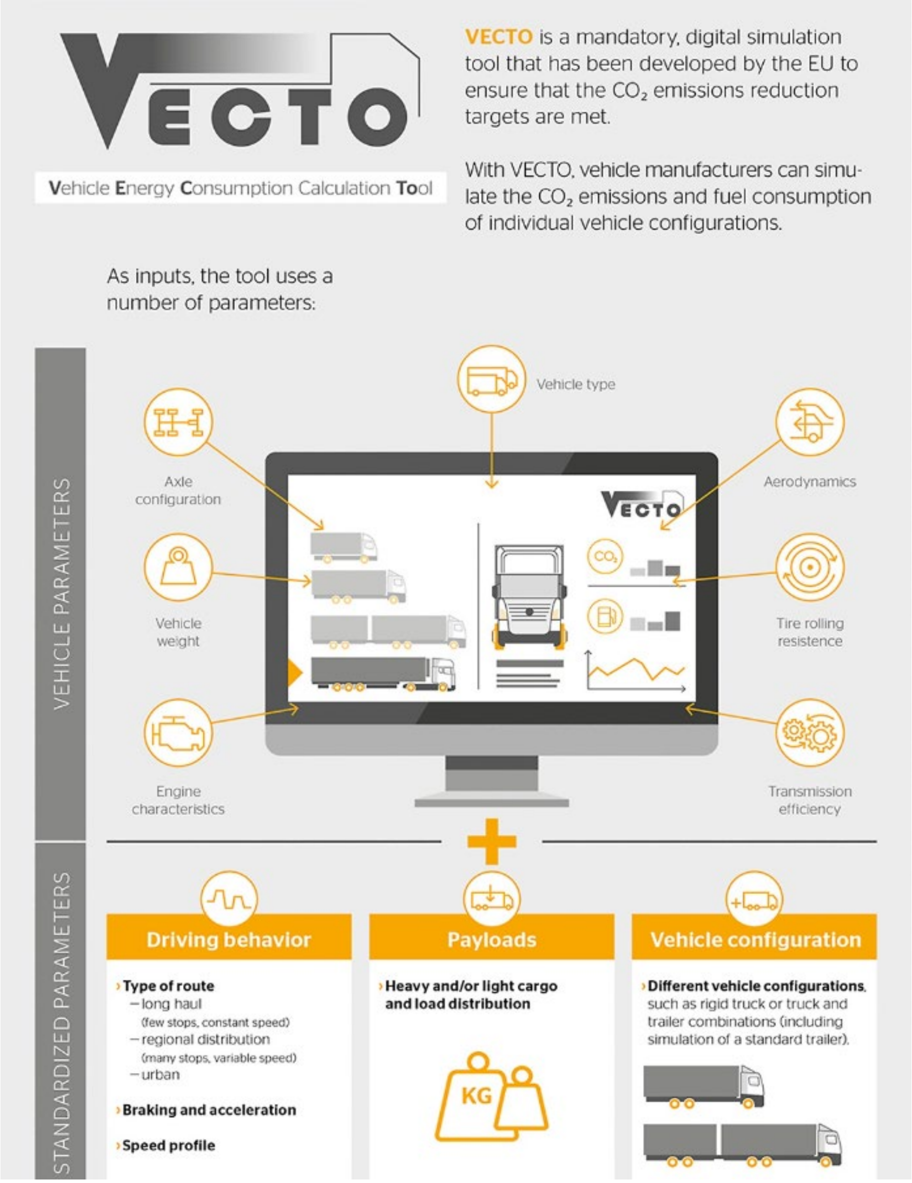


Figure 6: Schematics of the European VECTO simulation system (European Union, 2019b).

The Japanese fuel efficiency standards for heavy-duty vehicles apply to diesel-fueled vehicles with a GVW above 3.5 tons, including trucks and buses designed to carry more than 11 passengers. In total, there are 11 classes for rigid trucks and two classes for tractor trucks. The system is based on the "Top Runner" method. In this approach, the vehicle model with the best fuel efficiency in each vehicle type and weight class for the reference year is designated as the "Top Runner." The fuel economy levels of the top runner models in each vehicle class are then set as the target fuel economy values for the remaining vehicle models. Hybrids, electric vehicles, alternative fuel, and other advanced technology vehicles are excluded from the top runner system (ICCT, 2019).

Phase I called for a 9.7 % improvement for tractors and a 12.2 % improvement for other vehicle classes (other than tractors) over the model year (MY) 2002 baseline by 2015. For heavy-duty tractors with a GVW over 20 tons, the 2015 numerical target was 2.01 km/l or 49.7 l/100 km.

For Phase II, promulgated in 2019, year 2015 constitutes the baseline. On an average, fuel economy of trucks should improve by 11.9 % from 2015 to 2025. The 2025 numerical target for tractors with a GVW more than 20 tons is 2.32 km/l or 43.1 l/100 km.

In 2020, the Ministry of Economy, Trade and Industry (METI) adopted a "Well-to-Wheel" (WTW) approach in assessing energy consumption efficiency rates[3]. This approach takes into account the upstream energy consumption efficiencies of vehicles before electricity, gasoline or other fuels are supplied to vehicles, so that the fuel efficiency value of electric vehicles and plug-in hybrid vehicles can be compared with that of gasoline vehicles and other conventional vehicles. In the first stage the WTW approach applies for passenger cars towards 2030. This could well

[3] https://www.meti.go.jp/english/press/2020/0331_009.html

be an opening in general for the assessment of energy consumption and CO_2 emissions on a WTW basis.

The Chinese fuel efficiency regulations, implemented for new type approvals as of 2012, cover commercial trucks, dump trucks, tractors, coaches and buses with a GVW over 3,500 kg. There are 11 weight classes for rigid trucks and 8 classes for tractors. The overlapping in years stems from different timings for new type approvals and for all new vehicle sold.

Phase I (2012 - 2015), set fuel consumption limits for the various vehicle classes. For tractors, maximum fuel consumption was set to 38 - 56 l/100 km, depending on the vehicle weight (Figure 7). Phase II (2014 - 2020) sets targets relative to the 2012 levels, -11.5 % for trucks and -14 % for tractors (ICCT, 2013)

Phase III (2019 onwards) again sets targets relative to the Phase II levels, -13.8 % for trucks and -15.3 % for tractors. In the heaviest vehicles class, tractor-trailers with a GVW over 49 tons, the new limit is 40.5 l/100 km (TransportPolicy, 2020a).

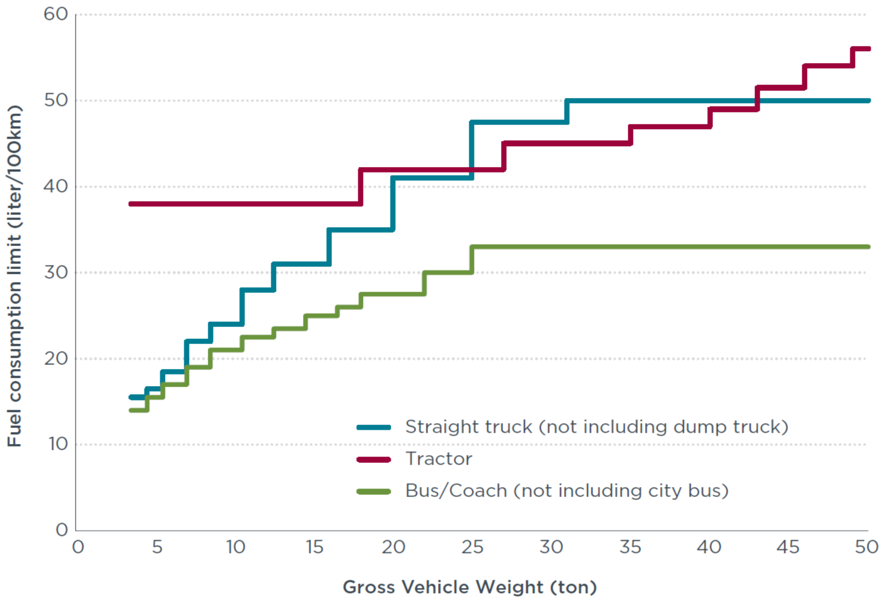


Figure 7: Chinese 2012 - 2015 fuel consumption limits for heavy-duty vehicles (ICCT, 2013).

In North-America, Canada and the United States, heavy-duty vehicle regulations are substantially aligned, with the introduction of heavy-duty CO_2 and fuel efficiency regulations in 2014. One notable difference, however, is that the US regulates both fuel efficiency and CO_2 while Canada regulates CO_2 only.

In the US, the Environmental Protection Agency (EPA), who is responsible for greenhouse gas (GHG) emission control, and the National Highway Traffic Safety Administration (NHTSA), who is responsible for fuel efficiency, have joint standards for the three main heavy-duty regulatory categories: combination tractors, heavy-duty pickup trucks and vans and vocational trucks. The regulations concern all medium- and heavy-duty road vehicles with a GVW of 8,500 lbs. or above (3,855 kg) and the engines that power them.

Phase 1 regulation, adopted in August, 2011, covers model years 2014 - 2018, with NHTSA fuel economy standards being voluntary in MY 2014 - 2015. Phase II covers the years 2021 – 2027 (DieselNet, 2020).

The sub-categories of combination tractors are based on three attributes: weight class, cab type and roof height. For a Sleeper Cab Class 8 tractor with a high roof, the 2017 values translate into 45 g CO_2/ton-km and 0.017 l/ton-km. The 2017 heavy-heavy-duty engine values translate into 626 g CO_2/kWh and some 193 g fuel/kWh (engine efficiency 43 %).

The 2027 values are 40 g CO_2/ton-km and 0,015 l/ton-km for the tractor and 588 g CO_2/kWh and some 182 g fuel/kWh (engine efficiency 46 %), respectively.

Table 2 (combination tractors) and Table 3 (engines) show the limit values of Phase 1 and Phase II. Required CO_2 and fuel consumption reductions vary by vehicle type and range from 6 – 23 % compared to a model year 2010 baseline (TransportPolicy, 2020b). Compared to Phase I, Phase II will reduce CO_2 emissions and fuel consumption by 3 - 17 %, depending on the vehicle category.

For a Sleeper Cab Class 8 tractor with a high roof, the 2017 values translate into 45 g CO_2/ton-km and 0.017 l/ton-km. The 2017 heavy-

heavy-duty engine values translate into 626 g CO_2/kWh and some 193 g fuel/kWh (engine efficiency 43 %).

The 2027 values are 40 g CO_2/ton-km and 0,015 l/ton-km for the tractor and 588 g CO_2/kWh and some 182 g fuel/kWh (engine efficiency 46 %), respectively.

Table 2: US Final Phase 1 (MY 2017) and II (MY 2027) Combination Tractor Standards (DieselNet, 2020).

Category	EPA CO_2 Emissions			NHTSA Fuel Consumption		
	g/ton-mile			gal/1,000 ton-mile		
	Low roof	Mid roof	High roof	Low roof	Mid roof	High roof
Final Phase 1 Standards (2017)						
Day Cab Class 7	104	115	120	10.2	11.3	11.8
Day Cab Class 8	80	86	89	7.8	8.4	8.7
Sleeper Cab Class 8	66	73	72	6.5	7.2	7.1
Final Phase 2 Standards (2027)						
Day Cab Class 7	96.2	103.4	100	9.4	10.2	9.8
Day Cab Class 8	73.4	78.0	75.7	7.2	7.7	7.4
Sleeper Cab Class 8	64.1	69.6	64.3	6.3	6.8	6.3
Heavy-haul Class 8	48.3			4.7		

Table 3: US engine standards for engines installed in tractors (DieselNet, 2020).

Category	Year	CO_2 Emissions	Fuel consumption
		g/bhp-hr	gallon/100 bhp-hr
MHD Engines	2014	502	4.93
	2017	487	4.78
	2021	473	4.65
	2024	461	4.53
	2027	457	4.49
HHD Engines	2014	475	4.67
	2017	460	4.52
	2021	447	4.39
	2024	436	4.28
	2027	432	4.24

As previously discussed, the **Canadian regulations** only encompass CO_2 emissions. Table 4 shows the CO_2 limits for tractors 2014 – 2020 in Canada. The 2017 values are in congruence with the US. 2017 values of Table 2.

In the case of heavy-heavy-duty engines, the Canadian 2017 limit value also corresponds to the one in the US, 460 g CO_2/bhp-hr or 626 g CO_2/kWh.

The Canadian regulations will be tightened in three steps, 2021 - 2023, 2024 - 2026 and 2027 and subsequent model years (Table 5). The 2027 values are again in congruence with the ones for the US.

The Canadian 2027 CO_2 value for heavy-heavy-duty engines designed to be used in tractors is the same as for the US- 432 g CO_2/bhp-hr or 588 g CO_2/kWh.

Table 4: Canadian CO_2 emission limit values for tractors throughout 2014 to 2020 (Government of Canada, 2018).

			CO_2 Emission Standard (g CO_2/short ton-mile)	
Item	Class	Characteristics	2014 to 2016 Model Years	2014 to 2016 Model Years
1	Class 7	Low-roof	107	104
2	Class 7	Mid-roof	119	115
3	Class 7	High-roof	124	120
4	Class 8	Low-roof with day cab	81	80
5	Class 8	Low-roof with sleeper cab	68	66
6	Class 8	Mid-roof with day cab	88	86
7	Class 8	Mid-roof with sleeper cab	76	73
8	Class 8	High-roof with day cab	92	89
9	Class 8	High-roof with sleeper cab	75	72

Table 5: Canadian CO_2 emission limit values for tractors from 2021 onwards (Government of Canada, 2018).

			CO_2 Emission Standard (g CO_2/short ton-mile)		
Item	Class	Characteristics	2021 to 2023 Model Years	2024 to 2026 Model Years	2027 and Subsequent Model Years
1	Class 7	Low-roof	105.5	99.8	96.2
2	Class 7	Mid-roof	113.2	107.1	103.4
3	Class 7	High-roof	113.5	106.6	100.0
4	Class 8	Low-roof with day cab	80.5	76.2	73.4
5	Class 8	Low-roof with sleeper cab	72.3	68.0	64.1
6	Class 8	Mid-roof with day cab	85.4	80.9	78.0
7	Class 8	Mid-roof with sleeper cab	78.0	73.5	69.6
8	Class 8	High-roof with day cab	85.6	80.4	75.7
9	Class 8	High-roof with sleeper cab	75.7	70.7	64.3

The European Union has been slow in introducing CO_2 limit values for heavy-duty vehicles. Regulation (EU) 2019/1242 (June 2019) sets CO_2 emission performance standards for new heavy-duty vehicles (European Union, 2019b). The European system differs from the other systems as it defines fleet average reference levels for the individual manufacturers which require them all to reach the same relative CO_2 reductions.

From 2025 on, manufacturers will have to meet the targets set for the fleet-wide average CO_2 emissions of their new trucks registered in a given calendar year. Stricter targets will start applying from 2030 on. The targets are expressed as a percentage reduction of emissions compared to EU average in the reference period (1 July 2019 –30 June 2020) (European Commission, 2020a):

- from 2025 onwards: 15 % reduction
- from 2030 onwards: 30 % reduction

The regulation encompasses the following vehicle categories:

- rigid lorries with an axle configuration of 4×2 and a technically permissible maximum laden mass exceeding 16 tons; 4 sub-categories
- rigid lorries with an axle configuration of 6×2; 4 sub-categories
- tractors with an axle configuration of 4x2 and a technically permissible maximum laden mass exceeding 16 tons; 3 sub-categories
- tractors with an axle configuration of 6x2; 2 sub-categories

The reference levels will be determined from 2019 and 2020 manufacturer specific data of new trucks, under a separate monitoring and reporting regulation, which entered into force in January 2019.

In determining the average specific CO_2 emissions, the specificities that are reflected in the different vehicle sub-groups should be considered. Consequently, the average specific CO_2 emissions of a manufacturer should be based on the average CO_2 emissions determined for each vehicle sub-group, including a weighting based on its assumed average annual mileage and average payload, which reflects the total lifetime CO_2 emissions. Due to the limited CO_2 emissions reduction potential of vocational vehicles, those vehicles should not be taken into account for the calculation of the average specific CO_2 emission (European Union, 2019b). Certain super credits apply for zero emission vehicles in calculating average specific CO_2 emissions.

In Korea, a CO_2 fuel regulation for heavy-duty vehicles is expected to be implemented in 2025. A simulation model based on vehicle dynamics- a Heavy-duty vehicle Emission Simulator (HES)-will be used. Vehicle dynamics models require specifications for input data such as engine characteristics, air drag resistance coefficient, rolling resistance coefficient, vehicle weight and mechanical efficiency of the gearbox. In accessing the performance of heavy-duty vehicles, it is important to accurately define the input variables of the simulation. In addition, it is necessary to consider the effects on fuel efficiency of technologies, which are not covered in the simulation model[4].

Summary of heavy-duty vehicle fuel efficiency and CO_2 regulations

Table 6 presents a summary of heavy-duty vehicle fuel efficiency and CO_2 regulations (data collected from multiple sources).

[4] Input from Chun-Beom Lee, Korea Automotive Technology Institute (KATECH), Korea

Table 6: Summary of heavy-duty vehicle fuel efficiency and CO_2 regulations (data from multiple sources).

Country/ region	Decision/ enacted	Vehicles covered	Truck categories (rigid/tractors)	Criteria	Combination tractor target (examples)	Expected impact
Japan	2005/2015	Diesel vehicle with GVW > 3.5 t	11/2	km/l	GVW > 20 t: 2.32 km/l (43.1 l/100 km) in 2025	11.9 % improvement from 2015 to 2025
China	Enacted 2012	Vehicles with GVW > 3.5 t	11/8	l/100 km	GVW > 49 t: 40.5 l/100 km 2019->	For tractors -14 % from 2012 to 2020
USA	2011/2014	Vehicles with GVW > 3.856 t	5/9	g CO_2/ton-mile, gal/1,000 ton-mile	Class 8 high-roof sleeper cab: 64.3 g CO_2/ton-mile, 6.32 gal/1,000 ton-mile (2027)	15 - 27 % reduction from 2017 to 2027
Canada	2013/2014	Vehicles with GVW > 3.856 t	5/9	g CO_2/ton-mile	Class 8 high-roof sleeper cab: 64.3 g CO_2/ton-mile (2027)	
EU	2019/2025	Vehicles with GVW > 16 t	6/5	Reduction (%) in CO_2 (g/ton-km) compared to manufacturer specific 2019/2020 reference	For all vehicles -15 % by 2025 and -30 % relative to manufacturer specific reference	-15 % by 2025 and -30 % by 2030 relative to 2019/2020

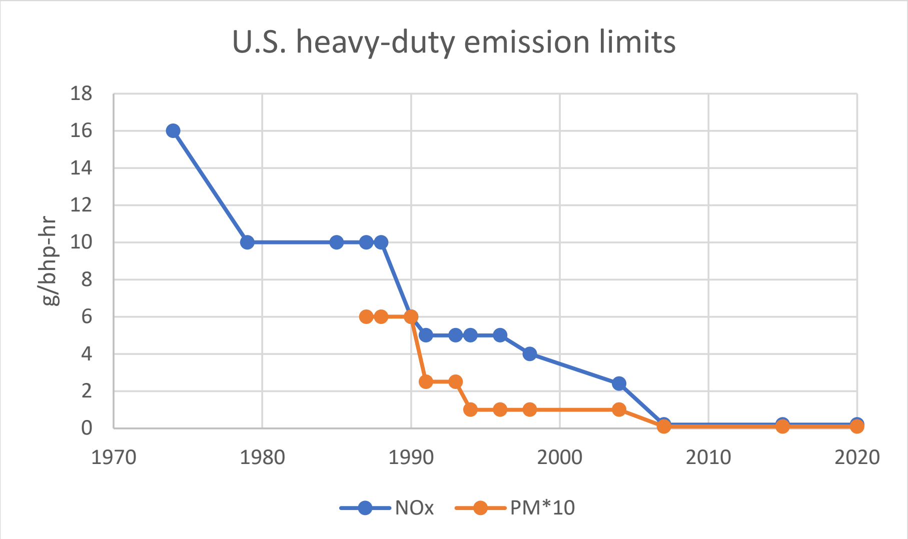
Regulated emissions

The first set of emission standards for heavy-duty engines were enacted in the US in 1974 (DieselNet, 2020). The first limit values were for carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NO_x) and combined HC + NO_x, and the values were 40 and 16 g/bhp-hr (54.4 and 21.4 g/kWh), respectively. The Euro I standards, introduced in 1992, had limits of 4.5 g CO/kWh, 1.1 g HC/kWh, 8.0 g NO_x/kWh and 0.36 g particulate matter (PM)/kWh (for engines with a maximum output of more than 85 kW) (DieselNet, 2020).

Since the days of the first regulations, a lot of progress has been made, including:

- more strict limit values
- addition of new criteria (e.g., particulate mass and number)
- switch from steady-state testing to more realistic transient-type testing
- harmonization of test procedures (e.g., Word Harmonized Transient Cycle (WHTC) and World Harmonized Steady-State Test Cycle (WHSC), however still different test protocols in the US (Federal Test Procedure FTP Transient) and in Europe (WHTC and WHSC)
- introduction of complementary off-cycle emission testing (OCE), e.g., not-to-exceed (NTE) and in-service conformity (ISC) requirements to ensure performance outside the standard testing regimes

Figure 8 shows the development of US and European heavy-duty limit values for NO_x and PM.



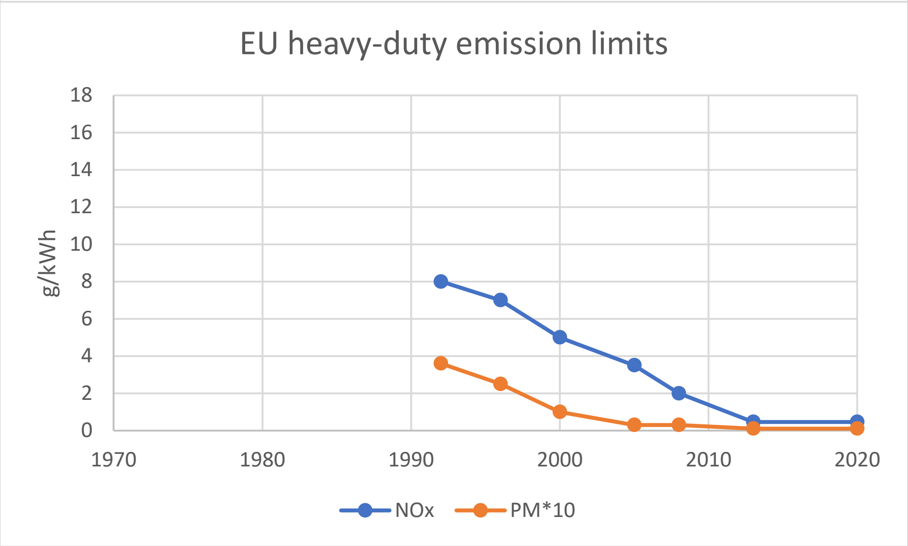


Figure 8: The development of US and European NO_x and PM values. Data from (DieselNet, 2020).

Figure 8 shows that even the current regulations, US 2007 (2010) and Euro VI (2013), are close to zero emissions in a historic perspective. Both these regulations include a kind of “real driving emissions” element. In the case of US, NTE applies (more sophisticated methods are under discussion). In Europe, the ISC is done with vehicles on the road using Portable Emission Measurements Systems (PEMS).

Table 7 (US) and Table 8 (EU) present the emission limit data in numeric form.

Table 7: US heavy-duty engine emission limits (DieselNet, 2020).

Year	CO	HC	HC + NO_x	NO_x	PM	
					General	Urban bus
	g/bhp-hr					
1974	40	-	16	-	-	
1979	25	1.5	10	-	-	
1985	15.5	1.3	-	10.7	-	
1987	15.5	1.3	-	10.7	0.60	
1988	15.5	1.3	-	10.7	0.60	
1990	15.5	1.3	-	6.0	0.60	
1991	15.5	1.3	-	5.0	0.25	0.25
1993	15.5	1.3	-	5.0	0.25	0.10
1994	15.5	1.3	-	5.0	0.10	0.07
1996	15.5	1.3	-	5.0	0.10	0.05
1998	15.5	1.3	-	4.0	0.10	0.05
2004	15.5	-	2.4	-	0.10	0.05
2007*)	15.5	0.14	-	0.20	0.01	

*) Fully phased-in 2010 (Canada has adopted these same standards)

Table 8: EU heavy-duty engine emission limits (DieselNet, 2020).

Steady-state testing								
Stage	Date	Test	CO	HC	NO_x	PM	PN	Smoke
			g/kWh				#/kWh	1/m
Euro I	1992,≤ 85 kW	ECE R49	4.5	1.1	8.0	0612		
	1992, >85 kW		4.5	1.1	8.0	0.36		
Euro II	1996.10		4.0	1.1	7.0	0.25		
	1998.10		4.0	1.1	7.0	0.15		
Euro III	1999.10 EEV	ESC & ELR	1.5	0.25	2.0	0.02		0.15
	2000.10		2.1	0.66	5.0	0.10		0.8
Euro IV	2005.10		1.5	0.46	3.5	0.02		0.5
Euro V	2008.10		1.5	0.46	2.0	0.02		0.5
Euro VI	2013.10	WHSC	1.5	0.13	0.40	0.01	8.0*10^{11}	
Transient testing								
Stage	Date	Test	CO	NMHC	CH_4*	NO_x	PM	PN
			g/kWh					#/kWh
Euro III	1999.10 EEV	ETC	3.0	0.40	0.65	2.0	0.02	
	2000.10		5.45	0.78	1.6	5.0	0.16	
Euro IV	2005.10		4.0	0.55	1.1	3.5	0.03	
Euro V	2008.10		4.0	0.55	1.1	2.0	0.03	
Euro VI	2013.10	WHTC	4.0	0.16	0.5	0.46	0.01	6.0*10^{11}

Some Euro VI provisions, including ISC testing and OBD requirements, are phased-in over several years. Later on in the experimental part of this report, comments are made on Euro VI Step C and Step D vehicles. Table 9 provided by AVL MTC in its report AVL MTC 2020/10 presents a comparison of requirements of Euro VI Step C, D and E legislation phases.

Table 9: Comparison of Euro VI Step C, C+, D and E. Table provided by AVL MTC.

Criteria	Euro VI C (before 01.01.2017) *	EURO VI C (after 01.01.2017)	Euro VI D	*Euro VI E*
Power threshold for valid window	20%	←	10%	←
Trip validity	50% of all windows must be valid. If not, power threshold can be reduced in steps of 1% to 15%	←	50% of all windows must be valid. After application of 90 percentile rule, min. 1 valid work based window in urban operation with respect to nitrogen oxides (NO_x)	←
Payload at TA	50-60% of max. payload	←	←	←
Payload at ISC	50-60% of max. payload	→	10-100% of max. payload	←
Trip duration	min. 5 times WHTC work or CO_2	→	4-8 times WHTC work or CO_2	←
Engine coolant temperature at beginning of test	-	→	T ≤ 303 K (30 °C) If ambient temperature >30 °C at beginning of test, coolant temp. max. ambient temp.+2 °C	←
Data evaluation start	Engine coolant temp. ≥ 343 K (70°C) or stabilized (+/- 2 K) for 5 min, no later than 20 min after engine start	→	Engine coolant temp. ≥ 343 K (70°C) or stabilized (+/- 2 K) for 5 min, no later than 15 min after engine start.	←
Cold engine start provision	-	-	-	*Analysis of "cold start" at 30°C $T_{Coolant}$ $CF_{total} = 0.14\ CF_{cold} + 0{,}86\ CF_{hot}$*
Determination of urban, rural and motorway share	Vehicle speed	→	- Geographical coordinates (map) or - First acceleration method	←
Average speed requirements for trip parts	-	→	Yes, see slide#6	←
Particulate number measurement	-	-	-	*Introduction of PN PEMS*

*Euro VI C requirements not including amendments by (EU) 2016/1718; *italic: Draft Commission Regulation (EU) .../... amending (EU) 582/2011, 04 December 2018*

Figure 9 (NO_x) and Figure 10 (PM) stemming from the 2016 "COMVEC" report (IEA AMF, 2016a) show that Euro VI certified vehicles, in most cases, delivered expected NO_x and PM performance. However, most of the older vehicles tested, Euro III - Euro V, had higher emissions than what could be expected. The straight lines in the figures show estimates for engine testing limit values (g/kWh) of the various emission classes converted into distance based values (g/km), enabling approximation of compliance.

The test cycle used in COMVEC was the World Harmonized Vehicle Cycle (WHVC), derived from the WHTC engine dynamometer cycle.

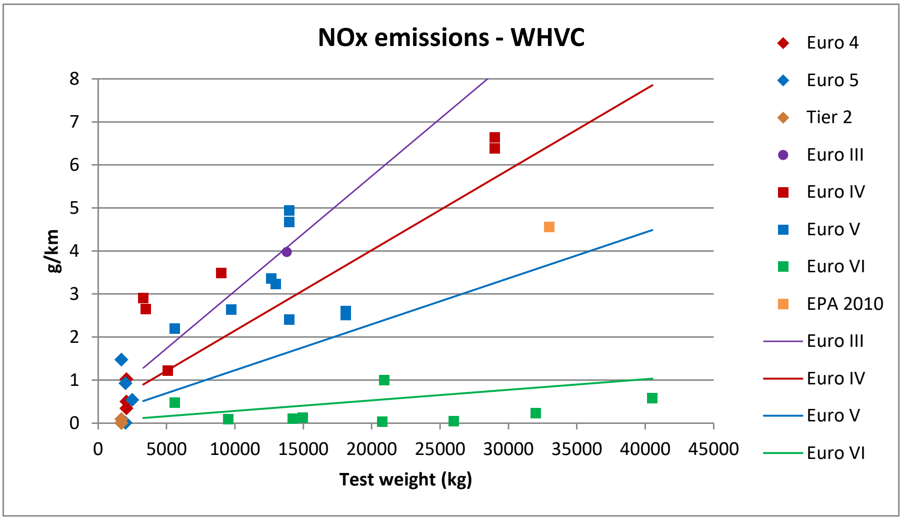


Figure 9: NOx emissions by emission class (IEA AMF, 2016a).

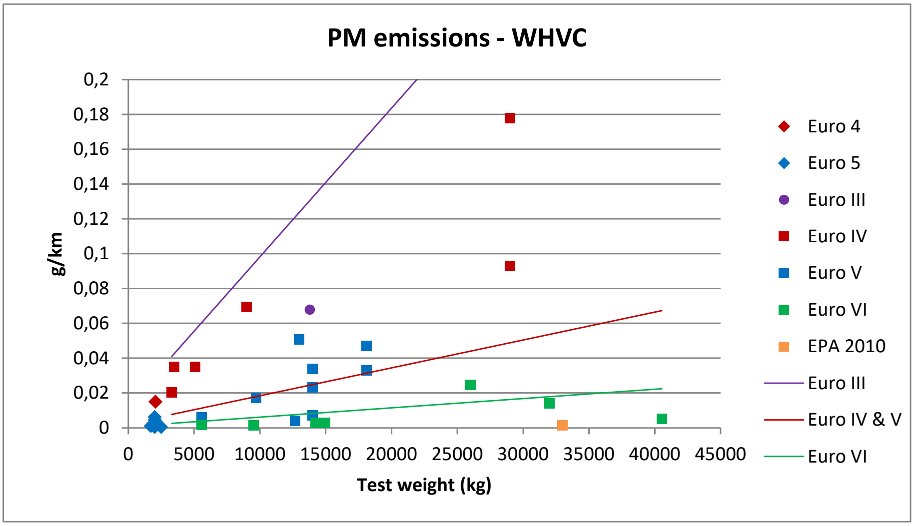


Figure 10: PM emission by emission class by emission class (IEA AMF, 2016a).

Many countries and regions in the world utilize either the US or the European heavy-duty emission regulations. For example, Japan used to have its own test procedure but as of 2016 the country follows the WHTC (DieselNet, 2020).

The following is a summary of current heavy-duty truck emission regulations in various countries and regions (DieselNet, 2020)(TransportPolicy, 2020c):

- US: 2007 Heavy-Duty Highway Rule, fully phased in 2010
- Canada: US 2007/2010
- Mexico: US 2007/Euro V as of 2019
- Argentina: Euro V as of 2018
- Brazil: P-7 corresponding to Euro V as of 2012
- Chile: US 2004/2007 as of 2015 and EU Euro V[5]
- EU: Euro VI as of 2013
- Russia: Euro V as of 2018
- China: phasing in China VI, equivalent to Euro VI, from 2019 to 2023
- India: transitioning directly from BS IV to BS VI (equivalent to Euro IV and VI), proposed timing 2020
- Japan: WHTC testing as of 2016, limits roughly equivalent to Euro VI
- Korea: Euro VI as of 2014 (earlier on Korea followed Japanese regulations)
- Thailand: Euro IV as of 2012
- Australia: Euro V, US 2007 or JE05 as of 2011

Recently in North-America there have been tighter emission standards for HDVs initiated by the United States Environmental Protection Agency (US EPA), the California Air Resources Board (CARB), and Environment and

[5] Chilean certification legislation allows OEMs to choose either US 2004/2007 as of 2015 or EU Euro V standard

Climate Change Canada (ECCC).

The US EPA introduced its Cleaner Trucks initiative (CTI) in 2018 and the goal of this initiative is to ensure emissions reductions occur in the real world in all types of truck operation, including emission control under low-load conditions (United States Environmental Protection Agency, 2020a). Similarly, CARB's proposed Heavy-Duty Engine and Vehicle Omnibus Regulation and Heavy-Duty Inspection and Maintenance Program encompasses many different program elements relating to the precedent heavy-duty low NO_x protocols. The CARB proposal envisions NO_x limits (FTP) of 0.05 g/bhp-hr from 2024 and of 0.02 g/bhp-hr from 2027.

The aforementioned regulations mandate for cleaner heavy-duty vehicles from auto manufacturers which is reflective of a shift from more traditional pathways of ensuring compliance under the regulations to an approach that ensures that the emission benefits are realized across all operating conditions of the vehicle. This new approach to HDV in-use compliance would involve the implementation of new vehicular technologies previously not available in this sector. The UC Riverside's Center for Environmental Research and Technology's Onboard Sensing, Analysis and Reporting Consortium (OSAR) has led to considerable research on the efficacy of in-use emission limits premised on reliable on-board continuous emissions measurement and reporting systems (UC Riverside, 2020). This is mentioned in this document primarily to highlight the increasing demand for testing that is more representative of real-world driving behaviors and operating conditions.

In addition to the tightened emissions standards and the consequential technological advances in emission reduction strategies that have been developed, it is also important to consider the role of regionally-available commercial fuels on the resulting emissions from vehicles. To provide background, in 2016 Canada announced the development of the Clean Fuel Standard (CFS) that would cover all fossil fuels used in Canada. The CFS aims to address three objectives: 1) To reduce emissions by lowering the lifecycle carbon intensity of fuels used in Canada, 2) to stimulate investment/innovation in low carbon fuels & technologies; and 3) to minimize compliance costs through flexible compliance options (Environment and Climate Change Canada, 2019).

Revisions of emission legislation are under discussion in Europe as well, as a part of the European Green Deal. Regarding Euro 7/VII, a roadmap has been drawn and an inception impact assessment has been carried out. After consultations, adaption by the Commission is scheduled for the fourth quarter 2021 (European Commission, 2020b).

Several approaches are under consideration:

- *The baseline scenario will consider no legislative changes to Euro 6/VI.*
- *Option 1 will consider a narrow revision of Euro 6/VI and addresses key simplification and coherence challenges in an increasingly complex environment. This option would involve setting up a single air pollutant emissions standard for cars, vans, lorries and buses. It would also involve simplifying the existing emission tests while keeping a focus on real-world testing.*
- *Option 2 will consider a wider revision of Euro 6/VI by including, in addition to the measures in option 1, more stringent air pollutant emission limits for all vehicles. This would involve stricter emission limits for regulated air pollutants and/or new emission limits for currently non-regulated air pollutants, including non-CO_2 greenhouse gas emissions.*
- *Option 3 will consider a comprehensive revision of Euro 6/VI by introducing, in addition to the measures in option 2, real-world emission monitoring over the entire lifetime of a vehicle. Data on air pollutant emissions collected through on-board monitoring (OBM) would subsequently support market surveillance and in-service conformity testing. These data may*

also be used for roadworthiness tests (i.e. periodic technical inspections and technical roadside inspections), and/or for automatically enabling a zero-emission mode depending on the location of a vehicle ("geo-fencing").

Technology options and development trends for commercial vehicles

General

A number of factors, including basic design of the vehicle, vehicle weight, driveline configuration and need for auxiliary power influence heavy-duty truck fuel efficiency. In addition, the way the vehicle is operated (driven and loaded) as well as weather conditions have implications on fuel efficiency.

Figure 11 shows the energy audit (where energy is used and lost) for a conventional Class 8 combination tractor.

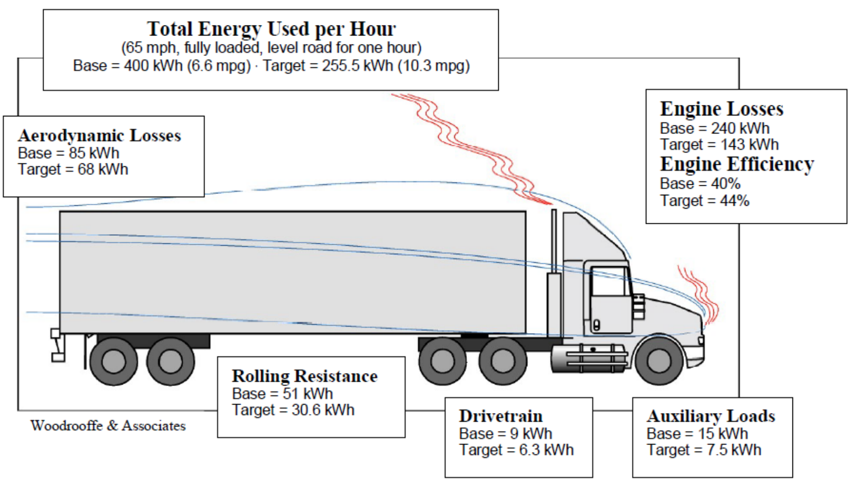


Figure 11: Energy audit for a conventional (MY 2000) Class 8 combination tractor (Bradley, 2000).

The picture stems from the 21st Century Truck Program where the baseline is MY 2000 technology, and the targets represent the original targets of the program. In this example, fuel input is 400 kW, equivalent to 6.6 mpg or 35.8 l/100 km at 65 mph or 105 km/h. In the end, 136 kW or 34 % is available to overcome driving resistances, aerodynamic drag and rolling resistances.

Measures to improve fuel efficiency of trucks include, amongst others:

- improved aerodynamics for reduced drag
- reduced curb weight (light-weighting)
- reduced rolling resistance (mainly tires)
- improved engine efficiency
- improved driveline efficiency (gearbox, final drive)
- reduced auxiliary power
- increased electrification (hybridization, electrically driven auxiliaries)

With any fuel consisting of carbon and hydrogen, fuel consumption and tailpipe CO_2 emissions correlate. The introduction of renewable fuels does not significantly change actual tailpipe CO_2 emissions (e.g., when switching from fossil diesel to renewable diesel or natural gas to biomethane), and therefore renewable fuels have to be appreciated on a well-to-wheel basis. Renewable fuels are an important element in decarbonizing the trucking sector even more so than for the passenger car segment (ART Fuels Forum, 2020).

Figure 12 presents example pathways for CO_2 reductions for heavy-duty diesel engines.

Table 10 presents a summary by IEA of near term-vehicle efficiency measures and their potential energy savings.

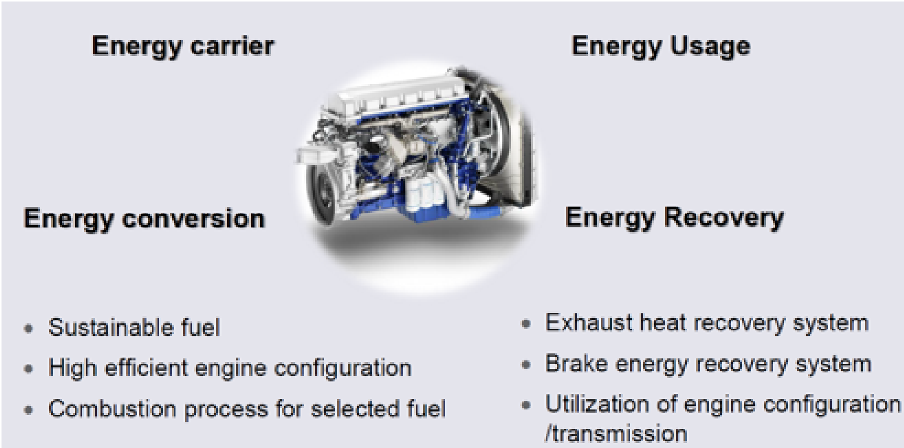


Figure 12: CO_2 reduction of heavy-duty diesel engines (Lundgren, 2014).

Table 10: Near-term vehicle efficiency measures with a net savings over the vehicle lifetime (IEA, 2017).

Measure	Description	Potential energy savings
Aerodynamics	A wide range of aerodynamic fittings (such as aft box tapers, aerodynamic tractor bodies, mud flaps, trailer tails, box skirts and cab/box gap fairings) can reduce the drag coefficient, thereby reducing road load.	Individual vehicle components reduce fuel use by 0.5-3%, depending on the truck type and aerodynamic retrofit.
Low rolling resistance (LRR) tyres; **Tyre pressure systems (TPS)**	LRR tyres can be designed with various specifications, including dual tyres or wide-base single tyres with aluminium wheels, and next-generation variants of these designs.	The potential ranges from about 0.5% to 12% in the tractor-trailer market. TPS alone could reduce fuel use by 0.5-2%.
Light-weighting	Broadly, all HDV vehicle types except utility trucks could cost-effectively reduce weight by upwards of 7% within the next ten years.	The CO_2 savings potential is about 1% by 2020, 2-3% by 2030 and 2.7-5% by 2050.
Transmission and drivetrain	Moving from manual to automatic/automated manual transmission can greatly improve efficiency. Adding gears, reducing transmission friction and using shift optimisation in manual automated or fully automated transmissions can also improve drivetrain efficiency.	Automatic/automated transmissions reduce fuel consumption by 1-8%, depending on truck type; other improvements lead to fuel savings of about 0.5-2.5%.
Engine efficiency	Engine improvements include increasing injection and cylinder pressures, both of which typically improve incrementally on a yearly basis.	Improvements in the coming decade could lead to fuel savings of approximately 4% (in service/delivery vehicles) to 18% (in long-haul trucks).
Idling reducing technologies	These include auxiliary power units and generator sets, battery air conditioning systems, plug-in parking spots at truck stops and thermal storage systems.	As much as 2.5% of the fuel consumed by road trucks may be due to idling operations. As such, this is an upper threshold on the potential fuel savings (energy savings are less).
Hybridisation	Parallel hydraulic hybridisation may be the most cost-effective near-term technology option for municipal utility vehicles, while electric hybridisation tends to be the best hybridisation option for most other mission profiles.	Dual-mode hybrid: 8-30% Parallel hydraulic hybrid: 15-25% Parallel hybrid: 6-35% – all ranges depend on vehicle type; gains are lowest (around 6%) on long-haul vehicles operating at constant highway speeds.

Aerodynamics

Figure 13 presents an aerodynamic concept truck. The manufacturer, German MAN states that thanks solely to its aerodynamic form, the MAN Concept S – with an appropriately modified trailer – uses up to 25 % less fuel than a comparable, conventional 40-ton semitrailer tractor (MAN, 2010). However, optimizing a combination tractor for aerodynamics can have side effects on vehicle total length and logistic operations, amongst others.

Figure 13: MAN's aerodynamic concept truck (Power Torque Magazine, 2012).

Vehicle weight

The 2016 "COMVEC" report shows the effect of weight on fuel consumption (Figure 14).

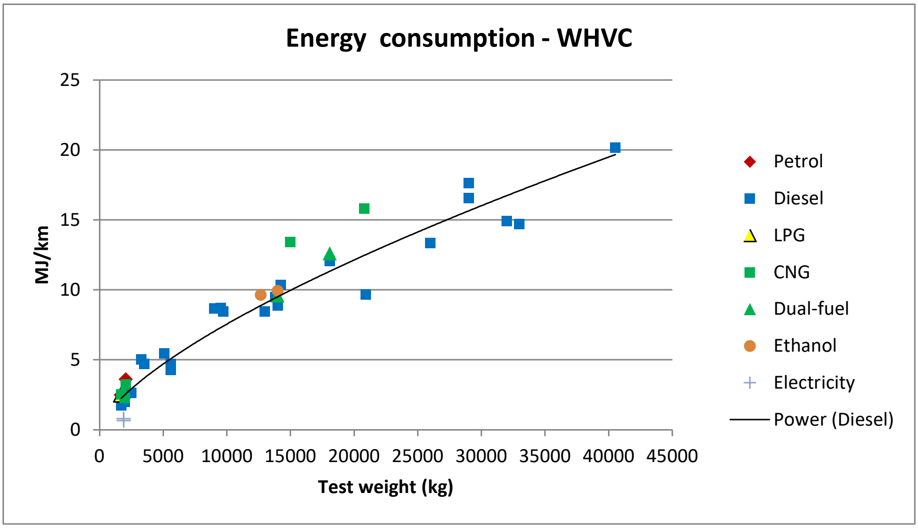


Figure 14: Energy consumption as a function of vehicle weight (IEA AMF, 2016a).

At around 40,000 kg, which is a typical weight for a semi-trailer combination, one ton of vehicle weight, added or deducted, corresponds to some 0.5 MJ/km or some 1.4 l/100 km in energy consumption in the transient WHVC cycle. Thus, at 40,000 kg, if the curb weight of the vehicle combination could be reduced with 2,000 kg, fuel consumption would be reduced 2.8 l/100 km, or in relative terms some 5 % in highly dynamic driving. Running at constant speed the savings would be much lower.

Transmission and drivetrain

A high number of gears in a HDV means that the engine can mostly be kept operating in an engine speed/load region delivering high efficiency. A manually operated mechanical gearbox is normally quite efficient in itself. However, with a manual gearbox, the influence of the driver on fuel consumption is significant. Traditional automatic gearboxes with a torque converted tend to waste energy in the slip of the converter. Nowadays, however, the torque converters are often locked, perhaps with the exception of the lowers gears.

Today many heavy-duty trucks are equipped with automated or robotized mechanical gearboxes, providing high efficiency and comfort for the driver, while eliminating the effects of less skillful drivers.

Engine technology

General

There is a wealth of engines and engine technologies suitable for heavy-duty vehicles. Most heavy-duty vehicles currently operate on diesel fuel. There is still potential to improve the traditional compression ignition (CI) diesel engine. New combustion schemes are under development. Alternative fuel vehicles, mainly methane fueled vehicles, are commercially available, as well as various types of renewable fuels.

Enhancing engine efficiency

The heavy-duty diesel engine is a highly efficient energy converter. The trucking industry is highly sensitive to fuel costs, and therefore high efficiency and low fuel consumption have traditionally been valued.

No sudden leaps in engine efficiency can be anticipated as progress takes place in small increments. Key elements in improving efficiency include (Schreier et al., 2014)(Schuckert, 2016):

- optimized combustion
- increased compression ratio
- optimized air handling including advanced turbocharging concepts
- variable valve timing
- optimized fuel injection
- sophisticated engine controls
- reduction of friction
- reduction of auxiliary power need and electrification of auxiliaries

- downsizing in combination with increased mean effective pressure and reduced engine speed
- ultimately waste heat recovery

In 2010, US Department of Energy (DOE) launched the SuperTruck initiative to improve heavy-duty truck freight efficiency of Class 8 trucks by 50 % (expressed in a ton-mile per gallon metric, reference year 2009). Phase II of the SuperTruck program, launched in 2016, aims at least doubling the freight efficiency. Four OEMs participate from the start: Cummins, Daimler, Navistar and Volvo. Activities cover a multitude of topics, e.g., improving the powertrain, partial electrification, improved aerodynamics and light-weighting (US DOE, 2016). In 2017, also Paccar joined (US DOE, 2017). Improving engine efficiency is a key topic in the program. The main targets of SuperTruck II are:

- a greater than 100 % improvement in vehicle freight efficiency
- demonstration of a minimum 55 % engine brake thermal efficiency (BTE)
- development of cost effective efficiency technologies

Figure 15 shows the steps to reach 55 % engine efficiency. To reach 55 % efficiency, waste heat recovery is needed. At the SuperTruck II Annual Merit review held in June 2020, achievements of 50 % BTE or above were reported. Cummins reported 53.5 % (Dickson and Damon, 2020) and Daimler 52.9 % (Villeneuve and Girbach, 2020). Navistar (Zukouski, 2020), Paccar (Meijer and Grover, 2020) and Volvo (Amar and Li, 2020) all reported BTE of some 50 %.

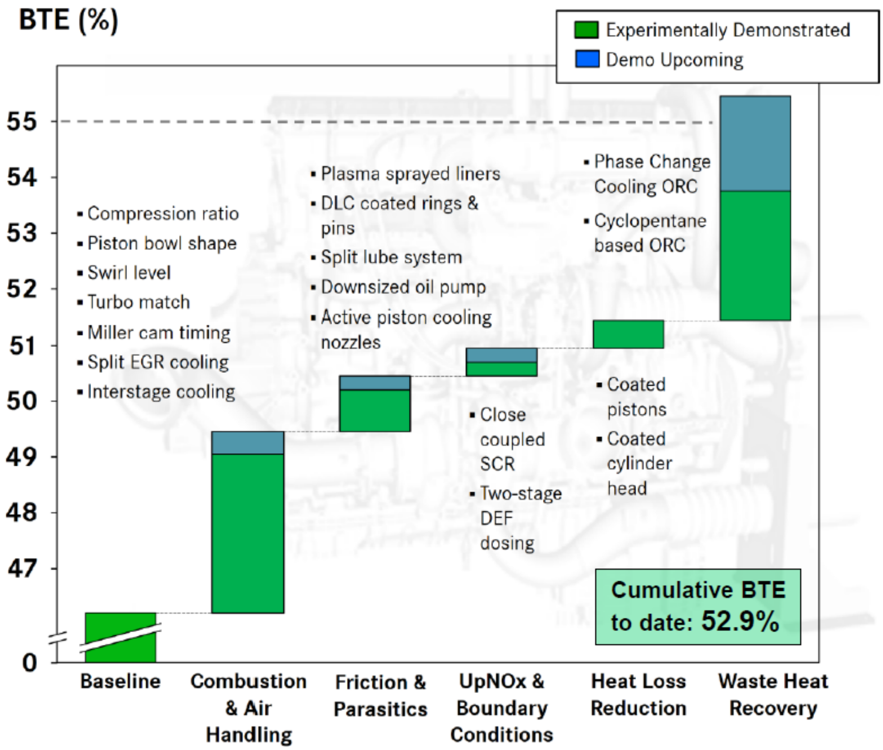


Figure 15: Steps towards 55 % engine efficiency (Villeneuve and Girbach, 2020).

Partners from across Europe (all in all 30 actors from 13 countries) are joining forces in the green vehicles project LONGRUN (2020 - 2023) to accelerate the path towards a smarter and more sustainable future. LONGRUN focuses on engine and fuels for heavy-duty engines. The objectives are (LONGRUN, 2020):

- *To achieve an internal combustion engine performance which reaches a 50 % target in terms of peak thermal efficiency; After-treatment systems integrated into hybrid powertrains with advanced engines.*

- *To achieve over 10 % energy saving (tank to wheel (TtW), excluding effects of plug-in hybrids) and correspondent CO_2 reduction; Realisation of robust ICE engine technology for use of future fuels (HVO, dual fuel mixtures), to achieve a major (>90%) CO_2 reduction well to wheel.*

Significant amounts of work have gone into the research and development of so-called low-temperature combustion schemes, e.g., Homogenous Charge Compression Ignition (HCCI), Partially Premixed Compression Ignition (PCCI) and Reactivity Controlled Compression Ignition (RCCI)(Tunér, 2014)(Reitz and Duraisamy, 2015)(Shim et al., 2019).

The primary motivation for developing these new combustion processes is lowering engine out emission levels (mainly NO_x and PM) stemming from low combustion temperature and fully or partly pre-mixed charge. In addition, there are efficiency gains due to the high combustion rate of partly or fully premixed charge combustion in comparison with diffusion type combustion, resulting in lower thermal losses. A study in 2017 demonstrated 7 % lower fuel consumption compared to baseline for a combined RCCI and dual-fuel combustion system, capable of meeting the Euro VI NO_x emission level without the need of exhaust after-treatment (García et al., 2017).

However, the alternative low-temperature combustion schemes have not yet been commercialized. Notwithstanding, early cycle pre-injections in common-rail type fuel systems are used to facilitate the combustion process. Figure 16 is a schematic of alternative concepts and innovation in engine development.

Engines designed for a specific mono-molecular fuel, e.g., di-methyl ether (DME), could provide benefits for efficiency as well as emission reductions (IEA AMF, 2020a). Also paraffinic diesel fuel can reduce emissions, particularly PM emissions, and improve efficiency slightly (IEA

AMF, 2017). Tunér of Lund University projects that a Double Compression Expansion (DCEE) Engine running on neat methanol could have the potential of reaching 60 % BTE (Tunér and Verhelst, 2020).

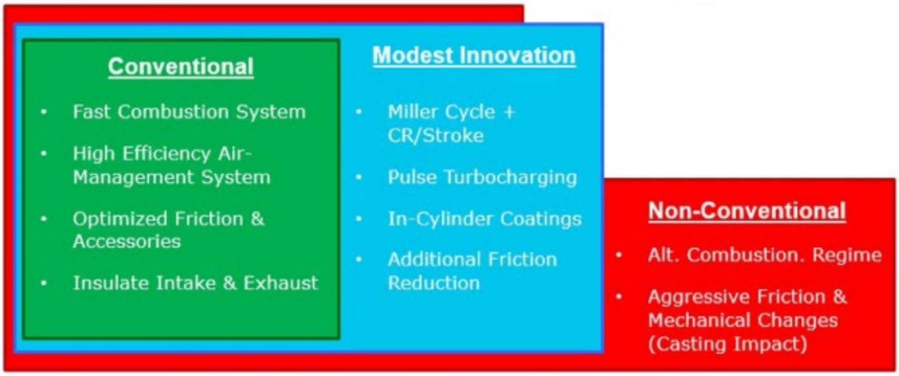


Figure 16: Alternative concepts and innovation in engine development (Meijer and Grover, 2020).

Optimizing engines merely for efficiency is not possible as there is a requirement to meet increasingly stringent emission regulations. Today all US 2007/2010 and Euro VI compliant engines are equipped with wall-flow particulate filters, which actually increase fuel consumption due to increase in back-pressure and also occasional forced increase in exhaust temperatures to facilitate filter regeneration.

As for NO_x emissions, US 2004 and Euro V regulations could be met using only exhaust gas recirculation (EGR) for NO_x control. One notable disadvantage of EGR was increase in fuel consumption. In the case of US 2007/2010 and Euro VI, all engines have selective catalytic reduction (SCR, urea catalyst) for NO_x control. Some manufacturers use SCR only, some a combination of mild EGR and SCR.

Figure 17 shows the emission control system of a Euro VI diesel engine.

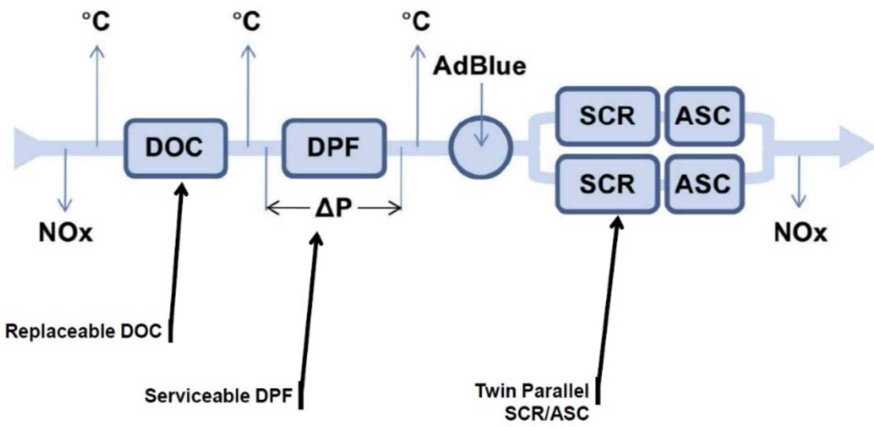


Figure 17: Schematics of the emission control system of a Euro VI diesel engine (Mackaldener, 2014). (DOC= diesel oxidation catalyst, DPF= diesel particulate filter, ASC= ammonia slip catalyst).

As discussed, over the past two decades regulatory requirements for reduced emissions by government agencies has led to considerable advancements in both engine and after-treatment technologies.

As the efficiency of ICEs go up, exhaust temperatures drop, which can be challenging for efficient exhaust after-treatment. Recent developments include cylinder deactivation and late intake valve closing as strategies that can reduce airflow and increase exhaust temperatures in heavy-duty diesel engines. These technologies can help catalyst-based after-treatment systems maintain effective emission control under low load operation, while also reducing fuel consumption (MECA, 2020).

Engines for alternative fuels

Conventional diesel process

The diesel engine is in fact quite fuel flexible. Paraffinic renewable diesel (hydrotreated vegetable oil HVO) is an example of a so-called drop-in fuel, which can be used in up to 100 % of the fuel blend without any engine modifications (Neste, 2016), (IEA AMF, 2020b). It is also possible to run diesel engines on 100 % conventional biodiesel (fatty acid methyl ester FAME, B100) (Union zur Förderungen von OEL- und Proteinpflanzen E.V., 2016). However, in the latter case some modifications are normally needed: change of some fuel system materials, improved fuel filtration and shortened service intervals (fuel filters, engine oil). The Euro VI regulation requires engines to be certified on the fuel they will be using, and consequently most European manufacturers have engines certified for HVO100 and some also for B100.

DME has good ignition properties, and is therefore, in principle, suitable as a fuel for diesel engines. However, DME must be kept under pressure to stay in liquid form. This coupled with the fact that DME has low viscosity and low lubricity set special requirements on the fuel injection system. Further, Isuzu of Japan (Isuzu, 2020) and the Volvo Group (Volvo Group, 2017) have conducted trials with DME as an automotive fuel. Annex 47 of IEA Advanced Motor Fuels Technology Collaboration Programme (TCP) contributed to the establishment of an ISO standard for automotive DME (IEA AMF, 2018).

Engines with assisted ignition

The fuels mentioned above can be combusted in the normal diesel process. Fuels with low ignition quality (meaning high octane numbers) such as methane (natural gas, biomethane) and high concentration alcohols cannot be used in conventional diesel engines, as they need some kind of ignition assistance.

There are four main options to provide assisted ignition:

1. Spark plugs
2. Pilot injection (dual-fuel)
3. Glow plugs
4. Additives (ignition enhancers for liquid fuels)

The two first options are used for gaseous fuels (methane), whereas all technologies have been either experimented or used for alcohols.

Gas engines

Table 11 presents an overview of combustion systems for gas engines.

Table 11. Combustion systems for gas engines (Koehler and Dahodwala, 2014).

	Spark-ignition λ=1	Spark-ignition lean-burn	DDF fumigation "retrofit"*)	DDF port injection "optimised"	DDF direct injection
Max. diesel substitution	100 %	100 %	50 – 85 %	75 – 85 %	95 %
Output with diesel	n/a	n/a	100 %	100 %	"Limp home"
Compression ratio	Otto	Otto	Diesel	Diesel	Diesel
Air-fuel ratio	Stoichiometric	Lean	Lean	Lean	Lean
Thermal load	High	Moderate	Diesel-like	Diesel-like	Diesel-like
Efficiency	Lower than diesel	Lower than diesel	Somewhat lower	Diesel-like (potentially)	Diesel-like (potentially)
Max. power	Lower than diesel	Lower than diesel	Diesel-like	Diesel-like	Diesel-like
Complexity	Low	Low	Moderate	Moderate	High
Effort to retrofit	n/a	n/a	Low	Moderate	n/a
Transient capability	Good	Moderate	Poor	Moderate	Good
CH_4 emissions	Low	High	Very high	High	Moderate (?)

Spark-ignited (SI) gas engines are the most widely used type of gas engines. SI gas engines, especially those engines running on stoichiometric mixture (λ=1) and utilizing a three-way catalyst (TWC), can deliver extremely low regulated emissions (NO_x, PM, non-methane hydrocarbons (NMHC) and even unburned methane (CH_4)). Lean-burn engines, which rely on a lean mixture for NO_x control have faded away as they cannot meet the most stringent requirements for NO_x and unburned methane.

The emission control system of a TWC equipped stoichiometric gas engine is much simpler compared to the one of a Euro VI diesel engine (Figure 18). The drawback of this type of engine is low efficiency, according to VTT's previous studies SI gas engines typically consume some 25 – 30 % more energy than diesel engines (IEA AMF, 2016a), (Nylund et al., 2014). For truck operations, Cummins Westport claims that the penalty is only some 10 – 15 % (Campbell, 2014).

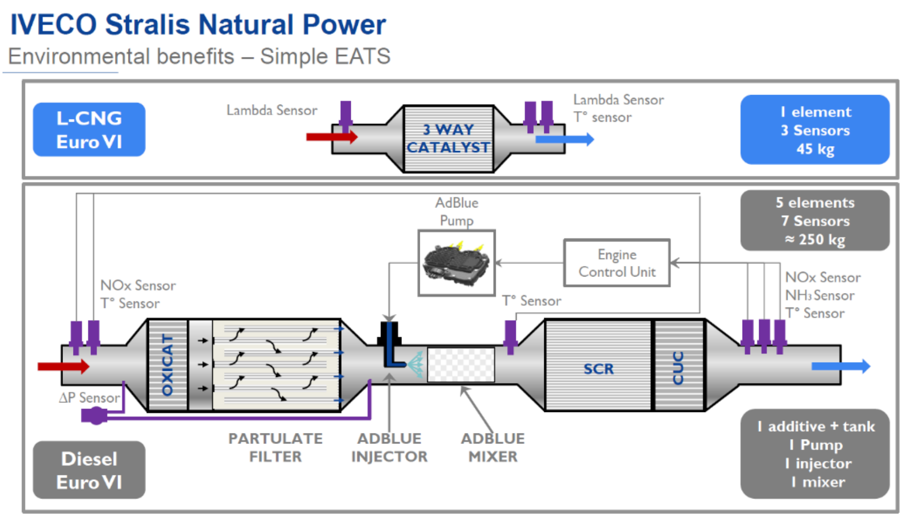


Figure 18: A comparison between Euro VI exhaust after-treatment systems for methane and diesel (Chandon, 2015).

In diesel dual-fuel systems (DDF) the ignition energy comes from diesel fuel. Premixed DDF means that methane gas is fed into the intake air of the diesel engine. The gas mixes with air and forms a homogenous mixture which is then compressed and eventually ignited by a diesel pilot spray. The gas can be fed through a single point which is often referred to as fumigation. Alternatively, the gas can be admitted into the intake manifold through individual injectors. This is often called port injection

DDF. The latter concept is more refined and enables controlled sequential injection of the gas.

In general, the premixed DDF system is relatively cost-effective, simple to install and enables the diesel engine to operate on “diesel fuel only” mode with full performance. The major drawbacks with the premixed system are high levels of unburned methane (methane slip) and knock-limited gas substitution rate over the full operating range of the engine (Broman, Robert; Ståhlhammar, Per; Erlandsson, 2010).

The methane slip stems from the scavenging process (unburned methane going through the engine during valve overlap) and from flame quenching. Due to the high methane slip, simple DDF systems cannot meet Euro VI emission requirements.

In a direct-injection DDF system (High Pressure Direct Injection, HPDI), both the pilot fuel and the main fuel (methane) are injected directly into the combustion chamber. Combustion corresponds to normal diesel combustion, i.e. diffusion type combustion. Direct-injection DDF is not knock limited, and the diffusion type combustion, with no risk for flame quenching, should give lower methane emissions than port-injected DDF.

For the automotive sector, the technology was developed by the Canadian technology company Westport (Westport, 2020). There was a 15-liter Westport HPDI engine on the North-American market, but this engine was discontinued rather quickly. As of 2018, Volvo is offering a 13-liter HPDI truck (Volvo Trucks, 2020).

According to Volvo, the only way to meet Euro VI is to implement direct-injection DDF technology, however, this technology comes with its own challenges as high-pressure injection of the gas is needed. If the fuel is in the gaseous state, the compression of the gas requires a substantial amount of energy and results in significant losses in total energy balance. On the other hand, in a vehicle running on liquefied natural gas (LNG), the pressure build-up can be done more efficiently in the liquid phase. With LNG, a cryogenic pump creates the pressure increase and subsequently, an evaporator turns the liquid into gas.

Furthermore, controlling a high-pressure gas jet is more difficult than controlling a liquid jet. The liquid jet has more inertia, and is therefore more predictable regarding diffusion while providing more energy in a given time. It might be challenging to achieve an optimum “spray pattern” for the gas in a wide range of different operating conditions (Kuensch, Z., Schlatter, S., Keskinen, K., Hulkkonen, T. et al., 2014).

Due to restrictions in space in automotive engines, both the pilot fuel and the gaseous fuel have to be injected through a mechanically challenging single twin injector. At high loads, the injection period of the gas becomes increasingly extended, due to the low energy density of the gas jet. Due to the construction of the injector, full power cannot be reached in diesel-only operation.

At least four manufacturers are offering 12 - 13 liter heavy-duty gas engines with an output of 400 hp or more:

- Cummins Westport[6]
- Iveco[7]
- Scania[8]
- Volvo[9]

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[6] https://www.cumminswestport.com/models/isx12n

[7] https://www.iveco.com/uk/products/pages/nuovo-stralis-natural-power.aspx

[8] https://www.scania.com/ae/en/home/experience-scania/news-and-events/middle-east-news/scania_s-latest-gas-engine-designed-for-long-distance-transport.html

[9] https://www.volvotrucks.com/en-ir/trucks/volvo-fh/volvo-fh-lng.html

Alcohol engines

Since the late 1970s, there has been an increasing amount of research activities on alcohols (ethanol and methanol) for heavy-duty engines. Some notable alternative ignition assistance technology studies include spark-assistance in Japan (Komiyama, K. and Hashimoto, I., 1981), dual-fuel in India (Padala et al., 2013) and glow-plugs in Germany and the US. In the early 90’s, Detroit Diesel offered a glow-plug assisted two-stroke alcohol engine, where ignition was secured with glow-pugs at low loads and by controlling scavenging and residual gases at high load (Toepel, R., Bennethum, J., and Heruth, 1983).

Within Annex 46 of the IEA AMF TCP, the Technical University of Denmark carried out experiments with a high compression diesel engine equipped with efficient intake air heating (80 ºC) to enable the engine run on neat ethanol without ignition assistance on high loads (IEA AMF, 2016b).

The only heavy-duty automotive alcohol technology concept that has reached commercial maturity is Scania’s technology with additive treated ethanol (hydrous ethanol with ignition improver and lubricity additives). Ethanol buses manufactured by Scania have been in operation in Swedish cities since 1989. Stockholm Public Transport began to replace its diesel buses with buses running on renewable fuels on the inner-city lines as early as the mid-80s (Nylund, 2015).

The first line of Scania’s ethanol engines was an adaptation of Scania's 9-litre diesel engine. The ethanol versions featured, amongst others, elevated compression ratio (28:1) to facilitate ignition, higher fuel delivery to compensate lower energy density of the fuel, and special materials for the fuel system. Unlike SI gas engines, the ethanol engine delivers diesel-like efficiency. This has been verified by e.g. VTT in various projects (IEA AMF, 2016a), (Nylund, 2015).

In 2018 Scania launched a new 13-litre ethanol engine, suitable for combination tractors. The new engine delivers 410 hp and a maximum torque of 2150 Nm. The Euro VI certified engine uses the same SCR system as its diesel counterpart for NO_x control (Scania, 2018). Also the new engine has increased compression ratio to facilitate ignition. The fuel system is now of common-rail -type (Scania's XPI), whereas the previous generations of ethanol engines were equipped with unit injectors.

Although the activity on alcohol fuels for heavy-duty road vehicles is currently quite low, there is significant interest in methanol as a marine fuel, as shown by Annex 56, "Methanol as Motor Fuels" by IEA AMF TCP (IEA AMF, 2020c).

Summary on engine technology

Currently, the conventional diesel engine is the prime power source in heavy-duty vehicles. There is still potential for enhancement of performance, and in most cases progress takes place in small increments. Advanced combustion systems have not yet reached commercial maturity.

Alternative fuel vehicles and renewable fuels, on the other hand, can be on the market, though still in rather limited volumes. Dedicated methane engines, running on natural gas or biomethane, dominate alternative engine technology. One manufacturer offers modified engines running on additive treated ethanol. Liquid oleo-type biofuels (HVO, FAME), on the other hand, can be used in unmodified or only slightly modified diesel engines.

Figure 19 shows development targets of the LONGRUN project.

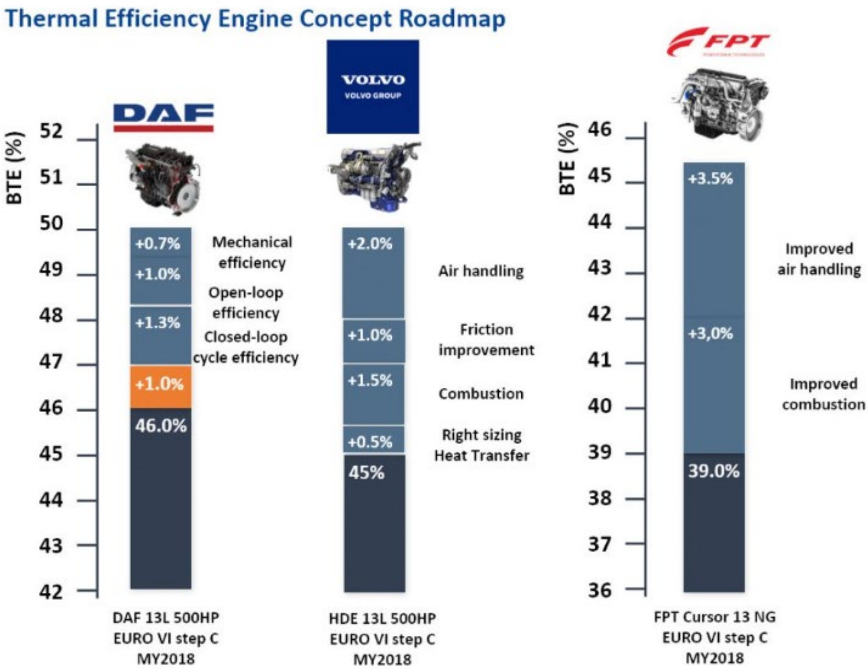

Figure 19: LONGRUN roadmap for engine efficiency (LONGRUN, 2020).

Production diesel engines achieve a BTE of some 45 %, spark-ignited methane engines a BTE slightly less than 40 %. The aim of LONGRUN is, despite the name, is to achieve 50 % for diesel engines and 45 % for gas methane engines in the relatively near future. SuperTruck II has already demonstrated BTE values above 50 % in the engine labs, and the target is set at 55 %. Theoretical studies and modelling have predicted that the ultimate potential with advanced combustion systems and monomolecular fuels is some 60 %. So to summarize engine efficiency (suggestive figures):

- 45 % BTE here and now
- 50 % BTE well before 2025
- 55 % BTE before 2030 (probably with WHR)
- ultimate potential 60 % (with advanced/unconventional combustion systems and monomolecular/tailored fuels)

Hybridization

All types of vehicles benefit from hybridization, at least to some degree. In relative terms, the biggest fuel efficiency gains are achieved for petrol engines and SI gas engines. In the heavy vehicle sector, hybrid propulsion systems are mostly used in city buses, but hybrid systems are also available for delivery vehicles and small size trucks. In principle, hybridization is also applicable to heavier goods vehicles.

The efficiency improvements with hybrid technology in conjunction with internal combustion engines (ICEs) stem from several features. Firstly, hybrid technology makes it possible to smooth out the operation of the ICE and to run the ICE on loads providing best fuel efficiency. Secondly, hybridization allows downsizing of the ICE, as the hybrid system serves as a temporary power reserve. Thirdly, hybridization enables start-stop and coasting (which turns off the engine when the vehicle is stopped or going downhill). Finally, hybrids recuperate braking energy otherwise lost as heat which significantly contributes to improved efficiency.

In the US, EPA and the United Parcel Service have developed a hydraulic hybrid delivery vehicle to explore and demonstrate the environmental benefits of the hydraulic hybrid for urban pick-up and delivery fleets (United States Environmental Protection Agency, 2020b).

However, the bulk of hybrid systems are hybrid electric vehicles (HEVs) and fall into two main groups; series hybrids and parallel hybrids. In a series hybrid, traction is supplied by an electric motor. In a parallel hybrid, as the name suggests, the electric machine operates in parallel with the internal combustion engine. Notwithstanding, a parallel hybrid can be designed so that operation in electric mode only is possible. Series hybrids are most suited for low-speed urban operations, whereas parallel hybrids, in principle, can also be applied to long-haul vehicles. A plug-in hybrid is a vehicle in which the battery can be charged from the electricity grid and they can be useful in urban conditions, but they have limited benefits in long-haul operations.

Fuel savings using HEV systems are dependent on the duty cycles and on the topology of the landscape. City bus services, with regular stop-and-go driving patterns, are ideal for hybrid applications. Annex 37, "Fuel and technology alternatives for buses" of IEA AMF TCP tested a number of hybrid city buses and found that fuel savings in the European Braunschweig bus cycle were in the range of 19 - 32 % (IEA AMF, 2012).

IEA's report "The Future of Trucks: Implications for Energy and the Environment" states that the fuel efficiency gains are lowest (around 6 %) on long-haul vehicles operating at constant highway speeds (IEA, 2017) .

Other measures

Energy efficiency can also be improved by affecting how vehicles are operated and by optimizing the logistics system. On the vehicle level, several manufacturers offer systems to support the driver such as various kinds of information systems for the driver and adaptive and predictive cruise control systems. Platooning is often mentioned as a technology to reduce fuel consumption. On the system level, additional measures include; route optimization and improved vehicle utilization through co-loading and backhauling (IEA, 2017).

Objectives

The original project description states:

"The purpose and objective of this project is to demonstrate and predict the progress in energy efficiency of heavy-duty vehicles, thus generating information to be used by transport companies, those procuring transport services and those forming transport policy. The project will encompass newest diesel technologies on different markets, but also alternative fueled vehicles and advanced powertrain configurations. On average, trucks account for some 25 % of energy use and CO_2 emissions in road transport. Heavy-duty trucks are one of the most challenging segments to electrify due to the operational range and restrictions in both length and weight. CO_2 emissions have to be brought down by improvements in energy efficiency and the use of low-carbon fuels. The European Union has set an indicative target of 30 % reduction of CO_2 emissions from heavy-duty vehicles by 2030 compared to level of 2019[10]. Many other regions in the world have similar fuel efficiency targets for HD vehicles. This project will form a basis for the understanding the performance of best available diesel and alternative fueled vehicles, and to estimate development towards 2030.

The methodology to be used comprises laboratory and on-the road testing as well as simulation of energy consumption of various types of heavy-duty vehicles. The participating laboratories will use common test protocols for actual vehicle testing, to ensure comparability of the results. In the actual testing, both energy consumption and tailpipe emissions will be measured. Energy efficiency and CO_2 emissions will be evaluated on a well-to-wheel basis".

[10] Later conformed in Regulation (EU) 2019/1242

Partners and sponsors

The HDV Performance Evaluation Annex was in principle organized as a task shared activity within IEA AMF. This means that each participating country performed commonly agreed research activities covering their own costs. However, there were also some monetary contributions (cost sharing) to the project. Japan funded a testing for a special gas quality in one on the methane trucks, and the Swedish Transport Administration (STA) contributed, in addition to task sharing, with funds for the coordination of the project. Eventually, all the research performed within the Annex by the participating countries was consolidated to one uniform Annex report.

VTT Technical Research Centre of Finland Ltd, with financial support from the Finnish Transport and Communications Agency Traficom, Gasum Oy, Neste Oyj, Proventia Oy, Posti Oyj, St1 Oy and STA acted as Operating Agent for the Annex.

The other participating countries were:

- Canada, Environment and Climate Change Canada, Emissions Research and Measurement Section and Transport Canada, Innovation Centre, ecoTECHNOLOGY for Vehicles Program, task sharing
- Chile, Ministry of Energy, task sharing
- Japan, through the Organization for the promotion of low emission vehicles (LEVO) and Japan Gas Association, cost sharing
- Korea, through the Korea Automotive Technology Institute (KATECH), task sharing
- Sweden, through STA, combination of task and cost sharing

The chassis dynamometer and on-road measurements were carried out by the following institutes:

- Canada: Environment and Climate Change Canada

- Chile: Center for Control and Vehicle Certification (3CV), Ministry of Transport and Telecommunications of Chile
- Finland: VTT
- Sweden: AVL MTC, on contract from STA

Simulation activities were performed in following institutes:

- Finland: VTT
- Korea: KATECH

Project content

The original project plan constituted of nine work packed listed below:

- WP 0: Collection and consolidation of existing data
- WP 1: Agreement on common test procedures and protocols
- WP 2: Vehicle chassis dynamometer testing
    - Contemporary diesel vehicles as well as alternative fuel vehicles in different vehicle categories
- WP 3: Vehicle on-road testing with PEMS
    - Contemporary diesel vehicles as well as alternative fuel vehicles in different vehicle categories
- WP 4: Vehicle on-road NO_x concentration monitoring
    - Contemporary diesel vehicles as well as alternative fuel vehicles
    - NO_x concentration monitoring during normal operation
- WP 5: HD vehicle simulation
    - Description of a simulation model developed in Korea
    - Simulation model for high capacity transport vehicles fuel consumption analysis
- WP 7: Aggregated test results
    - Analysis and comparison of chassis dynamometer and on-road test results generated within the Annex
- WP 8: Future projections of heavy-duty vehicle performance
    - Aggregating available data from similar studies such as US Super Truck programs and European counterparts
    - Cooperation with HEV TCP for future projection of heavy-duty vehicle CO_2 emissions and energy consumption
    - Mirroring of performance against legislative targets
- WP 9: Co-ordination of the project, synthesis and reporting
    - Administrative co-ordination, communication with the IEA AMF ExCo, synthesis of data, compilation of the Final Report and dissemination of the results

Cooperation with IEA HEV TCP

Annex 57 focuses on energy efficiency of heavy-duty trucks, covering conventional contemporary diesel vehicles as well as alternative fuel technologies: drop-in type renewable diesel fuel, spark-ignited CNG/LNG, dual-fuel HPDI for diesel and LNG as well as compression ignition ethanol (ED95). One of the objectives of Annex 57 is to make projections of the performance of internal combustion engine based powertrains into the future. Especially the prospects of meeting the upcoming heavy-duty vehicle CO_2 targets announced around the world are of interest.

The project participants acknowledge that electrification (hybrids, plug-in hybrids, battery-electric vehicles, fuel cell vehicles) will make progress not only in light-duty vehicles but also in heavy-duty vehicles over time. Therefore it was decided to include the dimension of electrification in the assessments.

Consequently AMF TCP invited the Hybrid and Electric Vehicle (HEV) TCP to join the work in investigating the CO_2 reduction potential of future powertrains suitable for long-haul trucking. Focus was on heavy-duty semi-trailer combinations with different powertrain and fuel options.

In practice this meant simulations of both ICE trucks and truck with varying degree of electrification, in the weight class of 40 tons. Parameters covered were energy consumption and CO_2 emissions, in a Tank-to-Wheel (TTW, vehicle legislation) as well as a Well-to-Wheel (WTW, overall impact) perspective.

For the joint exercise, AMF provided actual measurement data generated within Annex 57. HEV, on the other hand, provided simulation data generated within its Task 41 "Electric Freight Vehicles"[11].

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[11] IEA HEV TCP Task 41 Electric Freight Vehicles

Methodology

General

The activities within HDV Performance Evaluation (Annex 57) encompass actual vehicle testing, both in laboratory conditions (chassis dynamometer) and on road, estimations of overall energy use and GHG emissions as well as simulations of vehicle energy consumption when varying vehicle configuration and vehicle weight.

Chassis dynamometer measurements deliver precise and repeatable results, whereas PEMS type testing is mainly performed for in-service-compliance pass-or-fail type testing in real-life operation. For HDV Performance Evaluation it was concluded that these two test types would complement each other in a sensible way. Data for both types of testing is presented. Chassis dynamometer testing provides accurate data related to driven distance, in the form of MJ/km or g/km, alternatively MJ/ton-km or g/ton-km. This type of results are needed, e.g., when calculating emission inventories. PEMS testing primarily delivers emission results in the form of g/kWh at the engine crankshaft.

IEA AMF Annex 49 "COMVEC", reported in 2016, combined Well-to-Tank (WTT) and Tank-to-Wheel (TTW) data and energy use to form Well-to-Wheel (WTW) data.

As in the case of COMVEC, in this Annex 57 it was decided to use WTT data from the JEC - Joint Research Centre-EUCAR-CONCAWE collaboration on WTW[12]. The most recent edition, V5, was published in 2020. The Joint Research Centre (JRC) is run by the EU Commission. EUCAR is the European Council for Automotive R&D[13] and CONCAWE[14] is the platform for environmental research collaboration of the fuel

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12 https://ec.europa.eu/jrc/en/jec/publications/reports-version-5-2020

13 http://www.eucar.be/

14 https://www.concawe.eu/

refining industry. WTT and TTW data are used for WTW analysis for different powertrain options in the “Results and discussion” section.

Estimations of WTW and TTW CO_2 emission of powertrains with different fuel options and variable degree of electrification were carried out in cooperation with the Hybrid and Electric Vehicles TCP.

Vehicle testing

General

The commonly agreed test procedure generated in WP1 was used as a basis in each country for vehicle testing on chassis dynamometer and on-road. The motivation of this approach was to guarantee comparable results among all the measurement-performing institutes. For both testing methods, chassis dynamometer and on-road, one test cycle and route was selected. A common test cycle and route were deemed necessary to provide a reasonable amount of data for the basis of comparing different powertrain efficiencies and emissions.

For the fuel used in the chassis dynamometer and on-road tests, the following requirements were agreed upon:

- A low sulfur, max 15 ppm S diesel fuel
- Cetane index 45-55
- Density 800-850 kg/m3
- Biodiesel (FAME), max 7 % V/V (“baseline” diesel fuel)

In addition, the participants were free to add additional test cycles, loadings and fuels to their own test matrices.

The common test procedure was a recommendation and the individual participants are responsible for the quality and the relevance of the supplied data.

Chassis dynamometer

The WHVC was selected as a common test cycle for the chassis dynamometer as it is a chassis dynamometer derivative of the Euro VI heavy-duty engines type approval test cycle WHTC.

Figure 20 presents vehicle speed over the WHVC. The duration of the WHVC test is 1800 seconds and the length is 20.0 km. The test includes three segments, representing urban, rural and motorway driving[15]:

- The first 900 seconds represent urban driving with an average speed of 21.3 km/h and a maximum speed of 66.2 km/h. This segment includes frequent starts, stops and idling.
- The following 481 seconds represent rural driving with an average speed of 43.6 km/h and a maximum speed of 75.9 km/h.
- The last 419 seconds are defined as highway driving with average speed of 76.7 km/h and a maximum speed of 87.8 km/h

[15] https://dieselnet.com/standards/cycles/whvc.php

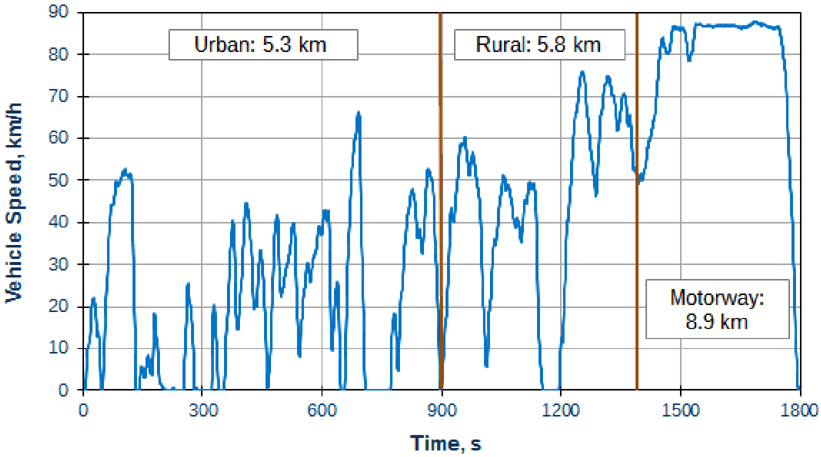

Figure 20: The WHVC cycle[15].

Commonly agreed chassis dynamometer test procedure included the following key elements:

- Before actual dyno setting, the vehicle is run according to the applicable test cycle
- Dyno setting is performed
- Soak over night
- Perform WHVC cold start. The dyno is heated prior to test – 80 km/h for 30min.
- Prior to WHVC hot start: run vehicle --> exhaust temp the same as end of WHVC cold. Thereafter hot soak (engine switched off) for 10 min, before start of WHVC hot start
- Recommendation to adjust test load to correspond of 50 % of the maximum permissible weight of the truck or vehicle combination
- Ambient temperature in test cell: 25±5°C

The recommendation for test load to correspond to 50 % of the total maximum permissible weight was decided to be used as it provided direct link to the previous IEA AMF HDV study COMVEC in which WHVC was also used as a common test cycle.

On-road measurements with PEMS

For on-road measurements with a PEMS device, the test procedure primarily followed the European Union legislation (European Union, 2011) for heavy-duty vehicles in-service conformity (ISC) testing.

Following key elements were agreed upon for the on-road measurements (see also Table 9):

- Route requirements
  - Approximately (app.) 20 % urban (avg. speed 15 - 30 km/h)
  - App. 25 % rural (avg. speed 45 - 70 km/h)
  - App. 55 % highway (avg. speed ever 70 km/h)
- Approximately means tolerance of +-5 %
- Duration of the test shall be chosen so that the accumulated work during the test is 4 - 7 times the work conducted in engine's type approval test or CO_2 emissions produced are 4 - 7 times the CO_2 emissions produced in the type approval test
- Vehicle payload: Recommendation for 55% of maximum payload
- Engine temperature is not exceeding 30°Cat start. The vehicle has been soaking overnight.

There were not specific requirements for the PEMS device itself. Commercial devices were used.

Test program (actual vehicle testing)

General

HDV Performance Evaluation focused on heavy-duty trucks performance measurements namely, energy consumption and emissions. There are different types of vehicle classifications used around the world (see Table 1). For example, in US the classification is based on the Gross Vehicle Weight Rating (GVWR) and divided into eight different classes[16]. Class 8 includes vehicles with GVWR over 14,696 kg or 33,000 lbs. whereas, in EU vehicles transporting goods are classified into three categories: N1 (GVWR up to 3,500 kg), N2 (3,500 – 12,000 kg) and- N3 (GVWR over 12,000 kg)[17].

As the Annex included heavy-duty vehicles from all around the world and the vehicle classification varies depending on the region and country, it was decided to use a simple customized classification for the Annex.

Vehicles specified in the project plan were divided into two main categories (Figure 21):

- Category 1: Medium to heavy-duty vehicles (GVW 5,000-18,000 kg)
    - Rigid trucks with two axles
    - EU N2-N3 delivery trucks and US Class 1-7 trucks
- Category 2: Heavy-duty trucks (GVW 18,000 - 44,000 kg)
    - Semi-trailer tractors and full-trailer trucks
    - EU N3 and US Class 8 tractors

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[16] US vehicle weight classification https://www.epa.gov/emission-standards-reference-guide/vehicle-weight-classifications-emission-standards-reference-guide

[17] EU vehicle weight classification https://www.transportpolicy.net/standard/eu-vehicle-definitions/

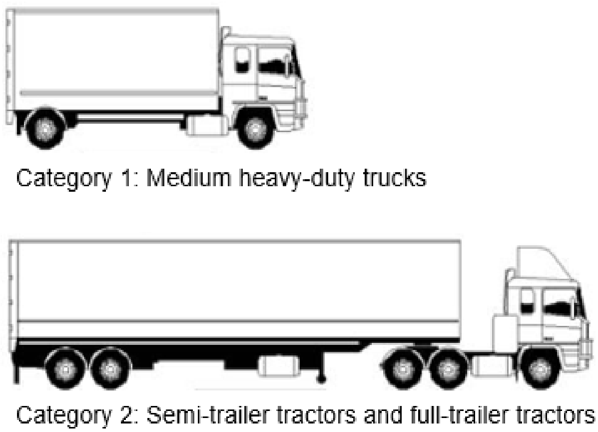

Figure 21: Vehicle categories in HDV Performance Evaluation.

Simulations extended to vehicle weights beyond 44,000 kg.

In the time frame covered by the Euro VI and US 2010 legislation several OEMs have introduced heavy-duty vehicle powertrains for alternative fuels. HDV Performance Evaluation included vehicles running with different type of fuels, conventional as well as alternative. Listed below are fuel options in both main categories:

- Category 1:
    - Diesel (EN590, Ultra Low Sulfur Diesel ULSD, Chilean commercial diesel fuel)
    - B20
- Category 2:
    - Diesel (ULSD, EN590)
    - HVO (EN15940)
    - CNG
    - LNG (HPDI dual-fuel and spark-ignition)
    - ED95

Biomethane was not used in the vehicle measurements. However, the assumption is that end-use performance, that is pollutant emissions such as NO_x, CH_4, PM and PN and efficiency, are the same for biomethane for vehicle use and fossil methane. The origin of methane (fossil or renewable) is taken into account in the WTW analysis.

Altogether, HDV Performance Evaluation measurement activities represented typical vehicles used in three different continents (Europe, North- and South-America). Vehicles used in the simulation activities represented typical vehicles used in Asia and Europe.

Key data (test setup and test procedures, vehicles and test fuels) for each participants is presented below. The texts originate from the individual participants and vary in the degree of detail and format of presentation. The ambition was that the participants should follow the jointly agreed test methodology as closely as possible.

Canada

General

The Canadian contribution to the AMF Annex 57 Test Program consists of an evaluation of exhaust emission and fuel consumption data from two diesel vehicles. A Class 7 and a Class 5 truck were tested both in-lab on a chassis dynamometer and on-road under real-world driving conditions using PEMS. According to the classification used in the HDV Performance Evaluation, both these vehicles fall into Category 1. The vehicles were tested with different loads, representing their respective unweighted (or empty) state, medium load, and high (or full) load.

In addition, the Class 7 vehicle was tested with a B20 fuel blend, which was included in this testing program to provide insights to the IEA on the HDV emission impacts of a regionally available alternative fuel. Furthermore, testing with B20 can deepen our own understanding of the expected impacts as the result of the implementation of Canada's Clean Fuel Standard, which incentivizes the use of a broad range of lower carbon fuels and alternative energy sources.

All testing was conducted at the Emissions Research and Measurement Section (ERMS) laboratories of Environment and Climate Change Canada (ECCC).

Test vehicles

The two test vehicles are recent model years and are outfitted with OEM emission control systems, including EGR, DOC, DPF and a SCR system. Both vehicles were tested with a US Certification diesel fuel.

Table 12 summarizes the characteristics of the vehicles used in Canada's test program.

Table 12: Characteristics of test vehicles (Canada).

	Class 7	Class 5
Model Year	2019	2018
Axle configuration	2x4	2x4
Engine Displacement (L)	7.7	6.7
Engine Configuration	Inline 6	V8
Engine Max Power (kW @ rpm)	280 kW @ 2200 rpm	246 kW @ 2600 rpm
Engine Max Torque (Nm @ RPM)	1355 Nm @ 1400 rpm	1017 Nm @ 1600 rpm
Transmission Type	Automatic	Automatic
GVWR (kg)	15,000	8,850
Vehicle Class	Heavy-Duty (Class 7)	Medium Heavy-Duty (Class 5)
Emission Controls[18]	DDI/TC/CAC/ECM/EGR/ DOC/PTOX/SCR-U/AMOX	TC/DFI/CAC/EGR/EGRC/DOC/ PTOX/ SCR-U/NOXS/UQS
Mileage (km)	5637	5055

Test fuels

The two test fuels used in this project were certification-grade Ultra Low Sulfur Diesel fuel (termed ULSD in this report) as well as a 20% by volume biodiesel blended fuel (B20). Test fuel characteristics are provided in
Table 13 below.

[18] DDI / DFI= direct diesel/fuel injection; TC = turbo charger ; CAC = charge air cooler ; ECM = engine control module ; EGR = exhaust gas recirculation; OC = oxidation catalyst ; PTOX = periodic trap oxidizer ; SCR-U = selective catalytic reduction - urea; AMOX = ammonia oxidation catalyst; EGRC = EGR cooler; NOXS = NOx Sensor ; UQS = urea quality sensor

Table 13: Test fuel characteristics (Canada).

	ULSD	B20
Specific gravity @ 60.0 F	0.857	0.860
Cetane number	41.5	46.6
Carbon content (% wt.)	87.4	84.9
Hydrogen content (% wt.)	12.6	13
Oxygen content (% wt.)	0.000	2.1
FAME (% vol.)	0	21
LHV (MJ/kg)	42.8	41.7

Test procedure and experimental matrix

For the in-lab testing portion of this program, the test vehicles were placed on a chassis dynamometer inside a temperature and humidity controlled test chamber. With the exhaust pipe connected to a Constant Volume Sampling system (CVS), the vehicle was driven on the chassis dynamometer rolls over the WHVC Test Cycle. The tailpipe exhaust from the vehicle was diluted with ambient air before being drawn through the CVS dilution tunnel, where a sample of that diluted exhaust was directed to an analyzer bench. The analyzer bench consists of several instruments for measuring exhaust components, including: carbon CO_2 and CO, which were measured using non dispersive infrared (NDIR) detection, NO_x measured using a chemiluminescent analyzer, and total hydrocarbons THC, which were measured using a flame ionization detector (FID). CH_4 was measured via gas chromatography (GC)-flame ionization detection (FID), and nitrous oxide (N_2O) was measured by GC with micro-electron capture detection. The PM emissions were collected with 47 mm filters according to the US Code of Federal Regulations, Section 1065 (CFR 1065) gravimetric method.

There were several important components of the vehicle setup for the on-road testing portion of this program. These included the PEMS instruments (i.e. the analytical instruments measuring tailpipe emissions); an external battery that delivered power to the PEMS equipment; an Exhaust Flow Meter (EFM) that provided real-time mass flow measurement; various heated sample lines that delivered the raw exhaust sample to the PEMS; and a GPS and Vaisala probe that recorded vehicle speed and environmental conditions.

PEMS equipment works by extracting raw exhaust samples from the tailpipe and supplying the gas into an analyzer bench. The instrument is used to measure emissions of CO, CO_2, NO, NO_2 and THC. Figure 22 displays the PEMS setup on the Class 5 HDV; a similar setup was incorporated for the Class 7 HDV and was placed inside the cargo compartment. For the on-road component of this program, the test consisted of a driving route that combines three different driving segments that are based on Act III of the European Union Real Drive Emissions (RDE) regulations outlined in Euro VI.

Table 14 summarizes the test matrix and number of test repeats for each test condition.

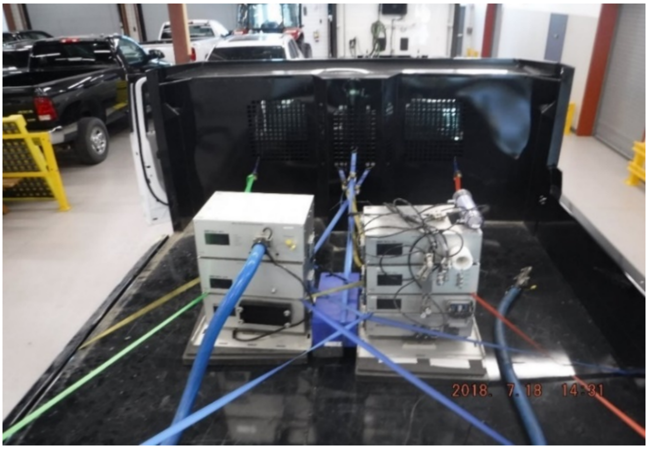

Figure 22: PEMS setup in the open cab of the Class 5 test vehicle for on-road testing.

Table 14: Experimental matrix (Canada).

Vehicle Loading	Fuel	Class 7 – Number of Repeats			Class 5 – Number of Repeats		
		WHVC Cold	WHVC Hot	RDE	WHVC Cold	WHVC Hot	RDE
Medium[19]	ULSD	2	2	-	2	2	-
	B20	1	1	-	-	-	-
High[20]	ULSD	2	2	3	1	1	-
	B20	-	-	3	-	-	-
Unloaded[21]	ULSD	2	2	2	-	-	2

Test cycle and route

The transient speed-time traces within the test sequences of both the WHVC and RDE cover a breadth of driving patterns one may expect to experience on-road, including more aggressive acceleration and stopping events and generally higher speeds than what is experienced in other traditional test cycles, such as the Federal Test Procedure (FTP-75). For reference, a kinematic comparison of the WHVC test cycle and a sample RDE driving trace is provided in Table 15. In addition to the innate variability of on-road test conditions, it should be noted that the two test vehicles likely have distinct performance characteristics when driven on the road. It should also be noted that the top speeds on the on-road testing part of this project were slightly under the EU's requirements for an RDE test.

Table 15: Comparison of test cycle/route kinematics.

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[19] Medium Load Test Weights: 10,902 kg (Class 7); 6,010 kg (Class 5)

[20] High Load Test Weights: 13,472 kg (Class 7 - WHVC); 12,279 kg (Class 7 – RDE); and 8,498 kg (Class 5)

[21] Unloaded Test Weights: 6,837 kg (Class 7); 4,357 kg (Class 5)

	WHVC				RDE [22]			
	Total Cycle	Phase 1	Phase 2	Phase 3	Total Route	Mode 1	Mode 2	Mode 3
Distance (km)	20.07	5.32	5.83	8.93	70.73	20.28	18.92	31.53
Avg speed (km/h)	40.12	21.26	43.6	76.69	51.64	37.16	46.74	75.23
Max speed (km/h)	87.81	66.22	75.91	87.81	104.01	63.03	82.99	104.01
Avg accel (m/s^2)	0.62	0.79	0.67	0.23	1.08	1.11	1.15	0.93
Max accel (m/s^2)	3.56	3.56	2.62	0.92	5.59	5.02	5.59	4.97

The speed versus time traces of a sample RDE test is shown below in Figure 23. The WHVC cold tests were conducted either as cold start tests (with preconditioning occurring 24 hours in advance) or as hot start tests. The WHVC hot start tests were conducted out of specification for the prescribed procedures for a WHVC hot-start test; this was due to an added time delay caused by additional modal analysis in the test cell. As such, the engine and emission controls were likely at a lower temperature than if the vehicle was tested with the defined soak period, which was shorter in duration. The RDE tests were run exclusively as cold start tests.

[22] The RDE Route used in this study is slightly different than the specified distance and speed requirements described in the EURO VI on-road testing procedures for HDVs.

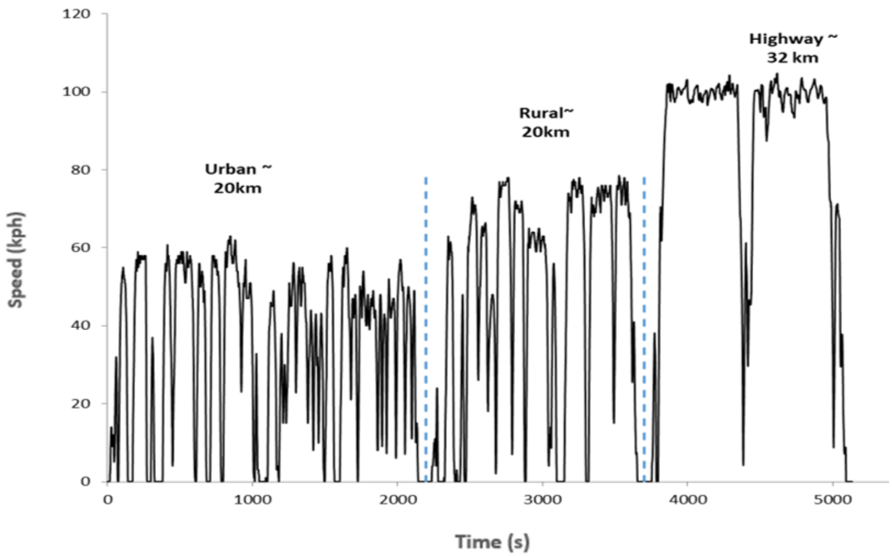

Figure 23: Sample speed versus time trace of the RDE route.

Chile

General

The Chilean contribution to the AMF Annex 57 Test Program consists of an evaluation of exhaust emissions and fuel consumption of three Category 1 diesel trucks, all of them tested in the Heavy-Duty Emission Laboratory of the Vehicle Control and Certification Center (3CV). Figure 24 presents a general view of the chassis dynamometer test facility at 3CV.

Figure 24: View of the 3CV test facility.

Test vehicles

All vehicles are model year 2020, Euro V compliant (which is the current Chilean requirement for trucks) and fitted with OEM emission control systems, e.g., EGR, DOC, SCR and DPFdium (50%) and high load (70%).

Table 16 presents data for the vehicles, all equipped with manual 5-speed gearboxes. Note the high curb weight of Truck A. The vehicles were tested with different loads representing medium (50%) and high load (70%).

Table 16: Characteristics of test vehicles (Chile).

ID	Engine	Curb mass (kg)	GVW (kg)	Load capacity (kg)	Test weight 50% load (kg)	Test weight 70% load (kg)
Truck A	CI, 3 L, SCR	3.635	6.500	2.865	5.067	5.640
Truck B	CI, 3 L, SCR	2.355	6.500	4.145	4.427	5.256
Truck C	CI 4 L, SCR	2.950	9.000	6.050	5.975	7.185
Common features: Euro V, diesel, rigid 4x2 configuration, 5 speed manual transmission						

Test fuels

The measurements were made using commercial diesel fuel, according to Chilean specifications, summarized in Table 17.

Table 17: Chilean diesel fuel specification.

Commercial Chilean diesel fuel	LHV (MJ/kg)	Density (kg/l)	Flash point (ºC)	Distillation 90% recovered (ºC)
	45.635	0.839	55 - 57	337 - 341

Test procedure and experimental matrix

The measurements were carried out by operating the vehicles on the chassis dynamometer, following the WHVC driving cycle.

Fuel consumption was measured gravimetrically, using an auxiliary tank on a scale (Figure 25). PM emissions were measured gravimetrically as well, drawing a diluted exhaust sample from the CVS system through a paper filter.

Figure 25: Equipment for measuring fuel consumption gravimetrically.

Tests were carried out on three medium-duty trucks for urban distribution, with a load capacity of 2.8, 4 and 6 tons, respectively (Table 16). For each truck, the measurement program was carried out with 50% and 70% load, performing both cold and hot start tests.

Finland

General

For AMF Annex 57, Finland provided chassis dynamometer, on-road and simulation data. VTT tested in total 6 heavy-duty trucks, all of them on the chassis dynamometer and 3 vehicles also on the road. Listed below are the categories of tested vehicles:

- Chassis dynamometer:
  - One Category 2 heavy-duty full-trailer tractor
    - Euro VI Step C
  - Five Category 2 heavy-duty semi-trailer tractors
    - Two Euro VI Step C
    - Three Euro VI Step D
- On-road:
  - Three Category 2 semi-trailer combination with 42 tons GVW
    - One Euro VI Step C
    - Two Euro VI Step D
- Simulation:
  - 3 HCT full-trailer combinations with up to 92 tons GVW

Three vehicles were tested on two fuels, two diesel vehicles on regular diesel and paraffinic renewable diesel HVO and one methane vehicle on pump grade compressed natural gas (CNG) and low methane number (MN) CNG.

All actual vehicle testing as well as the simulations were carried out by VTT.

Test vehicles

For AMF Annex 57, VTT in practice tested all fuel/technology options currently available in Finland for heavy-duty trucks on the chassis dynamometer. In addition to the traditional diesel engine powertrains (two of these were tested) there are also two alternative powertrains utilizing compression ignition available, namely the ED95 ethanol-diesel concept running on additive treated ethanol and the high-pressure direct injection (HPDI) dual-fuel technology for LNG. In addition, also two trucks equipped with spark-ignited methane engines were tested, one fueled with CNG and one with LNG.

Table 18 presents data for the vehicles tested at VTT. All the trucks tested at VTT were Annex 57 Category 2/EU Category N3 vehicles with a power of more than 400 hp and suitable to be used as semi- or full-trailer tractors.

Two of the vehicles, namely a diesel truck ("C") and a HPDI LNG truck ("D") from the same manufacturer, both with Euro VI Step D emission certification, were tested both in Finland and in Sweden, thereby providing information on the variability of results measured in different laboratories.

Test fuels

The two diesel trucks were tested on regular EN590 diesel fuel as well as on paraffinic renewable diesel (HVO) fulfilling the EN15940 standard. In the case of the methane vehicles, pump quality CNG or LNG was used, which in the case of Finland means a methane content of 95% or more. The spark-ignited CNG truck (Code A) was also tested on a low methane number (70) gas specifically delivered for testing purposes. The purpose of this was to mimic enrichment of higher hydrocarbons taking place in LNG due to methane boil-off, and to check how this affect vehicle performance. The testing had to be done with compressed gas, as there was no possibility to get special quality LNG. The ED95 truck was tested on pump quality ED95 (additive treated hydrous ethanol). Table 19 shows the main properties of fuels used in testing.

Table 18: Characteristics of test vehicles (Finland).

Id	Emission class	Chassis	Engine and EAT	Fuel	Transmission	Curb mass [kg]
Truck A	Euro VI Step C	Tractor 4x2	SI 13 L, 302 kW EGR+TWC	CNG	Automatic / Robot	8540
Truck B	Euro VI Step C	Tractor 6x2	SI 13 L, 338 kW TWC	LNG	Automatic / Robot	8257
Truck C*	Euro VI Step D	Tractor 4x2	CI 13 L, 345 kW EGR+DOC+ DPF+SCR	Diesel	Automatic / Robot	8100
Truck D*	Euro VI Step D	Tractor 4x2	CI HPDI dual-fuel 13 L, 345 kW EGR+DOC+ DPF+SCR	LNG-diesel	Automatic / Robot	8900
Truck E	Euro VI Step C	Rigid 6x2	CI 13 L, 302 kW EGR+DOC+ DPF+SCR	ED95	Automatic / Robot	9090
Truck F	Euro VI Step D	Tractor 4x2	CI 11 L, 315 kW EGR+DOC+ DPF+SCR	Diesel	Automatic / Robot	7202
Truck G**	Euro VI S Step D	Rigid 6x2	CI 13 L, 345 kW EGR+DOC+ DPF+SCR	Diesel	Automatic / Robot	-
Truck H**	Euro VI Step C	Rigid 6x2	CI HPDI dual-fuel 13 L, 345 kW EGR+DOC+ DPF+SCR	LNG-diesel	Automatic / Robot	-

* Vehicles tested also in Sweden

** In-service NO_x monitoring only

Table 19: Test fuel characteristics (Finland).

Fuel	LHV	Density	CHO m-%	Other
Pump CNG	49.1 MJ/kg	-	-	Methane number approx. 90, (CH_4: ~96.8 mol-%, C_2H_6: ~1.8 mol-%, C_3H_8: ~0.4 mol-%, N_2: 0.7 mol-%) Avg. values of grid gas
Low methane number (MN) CNG	49.5 MJ/kg	-	-	Methane number approx. 77, (CH_4: 94 mol-% and C_3H_8: 6 mol-%)
Pump LNG	49.7 MJ/kg (Truck B) 49.8 MJ/kg (Truck D)	-	-	CH_4: ~95 mol-%, C_2H_6: ~5.3 mol-%, C_3H_8: ~0.4 mol-%
EN590 diesel	43.0 MJ/kg	835 kg/m^3	H: 13.6 m-%, C: 86.4 m-%	Cetane index 54.5
EN15940 HVO	43.8 MJ/kg	780 kg/m^3	H: 14.6 m-%, C: 85.4 m-%	Cetane index 82.8
ED95	24.5* MJ/kg	828 kg/m^3	-	Hydrous ethanol content ~95 Vol% (incl. ~5 wt% H_2O) ~5 Vol% ignition improver, lubricant and other volatiles

*Average value of two different samples analyzed October 2019 and April 2020. LHV of ED95 can vary by estimation 24.1…25.0 MJ/kg depending on water content.

Test procedure and experimental matrix

VTT's heavy-duty chassis dynamometer is capable of simulating the inertia weight and road loads that buses and trucks are subjected to during normal on-road operation. The machine is 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 of GVW. Maximum absorbed power (continuous) is 300 kW at the driven wheels. For emission measurements VTT uses full-flow CVS dilution system. The analytical equipment (Pierburg CVS-120-WT CVS and analyzer set AVL AMA i60) is compliant with Directive 1999/96/EC. The analytical equipment was renewed in 2018.

For transient-type measurements of heavy-duty vehicles on a chassis dynamometer, VTT developed its own in-house method covering both emission and fuel consumption measurements. The method is partly based on SAE J2711[23], partly on the European Directive 1999/96/EC[24] on emission measurements. In June 2003, FINAS, the Finnish Accreditation Service, granted accreditation for the method of VTT (T259, In-house method, VTT code MK02E).

The same dynamometer settings, i.e. road load coefficients and test inertias were used for all the trucks. This ensured as similar as possible loading for the engines in the test cycles, with the aim to focus on differences in engine performance. All trucks were equipped with automated mechanic gearboxes. It was, however, not possible to compensate for differences in transmission and rear axle gear ratios.

In addition to the commonly agreed test program including cold start WHVC and hot start WHVC with test inertia corresponding to half payload, VTT also performed some additional tests:

- WHVC hot start cycle with an inertia of 30 tons
- WHVC hot start cycle with an inertia of 44 tons
- Test with a cycle simulating long-haul operations called HDVPerE, with an inertia of 30 tons inertia (shown in Figure 26)

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23 https://www.sae.org/standards/content/j2711_200209/

24 https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2000:044:0001:0155:EN:PDF

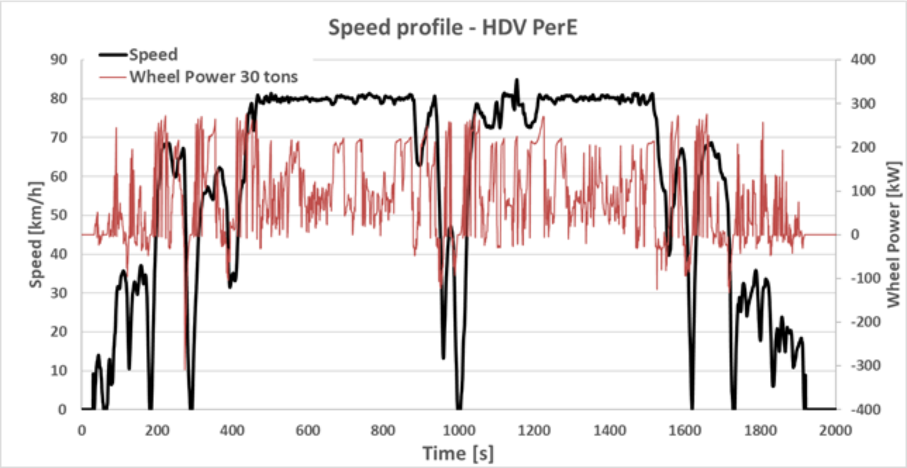

Figure 26: VTT's HDVPerE test cycle.

The HDVPerE is based on an actual route in Espoo, close to VTT's location. The motivation to run the test cycle simulating long-haul driving was to provide information on performance in typical long-haul conditions and to replicate the on-road measurement route as closely as possible on the chassis dynamometer, with the aim of comparing the differences of on-road and chassis dynamometer test methods. The road gradient was also taken into account when the cycle was transferred to the chassis dyno.

For the baseline chassis dynamometer measurements, VTT followed the commonly agreed chassis dynamometer test procedure, that is aggregated WHVC test (cold and hot) with approximately 50 % load. Each test involving cold testing was in principle repeated twice. Hot start cycles, whether WHVC or VTT's additional HDVPerE, were performed in a sequence of three consecutive cycles with a break of approximately 10 minutes in between for reading of sample bags.

Results for energy consumption and CO_2 emissions are based on hot testing and results for full test cycles (in most cases average of three measurements). However, in the case of WHCV, also some modal data is presented.

In the case of pollutant emissions, cold, hot and aggregated results are presented.

For trucks A (CNG), C (diesel), the diesel part of truck D (HPDI dual-fuel), E (ED95) and F (diesel), energy consumption is based on gravimetric metering of fuel consumption. In the case of truck A, a special setup with a pressure vessel on a scale was used. For the LNG trucks B and D, energy consumption is calculated from measured CO_2 emission. For truck B, 55.1 g CO_2/MJ is used for carbon intensity.

From carbon balance of the exhaust and the measured diesel consumption it was concluded that the share of diesel (energy) in HPDI truck D is on an average 8 %. In calculating total energy consumption for this vehicle, based on CO_2, a carbon intensity of 56.5 g CO_2/MJ is assumed. The contribution of AdBlue (urea) to CO_2 emissions was considered negligible.

In VTT's calculations of CO_{2eqv} emissions, CH_4 emissions are taken into account with a factor on 25 and N_2O with a factor of 298 relative to CO_2.

VTT used AVL M.O.V.E PEMS equipment for the on-road measurements. The instruments used were:

- AVL M.O.V.E GAS PEMS 492 (iS)
- AVL 496 PN-PEMS
- AVL M.O.V.E PM PEMS 494
- Sensors EFM-495 4" (Diesel and LNG vehicle)

Figure 27 shows the PEMS device installation and the semi-trailer used in the measurements. The PEMS device was installed inside the truck cabin. For the exhaust flow meter (EFM) and measurement probe an extension was installed at the end of the original exhaust pipe. Battery packs were used as energy source for the PEMS device.

Figure 27: PEMS device installation and semi-trailer used for the on-road measurements.

The three-axle trailer of common design was loaded to approximately 55 % of the full loading capacity. Depending of the truck the actual vehicle combination mass was 30 - 31 tons. Table 20 presents a summary of the test matrix at VTT.

Table 20: Experimental matrix (Finland).

	Chassis WHVC Cold (C)/ hot (H) start	Chassis HDVPerE Hot	PEMS Cold (C)/ hot (H) start	NO_x monitoring	Fuels
Truck A	30 ton C + H 44 ton H	30 t	-	-	Reg. CNG, Low MN CNG
Truck B	30 ton C + H 44 ton H	30 t	ISC (C) app. 30 tons HDVPerE (H) app. 30 tons	Yes	LNG
Truck C	30 ton C + H 44 ton H	30 t	ISC (C) app. 30 tons HDVPerE (H) app. 30 tons	-	EN590, HVO
Truck D	30 ton C + H 44 ton H	30 t	ISC (C) app. 30 tons HDVPerE (H) app. 30 tons	-	LNG/EN590
Truck E	30 ton C + H 44 ton H	30 t	-	-	ED95
Truck F	30 ton C + H 44 ton H	30 t	-	-	EN590, HVO
Truck G	-	-	-	Yes	EN590
Truck H	-	-	-	Yes	LNG/EN590

For continuous follow-up of NO_x performance, VTT installed monitoring system in three vehicles, the SI LNG truck (B), one diesel truck (G, corresponding to truck C) and one HPDI dual-fuel truck (H, corresponding to truck D). The ambition was to carry out a monitoring period of approximately one year for each truck. The used system was Proventia PROCARE Drive[25]. The Proventia PROCARE Drive system utilizes the following sensors:

- Commercial NO_x sensors designed for measuring diesel engine exhaust NO_x concentration [ppm], to be mounted up- and downstream the exhaust after-treatment device
- Temperature and pressure sensors upstream the exhaust after-treatment device
- GPS device for determination of location and speed

The system incorporates a data logger system, and all collected data is automatically transferred to customer-specific cloud storage, where data can easily be exported for reporting.

The PROCARE Drive system was originally developed for diesel engine exhaust NO_x concentration monitoring, and the it was successfully used in recent research project (Söderena et al., 2020) for estimating the NO_x emissions of diesel passenger cars. The project verified that the commercial NO_x sensor is adequate for diesel engine NO_x monitoring purposes.

Annex 57 also encompasses methane fueled trucks, both SI and HPDI dual-fuel technology. It was of interest to study the applicability of the PROCARE Drive technology for these trucks, as exhaust composition for methane engines differs from that of diesel engines (different NO to NO_2 ratio, some methane slip, higher concentration of water vapor, and in the case of SI methane (stoichiometric) no excess oxygen).

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25 https://www.proventia.com/

Sweden

General

Sweden provided chassis dynamometer and on-road data. Listed below are the categories of the tested vehicles:

- Two Category 1 heavy-duty rigid trucks
  - Euro VI Step C
- Four Category 2 heavy-duty semi-trailer tractors
  - Two Euro VI Step C
  - Two Euro VI Step D

The testing of all vehicles was carried out by AVL MTC (Sweden) on commission by STA. The results are presented in three separate reports made available to the HDV Performance Evaluation project:

- Test Report OMT 6003: Comparison of energy efficiency, CO_2- and regulated emissions on a CNG truck vs a diesel truck (the Category 1 vehicles)
- AVL MTC 2020/01: Emission effects from LNG –Heavy-duty vehicles (Euro VI Step C, Category 2 vehicles)
- AVL MTC 2020/10: Emission effects from LNG –Heavy-duty vehicles (Euro VI Step D, Category 2 vehicles)

Test vehicles

In both vehicle categories, 1 and 2, diesel vehicles constitute the reference, which are then compared to corresponding alternative fuel vehicles. The two Category 1 vehicles are both from one manufacturer, and the four Category 2 vehicles are all from another manufacturer. In Category 1, the alternative is methane (CNG) with spark-ignition and stoichiometric combustion. In Category 2 the alternative is liquefied methane (LNG) with HPDI dual-fuel technology.

The Category 2 vehicles form two pairs for comparison, diesel and HPDI dual-fuel with Euro VI Step C certification, and diesel and HPDI dual-fuel with Euro VI Step D certification, respectively. This gives insight to the changes in performance with evolving emission classification in general, but should also demonstrate whether the difference between diesel and HPDI dual-fuel changes when emission requirements evolve.

As mentioned previously, the two “Step D” vehicles were also tested by VTT in Finland.

Table 21 presents data for the vehicles tested in Sweden.

Table 21: Characteristics of test vehicles (Sweden).

Id	Emission class	Chassis	Engine and EAT	Fuel	Transmission	Curb mass [kg]
Truck	Euro VI Step C	Rigid 4x2 (refuse)	CI 9 L, 206 kW EGR+DOC+ DPF+SCR	Diesel	Automatic	11950
Truck	Euro VI Step C	Rigid 4x2 (delivery)	SI 9 L, 206 kW EGR + TWC	CNG	Automatic	9895
Truck	Euro VI Step C	Tractor 4x2	CI 13 L, 375 kW EGR+DOC+ DPF+SCR	Diesel	Automatic / Robot	9200
Truck	Euro VI Step C	Tractor 4x2	CI HPDI dual-fuel 13 L, 345 kW EGR+DOC+ DPF+SCR	LNG-diesel	Automatic / Robot	9955
Truck	Euro VI Step D	Tractor 4x2	CI 13 L, 345 kW EGR+DOC+ DPF+SCR	Diesel	Automatic / Robot	8100
Truck	Euro VI Step D	Tractor 4x2	CI HPDI dual-fuel 13 L, 345 kW EGR+DOC+ DPF+SCR	LNG-diesel	Automatic / Robot	8900

Test fuels

The diesel fuel used in the testing was Swedish Environmental Class 1 (MK1) diesel fuel (B7). MK1 diesel has lower content of aromatics and polyaromatics and lower density compared with typical European diesel fuel. Table 22 presents characteristics of the diesel fuel used by AVL.

Table 22: Diesel fuel characteristics (Sweden).

Fuel property	Unit	Result
Cetane number	-	57
Density @ 15ºC	kg/m^3	820
Sulphur	mg/kg	<5
Aromatics	vol.-%	5
FAME	vol.-%	6.4
Net heat of combustion	MJ/kg	42.64
Carbon content	kg C/kg fuel	85.66

The CNG and LNG used in the testing were commercially available qualities. Table 23 presents approximate composition of the CNG fuel. AVL did not report data on LNG composition.

Table 23: Approximate CNG composition (Sweden).

Fuel property	Unit	Result
Methane content	vol.-%	>97
Density @ 15ºC/1013.25 mbar	kg/Nm^3	0.715
Net heat of combustion	MJ/kg	~49.5
Carbon content	kg C/kg fuel	~0.75

The same fuels were used both for chassis dynamometer and on-road tests.

Test procedure and experimental matrix

The chassis dynamometer used by AVL is a twin-roller cradle dynamometer with 515 mm roller diameter. The maximum permitted axle load is 13 000 kg. Vehicle inertia is simulated by a change in flywheel weight 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 with 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 on the test cell computer for engine monitoring and for the measurement and collection of all data emanating from the vehicle, emission measurement system and test cell.

On the chassis dynamometer, the vehicles were driven according to the WHVC test cycle, with cold and hot start, as defined in the common test protocol.

AVL's laboratory is equipped with a full flow dilution system, i.e. the total exhaust is diluted using the CVS (Constant Volume Sampling) concept. 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. The particles are collected on Teflon-coated Pallflex™ filters and measured gravimetrically. The sampling of particle matter is in accordance with Directive 2005/55/EEC.

In addition to particle mass, AVL measured particle numbers (requirement for Euro VI) as well as particle size distribution. For particle numbers, a Condensation Particle Counter (CPC) instrument with a size range of 23nm to 2.5µm was used.

An Electrical Low Pressure Impactor (ELPI) was used for particle size distribution. In an impactor, the particles are classified according to their aerodynamic diameter. The ELPI impactor has 12 stages ranging from 7 nm to 10 µ.

For measuring gaseous regulated emissions and CO2, AVL MTC started with measuring diluted exhaust (Category 1 vehicles), but as of 2019, gradually moved to measuring raw exhaust gas (Category 2 vehicles).

In the first case, the equipment used for analyzing the gaseous regulated emissions consisted of double Horiba 9400D systems, with the possibility to measure both diluted and raw exhaust emissions on-line simultaneously. The sampling system fulfilled the requirements of Regulation (EU) 582/2011 in terms of sampling probes and heated lines etc.

In the latter case the sampling- and analyzing equipment are based on raw sampling systems, i.e. the exhaust is sampled from undiluted exhaust. In this case the equipment used for analyzing the gaseous regulated emissions consist of double Horiba MEXA 7000 systems plus EGR rate calculation module. Hereby exists the possibility to measure both tail pipe and engine out exhaust emissions on-line simultaneously. Also in this case the sampling system fulfils the requirements of Regulation (EU) 582/2011.

Measurement of nitrogen oxide (NO), nitrogen dioxide (NO_2) and CH_4 was made with a FTIR (Fourier Transform Infrared Spectroscopy) instrument.

For the on-road measurements, AVL MTC used PEMS equipment, AVL M.O.V.E, from the Austrian mother company. The instruments used were:

- Category 1 (Figure 28):
  - AVL M.O.V.E GAS PEMS 493
  - AVL M.O.V.E PM PEMS 494
    - Sensors EFM-HS 5” (Diesel vehicle)
    - Sensors EFM-HS 4” (CNG vehicle)

- Category 2:
  - AVL M.O.V.E 493 iX Gas PEMS
  - AVL 496 PN-PEMS
  - AVL 495 EFM, 5”, exhaust flow meter

In the case of the Category 2 trucks, the PEMS system was conveniently located inside a special semi-trailer used in the measurements (Figure 29).

Figure 28: AVL M.O.V.E PEMS system.

Figure 29: Special semi-trailer used by AVL MTC for on-road PEMS measurements.

On-road testing was performed using Step C+ and Step D routes developed by AVL. The routes have been developed to meet the requirements of EURO VI legislation for heavy-duty vehicles. The nominal trip shares can be seen in Table 24.

Table 24: Trip shares and target speeds for ISC/PEMS testing for EU class N3 vehicles (see also Table 9.

	Urban (0-50 km/h)	Rural (50-70 km/h)	Motorway (>75 km/h)
Euro VI Step C+ trip shares [% time] Tolerance: +5%	20	25	55
Euro VI Step D trip shares [% time] Tolerance: +5%	30	25	45

The two Category 1 vehicles, despite a difference in curb weight of more than 2000 kg, were tested using the same inertia (14 026 kg) and dynamometer settings on the chassis dynamometer. In the on-road measurements, total vehicle weight was 14 100 kg for both vehicles.

In the chassis dynamometer, all four Category 2 trucks were measured using the same inertia, 20 354 kg, which is close to the weight of the unladen semi-trailer combination.

In the on-road testing, the combinations were loaded to 55 % of maximum payload, resulting in a total weight of some 30 000 – 32 000 kg. In addition, the Step C HPDI truck was also tested with 10 % load.

Table 25 summarizes the Swedish test matrix.

Table 25: Experimental matrix (Sweden).

	Chassis WHVC Cold/hot	PEMS
Category 1 diesel	14 026 kg	14 100 kg
Category 1 CNG	14 026 kg	14 100 kg
Category 2 diesel Step C	20 354 kg	32 200 kg
Category 2 HPDI LNG Step C	20 354 kg	23 560/32 160 kg
Category 2 diesel Step D	20 354 kg	30 420 kg
Category 2 HPDI LNG Step D	20 354 kg	32 200 kg

Simulation program

General

To widen the evaluation methods beyond traditional chassis dynamometer and on-road measurement programs, simulation tools and simulations were included in the work program of Annex 57. Especially considering future technologies simulation tools provide an important way for analyses for new possible technologies.

Annex 57 includes two types of simulation (carried out by AMF participants):

1. Simulation tool developed by VTT for the assessment of fuel consumption and CO_2 emissions for High Capacity Transport (HCT) combined vehicles with varying axle configurations and masses
2. Simulation tool (Heavy-duty vehicle Emission Simulator, HES) generated by the Government of Korea for the estimation of fuel consumption of heavy-duty vehicles

Thus the main objectives in simulation activities are:

1. Investigate the potential of HCT combinations for fuel consumption and CO_2 emission reductions
2. To present a method developed in Korea for fuel consumption evaluation of heavy-duty vehicles of various configurations as a part of the type approval process

In addition, simulation activities are carried out in cooperation with HEV TCP, as mentioned previously. This joint exercise will be presented in a separate Chapter.

Finland

In the Finnish part of the simulation activities, computer simulation is used to study the effects of gross vehicle weight on fuel consumption. The studied vehicle combination is a high capacity transport unit (Figure 30[26]), which consists of a three-axle tandem driven tractor, a three-axle semitrailer, and a five- axle full trailer. The trailers are equipped with twin tires, except the last axle of the semitrailer and the last axle of the full trailer, which are steering axles with single tires. The total length of the vehicle combination is 32 meters, the maximum gross weight 88 tons and the curb weight around 37 tons. The height of the trailers is 4.4 meters, and the volume of the box body over 200 m^3.

Figure 30: Studied vehicle combination (picture from Eero Sjögren/Veho).

The simulation model consists of model blocks for the diesel engine, gearbox and the drivetrain, and a longitudinal dynamic model of the heavy-duty truck and trailer combination. The input to the simulation model is the reference speed of the vehicle and the slope of the road. The simulation model has a controller to model the driver's actions on

[26] Eero Sjögren Oy

the accelerator pedal position and brake pedal position in order to meet the requested vehicle speed. Another controller is defined to control the gearbox model. As an output, the simulation model defines the momentary engine torque, speed, and fuel rate based on the engine fuel consumption map for each time step. The driving resistances are based on a coast-down measurement done with a vehicle combination, which has a similar tractor unit and the same general configuration of the vehicle combination, but different dimensions for the trailers. The coast-down tests are done with loaded vehicle combination on dry asphalt.

The simulation model is validated using measured data gathered from the actual vehicle in operation. Data collected from the vehicle CAN bus and the GPS device. Figure 31 shows a validation plot for the simulation.

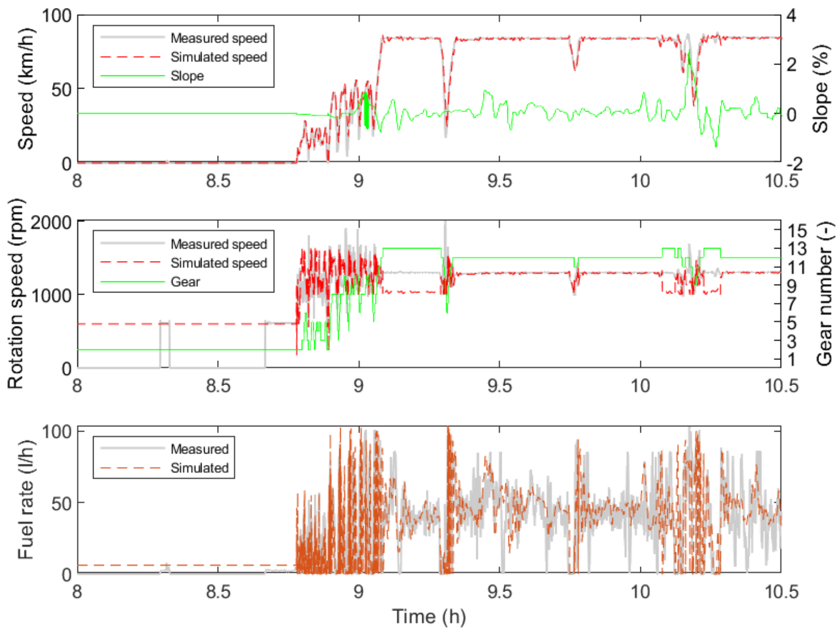


Figure 31: Measured and simulated values for the simulation model validation: vehicle speed, engine speed and fuel rate.

The first plot shows the measured vehicle speed, which is used as a reference in the simulation model, the simulated vehicle speed, and the slope of the road taken from the map data. The second plot shows measured and simulated engine load, and the third plot measured and simulated fuel rate.

Korea

Korea contributed with information on development and deployment of the **H**eavy-duty vehicle **E**mission **S**imulator (HES). The HES tool has been developed in the C# language as an executable file, and was developed by the National Institute of Environmental Research in Ministry of Environment Korea. During the development process, HES has been issued four times, with the latest version (v 1.09, 4th) launched in September of 2020. Figure 32 shows the development schedule of the HES tool.

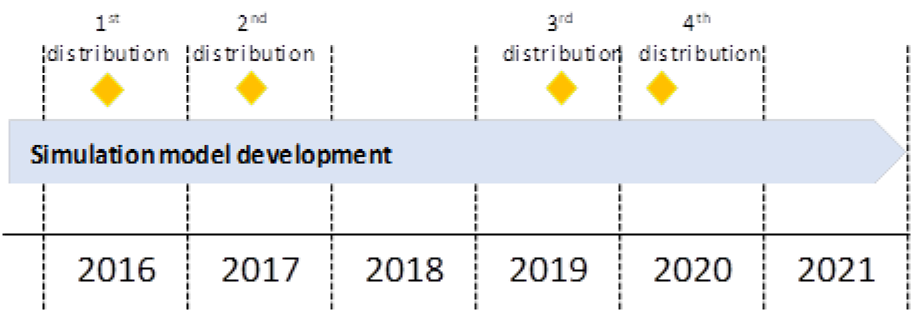


Figure 32: Development schedule of HES tool.

HES is based on longitudinal vehicle dynamics and composed of five components as follows:

- **Pre-processor module:** reading input data (vehicle specifications and velocity profile)
- **Chassis module:** calculating total resistance force acting on vehicle
- **Transmission module:** predicting gear position at each time step based on engine operating condition
- **Engine module:** determining engine torque & speed at each time step
- **CO_2 emission module:** predicting CO_2 emission based on fuel map & CO_2 emission factor of fuel

Figure 33 shows calculation flow and the main blocks of the model. Specific calculation methods for each model blocks and loading elements can be found in Appendix A.

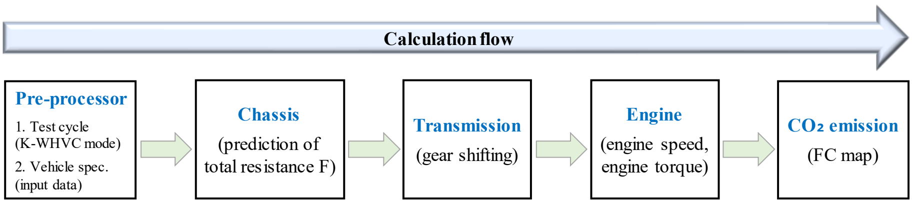


Figure 33: Calculation flow of HES model.

In 2019, the HES graphical user interface allowing the user to run HES without any installation process after downloading was launched. Figure 34 shows an example of the user interface, allowing adjustment of vehicle data. Figure 35 shows an example of simulation results.

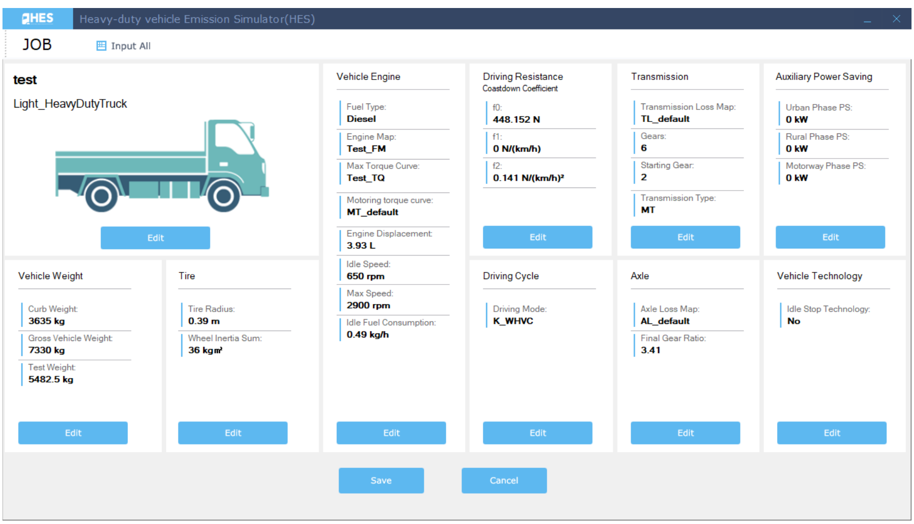
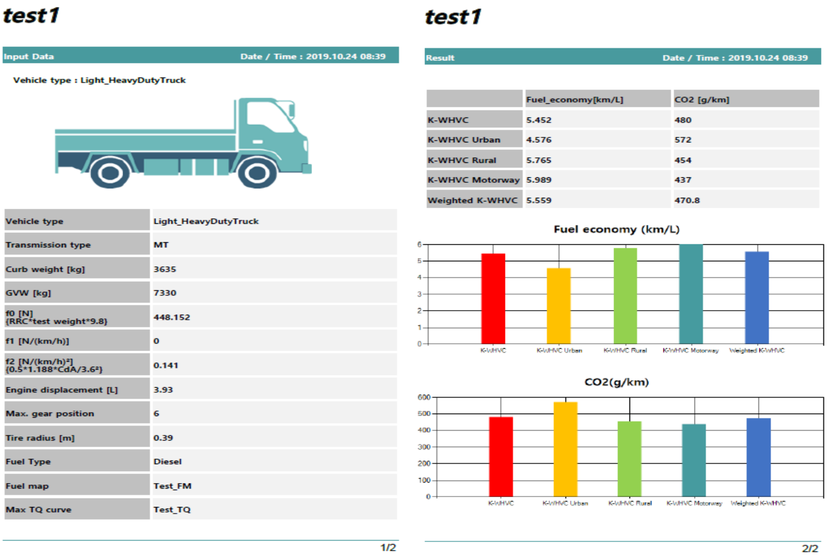


Figure 34: Example of HES user interface for adding the corresponding vehicle data.



test1

Input Data	Date / Time : 2019.10.24 08:39

Vehicle type : Light_HeavyDutyTruck

Vehicle type	Light_HeavyDutyTruck
Transmission type	MT
Curb weight [kg]	3635
GVW [kg]	7330
f0 [N] {RRC*test weight*9.8}	448.152
f1 [N/(km/h)]	0
f2 [N/(km/h)²] {0.5*1.188*CdA/3.6²}	0.141
Engine displacement [L]	3.93
Max. gear position	6
Tire radius [m]	0.39
Fuel Type	Diesel
Fuel map	Test_FM
Max TQ curve	Test_TQ

1/2

test1

Result	Date / Time : 2019.10.24 08:39

	Fuel_economy[km/L]	CO2 [g/km]
K-WHVC	5.452	480
K-WHVC Urban	4.576	572
K-WHVC Rural	5.765	454
K-WHVC Motorway	5.989	437
Weighted K-WHVC	5.559	470.8

2/2

Figure 35: Example of HES simulation result.

Results and discussion – actual vehicle testing

General

In this section, results of individual partners and as well as collated results are presented. **The extent of the data varies from partner to partner. In some cases, when presenting results from individual partners, the project coordinators have added figures based on the data supplied by the partners.** In some cases, the complete data sets are provided in appendices (e.g., hot and cold start WHVC, data by test phase, unregulated components etc.).

In the main body of this report the input from the partners is on the whole presented in the following manner:

- Results
    - Energy consumption
    - Greenhouse gas emissions
    - Pollutant emissions
- Discussion (provided by the partners)

The energy consumption and GHG emission values from chassis dynamometer testing presented in the graphs are in most cases based on measurements with fully warmed-up engines, reflecting typical operation of heavy-duty trucks. A cold WHVC gives some 5 % higher fuel consumption compared to a hot WHVC test.

Pollutant emissions, on the other hand, are shown for cold as well as hot testing (cold vs hot start) as temperature has a much higher impact on pollutant emissions than on fuel consumption. In some cases, weighted results are also shown[27].

[27] In Europe, weight factors in engine WHTC certification are 14% for cold start and 86% for hot start.

Energy consumption and GHG values are in most cases shown relative to driven distance, while pollutant emission values are either shown relative to driven distance or relative to work (work on the chassis dynamometer roller, alternatively work on the engine crankshaft). For vehicles equipped with robotized mechanical gearboxes, power transmission and auxiliary losses are estimated at some 15%, for vehicles with traditional automated transmissions at some 25%. In RDE testing, the values directly relate to work at the engine crankshaft.

For energy consumption, both absolute values (MJ/km) and values relative to vehicle test weight (MJ/km/1000 kg vehicle weight) are presented. The latter approach makes comparison of vehicles of different weight possible.

However, trucks are meant to carry loads, so the ultimate assessment would be to calculate energy consumption in MJ/ton-km of load carried or per ton of load capacity. Figure 36 from the "COMVEC" project shows how payload affects specific energy consumption (in MJ/km/1000 kg of payload weight). With zero payload, the value would be infinitely high.

It should be noted that it is challenging to exactly replicate true driving conditions (road loads) on the chassis dynamometer. Therefore the reported distance-related values should be considered approximate as the dynamometer settings may vary from laboratory to laboratory. Values related to actual work at the driving wheels, on the other hand, have better comparability.

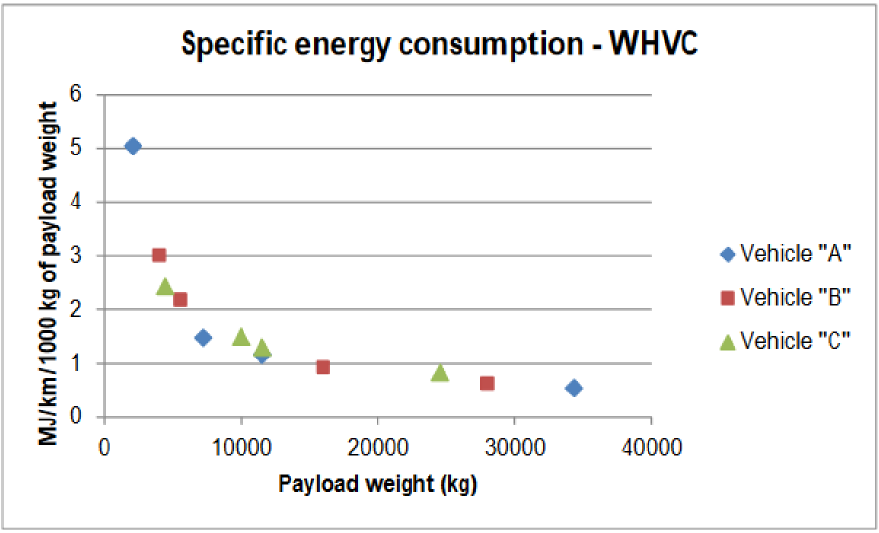


Figure 36: The effect of load on specific energy consumption (MJ/1000 kg of payload) for heavy-duty trailer combinations. Source "COMVEC".

The collated results combine the data from WHVC and on-road measurement according to Euro VI ISC regulation. Although the project partners agreed on a common test protocol, for practical reasons, there are some variations in procedures from laboratory to laboratory.

Collated results are presented in following way:

- Energy consumption with different fuel options
- Emissions with different fuel options
- WTW emissions of different fuel options

Canada

General

The Canadian section presents energy consumption and emission data for two diesel trucks, one Class 5 and one Class 7 truck, both falling into Category 1 for the current project.

The complete data sets (tables) are presented in Appendix B. The tables display the average emission rates and measurements of fuel consumption from the test repeats for each fuel, start type, and payload combination over the WHVC and RDE. Due to the limited number of repeat tests, determinations of statistically significant changes are not presented. Emission results that were at concentrations below the method quantification limit are denoted in the tables as *MQL*.

Figures relative to work relate to work at the engine crankshaft.

Energy consumption and CO_2 emissions

Figure 37 and Figure 38 show chassis dynamometer WHVC energy consumption (EC) for the two trucks expressed in MJ/km and MJ/km/1000 kg of vehicle weight. Values are for hot engines and ULSD diesel.

The Class 7 truck was tested with both ULSD and B20 on medium load. In the WHVC, B20 increased energy consumption 2 - 3.5% and volumetric fuel consumption 1.5 – 3% compared to ULSD.

When tested on road (RDE), the energy consumption of the unladen Class 5 truck was 7.5 MJ/km and 1.7 MJ/km/1000 kg of vehicle weight, respectively (aggregated values).

Figure 39 shows RDE energy consumption data for the Class 7 truck (ULSD fuel). In the RDE testing, B20 resulted in 0.5 – 2.5% higher volumetric fuel consumption and 1 – 3% higher energy consumption compared to ULSD, slightly lower values compared to WHVC in the chassis dynamometer.

Figure 40 (Class 5) and Figure 41 (Class 7) show CO_{2eqv} emissions (with ULSD).

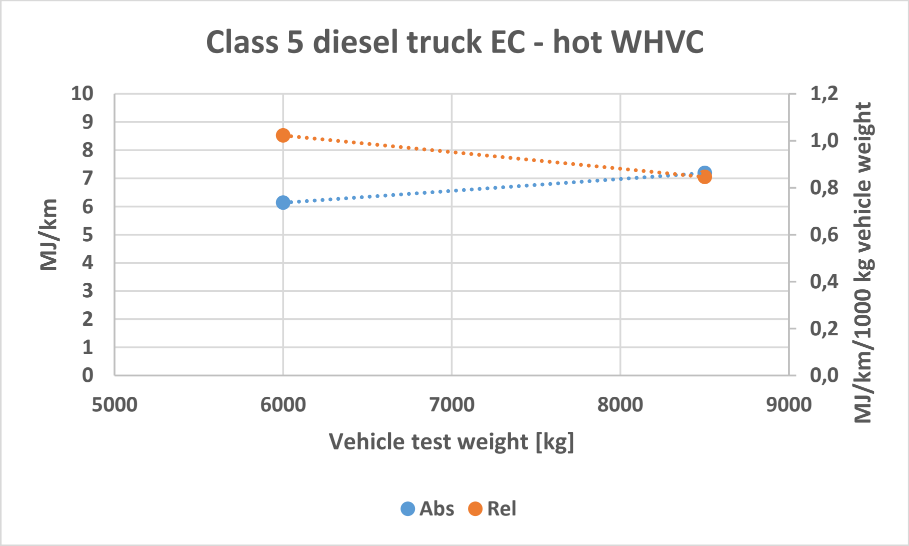


Figure 37: Class 5 diesel truck energy consumption (hot WHVC, medium and high load).

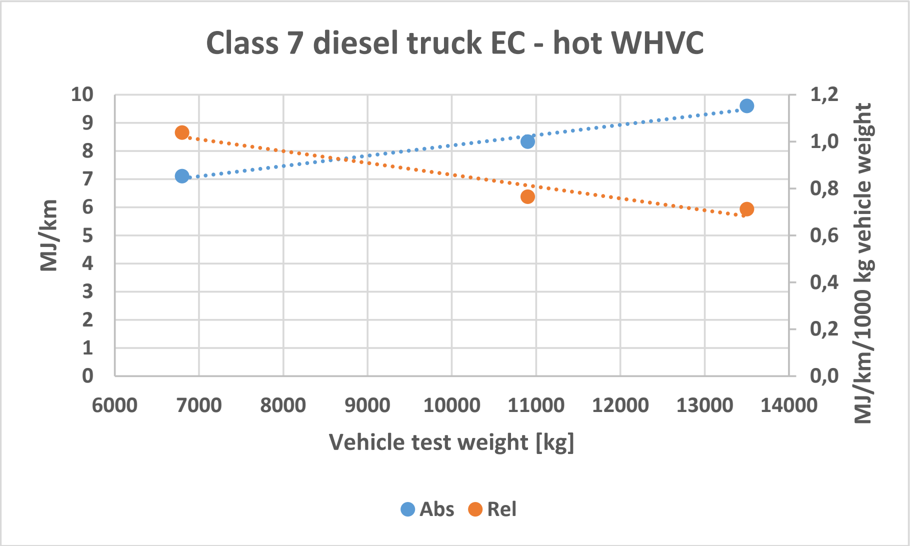


Figure 38: Class 7 diesel truck energy consumption (hot WHVC, unladen, medium and high load).

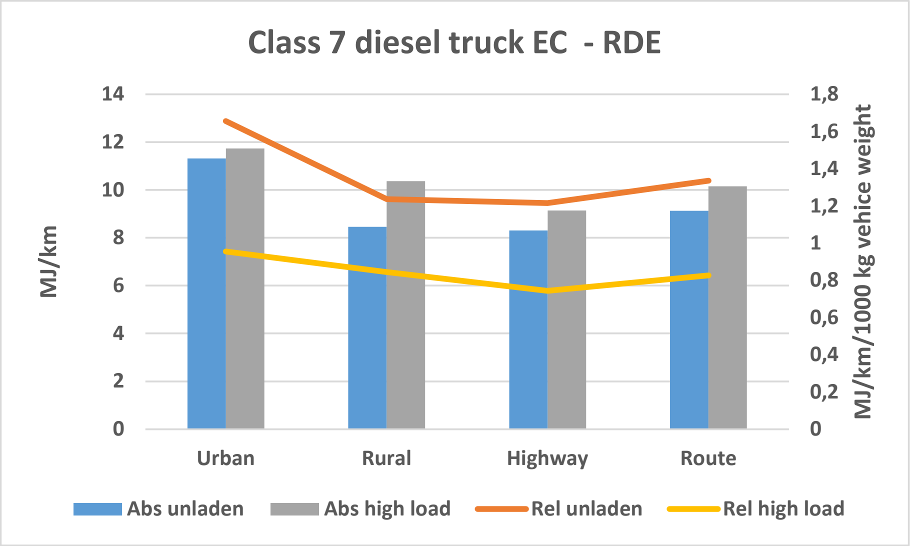


Figure 39: Class 7 diesel truck energy consumption (RDE, unladen and high load).

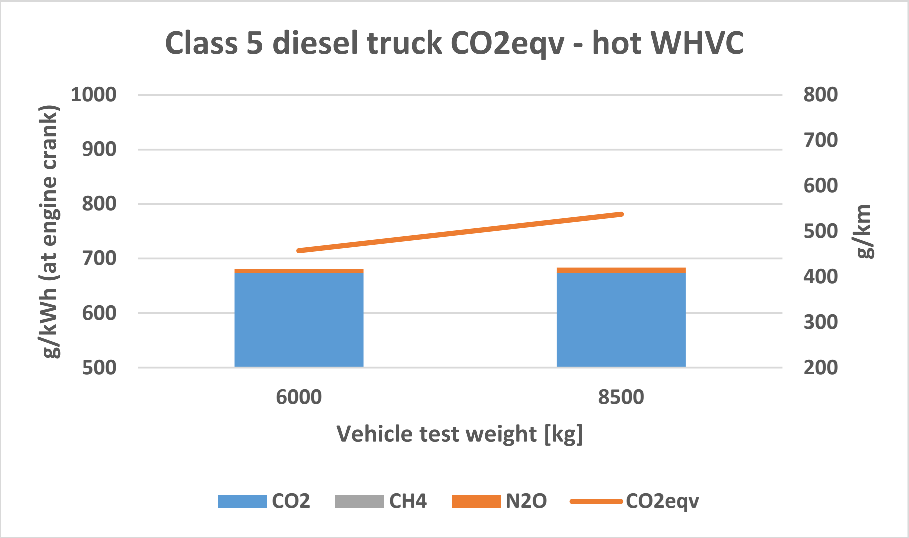


Figure 40: Class 5 diesel truck CO_{2eqv} emissions (hot WHVC, medium and high load).

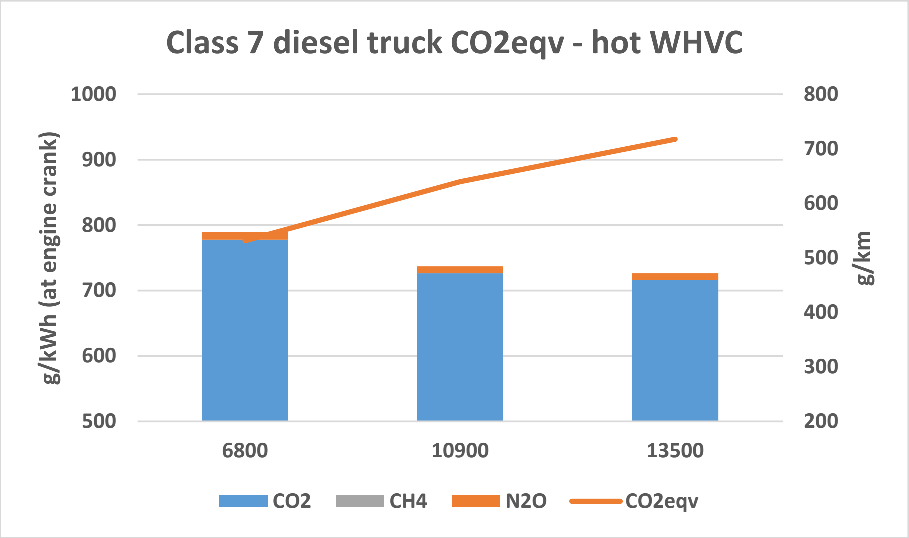


Figure 41: Class 7 diesel truck CO_{2eqv} emissions (hot WHVC, unladen, medium and high load).

Relative to the work at the engine crankshaft, the fuel consumption and GHG values translate as follows:

- Category 5 truck:
    - Specific fuel consumption ~ 215 g/kWh
    - Specific CO_{2eqv} emission ~ 680 g/kWh

- Category 7 truck:
    - Specific fuel consumption ~ 225 – 250 g/kWh
    - Specific CO_{2eqv} emission ~ 725 – 790 g/kWh

Pollutant emissions

Figure 42, Figure 43, Figure 44 and Figure 45 show pollutant emissions for the WHVC testing. Results are shown relative to driven distance as well as to work on the chassis dynamometer roller.

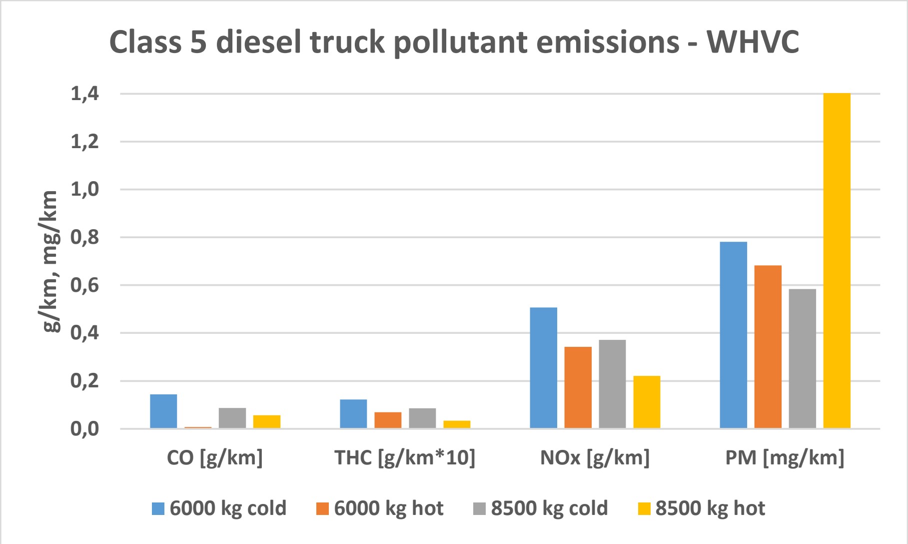


Figure 42: Class 5 diesel truck pollutant emissions, WHVC in g/km, ULSD fuel. PM for 8500 kg hot 2.9 mg/km.

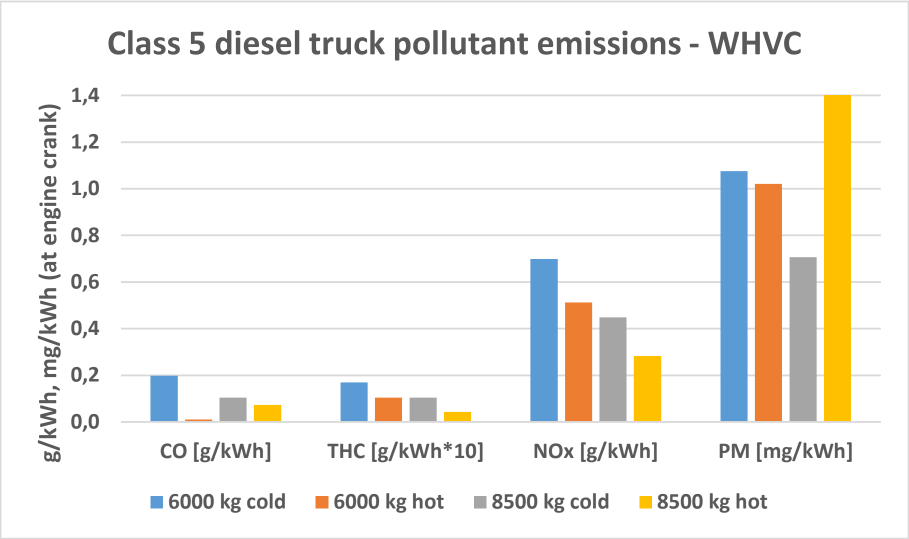


Figure 43: Class 5 diesel truck pollutant emissions, WHVC in g/kWh, ULSD fuel. PM for 8500 kg hot 3.7 mg/kWh.

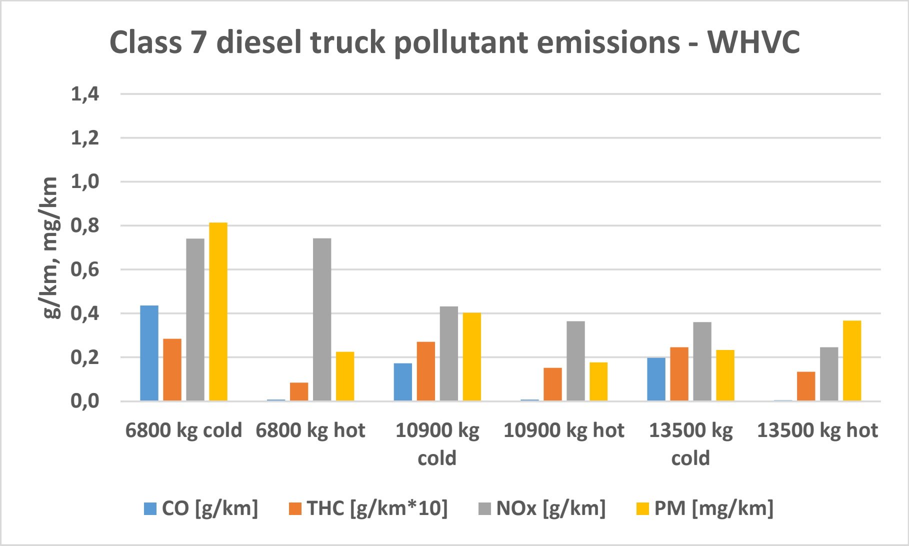


Figure 44: Class7 diesel truck pollutant emissions, WHVC in g/km, ULSD fuel.

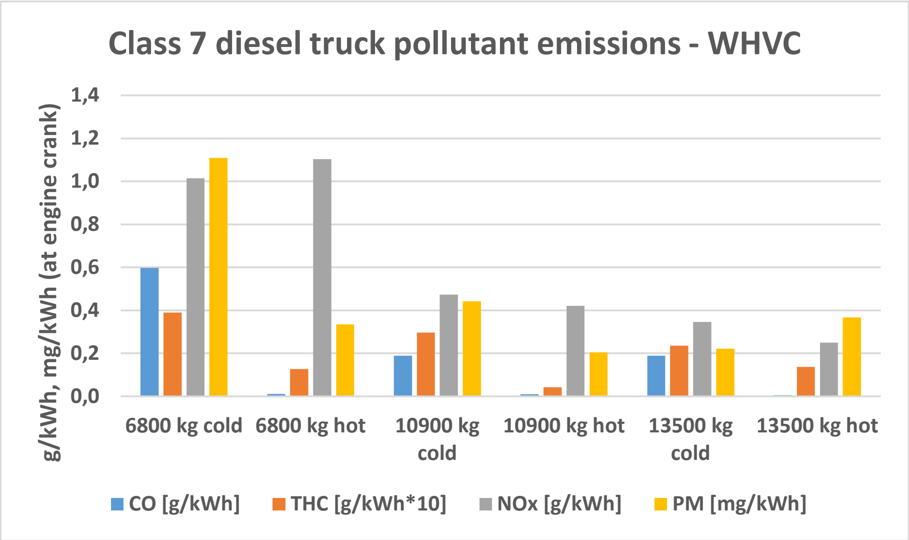


Figure 45: Class 7 diesel truck pollutant emissions, WHVC in g/kWh, ULSD fuel.

Figure 46 shows effects (relative) of B20 versus ULSD. The results are for the Class 7 truck and medium load in the WHVC cycle.

Figure 47, Figure 48, and Figure 49 show results (gaseous pollutant emissions) for RDE testing for the two vehicles, and Figure 50 the effect of B20 in the Class 7 vehicle when tested on road.

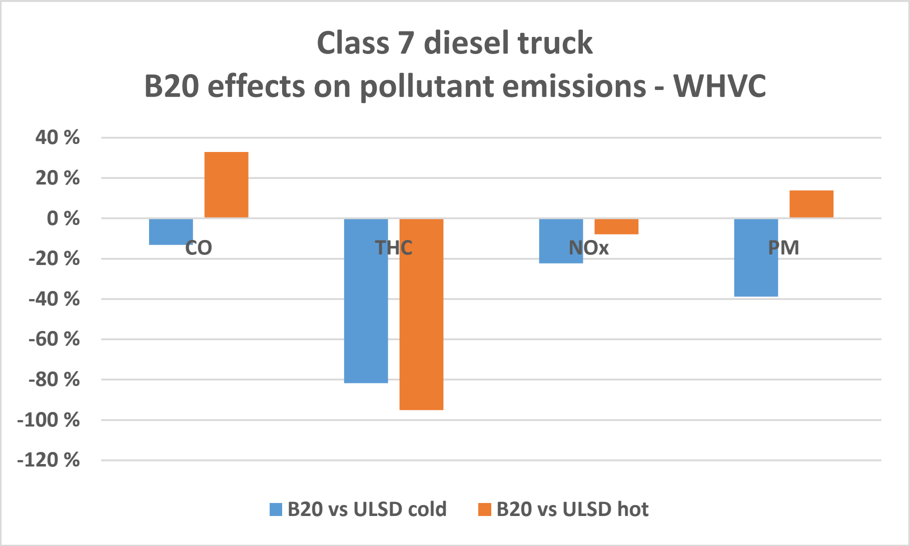


Figure 46: Effect of B20 on pollutant emissions, WHVC, medium load (reference ULSD).

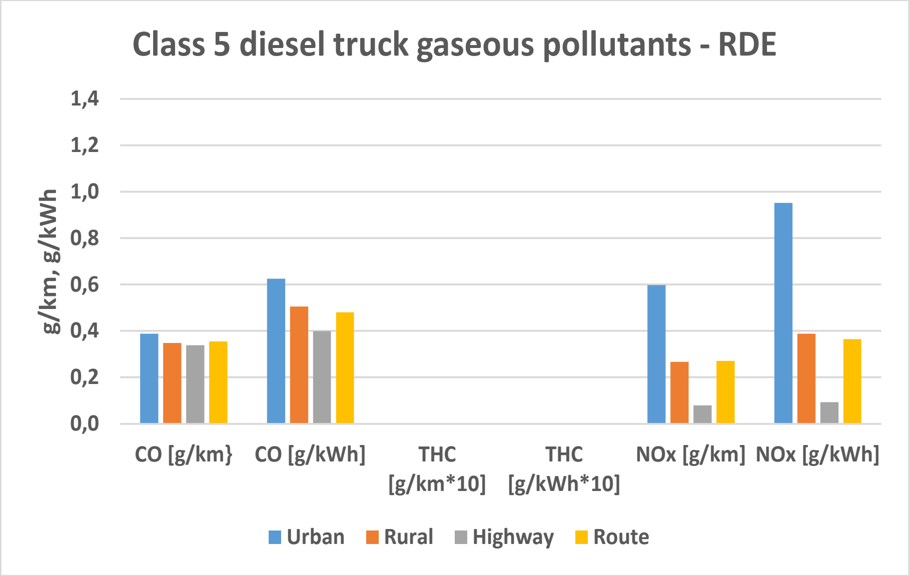


Figure 47: Class 5 diesel truck pollutant emissions, RDE, unladen vehicle.

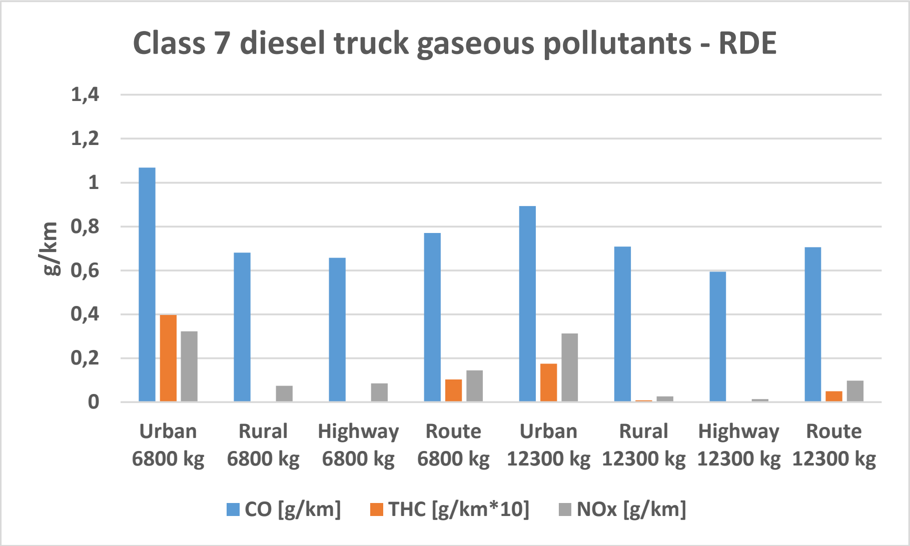


Figure 48: Class 7 diesel truck gaseous pollutant emissions, RDE in g/km, unladen and high load.

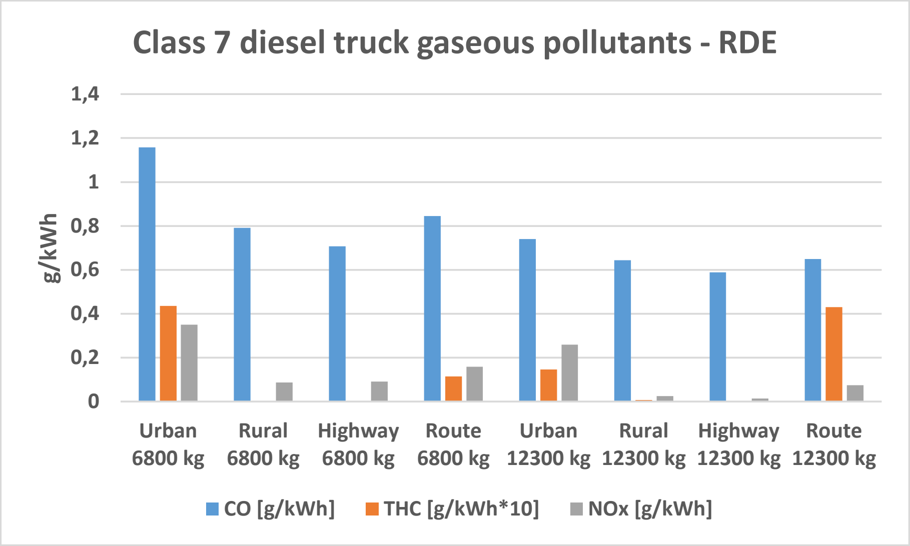


Figure 49: Class 7 diesel truck gaseous pollutant emissions, RDE in g/kWh, unladen and high load.

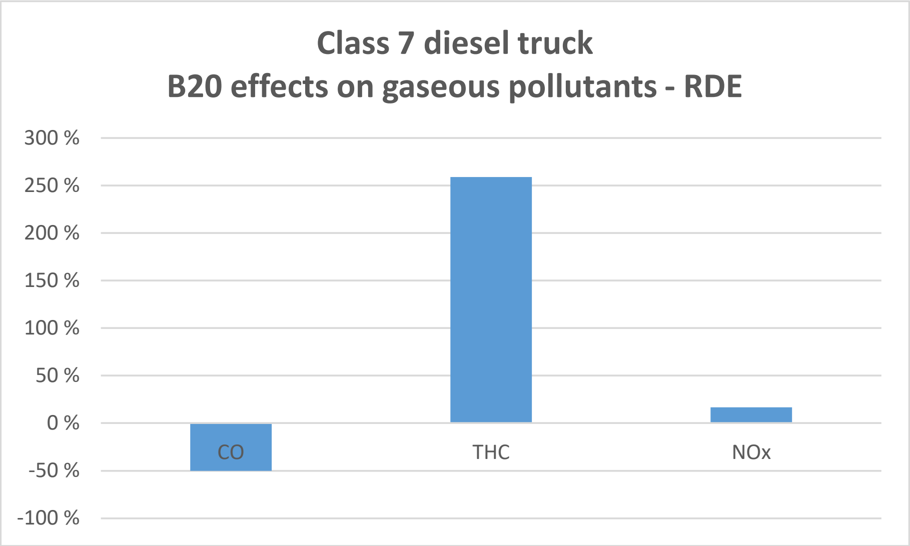


Figure 50: Effect of B20 on gaseous pollutant emissions, RDE, high load (reference ULSD).

Discussion

The primary objective of this report and its associated testing program was to determine emissions from HDVs operating under varying operating conditions. As such, the emissions results of two North American commercially available HDVs tested in-lab on the WHVC test cycle are presented. In addition, these two vehicles were tested on-road in order to capture their real-world emissions along an EU-RDE-based test route in Ottawa, Canada. These on-road results offer insight into further assessments of how emissions results may differ between in-lab and on-road, as well as provide insight to future determinations on the applicability of test cycles such as WHVC, given a North American vehicle, road, and driver.

In regards to the emissions results themselves, this work illustrated the close relation between vehicle load, CO_2 emissions, and fuel consumption.

Namely, increased load on both of the test vehicles resulted in more fuel consumed and higher emissions of CO_2. Furthermore, the emissions of CO_2 (and related impacts on fuel consumption) were lower for hot starts compared to the cold-start test condition.

In relative terms, the Class 5 truck proved to be slightly more fuel efficient than the Class 7 truck.

Regarding the greenhouse gas contributions of CH_4 and N_2O, both of these constituents were emitted in very low concentrations. CH_4 emissions were especially low in hot start tests where the measured emission concentrations would frequently border the lower method detection limit. Emissions of N_2O increased with vehicle load and overall contributed between 1 and 2% of the calculated CO_2-equivalent emissions.

The emissions of NO_x were observed to be higher with the lowest load test condition compared to the other heavier loads. It is possible that this may be correlated to lower exhaust temperatures at engine start-up at a lower load. Accordingly, a lower vehicular load may lengthen the amount of time for NO_x control strategies to take effect. Research efforts that involve investigating on-board NO_x sensor warm-up times, related impacts on dosing strategy, and subsequent impacts on NO_x emissions, are currently underway at the ECCC.

PM emissions were generally below 1 g/km and thus demonstrated a high effectiveness of each vehicle's DPF. In many instances the heavier Class 7 vehicle exhibited lower PM emissions than the lighter Class 5 vehicle. This suggests that other factors, in addition to the DPF, which can influence a vehicles' management of PM, were at play. It is theorized by the authors of this report that the low PM emissions observed on the Class 7 vehicle is related to the cam-phasing capability of this vehicle's engine. This rationale is supported by other research which has found that delaying an engine's intake valve can result in more than a 25% reduction of particulate emissions (Rodriguez and Cheng, 2016). Furthermore, the

Class 5 vehicle exhibited higher than expected PM emissions at medium load on the WHVC-hot start. However, due to limited test data it is unclear if this is indicative of a finding or an experimental artefact.

In addition, emissions of CO and THC were significantly reduced in hot start tests compared to the cold start and this was observed for all test loads. This is indicative of the requisite warm-up period needed before the vehicle's emission controls have reached their optimum operating temperature. Despite elevated emissions at the cold start, emissions of CO and THC were overall relatively low both in the lab and on the road. Upon examination of the emissions of CO from the WHVC cold start, it is evident that the majority of CO emissions occur in the first (i.e. "Urban Mode") phase of the test, whereas for the WHVC hot start, this initial phase produces little to no CO.

It was observed that CO_2 emissions were relatively similar between the in-lab WHVC and the on-road RDE. However, with the exception of Phase 1 of the WHVC-cold high load results, CO_2 emission rates were higher on-road. This could be attributed to the fact that vehicle speeds are also generally higher on the RDE compared to the WHVC and exhaust temperatures can also be assumed to be higher, supporting an improved conversion efficiency within the NOx emission control system. Test results would support this observation as NO_x was lower on the RDE compared to the WHVC.

In regards to the tests performed with B20 fuel, it is important to state that the ability for comparison is limited due to the low number of repeated tests. However, from the limited dataset in this study, it is apparent that the B20 emissions were in line with ULSD for the test conditions in this program.

Chile

General

The Chilean part presents chassis dynamometer fuel consumption and PM data for three Category 1 diesel trucks (PM results for two trucks). All trucks were tested on two different loads, 50 and 70%.

Energy consumption and CO_2 emissions

Figure 51 presents absolute and Figure 52 relative energy consumption for WHVC. Figure 53 shows CO_2 emissions (calculated from fuel consumption assuming 73.2 g CO_2/MJ fuel). Figure 54 shows PM emissions for two of the test vehicles.

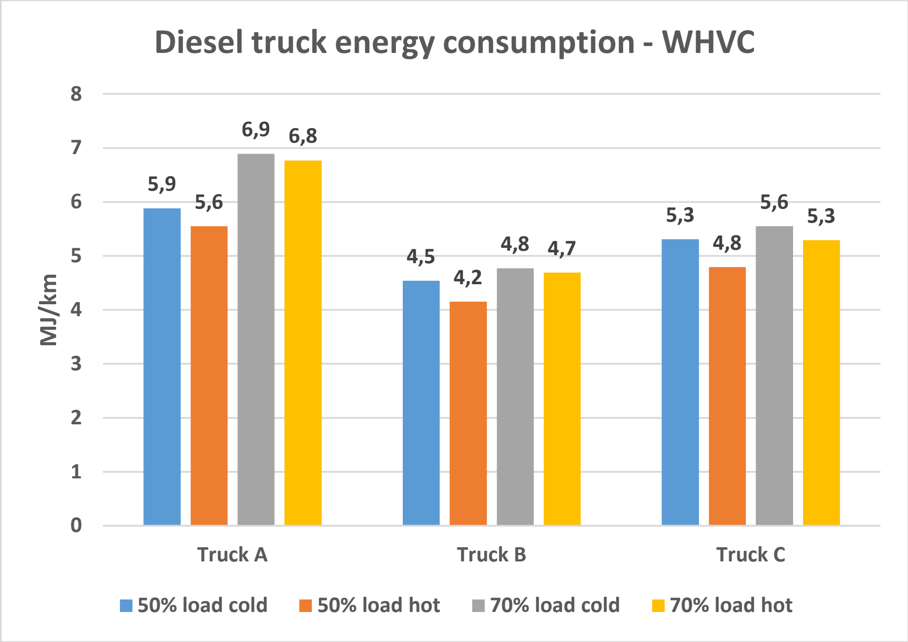


Figure 51: Diesel truck energy consumption, cold and hot WHVC.

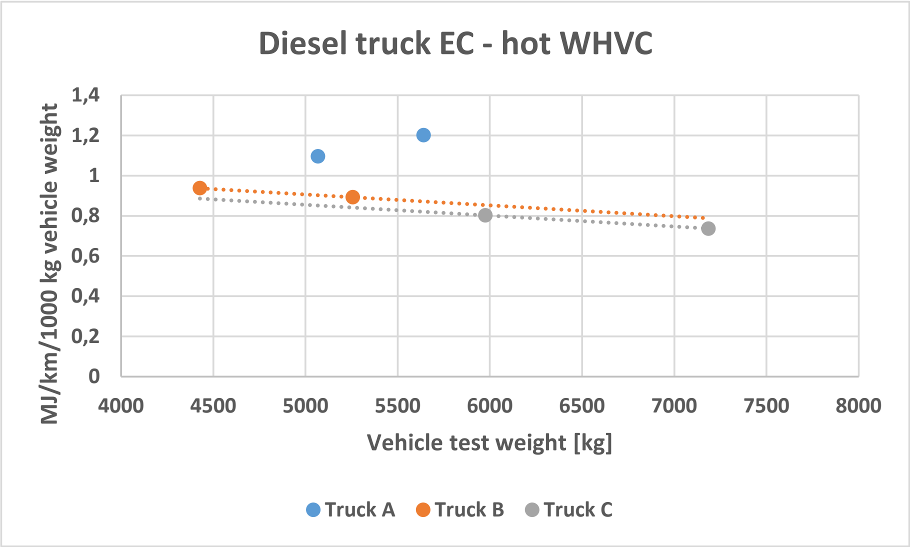


Figure 52: Diesel truck energy consumption relative to weight, hot WHVC.

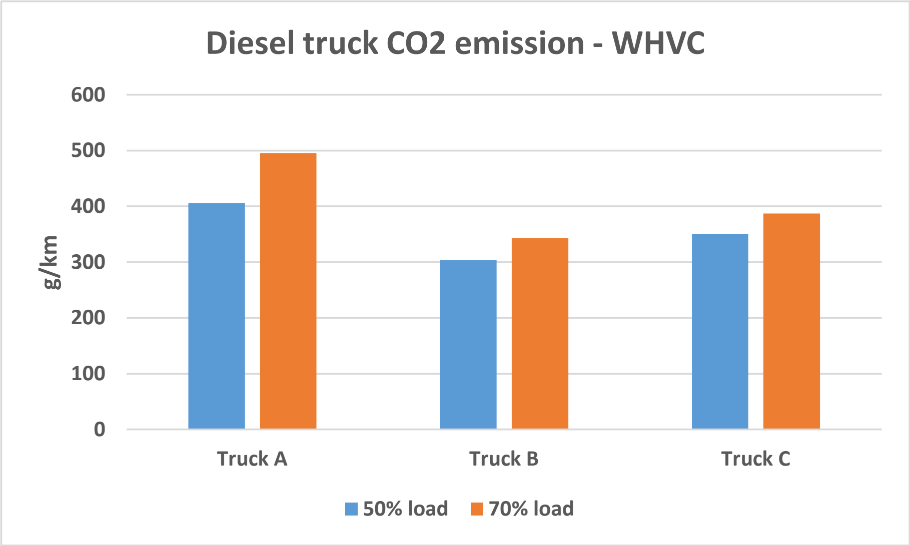


Figure 53: Diesel truck CO_2 emissions, hot WHVC.

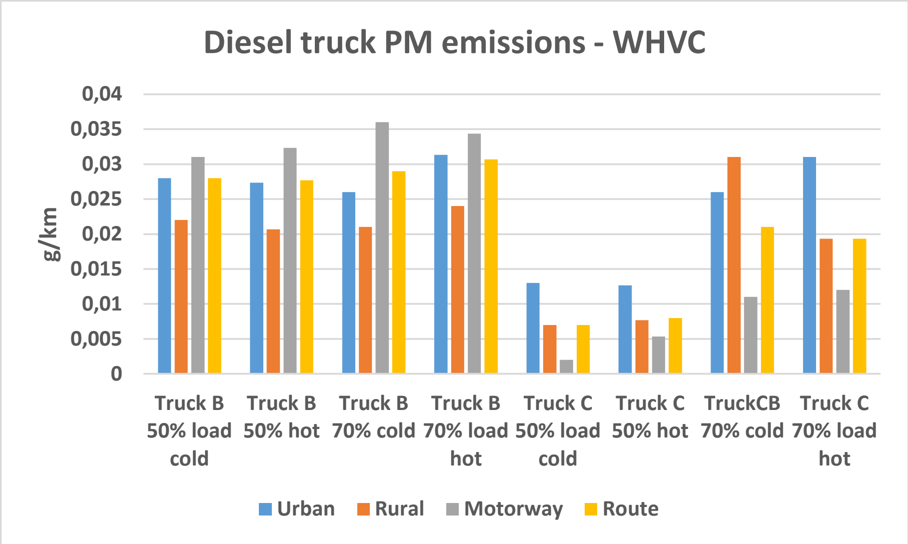


Figure 54: Diesel truck PM emissions, WHVC.

Discussion

The main objective of the measurements carried out is to determinate the energy consumption of different configurations of heavy-duty vehicles in different driving conditions.

For the three trucks measured, the energy consumption in the cold test is on average some 5% higher compared to the hot test (for the total route). For the first phase (urban) the difference is some 10 – 40%, and is highest for Truck C. The increase in fuel consumption stems from the higher fuel injection required in cold starting giving a lower performance during the urban phase. In the rural and motorway driving phases differences are small as the vehicles have already reached their normal operating temperature.

Over the total WHVC cycle, truck A has the highest energy consumption, both in absolute and relative terms, although being in between trucks B and C regarding test weights.

Figure 52 shows that trucks B and C deliver similar energy consumption relative to vehicle weight, values going down with increasing vehicle weight. Vehicle A shows relative values 20 – 35% higher compared to the two other vehicles, and relative energy consumption increases with increased vehicle weight, which normally is not the case. Truck A has the highest relative energy consumption in all of the phases of the WHVC, the difference to the two other vehicles being at minimum in the urban phase.

Truck B have relatively stable PM emissions in all conditions (temperature, load and cycle phase). However, for this vehicle PM emissions are at maximum in the motorway phase.

In the case of truck C there are variations in the results, load having significant impact on PM emissions. For this truck PM emissions are on average at maximum in the urban phase.

Finland

General

Finland contributed Annex with chassis dynamometer and on-road measurements. In addition, simulation results of HCT vehicle combination and NO_x concentration monitoring were provided.

VTT focused on the heaviest vehicle segment, in this case Category 2 vehicles for trailer combinations. In this Category, VTT tested all in all six vehicles representing four different combustion systems, enabling a direct comparison of technologies:

- Compression ignition
  - Conventional diesel
  - Additive treated ethanol
  - HPDI dual-fuel methane/diesel
- Spark-ignition
  - Stoichiometric methane

Chassis dynamometer measurements with all six trucks were performed according to the procedure specified in the Vehicle testing section. Most of the chassis dynamometer data presented is for the WHVC and 30 ton inertia, using the same dynamometer settings for all vehicles. Additional data include 44 ton inertia in the WHVC as well as data for VTT's HDVPerE cycle with 30 ton inertia.

Three vehicles were tested with two fuels, two diesel trucks with regular diesel and HVO, and the CNG truck on pump grade CNG and low methane number CNG.

The principal Figures show results for "base fuels", and the effects of parallel fuels (diesel/HVO and regular/low methane number CNG) are shown separately.

Chassis dyno data on energy consumption and CO_2 emissions is shown for hot testing (30 and 44 ton), pollutant emission results are shown for both cold and hot testing (30 ton).

In the case of chassis dynamometer measurements, values relative to work relate to work at the chassis dynamometer roller.

On-road testing was done for three trucks, diesel, HPDI dual-fuel methane/diesel and spark-ignited LNG. To assess the differences between chassis dynamometer and on-road testing the HDVPerE cycle, designed to simulate typical long-haul operations, was driven both on the chassis dynamometer and on the road.

The complete data sets for chassis dynamometer and on-road tests (tables) are presented in Appendix C.

Continuous NO_x concentration monitoring in normal service was carried out for three trucks, truck B and two truck corresponding to trucks C (denoted G) and D (denoted H). Depending on the truck the monitoring period was 9 to 11 months.

Energy consumption and CO_2 emissions

Figure 55 (30 ton) and Figure 56 (44 ton) show chassis dynamometer WHVC energy consumption for the six trucks expressed in MJ/km and MJ/km/1000 kg of vehicle weight. Values are for hot engines and "regular pump quality" fuels. Figure 57 correspondingly shows data for the HDVPerE cycle at 30 ton.

Figure 58 (total cycles), Figure 59 (WHVC by mode, 30 t) and Figure 60 (WHVC by mode, 44 t) present relative differences in energy consumption. Figure 62 shows engine efficiency for the motorway part of the WHVC. Figure 61 presents energy consumption for the on-road measurements.

Regarding energy consumption, the vehicles fall into two groups, spark-ignited gas vehicles with high energy consumption and vehicles running on the diesel process, with more moderate energy consumption. HPDI LNG has slightly higher energy consumption than average diesel.

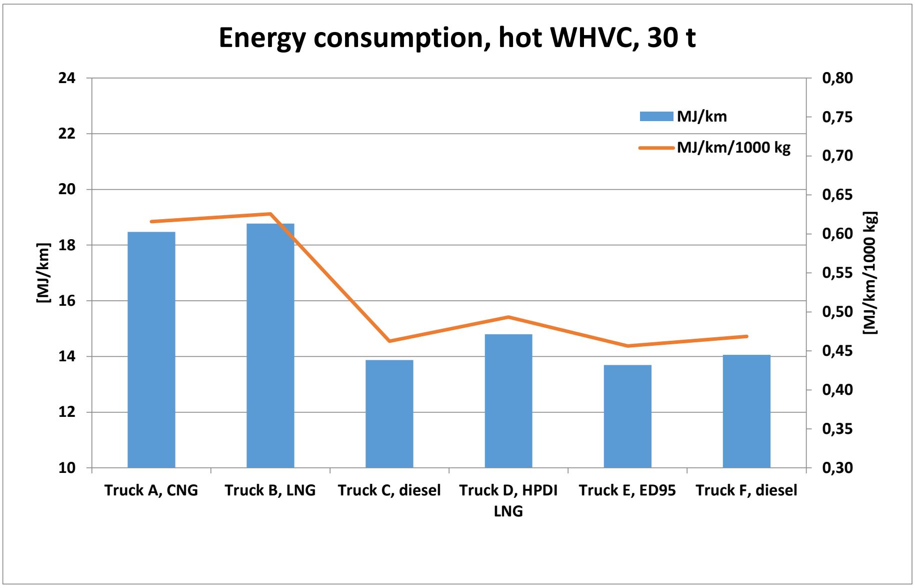


Figure 55: Energy consumption (hot WHVC, 30 t).

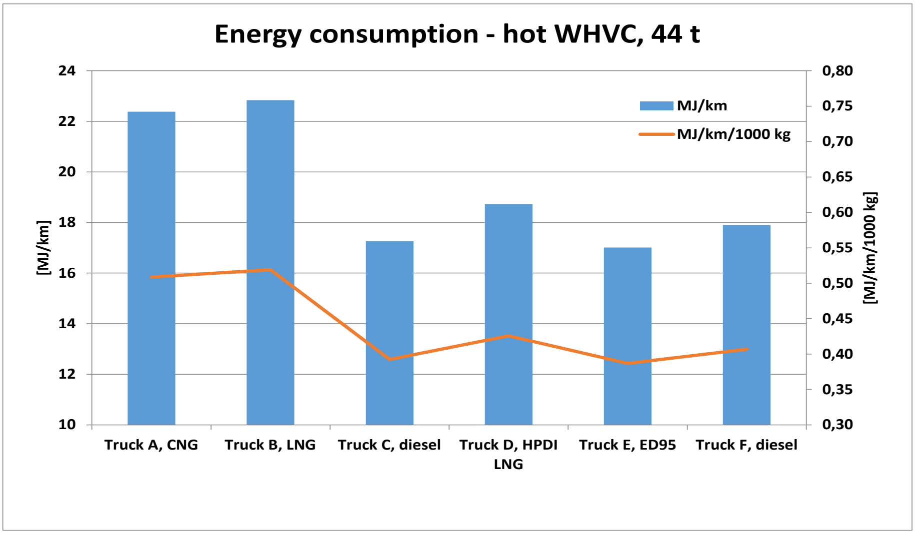


Figure 56: Energy consumption (hot WHVC, 44 t).

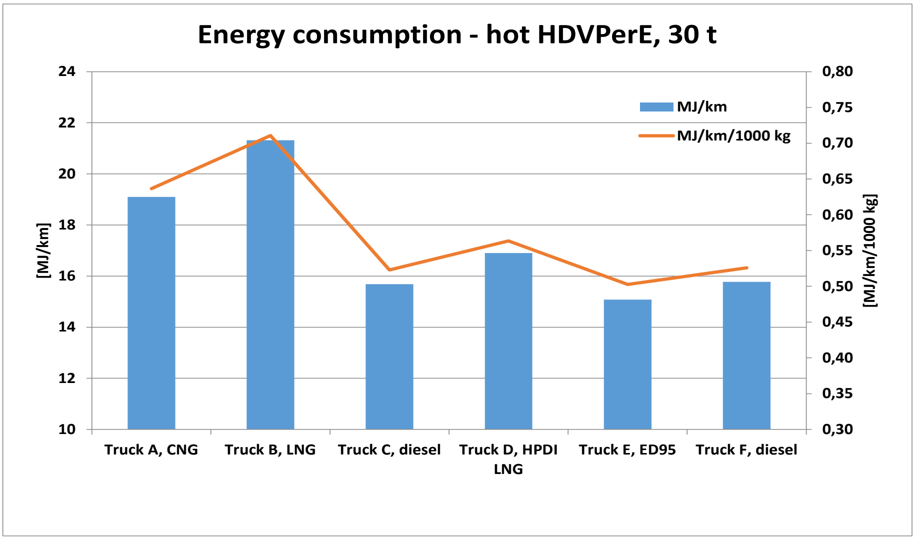


Figure 57: Energy consumption (hot HDVPerE, 30 t).

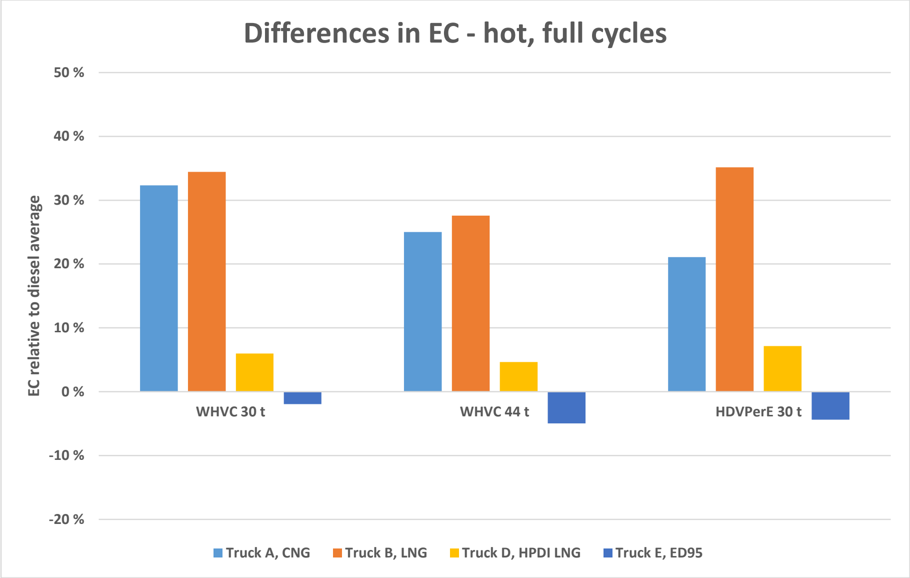


Figure 58: Energy consumption (hot testing, full cycles) relative to diesel average.

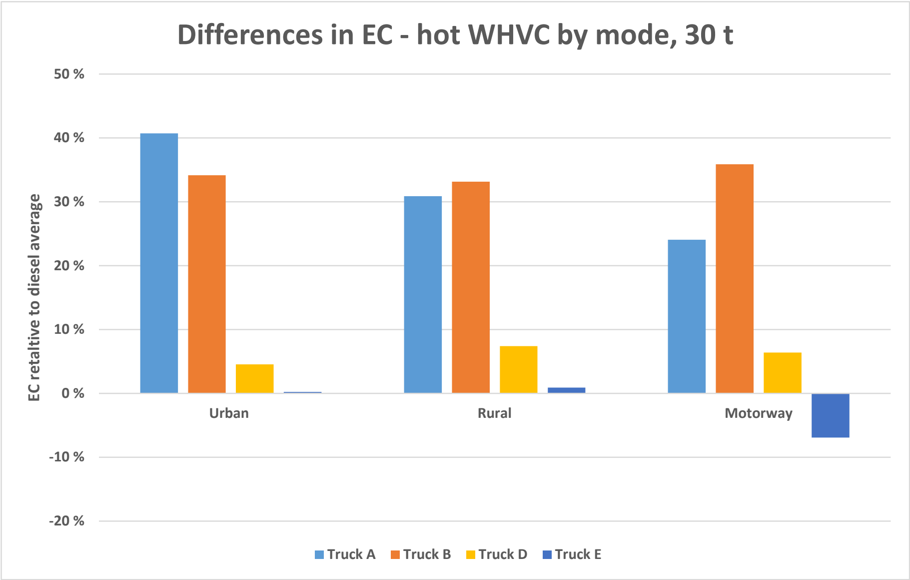


Figure 59: Energy consumption (hot testing, WHVC 30 t by mode) relative to diesel average.

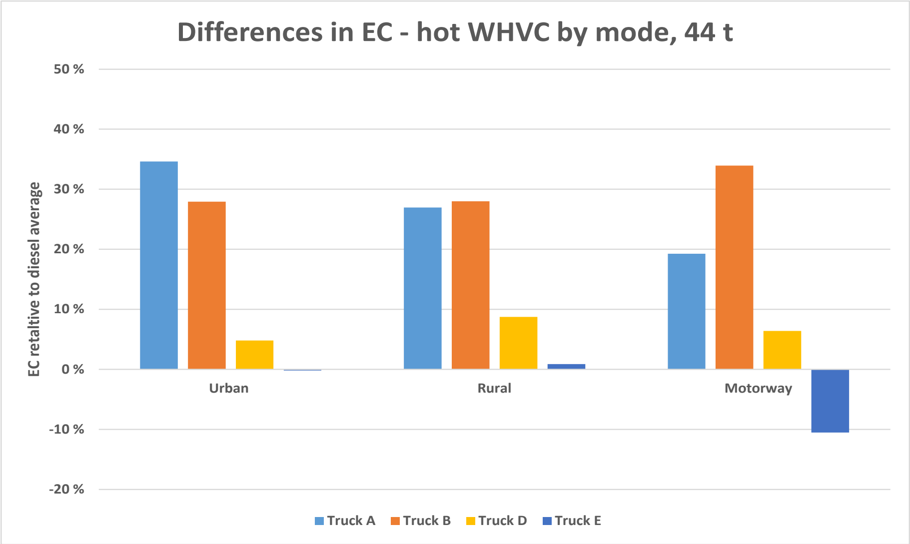


Figure 60: Energy consumption (hot testing, WHVC 44 t by mode) relative to diesel average.

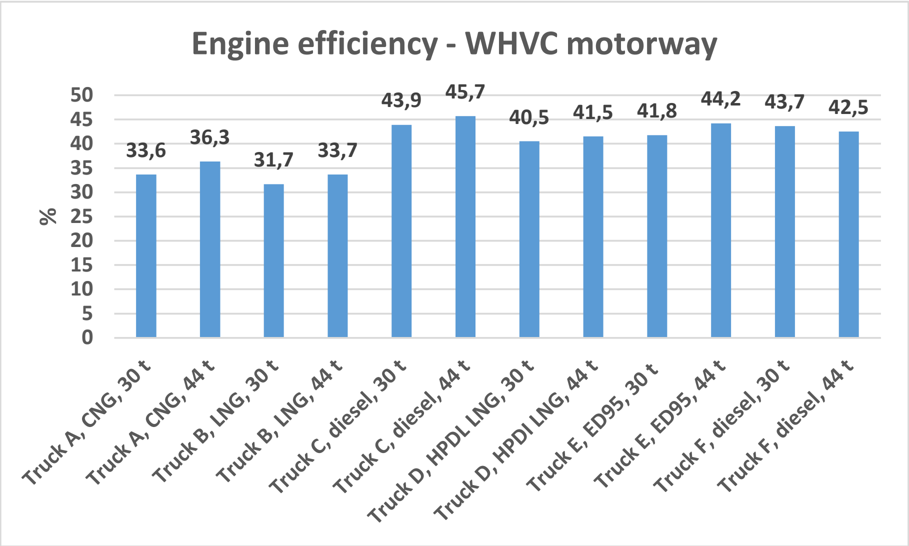


Figure 62: Engine efficiency for the WHVC motorway part.

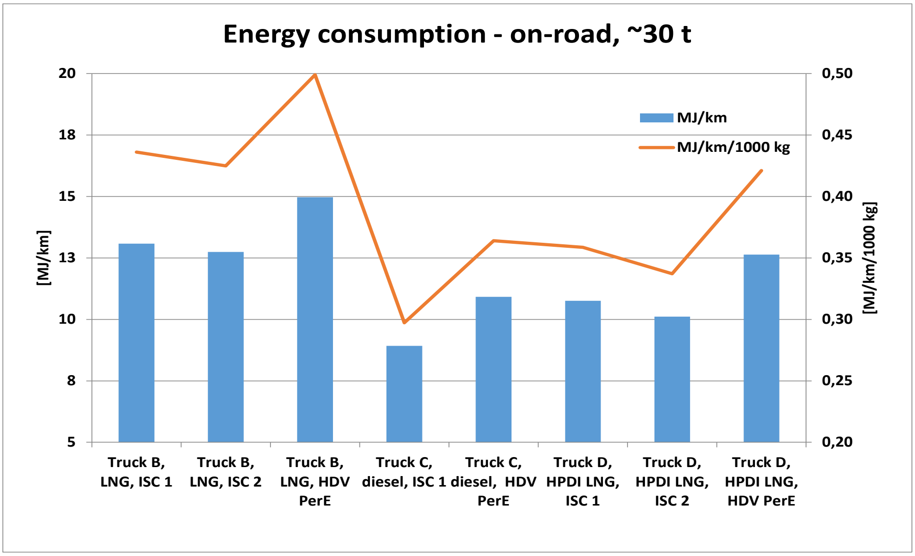


Figure 61: Energy consumption (on-road measurements, ~30 t).

CO_{2eqv} emissions based on chassis dynamometer measurements are presented in g/kWh (at the driving wheels) and g/km in Figure 63, Figure 64 and Figure 65 (WHVC 30 and 44 t, HDV PerE 30 t). Figure 66 shows CH_4 emissions and Figure 67 N_2O emissions for WHVC (cold as well hot starts). Figure 68 presents $CO2_{eqv}$ values relative to vehicle weight in g/km/1000 kg of vehicle weight. Figure 69 presents CO_2 emissions for the on-road measurements.

Spark-ignited methane vehicles can, at best, deliver a small reduction (some 5%) in CO_{2eqv} emissions compared to diesel. The same applies for ED95. HPDI LNG, on the other hand, on an average delivered a 14 % reduction compared to diesel (18% for CO_2 only). N_2O contributes to CO_{2eqv} emissions especially in the case of HPDI LNG.

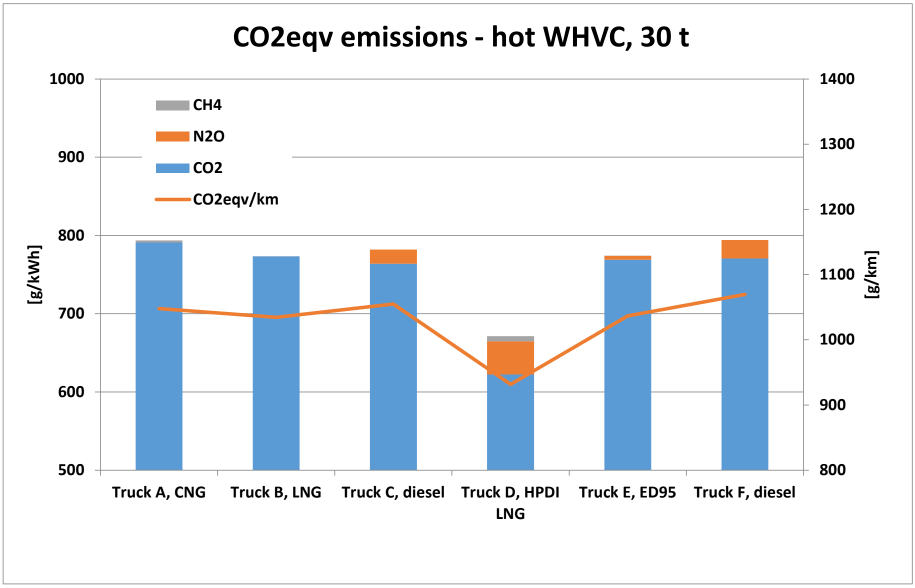


Figure 63: CO_{2eqv} emissions (hot WHVC, 30 t). Values in g/kWh relate to work at the driving wheels.

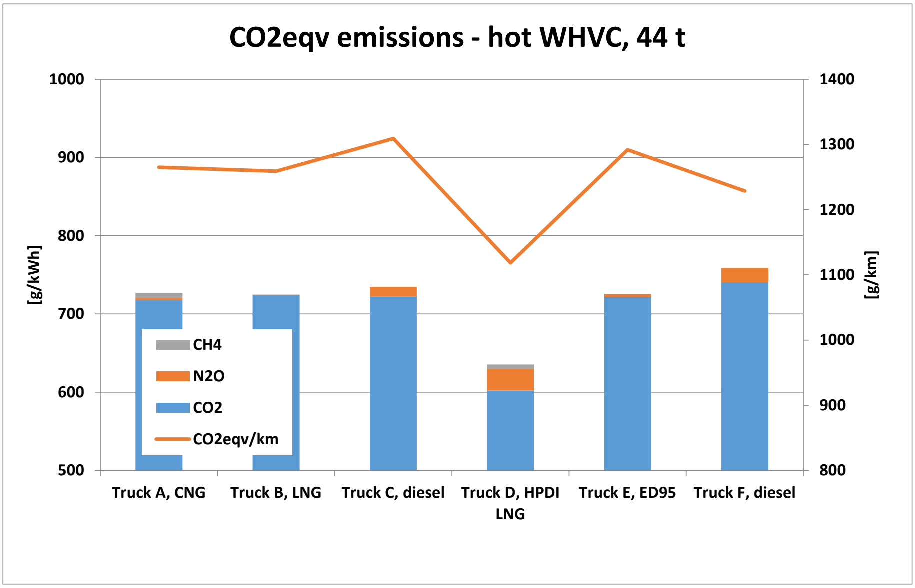


Figure 64: CO_{2eqv} emissions (hot WHVC, 44 t). Values in g/kWh relate to work at the driving wheels.

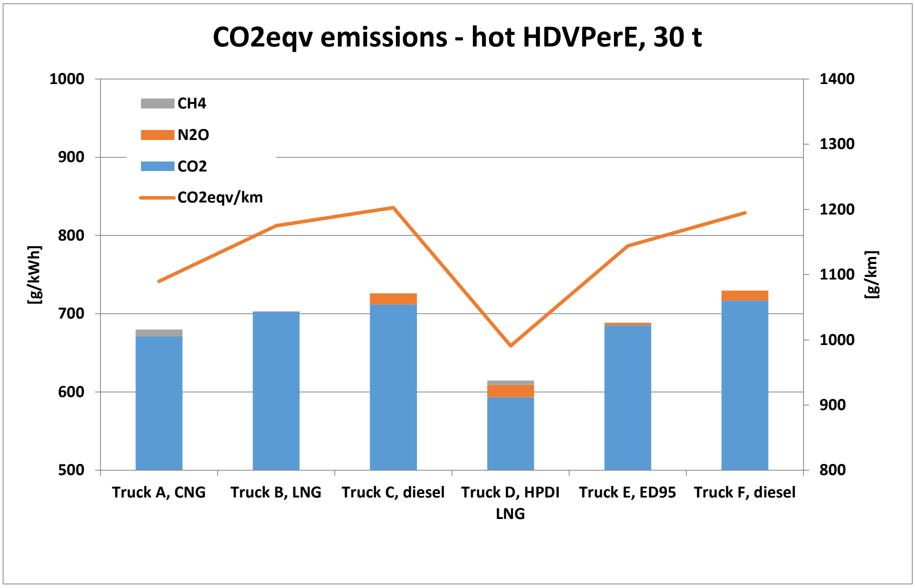


Figure 65: CO_{2eqv} emissions (hot HDVPerE, 30 t). Values in g/kWh relate to work at the driving wheels.

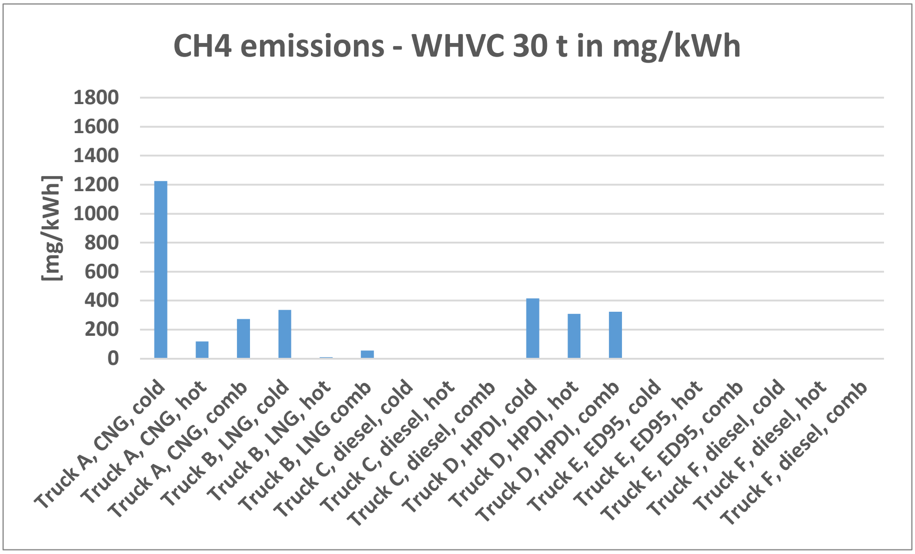


Figure 66: CH_4 emissions (cold and hot WHVC, 30 t). Values relate to work at the driving wheels.

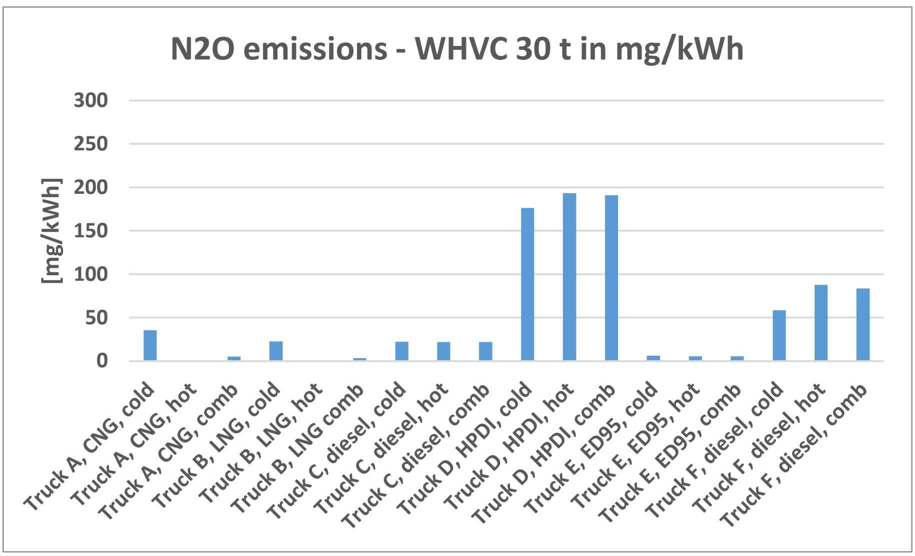


Figure 67: N_2O emissions (cold and hot WHVC, 30 t). Values relate to work at the driving wheels.

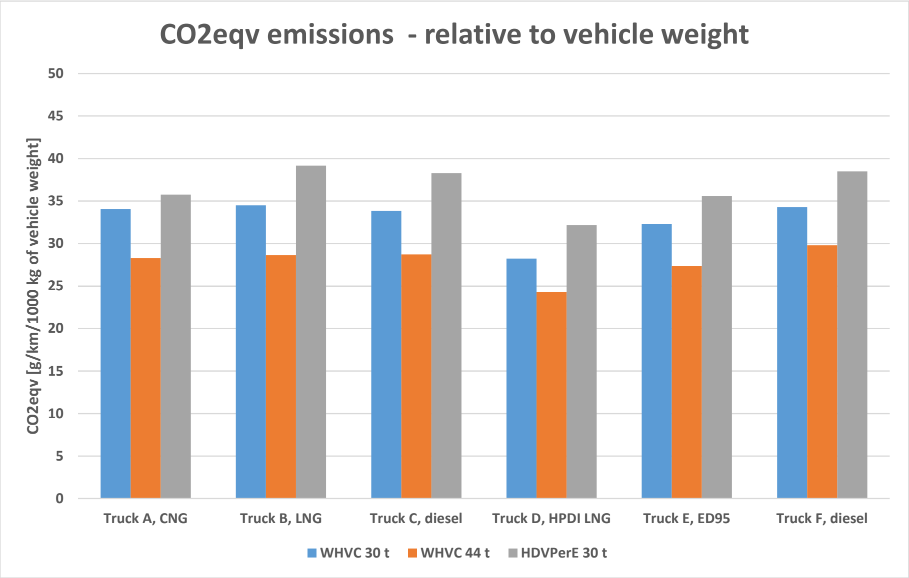


Figure 68: CO_{2eqv} emissions relative to vehicle weight.

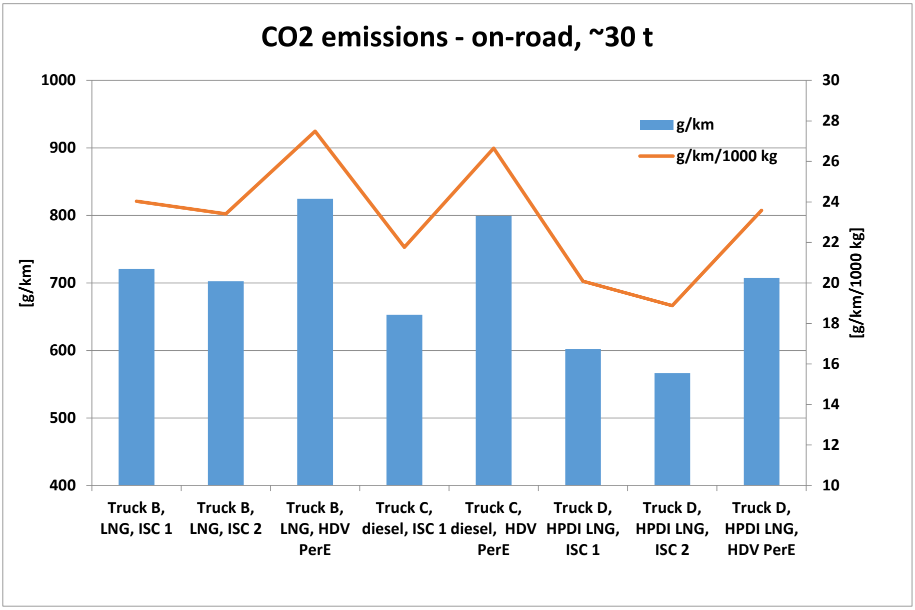


Figure 69: CO_2 emissions (on-road measurements, ~30 t).

Pollutant emissions (NO_x, PM and PN)

NO_x, PM (mass) and PN (number) emissions are presented for WHVC at 30 t load. Figures show cold, hot and combined (weighting cold 14% and hot 86%) results. The data presented is for “base fuels”. The cold start test with regular CNG in truck A failed. For this vehicle, the cold WHVC data for the special low methane number gas is used instead (also in Figure 66 and Figure 67). A comparison of the two gas qualities (hot tests) is shown separately later on.

Results are presented relative to work at the driving wheels (g/kWh) and driven distance (g/km). Figure 70 and Figure 71 are for NO_x, Figure 72 and Figure 73 for PM and Figure 74 and Figure 75 for PN.

NO_x and PN results from on-road measurements are presented in Figure 76 and Figure 77 (values related to work at the engine crank).

All in all, NO_x and PM values were quite low, well below Euro VI limit values. However, spark-ignited methane truck A emitted high numbers of particles, as did the HPDI LNG truck in when tested using the HDVPerE cycle on-road.

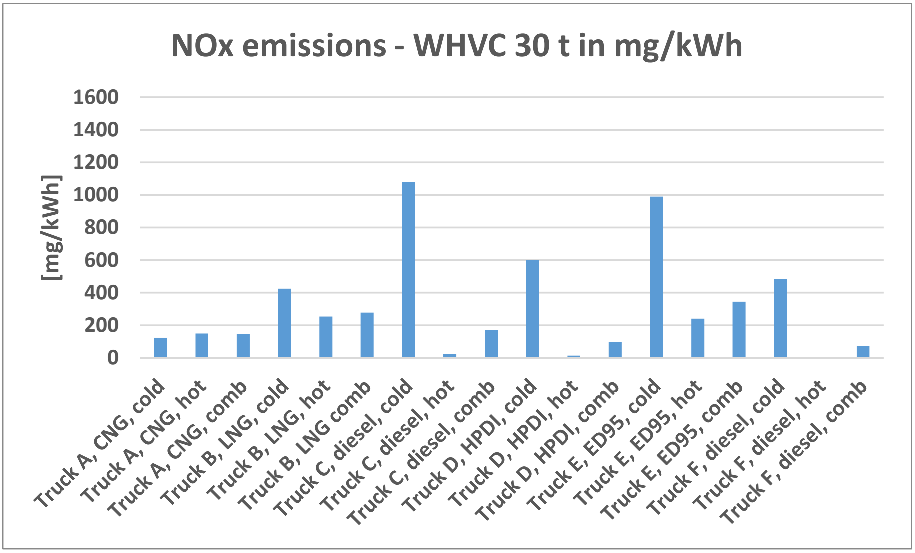


Figure 70: NO_x emissions (cold and hot WHVC, 30 t). Values relate to work at the driving wheels.

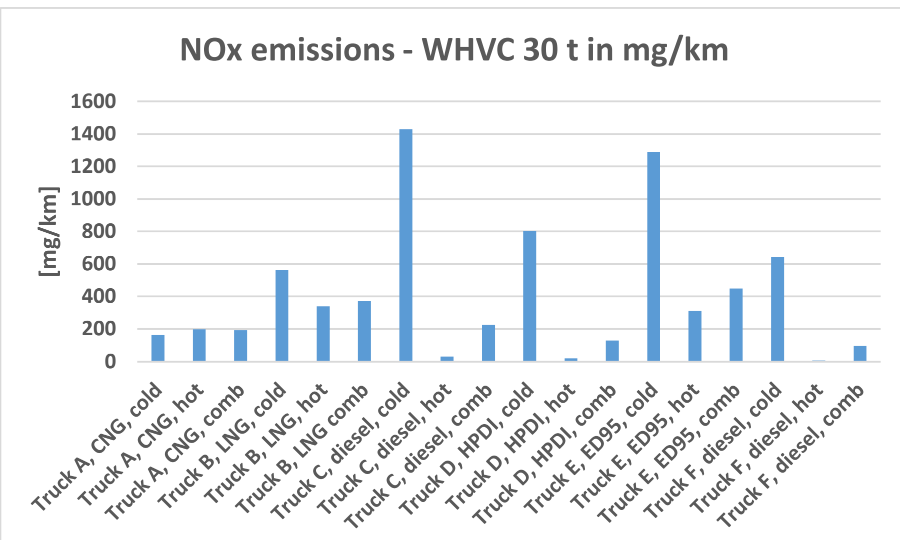


Figure 71: NO_x emissions (cold and hot WHVC, 30 t). Values in mg/km.

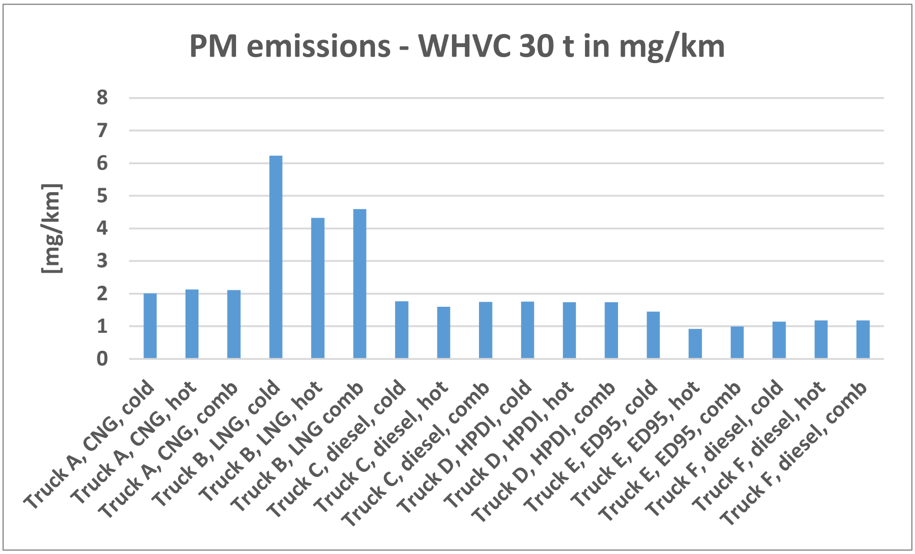


Figure 72: PM emissions (cold and hot WHVC, 30 t). Values relate to work at the driving wheels.

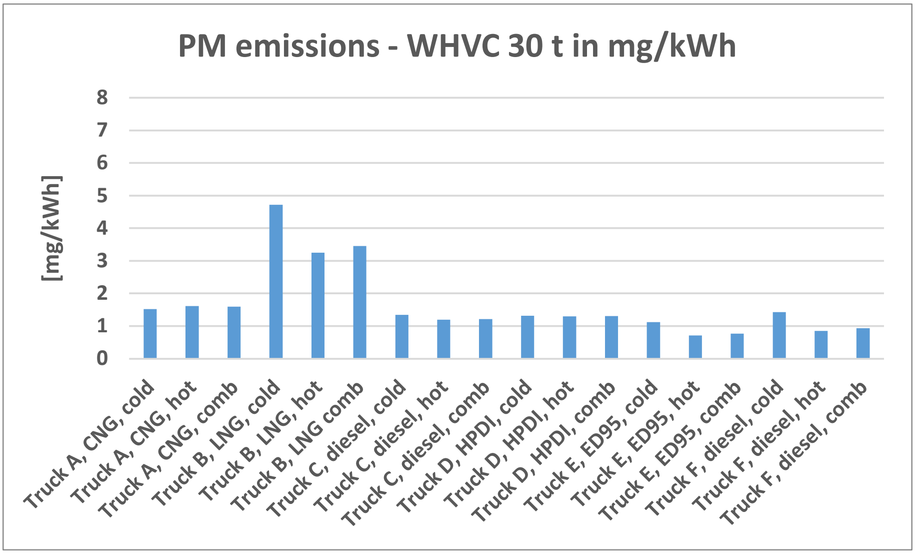


Figure 73: PM emissions (cold and hot WHVC, 30 t). Values in mg/km.

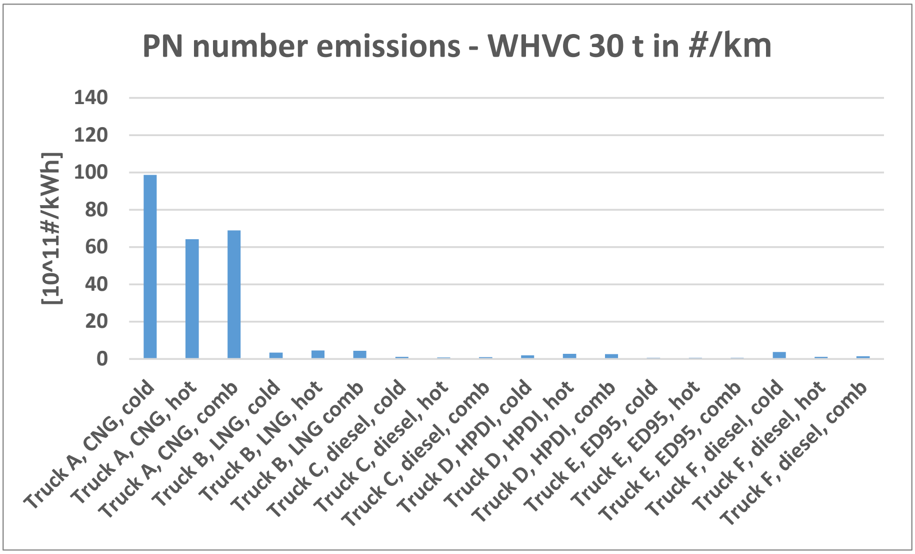


Figure 74: PN emissions (cold and hot WHVC, 30 t). Values relate to work at the driving wheels.

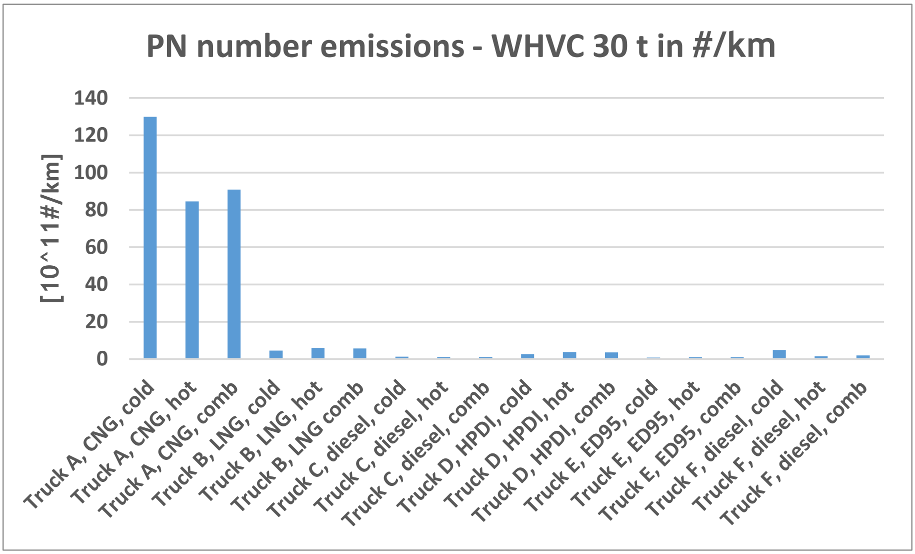


Figure 75: PN emissions (cold and hot WHVC, 30 t). Values in #/km.

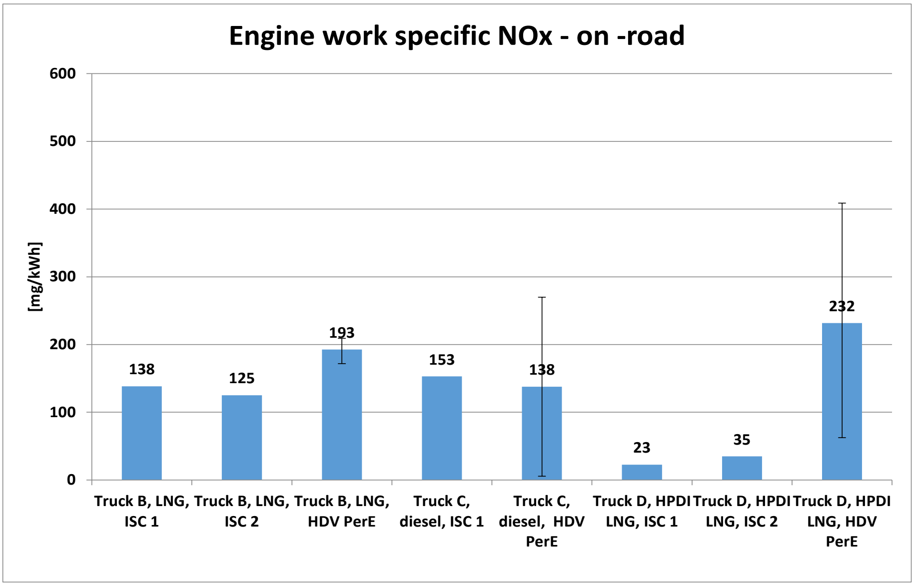


Figure 76: NO_x emissions (on-road measurements, g/kWh relative to engine work).

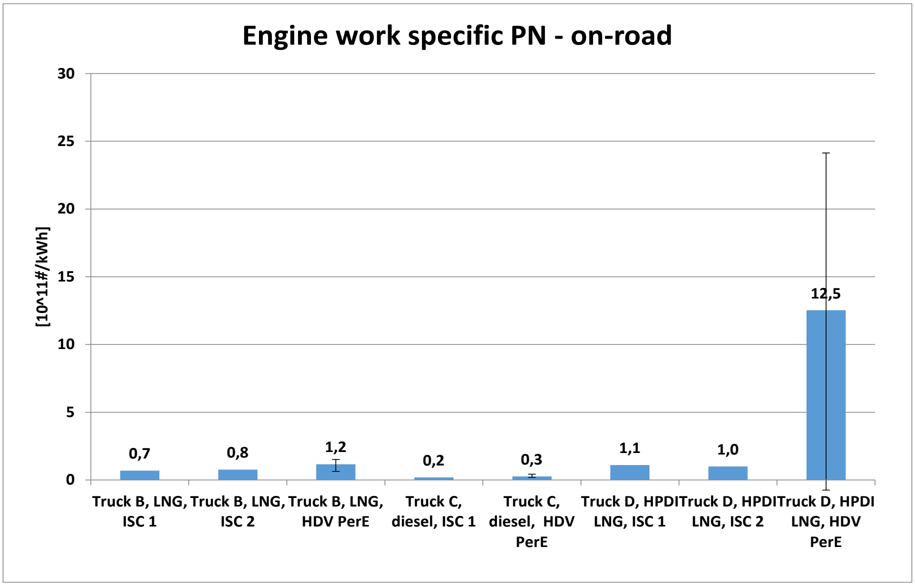


Figure 77: PN emissions (on-road measurements, g/kWh relative to engine work).

Substitute fuels

The CNG truck (truck A) was tested on **two gas qualities**, Finnish pump grade CNG and low MN CNG. The comparison is presented in Figure 78 showing relative results for hot WHVC testing.

HVO is tested in two trucks, the conventional diesel trucks C and F running both WHVC and HDVPerE test cycles. Also in this case results are from hot testing. Figure 79 shows relative results.

The effects of fuel switches on energy consumption are minimal, as can be expected. However, in relative terms, effects on individual pollutants can be substantial, varying from component to component as well as varying in direction.

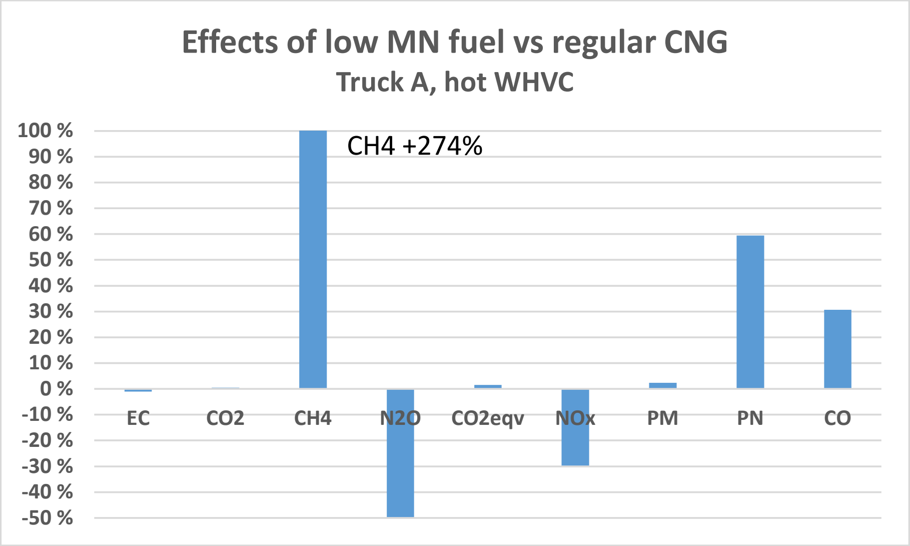


Figure 78: Effects of low methane number gas on performance (reference pump quality CNG).

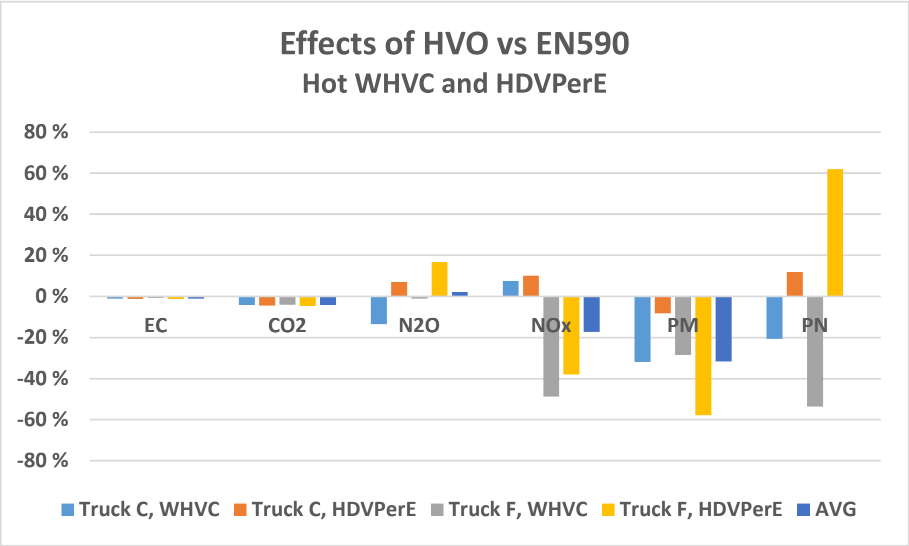


Figure 79: Effects of HVO on diesel truck performance (reference EN590).

Comparison of chassis dynamometer and on-road measurements

A comparison between chassis dynamometer and on-road measurements is carried out by running the HDVPerE cycle both on the chassis dynamometer and on the road. Figure 80 shows speed traces and Figure 81 cumulative work at the engine for truck B. A similar comparison was also carried out for trucks C and D.

Speed traces are rather similar in chassis dynamometer and on-road testing. There is, however, a rather significant difference in the amount of work accumulated over the cycle.

The difference in cumulative work between the on-road and chassis dynamometer tests arises from handing of gradient simulation on the chassis dynamometer. In actual running conditions on the road, the engine load is reduced going downhill, even down to zero, depending on how steep the downhill is. This was not the case on the chassis dynamometer, as the engine was subjected to load even in simulated downhill conditions. This means that on the chassis dynamometer, the effect of the gradient on power demand in downhill sections of the cycle was not replicated correctly. As a consequence, accumulated work on chassis dynamometer was some 30 to 40 % higher compared to the on-road measurements.

The outcome seen in Figure 81 means that the chassis dynamometer in this particular case, when gradient simulation is included, subjects the test vehicle to loads higher than in real-life conditions. Similar results were found for trucks C and D. It should be noted that normal chassis dynamometer testing does not include simulation of road gradient. Therefore, the WHVC test results, without any simulation of gradient, produced by the participants in this project should be comparable, and the results should be backwards comparable with, e.g., the results of the previous “COMVEC” project.

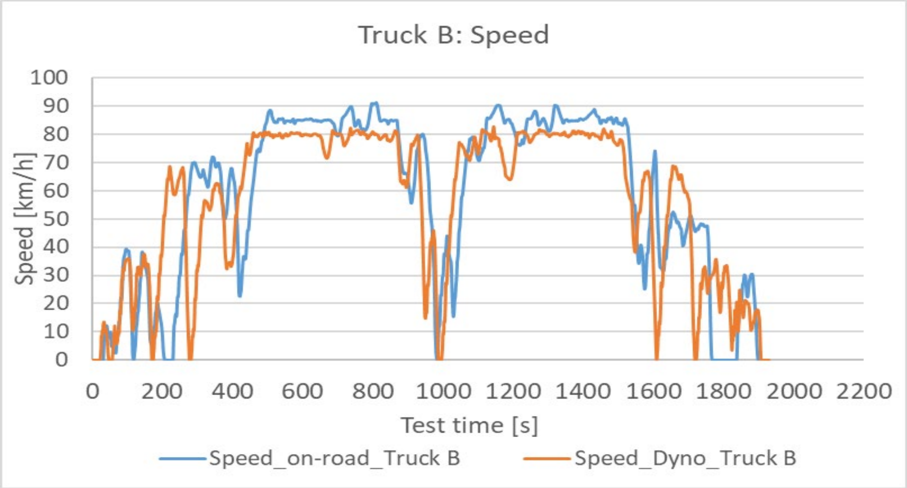


Figure 80: Speed profile comparison between measurements on-road and chassis dynamometer, truck B.

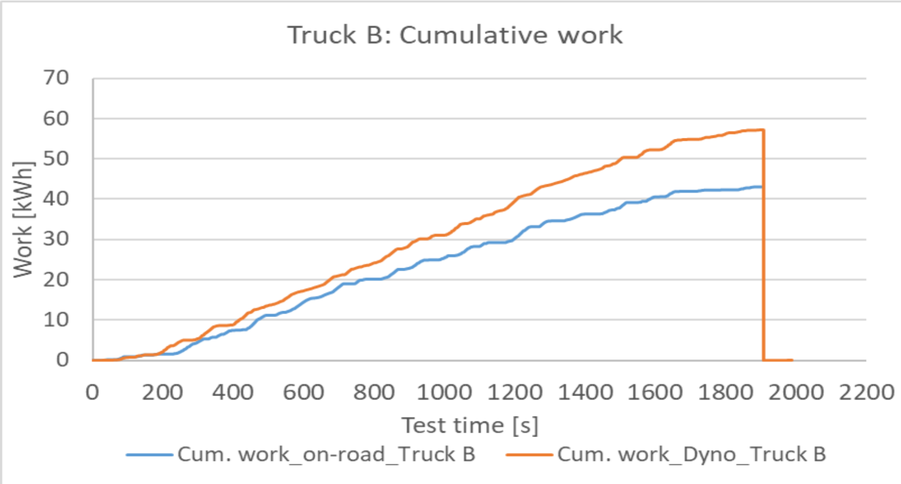


Figure 81: Comparison of cumulative work on engine between measurements on-road and chassis dynamometer, truck B.

NO_x-concentration on-road monitoring

In this section NO_x concentration monitoring results are presented. On-road monitoring were performed for three trucks:

- Truck B, which also was tested on the chassis dynamometer and with the PEMS device on-road
- Rigid truck G, which has similar Euro VI Step D engine as truck C
- Rigid truck H, which in principle has the same HPDI LNG engine as truck D, but is certified to Euro VI Step C (truck D is of Step D)

Each truck was operating long-haul, to inland Finland and back, one leg being typically some 350 km (e.g., Helsinki – Jyväskylä – Helsinki), and typical daily mileage was between 700 to 900 km. Truck B was also operating occasionally from Helsinki to Oulu, one leg being 600 km.

Figure 82 shows average pre- and post-SCR (exhaust after-treatment, EAT) NO_x concentrations and average NO_x conversion efficiency throughout the whole monitoring period. Figure 83 shows the daily average NO_x concentration for each truck throughout the whole monitoring period. It was decided to include data only from days in which driving exceeded two hours. The reasoning here was that driving less than two hours per day does not represent typical long-haul operation.

The monitoring system on truck B was out of order during the winter period 2020 (January-March). The first time malfunction was due to condensed water in the pressure sensor, and the second time due to faulty NO_x sensors. This can be seen in Figure 83 as a lack of data.

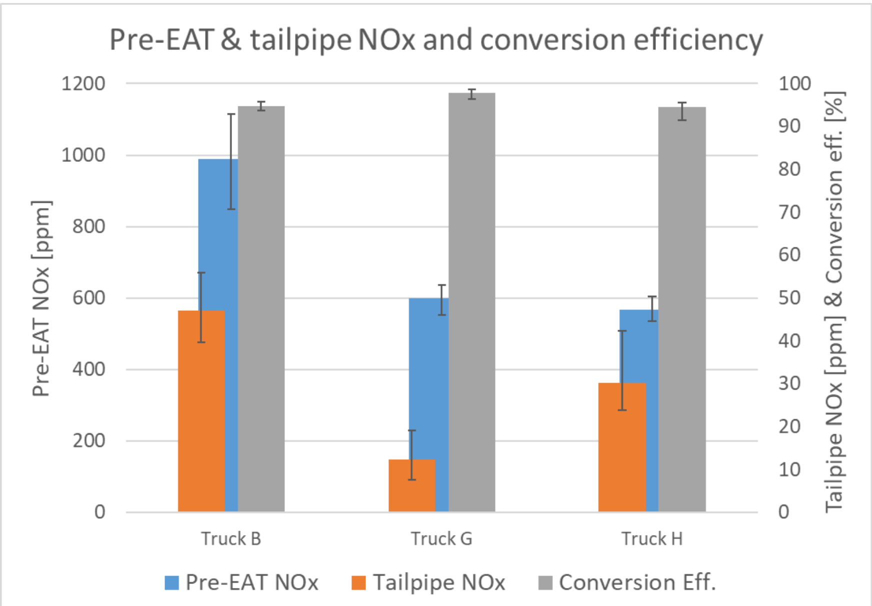


Figure 82: Average pre- and post-EAT tailpipe NO_x concentration and conversion efficiency during the monitoring period.

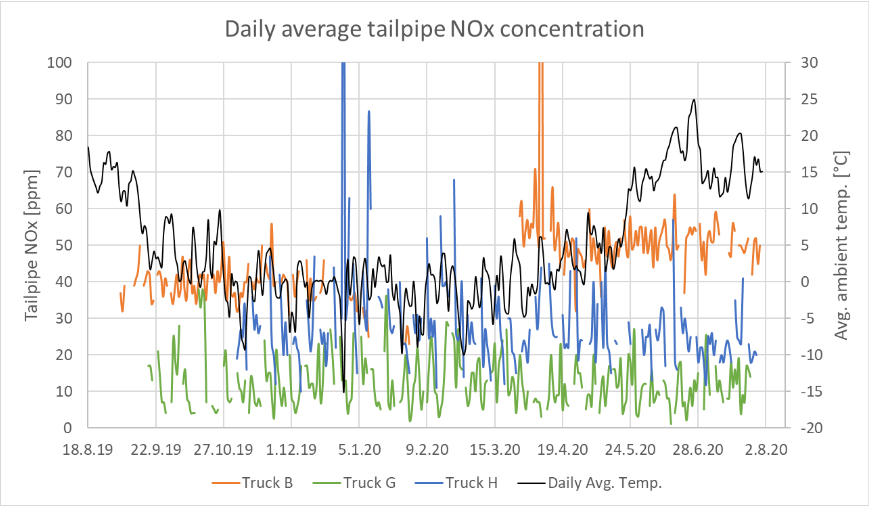


Figure 83: Daily average tailpipe NO_x concentrations throughout the monitoring period. Average temperature is shown for Jyväskylä.

One objective for the NO_x concentration monitoring was to compare the NO_x sensors used in the PROCARE Drive device with NO_x measurements using PEMS and the AVL AMA i60 analyzer set in VTT's chassis dynamometer laboratory. The comparisons were made using the SI LNG truck B.

In Figure 84 and Figure 85 the PROCARE Drive NO_x concentration reading is compared with readings of the PEMS system and the AVL AMA i60 analyzer. The comparison to the PEMS device is made on-road driving the HDVPerE cycle. The comparison to the AVL AMA i60 analyzer is made in the laboratory driving hot start WHVC on the chassis dynamometer. Both tests were made with actual or simulated inertia of approximately 30 tons.

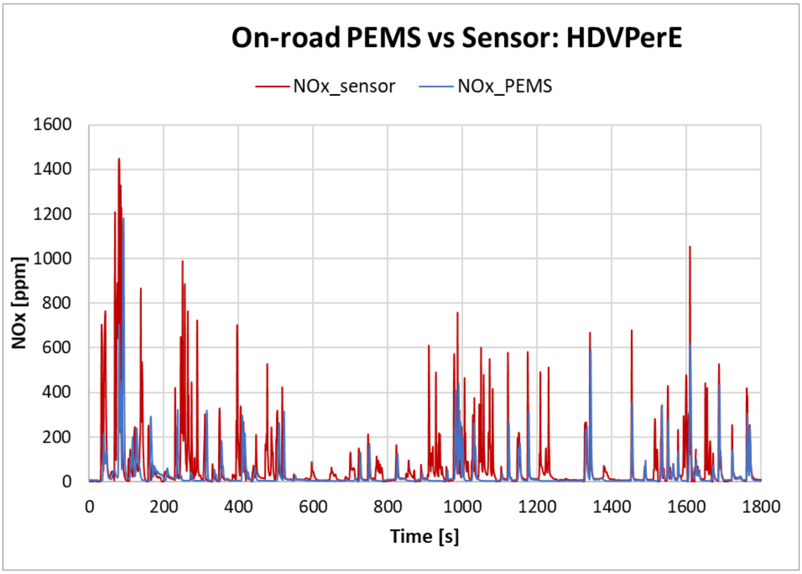


Figure 84: Comparison of PROCARE Drive and PEMS devices for NO_x concentrations. On-road test following the HDVPerE cycle.

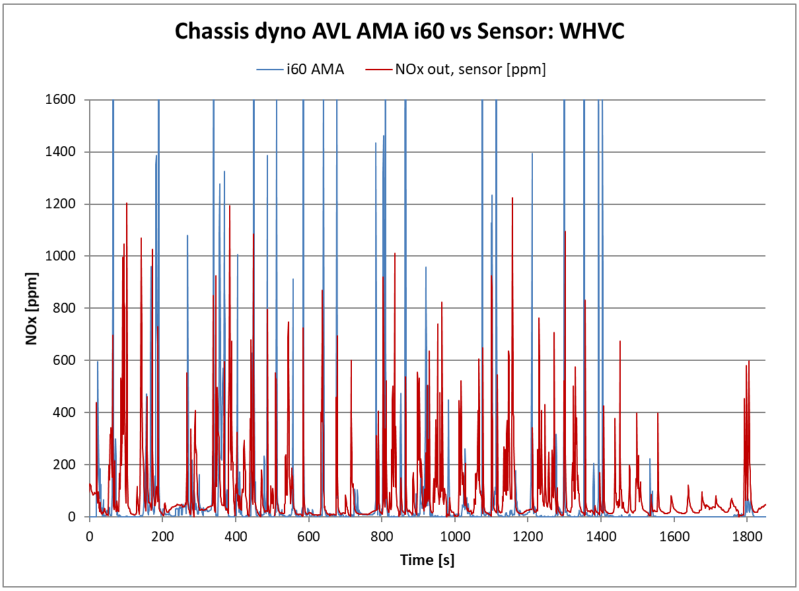


Figure 85: Comparison of PROCARE Drive and AVL AMA i60 devices for NO_x concentrations. Hot WHVC chassis dynamometer test.

Discussion

General

The Finnish contribution provides a solid comparison of the performance of technology and fuel alternatives in the heaviest truck segment. As all trucks, representing four different fuel or combustion technology alternatives were tested on the chassis using the same dynamometer settings, the results to a very high degree describe the performance of the engine themselves, especially as all trucks were equipped with robotized mechanical gearboxes. Some differences may arise from variations in gear ratios and shift strategies, but all the same the values related to work at the driving wheels form a solid base for comparisons.

Energy consumption and CO_2 emissions

The main observation is that there is a significant difference in energy consumption between engines operating on compression ignition (conventional diesel, HPDI methane and ED95) compared to SI methane engines. The additional energy consumption for SI methane engines over full test cycles is 27% (HDVPerE, 30 t) to 32% (WHVC, 30 t).

The two SI methane trucks performed slightly differently. When looking at WHVC modal results, truck A shows highest energy consumption in the urban phase, as expected. For truck B, on the other hand, energy consumption is at its highest in the motorway phase.

The two diesel trucks, C and F, show rather similar energy consumption, as the difference on an average between the tow trucks is less than 2 %. Compared to the two diesel trucks, the HPDI truck D has 6 - 7% higher energy consumption and the ED95 truck E 2 – 4% lower energy consumption, independent of the cycle and load.

Energy consumption is 1 – 6% higher in cold testing versus hot testing, the difference is at minimum for ED95 truck E and highest for all three trucks using methane, A, B and D.

In the hot WHVC motorway phase, depicting true long-haul service, highest engine efficiency was 46% for diesels, 42% for HPDI LNG and 36% for SI methane.

CO_2 emissions relate directly to energy consumption and specific CO_2 emission (g CO_2/MJ) of the fuel. In this respect, methane has an advantage over diesel fuels, 55.1 g CO_2/MJ for methane and 73.2 g CO_2/MJ for diesel. However, for CO_{2eqv} emissions, also methane and N_2O have to be taken into account. Some methane slip can be seen in all gas engines (Figure 66). Some SCR catalysts, depending on the chemistry, tend to form N_2O (Figure 67, particularly trucks D and F).

The CO_{2eqv} emissions of the two SI methane trucks fall in the range of -9 to $\pm$0% relative to the diesel average, depending on the cycle. The benefit from the chemical composition of methane (lower CO_2 intensity compared to diesel) is nullified by the low thermal efficiency of the SI engines. The ED95 truck delivers somewhat lower CO_{2eqv} emissions than diesel, on an average -2% (+2…-5%) relative to diesel.

The only technology that really lowers tailpipe (TTW) CO_2 and CO_{2eqv} emissions is HPDI dual-fuel, which on an average delivers 18% (CO_2 only) and 14% (CO_{2eqv}) lower emissions than diesel. This stems from chemistry of the main fuel (methane) and engine efficiency only moderately lower compared to conventional diesel engines.

On-road measurements were done with three trucks, truck B (SI methane), C (diesel) and D (HPDI dual-fuel). Comparing HDVPerE energy consumption values from chassis dynamometer and on-road testing reveals than the on-road values are some 25 – 30% lower. Differences can also be seen when studying cumulative work.

Regarding energy consumption, on-road testing ranks the trucks in the same order as chassis dynamometer testing; highest for truck B (SI LNG) and lowest for diesel (C), with HPDI LNG (D) in between. However, the differences are now higher. For the HDVPerE cycle, additional consumption for truck B is 37% (35% in the chassis dynamometer) and 16% (7% in the chassis dynamometer) for truck D, relative to diesel truck C. In ISC testing, corresponding values are 45% for truck B and 17% for truck D.

On the road, truck B emits 3 – 9% more CO_2 than diesel truck C, whereas truck D emits 10 – 11% less than the diesel (CH_4 and N_2O not accounted for).

<u>Pollutant emissions</u>

For all vehicles, the aggregated (combined cold and hot) WHVC NO_x value is less than 400 mg/kWh at the driving wheels. The ED95 truck E has the highest value, 345 mg/kWh. Relative to work on the engine crankshaft, taking into account losses in the transmission and auxiliaries, this would be equivalent to some 300 mg/kWh. The conclusion here is that regarding NO_x emissions all truck are within Euro VI requirements with a clear margin (actual engine certification limit value is 460 mg/kWh, for ISC testing, a conformity factor (CF) of 1.5 applies).

Temperature (cold vs hot start) has a significant effect on the NO_x emissions of SCR catalyst equipped trucks (trucks C, D, E and F). The sensitivity to temperature of the SI engines with TWCs (trucks A and B) is much smaller. This indicates that a TWC reaches operating temperature much faster than a SCR catalyst.

With the exception of the SI LNG truck B, all trucks have aggregate PM emissions of less than 2 mg/kWh at the driving wheels. The value for truck B is 3.5 mg/kWh at the driving wheels, which related to work on the crankshaft would be some 3 mg/kWh. Again, this is well below the actual certification limit for engines, 10 mg/kWh. Test temperature has moderate or no effect on PM emissions.

The certification limit for PN is 6*10^11/kWh at the engine crankshaft. Trucks B to F are all below this value. Truck A, however, has remarkably high PN emissions, an order of magnitude higher than the limit value. As truck B has acceptable PN emissions, the SI combustion system per se should not be the cause of the high PN emissions. For truck A, the explanation could be either bad engine oil control or some problems in the EGR system.

In on-road testing, NO_x values related to work on the engine crankshaft are from 23 to 232 mg/kWh (average values), truck D producing the lowest (ISC) as well as the highest (HDVPerE) value. Variation from test to test is huge, as often is the case in PEMS on-road measurements. However, even the highest individual value, 400 mg/kWh in HDVPerE, is well below ISC requirements.

In most of the on-road tests, PN number emissions are some 1*10^11/kWh at the engine crankshaft. The only exception is truck D in HDVPerE, emitting on average PN of some 12*10^11/kWh, twice the actual Euro VI certification limit value. Also in this case, variation from test to test is high. In chassis dynamometer testing, truck D produced low PN emissions.

Substitute fuels

In the CNG truck A, the low MN fuel has negligible effects on energy consumption, CO_2 emissions and PM emissions (mass). Unburned methane increased significantly, almost 300%, but as N_2O is reduced some 50% there is no significant change in CO_{2eqv} emissions. Particle numbers increase some 60% and CO some 30%, while NO_x was reduced some 30%. The basic performance (efficiency) of the engine is not affected, but a change in stoichiometry results in increase of unburned components (CO,

CH_4) as well as particle numbers but a reduction of NO_x.

In current diesel vehicles, the DPF and SCR effectively reduce PM, PN and NO_x emissions, defining emission levels. However, the functioning of the exhaust after-treatment systems is not necessarily that stable, so typically both particulate and NO_x emissions vary from test to test. This makes assessments of effects of fuel quality on emissions challenging. HVO is compared with regular EN590 diesel fuel in two trucks, C and F, in two cycles, WHVC and HDVPerE. The results for particulate and NO_x emissions should be considered suggestive.

With HVO, particle number emission increase in one truck and decreases in the other. The same phenomena can be seen for NO_x. On an average, there is no change in PN emissions, and a slight decrease, some 15 %, in NO_x emissions. For PM emissions, NO_x emissions and energy consumption the results are consistent and show reductions: -30% for PM, 4% for CO_2 and 1 % for energy consumption. The reductions in CO_2 emissions and energy can be directly attributed to fuel properties and chemistry. Specific CO_2 is lower for HVO, 70.8 g CO_2/MJ compared to 73.2 g CO_2/MJ for conventional diesel. HVO has high Cetane number, which is beneficial for engine efficiency. Thus, the consistent reduction in CO_2 is a combination of a small increase in engine efficiency and a more favorable hydrogen-to-carbon ratio of the paraffinic HVO fuel.

The fuel comparison was done with fully warmed-up engines, as repeatability from test to test is smaller than for cold start testing. In addition, in the heaviest truck segment, operation is typically warmed-up operation. In the case of diesel engines, the high Cetane number HVO fuel might have given additional benefits in clod start testing, both regarding efficiency and emissions of unburned components.

Chassis dynamometer versus on-road testing

A comparison of chassis dynamometer and on-road testing using VTT's HDVPerE cycle revealed that the accumulated work was significantly higher in the chassis dynamometer that in on-road testing. The HDVPerE cycle included simulation of road gradient, and it could be concluded that in simulated downhill driving, the dynamometer put load on the engine, whereas in real life, the vehicle part of the time rolled freely without any output from the engine. If chassis dynamometer testing is to include simulation of road gradient, more calibration work has to be made to guarantee accurate results.

On-road NO_x concentration monitoring

The results of NO_x concentration monitoring in Figure 82 and Figure 83 show that all exhaust gas after-treatment systems, TWC in truck B and SCR in trucks G and H, worked relatively well throughout the monitoring period. Notwithstanding, a couple of days with high post after-treatment NO_x concentrations were encountered for truck B and H during the winter period when the temperature was close to 0 °C or clearly under.

On an average, engine-out NO_x concentration was some 1000 ppm and tailpipe concentration some 50 ppm for the SI LNG truck B. Engine out NO_x concentration fluctuated more than tailpipe NO_x concentration. The average NO_x conversion efficiency was around 95 %.

Figure 83 reveals that after the damaged NO_x sensors were replaced, average post-after-treatment concentrations measured by the system increased approximately 10 ppm compared to levels before the failure of the system. No clear reason for this could be identified. The replacement NO_x sensor was of the same type as the one originally installed and should have had the same characteristics.

The Euro VI Step D diesel truck (G) had an average engine-out NO_x

concentration of some 600 ppm and a tailpipe NO_x concentration of some 10 ppm. Stable effective operation with low fluctuation lead to a NO_x conversion efficiency of around 98%.

The Euro VI Step C HPDI dual-fuel truck H also had an average engine-out NO_x concentration of some 600 ppm, but the tailpipe NO_x concentration was higher, some 30 ppm. This leads to a NO_x conversion efficiency of approximately 95%, same as for truck B.

Overall, the results are well in line with the chassis dynamometer results. Truck C (diesel) and D (HPDI dual-fuel) had the low NO_x emissions on the chassis dynamometer, and truck G, basically equal to truck C, performed very well in the field. Truck H had the same HPDI LNG engine as truck D, but it was of the previous generation Euro VI Step C. This can explain the difference compared to truck G in the field.

The PROCARE Drive NO_x concentration monitoring system was compared with NO_x measurements using PEMS and the AVL AMA i60 analyzer set. The test were carried out with the SI LNG truck B. Figure 84 shows that the NO_x sensor of the PROCARE Drive system in most cases detect the same NO_x peaks as the PEMS device when driving the HDVPerE test on-road. However, it can also be seen that the sensor of the monitoring system seems to overestimate the peaks and in some cases even measures peaks that PEMS device does not detect. This is reflected in the cumulative NO_x emissions. Cumulative NO_x emissions over the presented cycle measured with PEMS device were around 7.2 g of NO_x whereas measured with the PROCARE sensor cumulative emissions were around 18 g of NO_x. Overall, the concentration level measured with the monitoring system is higher than that detected by the PEMS device. This is also directly reflected in NO_x emissions.

Figure 85 shows the comparison with the AVL AMA i60 device for hot start WHVC. In this case, the NO_x sensor seems to underestimate most of the peaks. However, it seems to be more sensitive in the way that it detects peaks that the AVL AMA i60 did not detect, showing the kind of rapid response seen in the on-road testing. Also in this case the monitoring system gives a higher overall concentration than the reference instrument.

All in all, the sensor seems to overestimate NO_x levels in case of SI-LNG engine. An explanation for this might be that in the case of SI methane, the sensor suffers from cross interference with some exhaust gas components typical for a methane burning engine. Possible other reasons for misdetections might be the stoichiometric exhaust gas with close to zero excess oxygen and high share of water in exhaust gas.

Sweden

General

Sweden contributed with chassis dynamometer and on-road measurements of six Category 2 vehicles, two rigid trucks and four tractors. In the case of the rigid trucks, comparison is between diesel and spark-ignited methane. In the case of the tractors, comparison is two dimensional: diesel versus HPDI dual-fuel, on one hand and Euro VI C versus Euro VI D certification, on the other hand.

The results from the two groups of vehicles are presented separately as the vehicles are intended for different types of services (local operations versus long haul). The rigid trucks were tested in the chassis dynamometer. The tractors were tested in the chassis dynamometer and on-road. Most of the figures presented for the tractors encompass results from chassis dynamometer as well as on-road testing.

Comparison between diesel and CNG (rigid trucks, Euro VI)

Energy consumption and CO_2 emissions

Figure 86 shows a comparison of measured energy consumption from the CNG and the diesel vehicle. As shown, the CNG vehicle consumed more energy per kilometer (MJ/km) than the diesel vehicle in all tests. The difference in energy consumption ranged from 16 to 26%. The difference was smaller during cold starts and larger in cycles with more urban driving.

Both vehicles were tested with the same weight, 14 tons. Relative to vehicle weight, the energy consumption ranges from 0.57 to 1.29 MJ/km/1000 kg vehicle weight for the diesel vehicle and from 0.73 to 1.58 MJ/km/1000 kg vehicle weight, depending on cycle and test condition.

Figure 87 shows CO_2 emissions.

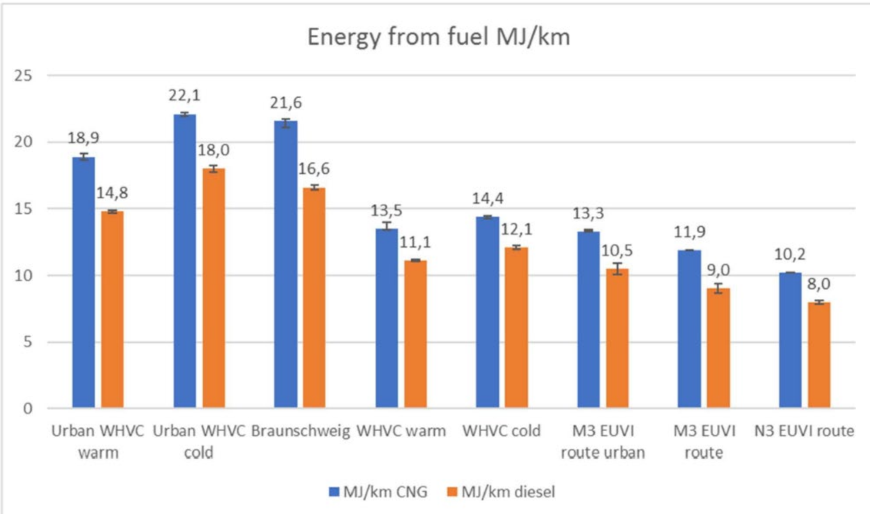


Figure 86: Energy consumption.

The CNG emitted slightly lower levels of CO_2 from its tailpipe during all cycles (Figure 87). The difference on the chassis dynamometer varied from ~1 % in the Braunschweig cycle to 9.8% in the WHVC cold cycle. The difference on the road varied from 1.5% in the M3 route to 5.8% in the N3 route. This is a far lower difference compared with the difference in carbon content in the fuels.

When including CH_4 and N_2O in the overall GHG emissions, the advantage was eliminated in the cold WHVC, but due to the relatively small CH_4 emissions from the warmed up vehicle, a small advantage remained in the other cycles. Figure 88 shows CO_{2eqv} emissions. CH_4 and N_2O are taken into account with Global Warming Potential (GWP) for 20 (GWP20) and 100 (GWP100) years.

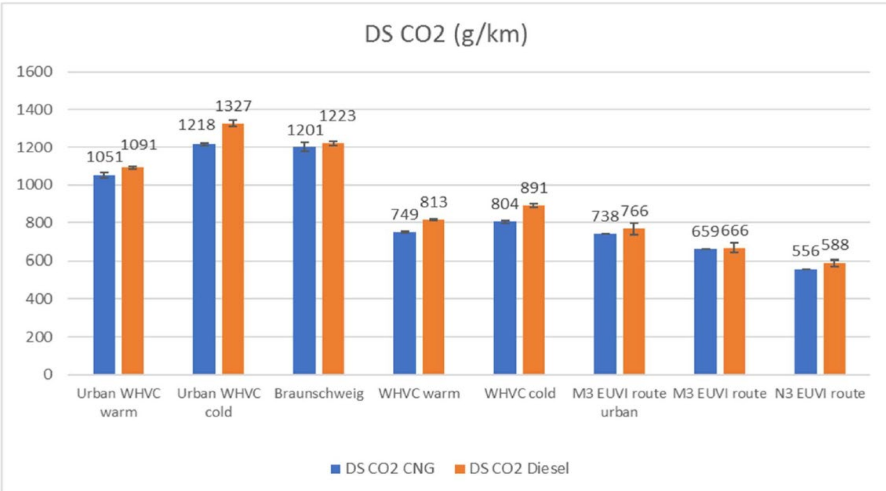
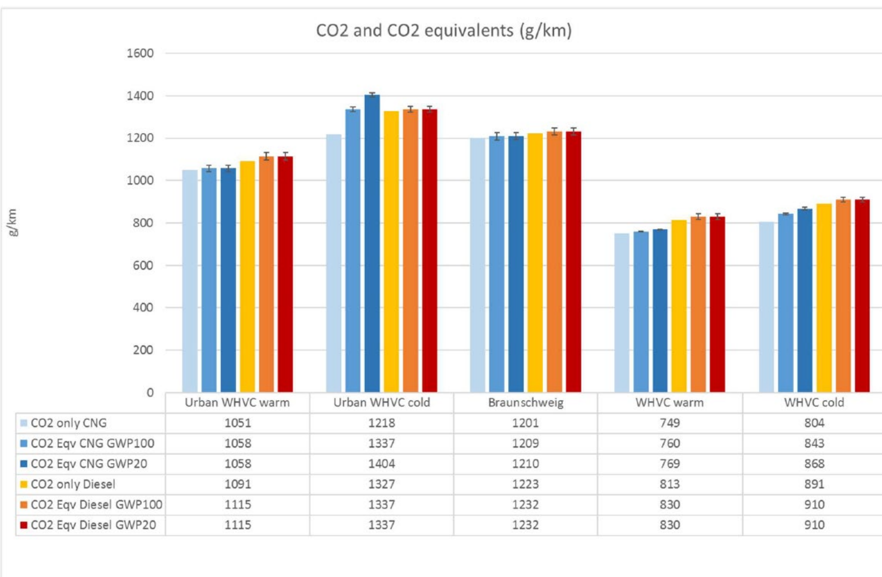


Figure 87: CO_2 emissions.



	Urban WHVC warm	Urban WHVC cold	Braunschweig	WHVC warm	WHVC cold
CO2 only CNG	1051	1218	1201	749	804
CO2 Eqv CNG GWP100	1058	1337	1209	760	843
CO2 Eqv CNG GWP20	1058	1404	1210	769	868
CO2 only Diesel	1091	1327	1223	813	891
CO2 Eqv Diesel GWP100	1115	1337	1232	830	910
CO2 Eqv Diesel GWP20	1115	1337	1232	830	910

Figure 88: CO_{2eqv} emissions.

The CNG vehicle in this study is of Euro VI emission standard and only relatively small amounts of CH_4 can be seen in the tailpipe emissions in warmed-up conditions. There is no methane coming from the diesel vehicle in any test (Figure 89).

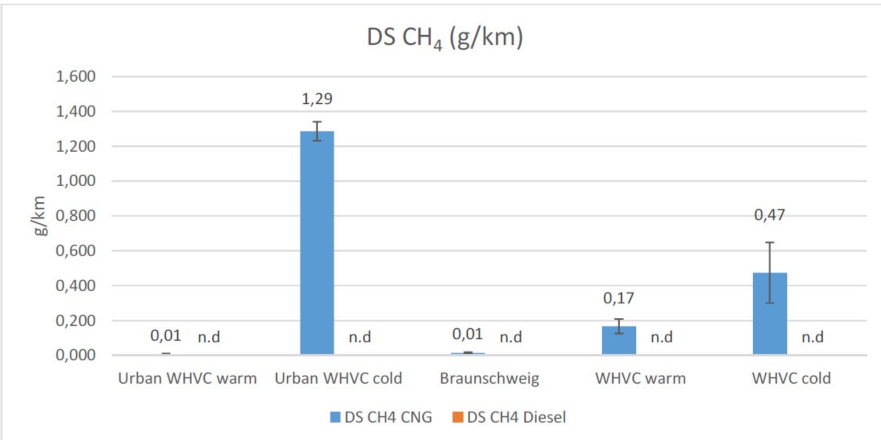


Figure 89: CH_4 emissions.

Pollutant emissions (NO_x, PM and PN)

Figure 90 shows NO_x emissions, Figure 91 split between NO and NO_2, Figure 92 THC emissions, Figure 93 PM emissions and Figure 94 PN emissions.

The CNG vehicle had a small advantage in NO_x emissions in all cold start test cycles on the chassis dynamometer. However, no significant difference could be seen during the hot start tests. The ambient temperature difference during the PEMS tests (20˚C for the CNG vehicle and 4˚C for the diesel vehicle) had no significant effect on the result. The CNG vehicle emits practically no direct NO_2.

THC values are low for the diesel vehicle. In the case of the CNG vehicle, although the greater part of THC is CH_4, there is still a considerable portion of non-methane hydrocarbons (NMHC).

In all tests, PM was higher from the diesel vehicle than for the CNG vehicle. PN numbers, on the other hand, were significantly higher for the CNG vehicle compared to the diesel vehicle.

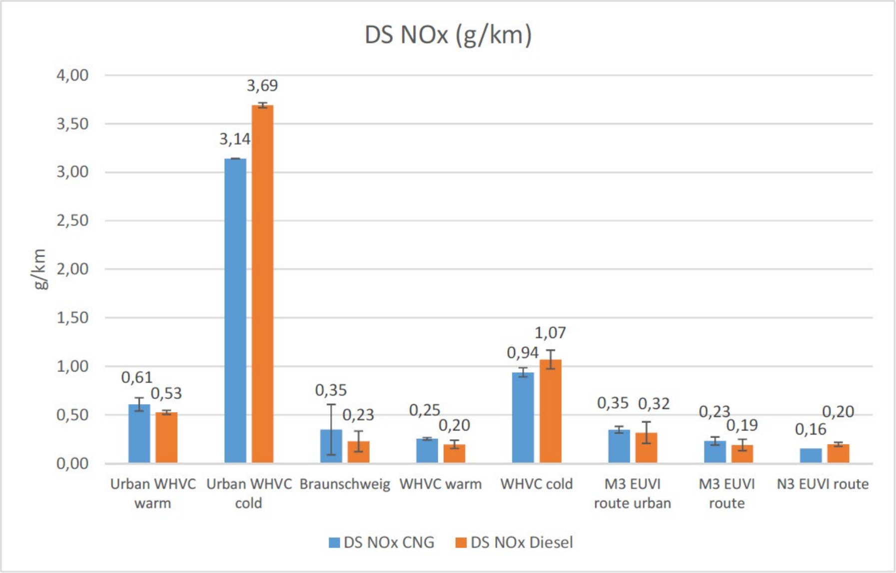


Figure 90: NO_x emissions.

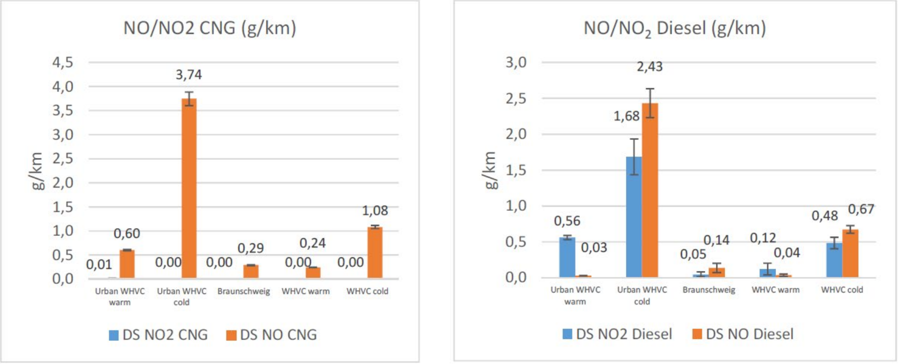


Figure 91: NO/NO_2 emissions.

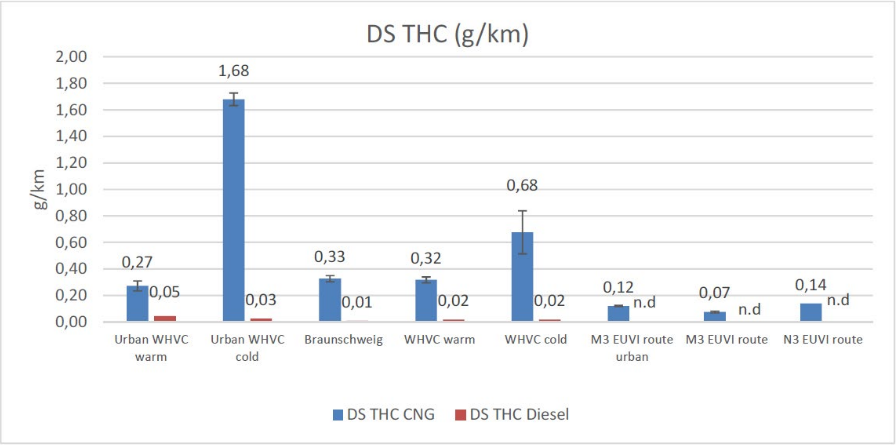


Figure 92: THC emissions.

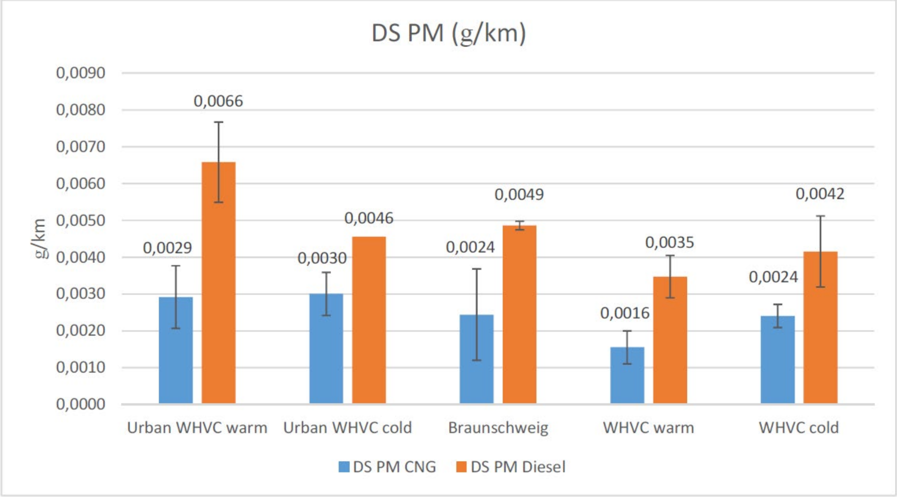


Figure 93: PM emissions.

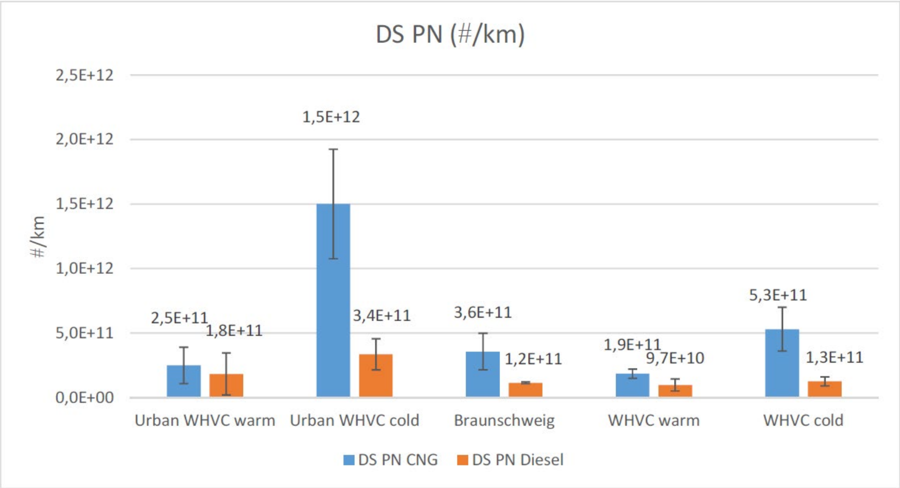


Figure 94: PN emissions.

Discussion

The specific carbon intensity of methane, expressed g CO_2/MJ, is some 25% lower compared to diesel. However, the tailpipe CO_2 emission is a product of engine efficiency and fuel carbon intensity. Because throttling is needed at part load and the compression ratio is limited to avoid knock, the efficiency of the SI stoichiometric gas engine is considerably lower than that of the diesel engine. In this case, the CNG truck consumes 16 – 26% more energy than the diesel truck. This partly offsets the benefits of the lower carbon content for the CNG fuel. With CNG, CO_2 emissions were 1 – 10 % lower compared to diesel.

On the chassis dynamometer, the vehicles were tested using both the WHVC and the Braunschweig test cycle. Figure 86 shows that regarding energy consumption, the urban part of WHVC and the overall Braunschweig cycle deliver roughly equivalent energy consumption.

Typically the addition from CH_4 and N_2O to total GHG emissions was less than 0.5% in the hot cycles compared with the CO_2-only case. When testing included cold start, the addition was higher, approximately 5-8% (WHVC, cold start). In cold start testing, the CH_4 slip further reduces the advantage of methane.

The TWC of the CNG vehicle seems to light off faster than the SCR catalyst on the diesel, therefore a small advantage regarding NO_x for the CNG vehicle in testing with cold start.

NO_x is made up of both NO and NO_2. However, NO_2 is considered to have a greater impact on human health than NO. NO can easily be oxidized to NO_2 and in modern diesel vehicles, an increase of NO_2 is sometimes induced in the oxidation catalyst in order to improve the performance in the downstream components of the after treatment system. Unfortunately, the increased level of NO_2 often reflects in the tailpipe emissions from diesel vehicles. For the CNG vehicle, the majority of the NO_x emissions were NO while for the diesel vehicle, a great part of the NO_x emissions were NO_2.

In the past, CNG vehicles have had an advantage over diesel vehicles regarding NO_x emissions, but in this case the testing indicates that the transition to Euro VI has, for heavy-duty diesel vehicles, been very effective in cutting overall NO_x emissions.

The CNG vehicle emits some methane emissions during the cold starts and, in addition, during the motorway phase of each test where the exhaust flow increases and the TWC capacity probably reaches its reduction limit. For the PEMS tests, only THC is measured, not methane. Assuming most of the THC consists of methane, the same phenomena of increased methane emissions during the motorway phase can be seen also in the PEMS tests.

The diesel truck emits low levels of THC/NMHC, just as expected from a Euro VI Diesel vehicle with a well-functioning DOC. The CNG truck showed significantly higher levels of NMHC, also appearing to be rather constant in all cycles and is most likely caused by engine oil.

PM emissions were very low, and well below the EU standard. In all tests, particularly the cold start tests, the PN emissions were significantly higher for the CNG vehicle than for the diesel vehicle. The PN levels correlate well with THC which, for the CNG vehicle, indicates PN emissions in the form of small volatile particles originating from the engine oil consumption across the piston rings as the stoichiometric engine throttles and induces low pressure in the combustion chamber.

The measurements performed were limited to a low number of vehicles, and to be able to draw any clear conclusions regarding the energy efficiency of the latest generation gas engines, more vehicle specimens need to be tested. Older generation CNG vehicles are often associated with high levels of unburned methane slipping through the engine in the combustion process. The CNG truck in this study is of Euro VI emission standard and only relatively small amounts of CH_4 can be seen in the tailpipe emissions.

Comparison between diesel and HPDI dual-fuel (tractors, Euro VI C and D vehicles)

General

As stated previously, in the case of the tractors, comparison is two dimensional: diesel versus HPDI dual-fuel, on one hand and Euro VI C versus Euro VI D certification, on the other hand. Testing the Step C and Step D tractors was part of the Swedish ISC testing program.

When testing the Step D trucks, PEMS testing was repeated for Step C trucks, so some Step D Figures also include Step C results as a reference.

The two Step D vehicles were the same individuals that were also tested in Finland. However, a direct comparison between Finnish and Swedish test results for these vehicles is difficult. In Sweden, the WHVC chassis dynamometer tests were done simulating an inertia of some 20 tons (limited by the chassis dynamometer), whereas VTT tested simulating inertia of 30 and 44 tons. However, on road-testing in both Finland and Sweden was done with vehicle weights of some 30 tons.

Energy consumption and CO_2 emissions

Figure 95 (Step C) and Figure 96 (Step D) show energy consumption. The general outcome is that HPDI LNG delivers almost identical energy efficiency as diesel.

Figure 97 and Figure 98 show CO_2 emissions. In the chassis dynamometer, in repeatable conditions, HPDI LNG shows a consistent reduction of some 25% compared to diesel. With equivalent fuel efficiency, this is what is to be expected, based on the difference in carbon intensity of the fuels.

Figure 95 to Figure 98 are drawn by the coordinators of the project. The energy consumption for the HPDI LNG vehicles is calculated from the CO_2 emission, assuming a carbon intensity of 56.5 g CO_2/MJ for diesel (8%) and LNG (92%) mix. This corresponds to the methodology used in VTT's measurements (e.g., Figure 55 to Figure 57)

There are some methane slip from the HPDI LNG engines, contributing to the CO_{2eqv} emissions. However, even more important, both types of Step C vehicles generate significant amounts of N_2O, which has a GWP more than tenfold higher than that of methane.

Figure 99 shows CH_4 emissions, and Figure 100 shows N_2O emissions. Figure 101 and Figure 102 show CO_2 equivalent emissions when taking CH_4 into account with a factor 25 and N_2O with a factor of 298, relative to CO_2.

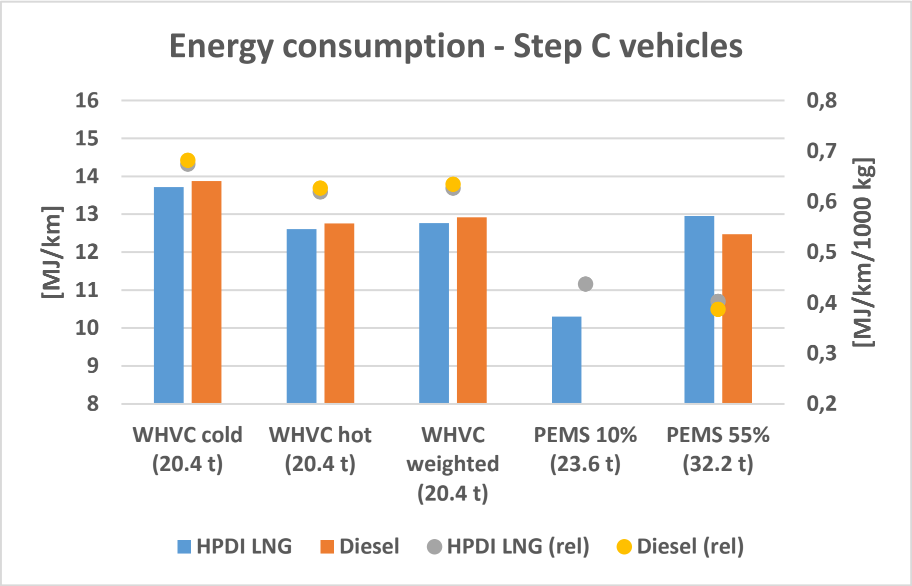


Figure 95: Energy consumption, Step C vehicles.

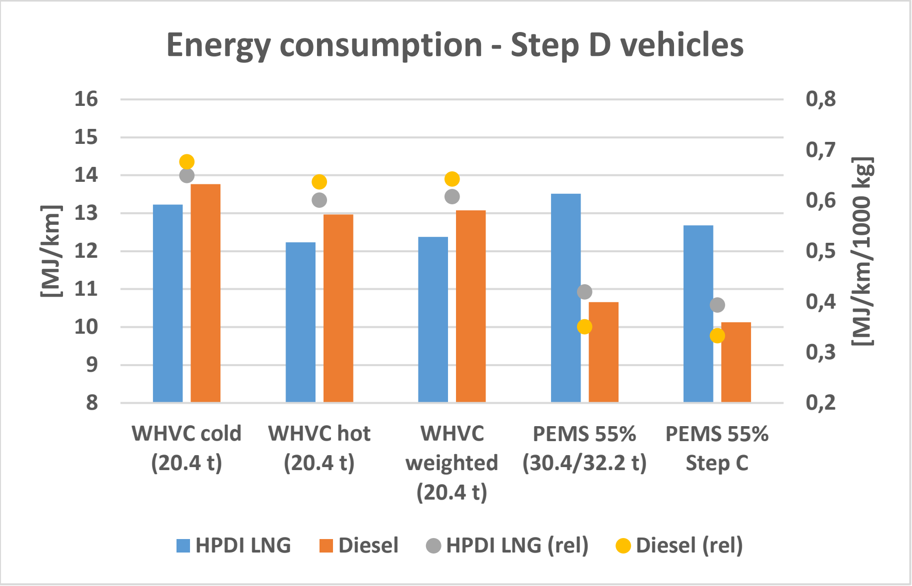


Figure 96: Energy consumption, Step D vehicles (Step C as a reference).

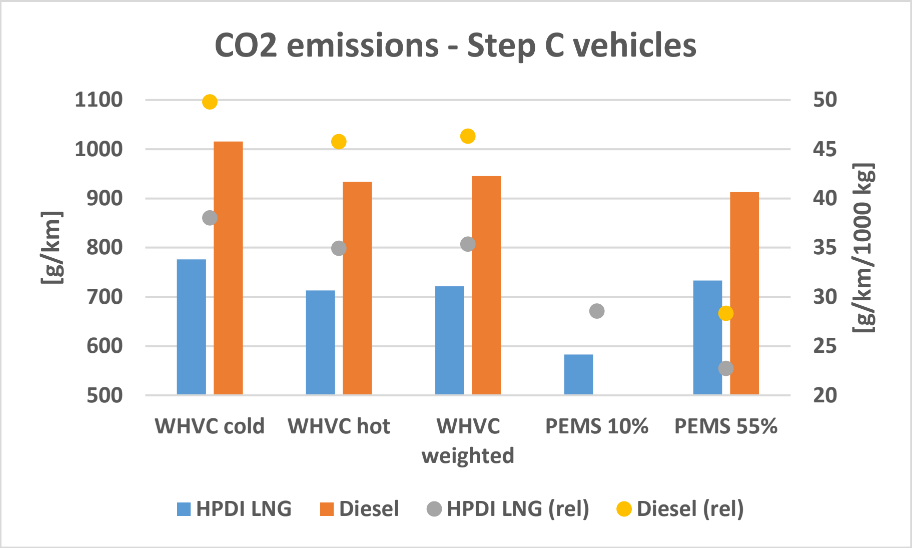


Figure 97: CO_2 emissions, Step C vehicles.

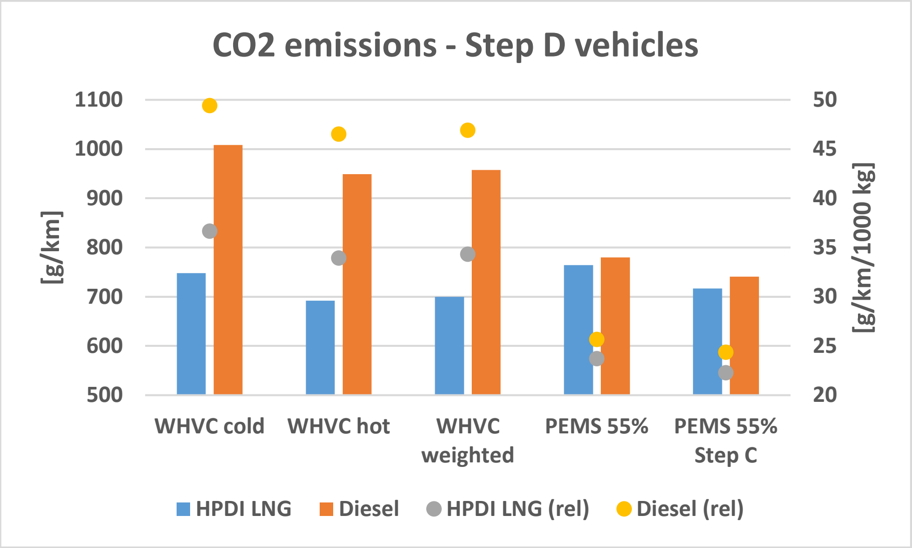


Figure 98: CO_2 emissions, Step D vehicles (Step C as a reference).

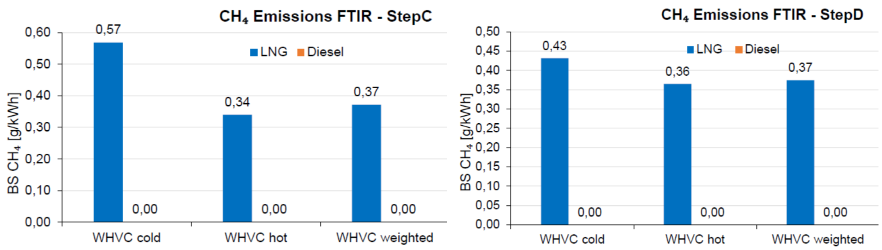


Figure 99: CH_4 emissions, Step C and D vehicles.

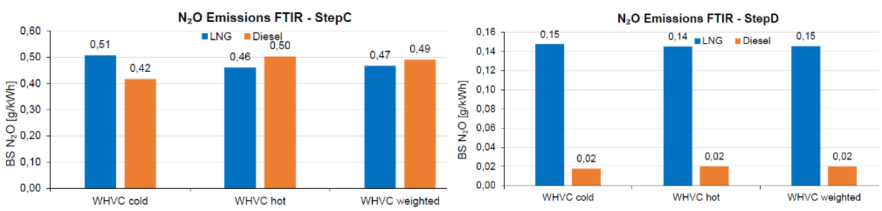


Figure 100: N_2O emissions, Step C and D vehicles.

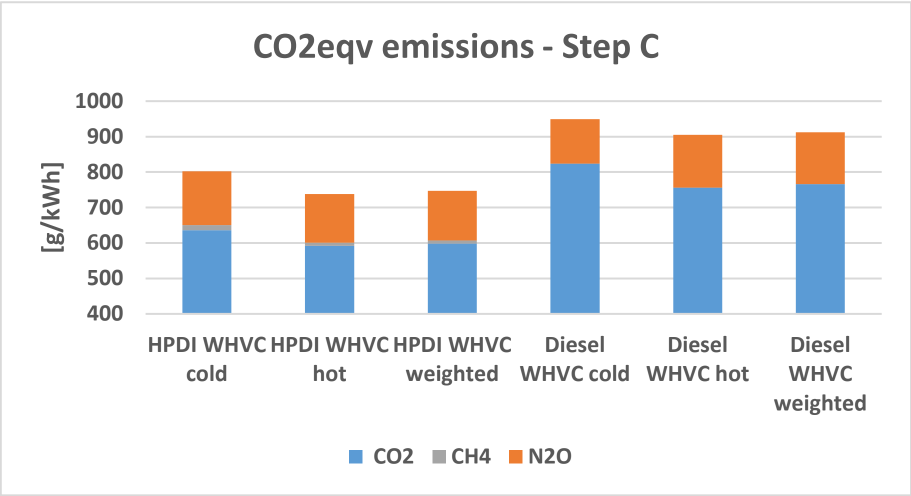


Figure 101: CO_{2eqv} emissions, Step C vehicles.

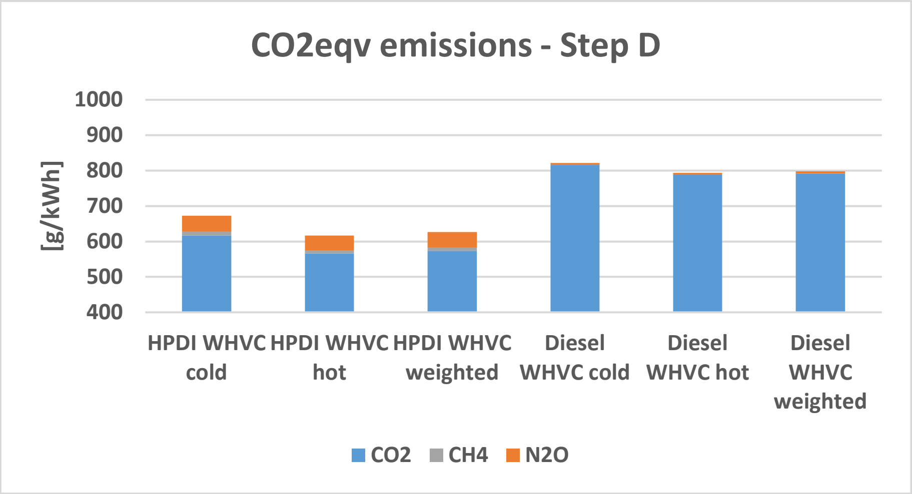


Figure 102: CO_{2eqv} emissions, Step D vehicles (values relative to engine work).

Pollutant emissions (NO_x, PM and PN)

Figure 103 and Figure 104 present NO_x emissions, Figure 105 and Figure 106 PM emissions and Figure 107 and Figure 108 PN emissions.

All NO_x values were well within the ISC requirements, and except for the Step D diesel truck in the WHVC test, also below the actual Euro VI certification limit value.

All measured PM values were low (chassis dynamometer testing). As for PN emissions, the diesels are below the Euro VI limit value of 6*10^11 #/kWh, whereas the HPDI LNG vehicles in some cases were slightly above the limit.

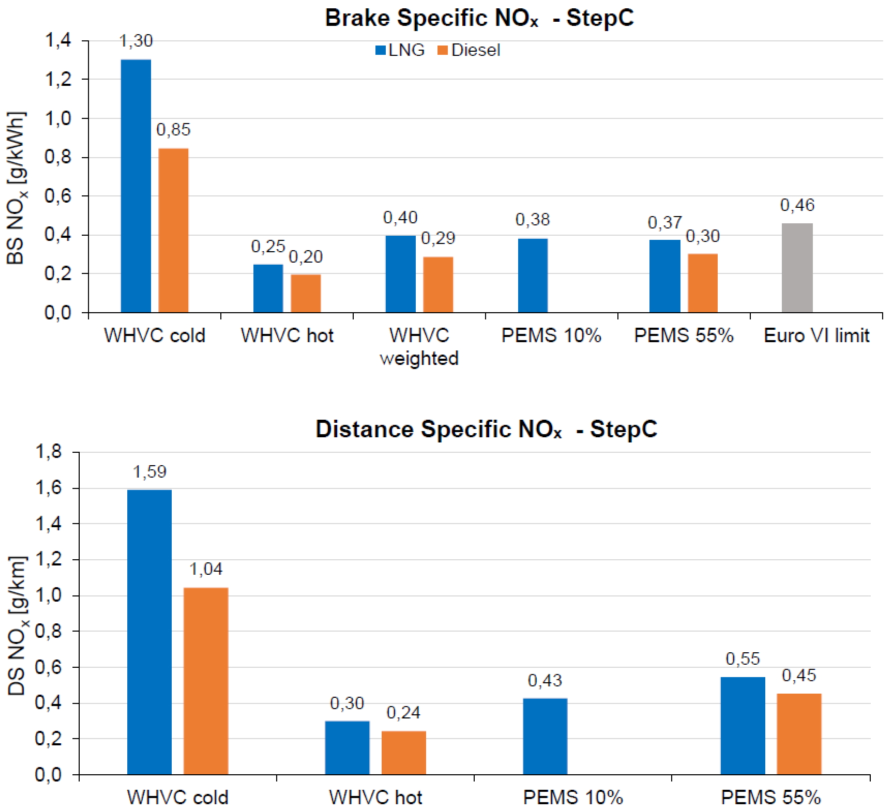


Figure 103: NO_x emissions, Step C vehicles.

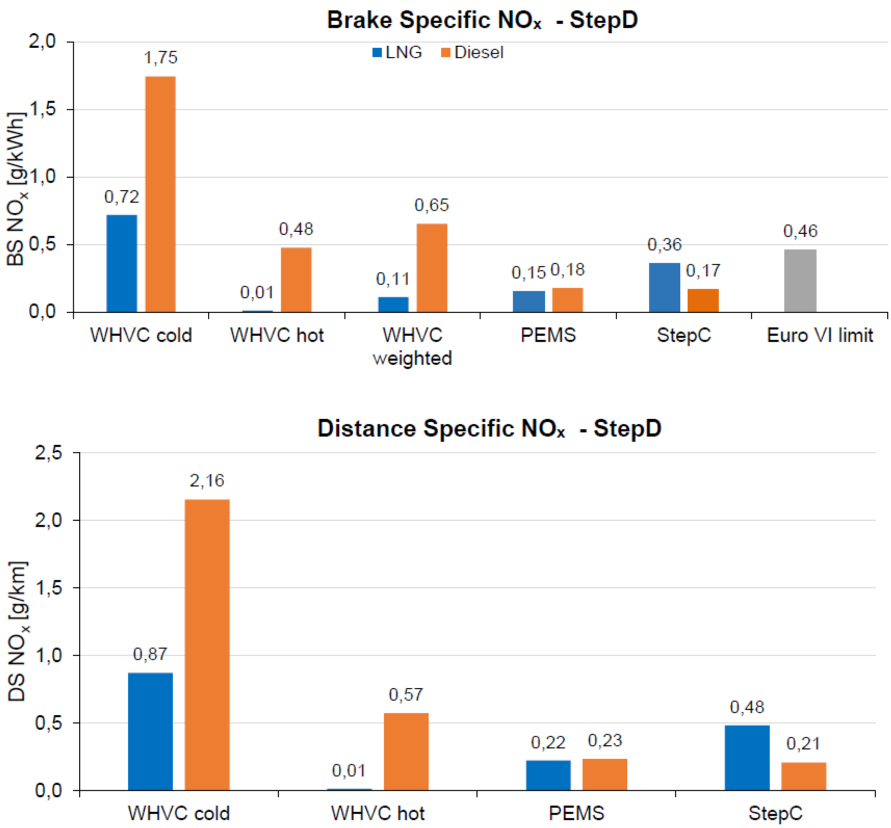
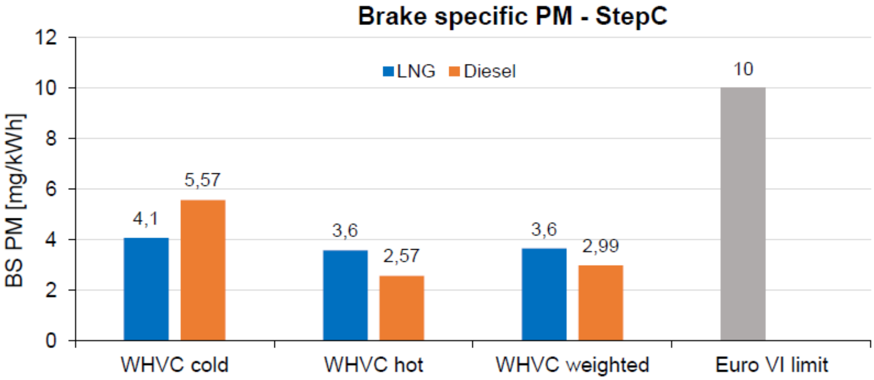


Figure 104: NO_x emissions, Step D vehicles.



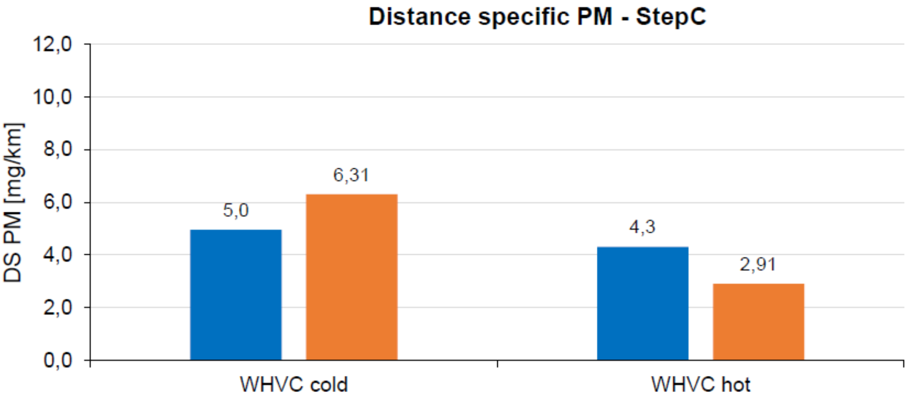


Figure 105: PM emissions, Step C vehicles.

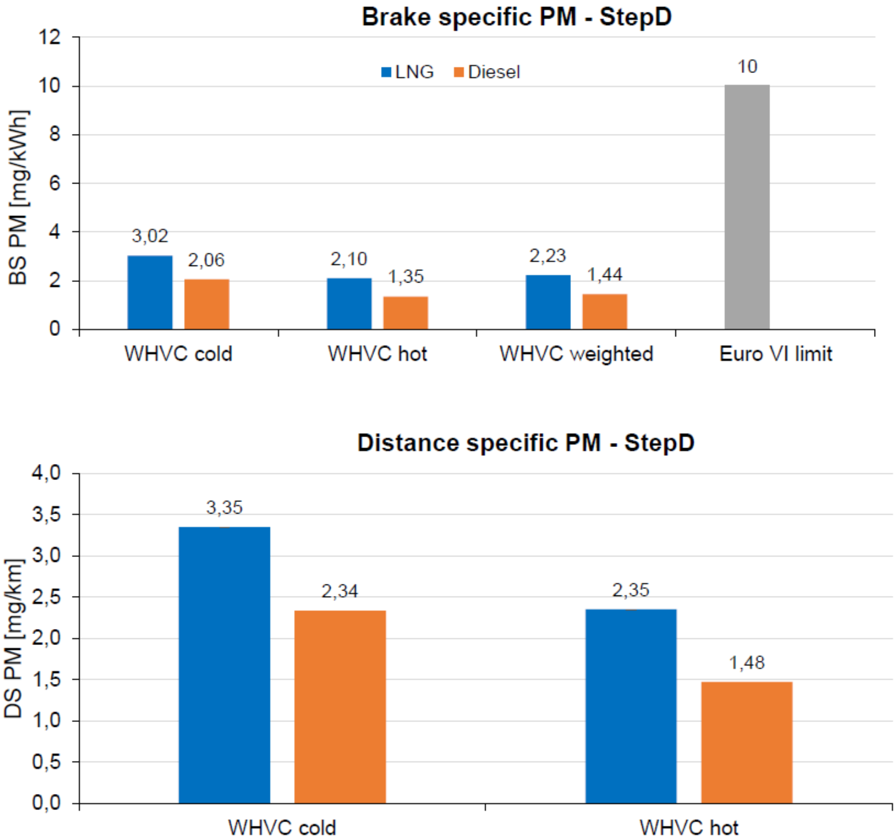


Figure 106: PM emissions, Step D vehicles.

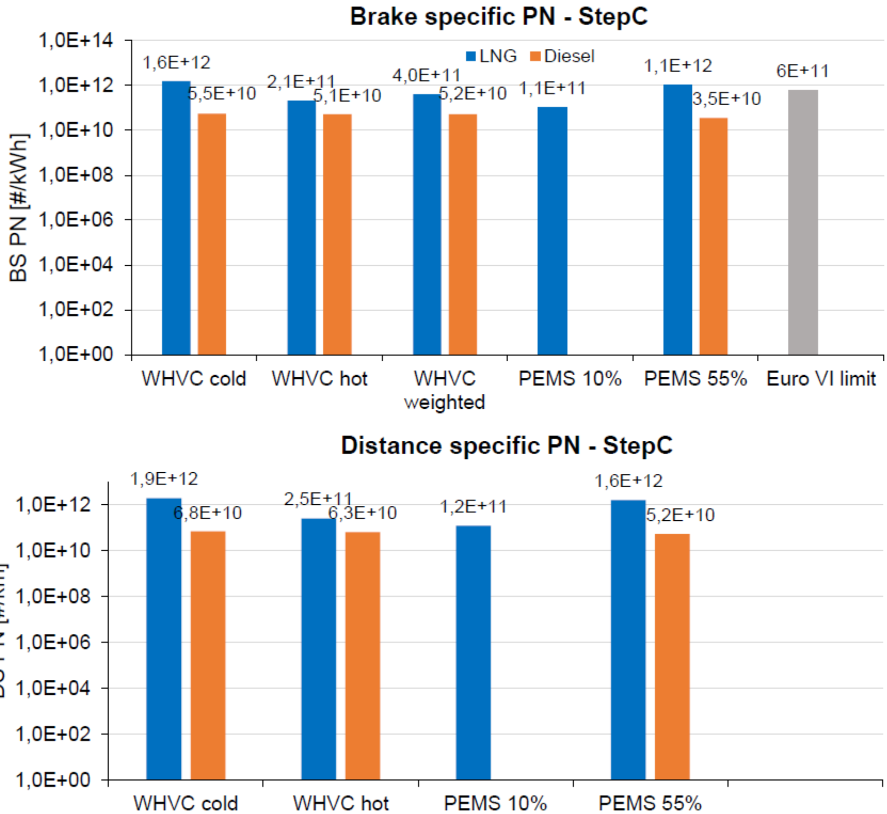


Figure 107: PN emissions, Step C vehicles.

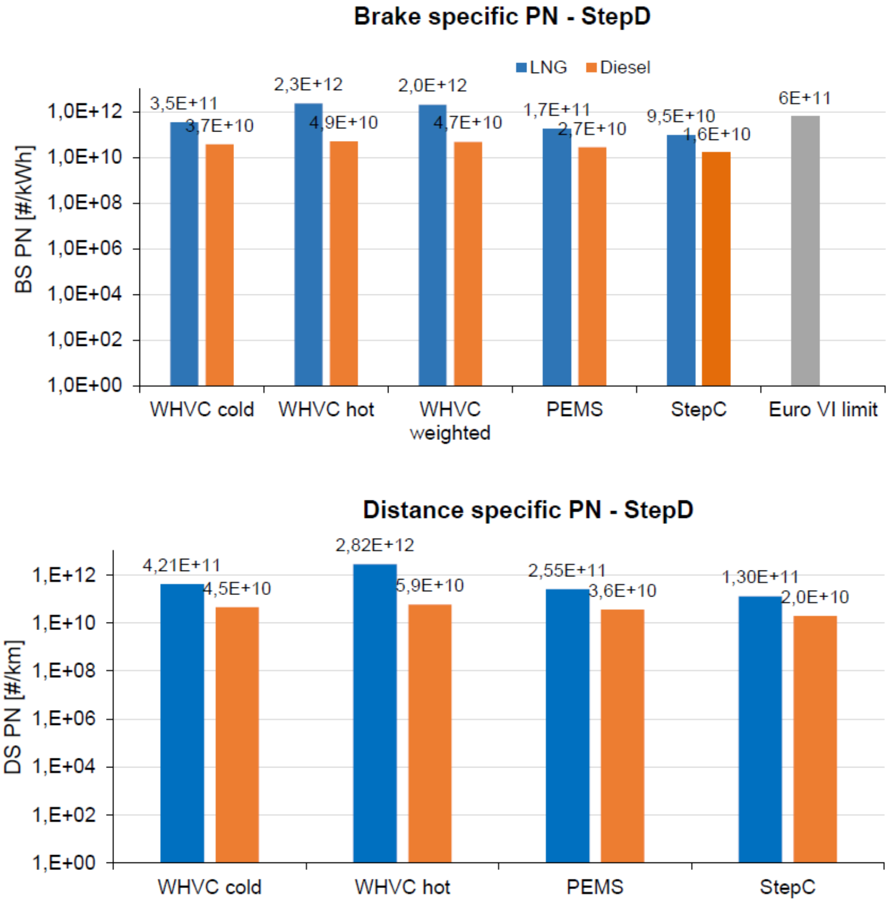


Figure 108: PN emissions, Step D vehicles.

Discussion

Looking at the results from Step C and D vehicles, the main difference can be found in N_2O emissions, and consequently in CO_{2eqv} emissions. Differences in any other parameter fall within repeatability of the tests. The Swedish measurements confirm that HPDI LNG delivers diesel-like efficiency, significantly higher than that of spark-ignited methane engines. When CH_4 and N_2O emissions are under control, HPDI LNG can deliver quite substantial reductions in CO_{2eqv} emissions.

Step C and Step D diesel vehicles have almost the same energy consumption when tested in repeatable conditions on the chassis dynamometer. There are some scatter in the on-road test results, which in fact can be expected due to the nature of on-road testing.

In the case of Step C vehicles, diesel and HPDI LNG delivered almost identical fuel efficiency in all tests.

For Step D vehicles, HPDI LNG delivered even lower energy consumption than diesel on low loads in the chassis dynamometer, but on high load in on-road conditions (PEMS 55%), the relative fuel consumption (MJ/km/1000 kg vehicle weight) was some 20% higher compared to diesel. This was also true for the on-road repeat tests of Step C vehicles. This might be explained by differences in the realization of the tests, and not differences in actual performance.

As said, HPDI LNG shows a consistent reduction of some 25% compared to diesel. For HPDI LNG, the methane slip adds 1 – 2% to CO_{2eqv} emissions for both Step C and D. For Step C vehicles, the contribution from N_2O is extremely high, some 15% for diesel and some 20% for HPDI LNG. For Step D the contribution is significantly reduced, to a mere 1% for diesel and 7% for HPDI LNG. For Step D, HPDI LNG delivers a reduction of some 20% in $CO2_{eqv}$ emissions compared to diesel. VTT’s average results for the same pair of vehicles was slightly lower, 16 %.

All in all, the vehicles delivered low NOx emissions. NOx conformity factors (CF) pass the ISC criteria for both Step C and D vehicles. For some reason, the Step D diesel had higher NO_x emissions than the Step C vehicles.

The CH_4 emissions of the HPDI LNG vehicles were some 0.4 g/kWh, thus below the Euro VI limit value of 0.5 g/kWh. The diesels had no CH_4 emissions and very low THC emissions.

PM emissions were low for all vehicles. The HPDI LNG vehicles had slightly higher PM emissions than the diesels.

The same applies for PN emissions, they are slightly higher from HPDI LNG than from diesel. All diesel values were below the Euro VI limit value, whereas for some tests the HPDI LNG vehicles exceeded the value somewhat.

Aggregated results

General

In this chapter aggregated results based on the contributions by the individual partners are presented analyzed. The partners tested the following vehicles:

- Canada:
    - two Category 1 diesel trucks, one truck also on B20
- Chile
    - three Category 1 diesel trucks
- Finland
    - six Category 2 trucks
        - two diesel, both also on HVO
        - two spark-ignited methane (CNG/LNG), one truck also on a low MN gas
        - one HPDI dual-fuel methane
        - one ED95
- Sweden
    - Two Category 1 trucks
        - one diesel
        - one CNG
    - four Category 2 trucks
        - two diesel, Euro VI Step C and D
        - two HPDI dual-fuel methane, Euro VI Step C and D

In addition, some reference is made to the previous “COMVEC” project.

The focus of the project at hand, HDV Performance Evaluation, is on energy efficiency and CO_2 emissions. Therefore most aggregated results presented relate to these parameters. As for pollutant emissions, only NO_x and PM emissions are presented. The results are presented in such a way that a comparison to the results of the “COMVEC” project can be done.

Chassis dynamometer testing

The results for energy consumption and CO_2 emissions are presented either relative to test weight (…/km/1000 kg of vehicle weight) or directly to driven distance (…/km). Pollutant emissions are presented relative to driven distance (g/km). When looking at absolute values related to driven distance one should keep in mind that in this case the size of the vehicle is not factored in. Results for N_2O, which are relevant for the comparison of Euro VI Step C and D vehicles, are presented relative to work at the driving wheels (g/kWh). In all figures x-axis is vehicle test weight.

Sweden provided test results for two pairs of Euro VI Category 2 trucks, diesel Step C and D, and HPDI LNG Step C and D, respectively. The pairs of Step C and D are identified in the figures, when relevant.

First a set of figures based on results generated within Annex 57 is presented. The first four Figures (Figure 109 to Figure 112) show specific energy consumption and CO_2 emissions. Figure 113 presents N_2O emissions. Energy consumption, CO_2 and N_2O data presented here is based on hot start WHVC testing.

Results for NO_x are shown as cold, hot and aggregated results (Figure 114 to Figure 116). Figure 117 presents hot start PM emissions. Aggregated results are available vehicle weights up to 30 tons, hot start results up to 44 tons.

The last two figures (Figure 118 and Figure 119) incorporate results from the “COMVEC” project. The objective of presenting the results in this way is to highlight differences in energy efficiency between contemporary Euro VI and US2010 vehicles and vehicles representing previous Euro stages.

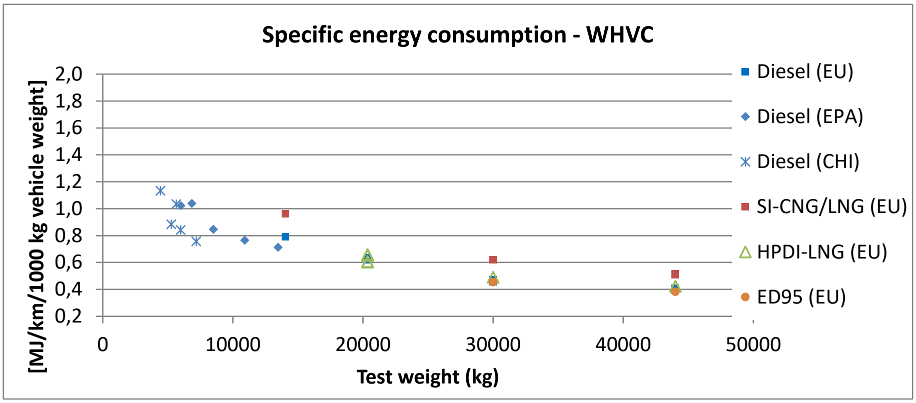


Figure 109: Ton-kilometer specific energy consumption of Euro VI, EPA 2010 and Chile 2015 trucks.

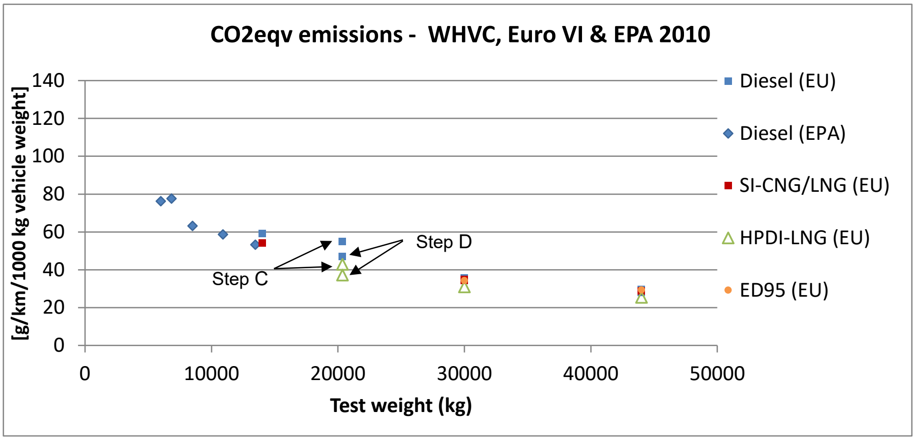


Figure 110: Ton-kilometer specific CO_2 equivalent emissions of Euro VI and EPA 2010 trucks.

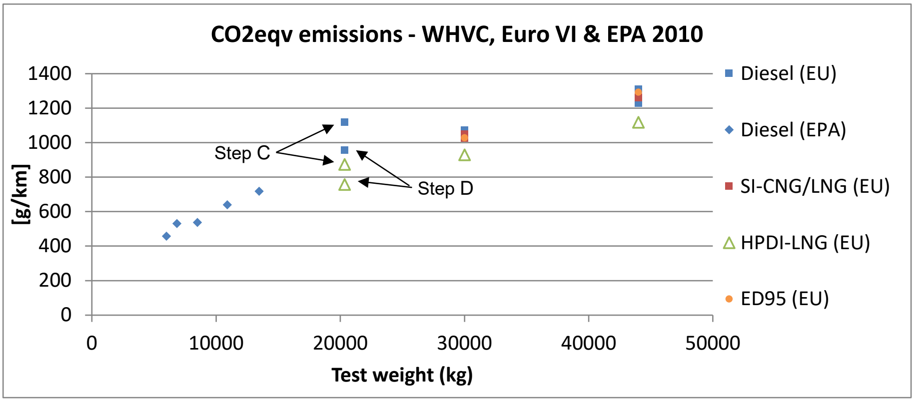


Figure 111: Distance specific CO_{2eqv} emissions of Euro VI and EPA 2010 trucks.

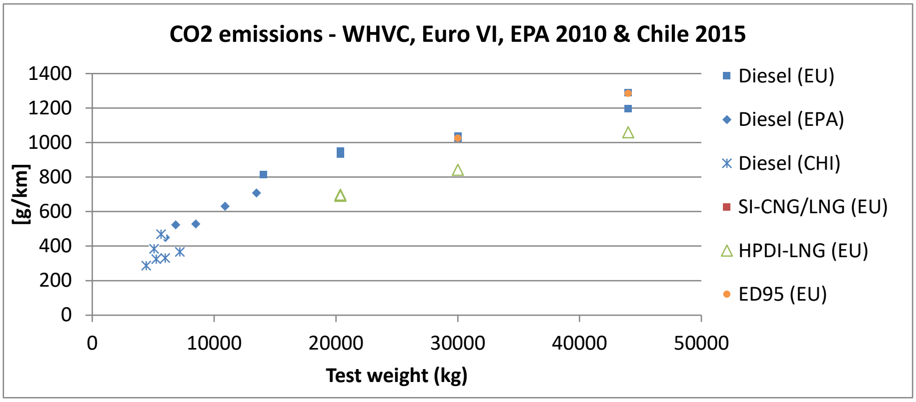


Figure 112: Distance specific CO_2 emissions of Euro VI, EPA 2010 and Chile 2015 trucks.

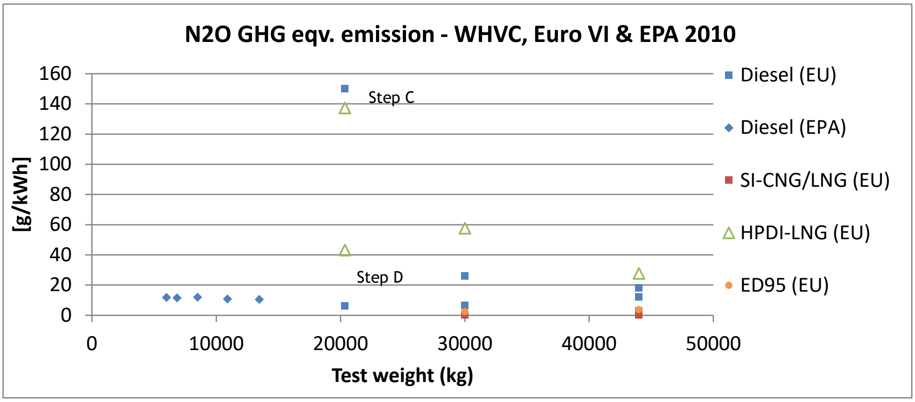


Figure 113: N_2O (in CO_{2eqv}) emissions of Euro VI and EPA 2010 trucks.

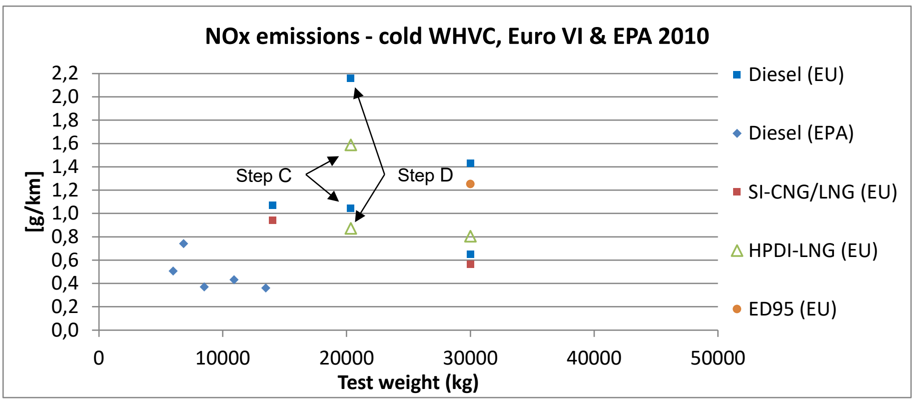


Figure 114: NO_x emissions of Euro VI and EPA 2010 trucks (cold start WHVC).

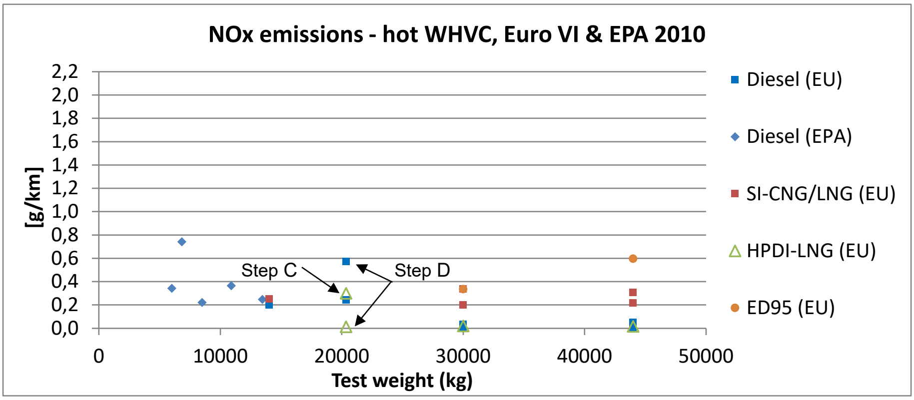


Figure 115: NO_x emissions of Euro VI and EPA 2010 trucks (hot start WHVC).

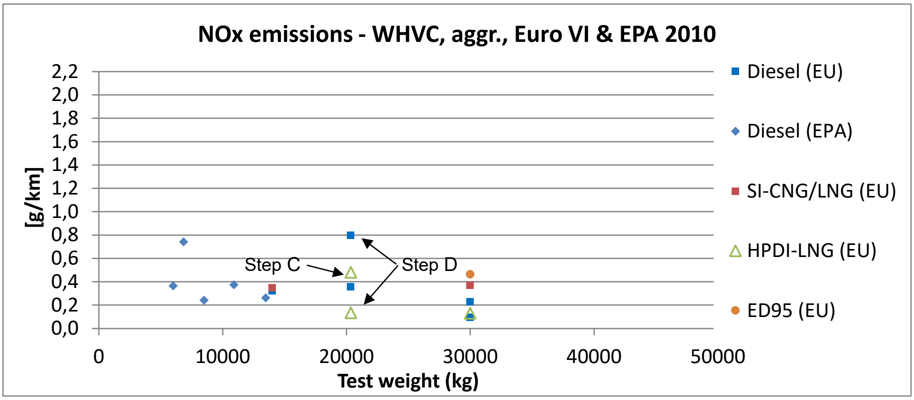


Figure 116: NO_x emissions of Euro VI and EPA 2010 trucks (aggregated WHVC).

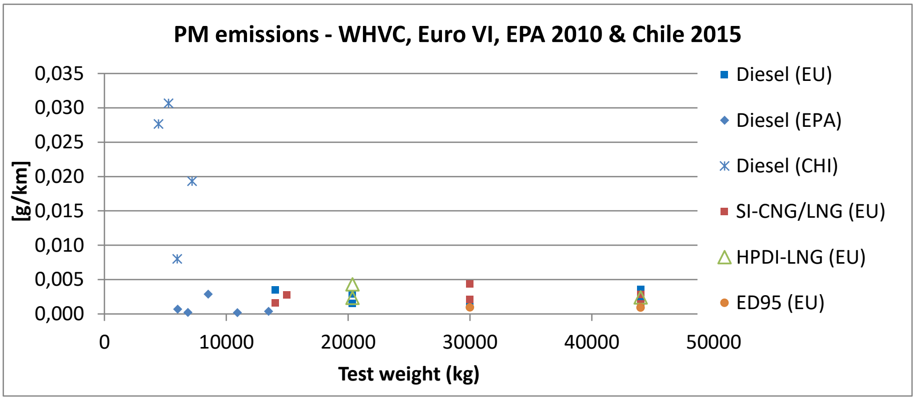


Figure 117: PM emissions of Euro VI, EPA 2010 and Chile 2015 trucks (hot start WHVC).

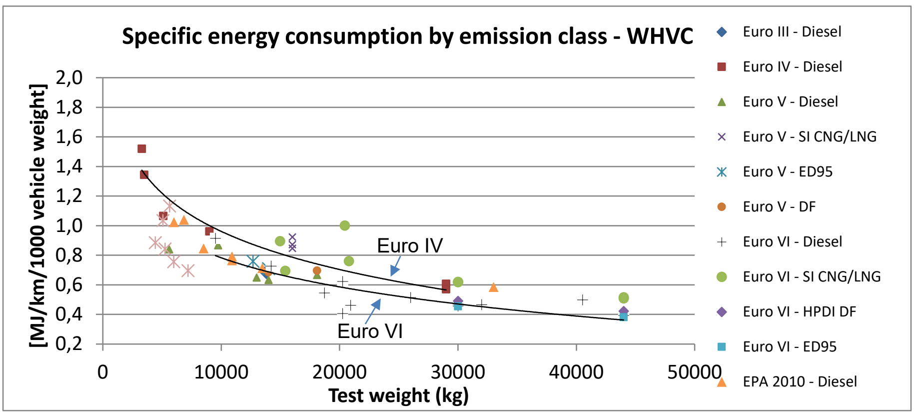


Figure 118: Ton-kilometer specific energy consumption of Euro III -VI, EPA 2010 and Chile 2015 trucks. Trendlines for Euro IV and Euro VI diesel vehicles.

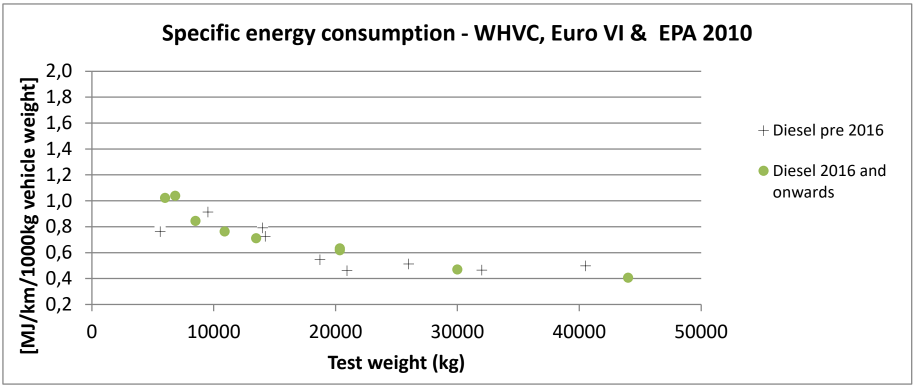


Figure 119: Ton-kilometer specific energy consumption of pre 2016 and newer diesel trucks (Euro VI and EPA 2010 trucks).

Discussion – chassis dynamometer testing

The results from HDV Performance Evaluation confirms what already "COMVEC" pointed out, relative to mass, larger vehicles are more energy efficient than smaller ones. The most important factor affecting energy consumption is vehicle mass, both in absolute and relative terms. Figure 109 shows that the scatter in specific energy consumption is at maximum for the lightest vehicles tested. High fuel efficiency is probably not the prime criteria in the design of medium heavy-duty vehicles, whereas tractors for long-haul services are built to be as fuel efficient as possible.

The second most important factor affecting fuel consumption is the choice of combustion technology. Engines based on compression ignition and liquid fuels, in this case diesel and ED95, deliver highest efficiency. Although there have been claims that the efficiency of SI methane engines has improved, SI engines still have some 30% higher energy consumption compared to CI engines. A new interesting technology is direct injection diesel-methane HPDI dual-fuel technology, delivering almost diesel-like efficiency.

CO_{2eqv} emissions first and foremost depend on the amount of energy used and the CO_2 intensity of the fuel. This means that the favorable CO_2 intensity of methane compensates the low efficiency of SI methane engines to the extent that diesels and SI methane engines in practice deliver equivalent CO_2 emissions.

However, also unburned methane and N_2O can contribute to CO_{2eqv} emissions. Older lean-burn SI methane engines and port-injected dual-fuel engines had high methane emissions. The stoichiometric SI gas engines tested now have quite low methane emissions. The HPDI dual-fuel engines can emit some unburned methane, but the contribution of methane to total CO_{2eqv} emissions was not significant in any case (Figure 110 to Figure 112).

In SCR equipped vehicles, N_2O can make a rather significant contribution to CO_{2eqv}. This was particularly true for the Euro VI Step C Category 2 vehicles tested in Sweden, both for the diesel and the HPDI truck. Even for the Euro VI Step D vehicles the contribution of N_2O to CO_{2eqv} emissions is evident, less so for the vehicles tested in Canada. The Category 2 Step C trucks tested in Sweden had N_2O emissions of some 150 g CO_{2eqv}/kWh. Step D brought values down to some 5 g/kWh for the diesel and 40 g/kWh for the HPDI truck. SI methane engines have N_2O emissions close to zero (Figure 113).

The overall outcome is that diesel (Step D and EPA 2010), SI methane and ED95 deliver roughly equivalent CO_{2eqv} emissions (Figure 110). The Step C diesel tractor tested in Sweden at 20,000 kg was clearly above average. At this test weight, the Step C HPDI tractor had average CO_{2eqv} emissions, whereas the Step D HPDI tractor had some 15% lower emissions compared to average. The testing in Finland confirmed the benefit of the Step D HPDI technology. This highlights the importance of controlling N_2O emissions.

Figure 114 shows that cold start WHVC NO_x emissions are quite high for all engine options. A clear difference can be seen between Step C and D vehicles, the Step C diesel tractor showing by far the highest absolute NO_x values. For all other vehicles except the vehicles tested in Canada, hot start testing results in significantly lower NO_x emissions, in some cases practically zero emissions (Figure 115). It is worth noticing that all vehicles tested in Finland, whether tested at 30 or 44 tons with hot start, have a NO_x value of 0.6 g/km or lower.

PM emissions are low for the European and Canadian vehicles, but rather high for the Chilean vehicles (Figure 117). The reason for this is most probably that the Chilean vehicles are certified to Euro V with less severe requirements than EPA 2010. Furthermore, the Chilean vehicles are, on an average, more fuel efficient than the Canadian vehicles in the same weight range.

Figure 118 shows a comparison of specific fuel consumption data for "COMVEC" and HDV Performance Evaluation. "COMVEC" covered vehicles ranging from Euro III to Euro VI. The figure show trendlines for Euro IV and Euro VI diesel vehicles. The curves suggest that, on an average, Euro VI vehicles are more fuel efficient than Euro IV vehicles, even though the levels of pollutant emissions have been significantly reduced.

In Figure 119 Euro VI class diesel vehicles are divided into two sub-groups: 1) Vehicles up to MY 2015, and 2) Vehicles MY 2016 and onwards. The objective is to identify whether there has been progress in energy efficiency within Euro VI. The result is not unambiguous, as the data points suggest.

On-road testing

On-road PEMS measurements were performed in Canada, Finland and Sweden. Canada provided results for test weights from some 4 to 12 tons. Sweden provided results from Step C and D diesel and HPDI-LNG trucks from 24 to 32 tons. In Finland, SI-LNG, HPDI-LNG and diesel trucks were tested at a weight of around 30 tons. In on-road testing, the results for energy consumption were derived from measured CO_2 emissions and the carbon intensity of the fuels:

- 73.2 g CO_2/MJ for diesel
- 55.1 g CO_2/MJ for LNG
- 56.5 g CO_2/MJ for the mix of LNG and diesel in the HPDI trucks[28]

In Figure 120 and Figure 121 energy consumption and CO_2 emissions are presented on a ton-kilometer basis. Figure 122 and Figure 123 show NO_x emissions relative to distance and engine work.

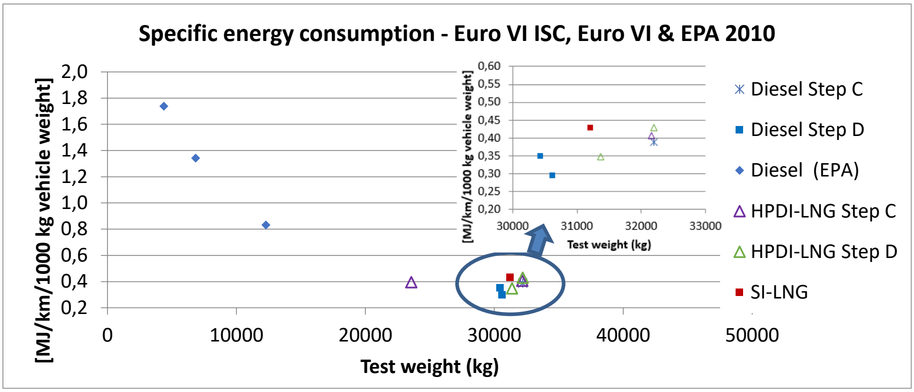


Figure 120: On-road ton-kilometer specific energy consumption (Euro VI ISC route).

[28] VTT's measurements indicated that the energy share of diesel in the HPDI truck was in average close to 8%

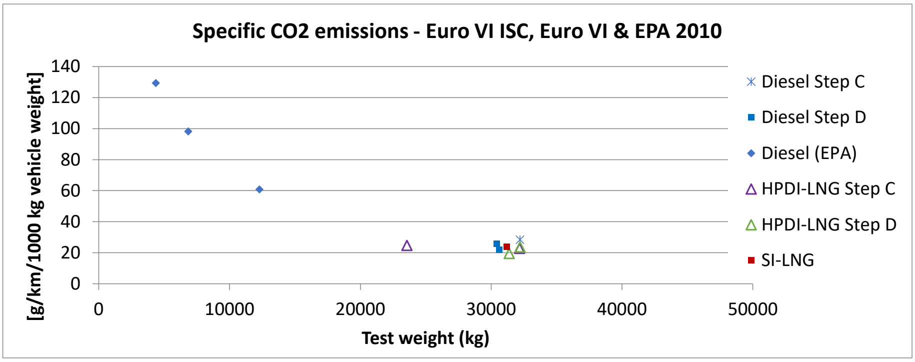


Figure 121: On-road ton-kilometer specific CO_2 emissions (Euro VI ISC route).

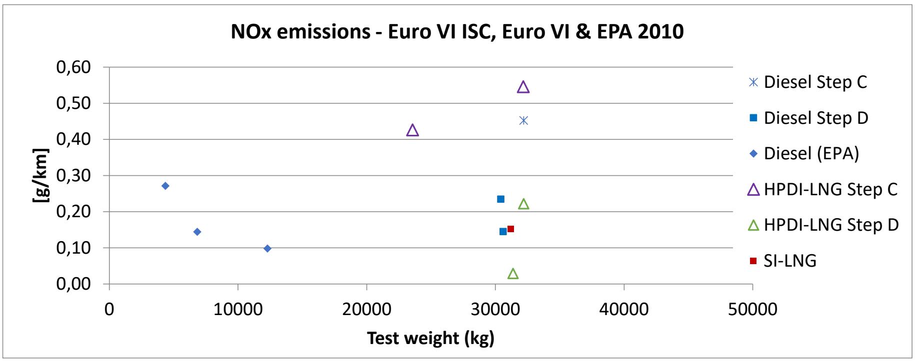


Figure 122: On-road distance specific NO_x emissions (Euro VI ISC route).

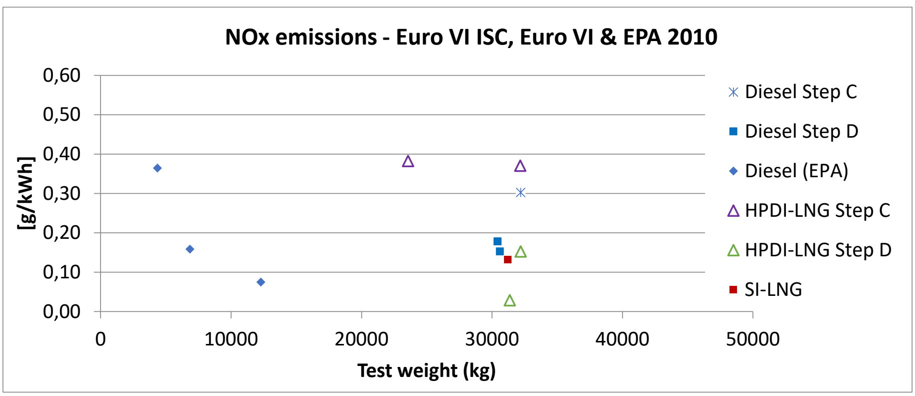


Figure 123: On-road engine work specific NO_x emissions (Euro VI ISC route).

Discussion

On-road ISC testing is by nature pass/fail type regulative testing for pollutant emissions. The results are related to engine work, and this dampens the effects of variations from test to test (traffic conditions, speed, accumulated work, ambient conditions etc.). When results are presented relative to distance, there is bound to be more variation from test to test, and thereby technology comparisons become imprecise. Chassis dynamometer measurements are better suited for accurate measurements of energy consumption and CO_2 emissions.
Notwithstanding, the on-road testing resulted in rather similar results for energy consumption and CO_2 emissions as chassis dynamometer testing. The crucial factor affecting energy consumption and CO_2 emissions is vehicle weight. The blown-up part of Figure 120 suggest that that HPDI LNG could consume as much as 40% more energy than diesel and have equivalent energy consumption compared to SI technology, which is not really true.

A comparison of on-road results with the aggregated chassis dyno results in Figure 109 reveals that driving on-road according to the Euro VI ISC requirements leads to less work per km for trucks with a weight of more than 20 tons. This stems from the fact that the ISC route for trucks over 18 tons focuses on rural and highway driving, which usually do not include many accelerations as the WHVC cycle. On the road, all vehicles tested at around 30 tons delivered roughly equal CO_2 emissions (Figure 121).

The scatter in NO_x emissions is substantial. Values relative to distance do not necessarily increase with vehicle weight, as the Step D vehicles and the SI-LNG truck tested at some 30 tons deliver equal or even lower NO_x emissions than vehicles tested at some 10 tons (Figure 122). On-road NO_x levels are in general somewhat lower than for chassis dynamometer testing.

Figure 123 shows that all measured NO_x values (in g/kWh at the engine crank) are below the actual Euro VI limit value of 0.46 mg/kWh. ISC testing allows a CF factor on 1.5, so value are well below legal requirements.

Results and discussion – Simulation

General

In this section, results of simulation activities in Finland and Korea are presented and discussed. The joint AMF/HEV activity is presented in a separate Chapter.

There was no common agenda for the simulation activities, as Finland focused on simulations of HCT combinations and Korea on simulations related to vehicle certification.

Finland

In Finland, a simulation model for HCT combinations was developed. The model was validated by carrying out actual on-road measurements. Table 26 shows validation results for a set of measured trips between Oulu and Helsinki (~ 600 km) in May and June in 2020. The values include the vehicle weight, travelled distance, fuel consumption and engine work per travelled distance. For each simulated trip, the mass of the vehicle combination is an average value over time based on the vehicle mass signal in the vehicle CAN data.

The simulated driving cycle was based on the real driving route from Oulu to Helsinki. The driving cycle for the simulation was constructed from road segments defining elevation, segment curvature, and speed limitation. For each segment the reference speed was defined using the speed limit and curvature information, to set the reference speed in a realistic way in tight turns. The modelling of the driving cycle does not take into account the effect of traffic lights or other vehicles, which means that the number of accelerations and decelerations in the real driving is likely to be higher than in the simulation. This means that the simulated fuel consumption can be assumed to be an ideal value and lower than the actual one. However, by using the procedure for the driving cycle definition and computer simulation, comparable energy consumption values for each simulated vehicle mass can be defined.

Table 26: Measured and simulated values for the fuel consumption and engine work during test period.

Measured values					Simulated values	
Mass	Distance	Average speed	Fuel consumption	Engine work	Fuel consumption	Engine work
ton	km	km/h	l/100 km	kWh/km	l/100 km	kWh/km
75.5	601	76	53.3	2.56	52.2	2.58
60.5	573	78	43.9	2.13	46.4	2.28
76.2	634	76	52.3	2.50	51.0	2.53
66.8	575	73	47.9	2.29	47.8	2.35
66.4	504	73	49.3	2.35	48.2	2.38
59.1	579	76	45.1	2.19	45.9	2.25
77.8	504	75	49.8	2.37	51.8	2.57
62.0	581	75	43.4	2.09	46.1	2.26
37.8	574	80	33.1	1.66	38.7	1.87
60.2	545	78	47.5	2.30	46.9	2.31
65.7	468	75	48.8	2.31	48.5	2.39
60.9	576	79	47.5	2.29	48.1	2.36
67.0	449	77	48.7	2.31	49.7	2.45
73.5	505	79	56.7	2.63	51.9	2.57

The average difference between the simulated and the actual values for the fuel consumption is 3 % and for the engine work per travelled distance 4 %. Some simulated trips show a larger difference, which may be caused by uncertainties in input data, e.g., gross vehicle weight, which is based on average CAN bus data. On an average, the simulated engine work is below the measured values. One reason for this is that the simulation model does not include any consumption by auxiliaries. By applying an estimation of the auxiliary power consumption, the difference in engine work would decrease, and at the same time the difference in fuel consumption would increase. The simulation model does not have a function to optimize gear change for the best fuel economy. Instead, the model uses fixed engine speed limits for gear changes. The functionality of rolling in neutral gear is lacking. In real driving, these functions are assumed to decrease the fuel consumption with few percent units.

The simulation model is used to study the effect of vehicle gross weight on the total energy consumption per travelled distance and transported tons (net load). Figure 124 shows the energy consumptions and specific CO_2 emissions per ton-km as a function of gross vehicle weight varying weight from 64 tons to 92 tons. The weight of the unladen vehicle combination is 37 tons. Simulation results are also presented in Table 27. The calculated fuel consumption and work data indicate average efficiency of about 46% at the engine level. The vehicle weight seems to have only a minor effect on the engine efficiency. Figure 125 shows absolute fuel consumption and specific CO_2 emissions per ton-km. Specific CO_2 emissions are reduced significantly as the vehicle combined weight increases. It emphasizes the huge potential that the high-capacity transport vehicles can provide. A 40 % reduction in CO_2 emissions per ton-kilometer can be achieved when moving from 64 tons to 92 tons (Figure 125).

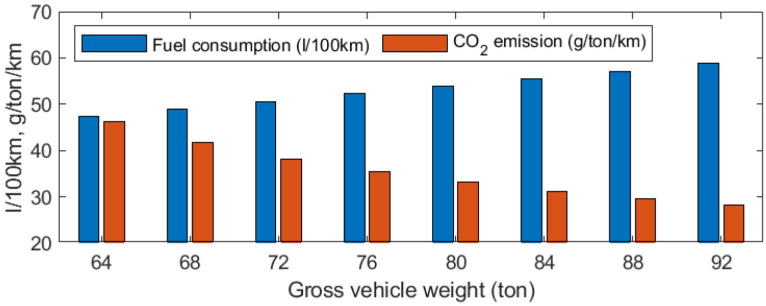


Figure 124: Fuel consumption and specific CO_2 emission per ton-km as a function of gross vehicle weight.

Table 27: Simulation results for variated gross vehicle weight on route from Oulu to Helsinki.

Vehicle mass	Average speed	Fuel cons.	Fuel cons.	Engine work	Energy Cons.	Specific CO_2 emission	Specific CO_2 emission
ton	km/h	l	l/100km	kWh	MJ/km/ton vehicle	g/km/ton vehicle	g/km/ton payload
64	75.8	280.2	47.3	1280	0.26	19.4	46.2
68	75.6	290.2	48.9	1327	0.26	18.9	41.7
72	75.5	299.9	50.6	1373	0.25	18.5	38.2
76	75.2	309.9	52.3	1419	0.24	18.1	35.4
80	75	319.4	53.9	1464	0.24	17.7	33.1
84	74.8	328.9	55.5	1509	0.23	17.4	31.2
88	74.6	338.6	57.1	1555	0.23	17.1	29.6
92	74.3	348.3	58.7	1600	0.23	16.8	28.2

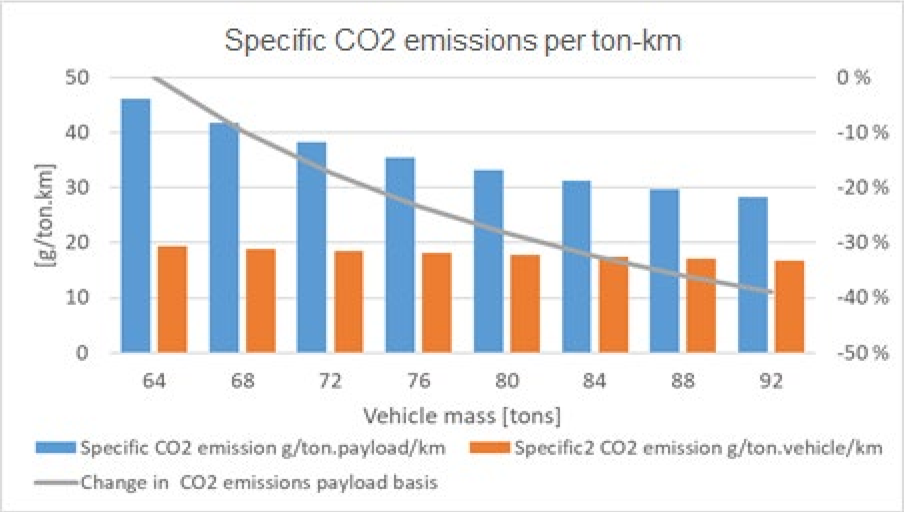


Figure 125: Ton-km specific CO_2 emissions in relation to vehicle mass and payload.

Korea

Correlation analysis between HES and VECTO

In Korea, the work focused on the HES simulation model intended for use as a part of the type approval process, and correlation between HES and VECTO.

Correlation analysis with HES and the VECTO model was done with 42 different cases of vehicle models. Simulations were carried out with both models, HES and VECTO. The regression coefficient for the sample of 42 simulation cases was 0.9845 and determination coefficient was 0.9932. Figure 126 shows the correlation between the HES and VECTO.

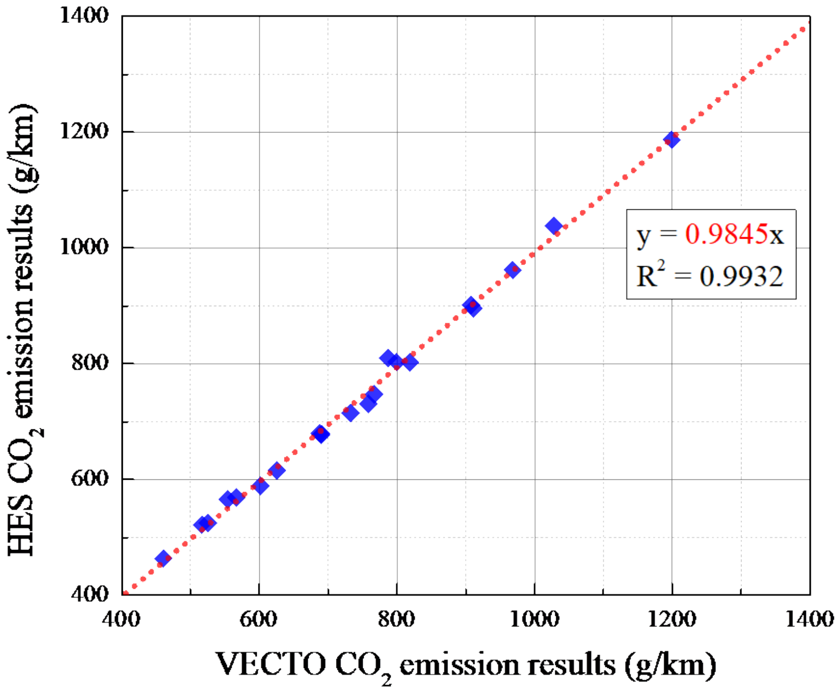


Figure 126: Correlation between the HES and VECTO model.

The HES model was also used to estimate development of CO_2 emissions from road transport in Korea. Figure 127 shows predicted CO_2 emissions as a function of gross vehicle weight. The Figure is based on simulation of some 400 Korean heavy-duty vehicles. The values are for half load and the Korean K-WHVC driving cycle.

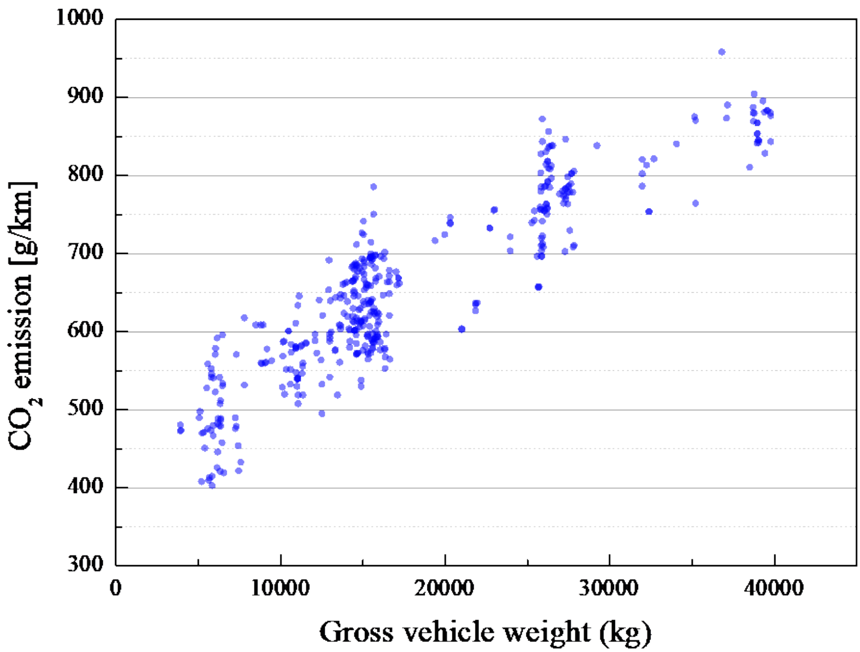


Figure 127: GHG emissions prediction as a function of GVW.

Key figures for the Korean heavy-duty vehicle sector (Figure 128, based on HES simulation result, national vehicle statics and vehicle travelled data):

- CO_2 emission from Korean HDV in 2017: 21.25 million ton (21.6% of transportation emission)
- CO_2 emissions from rigid trucks: 66.7%
- CO_2 emissions from buses: 22.3%
- CO_2 emissions from tractors: 11.1%

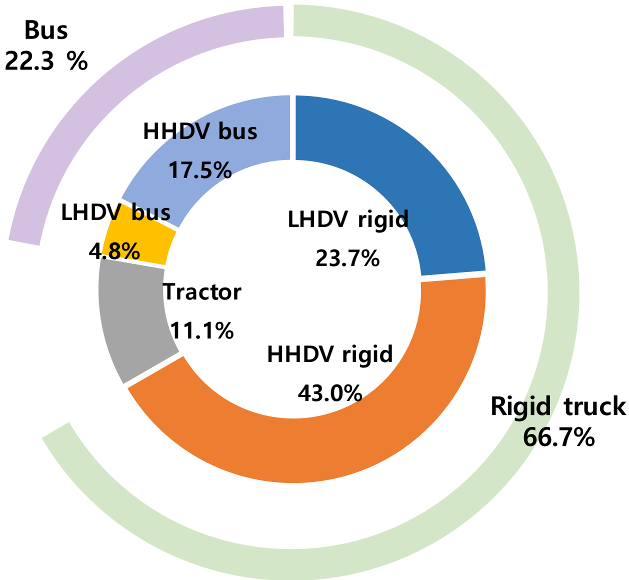


Figure 128: Share of CO_2 emissions for different vehicle categories based on simulations.

In the business-as-usual (BAU) scenario, the CO_2 emissions from Korean heavy-duty vehicles will be 26.48 million tons in 2030 (Figure 129).

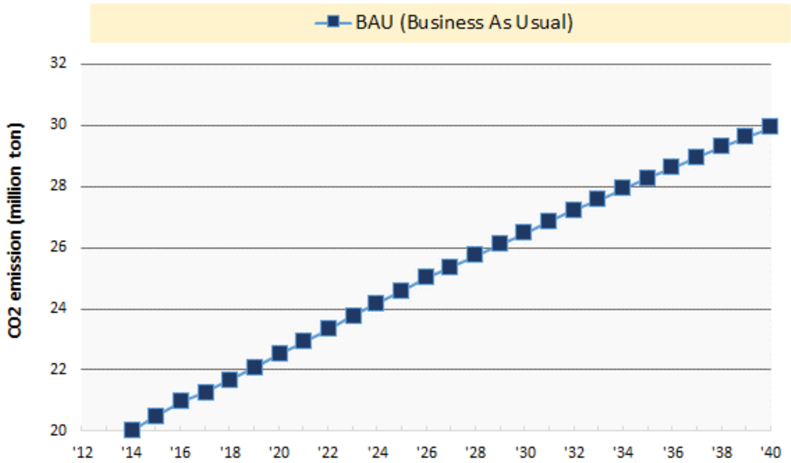
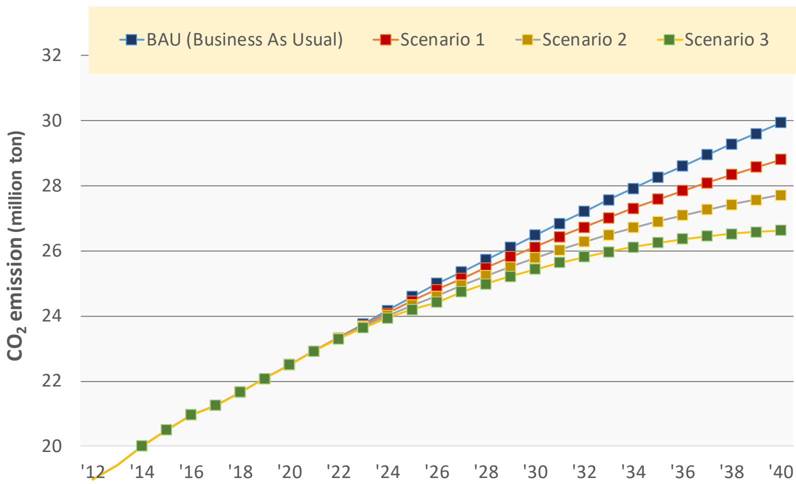


Figure 129: CO_2 emissions increase in Business as Usual case.

Alternative scenarios were developed with the following assumptions:

- Scenario 1: From 2021, 1% annual CO_2 reduction for new HDVs.
- Scenario 2: From 2021, 2% annual CO_2 reduction for new HDVs.
- Scenario 3: From 2021, 3% annual CO_2 reduction for new HDVs.

The alternative scenarios in comparison with BAU are shown in Figure 129. In 2030, Scenario 3 would result in a reduction of 1.04 Mt CO_2 annually, in relative terms about 7%.



The amount of CO_2 reduction compared to BAU scenario in 2030		
Scenario 1	Scenario 2	Scenario 3
0.355 Million ton	0.699 Million ton	1.04 Million ton

Figure 130: CO_2 emissions in case of three reduction scenarios.

Joint AMF and HEV assessment of potential of CO_2 reductions for heavy-duty trucks

General

Within HDV Performance Evaluation, the performance of current state-of-the-art HDVs was evaluated using chassis dynamometer and on-road measurements. As a result, a comprehensive comparison of different ICE based options can be presented.

In addition to presenting a snapshot of the performance of contemporary vehicles, the project also aims at presenting a look into the future evaluating how upcoming CO_2 regulations can be met.

For projections into the future, IEA AMF TCP and IEA HEV TCP carried out a joint exercise estimating the energy consumption and CO_2 emissions of possible future powertrain options for typical semi-trailer long-haul operations. Energy consumption and CO_2 emissions were analyzed both on TTW (end-use or tailpipe) and WTW (overall impact) basis. The WTT data needed for this stems from the newest version of the JEC Well-to-Tank report v5[29].

The main objective of the work was to evaluate the potential of various powertrain alternatives in meeting future CO_2 limits for trucks. The targets set by EU, -15% by 2025 and -30% by 2030, were used as reference. It should be noted that the reduction targets are set for complete vehicles, not engines only.

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[29] https://ec.europa.eu/jrc/en/publication/eur-scientific-and-technical-research-reports/jec-well-tank-report-v5

Methodology

AMF made use of chassis dynamometer data generated in Finland for the project at hand. AMF provided actual data for ICE powered trucks (diesel, SI-LNG, HPDI-LNG and ED95). HEV used simulation data generated within the HEV Task 41 Electric Freight Vehicles[30]. HEV provided simulation data for hybrid, fuel-cell and battery electric powertrains. HEV's energy consumption simulation is based on a techno-economic evaluation approach for the assessment of future commercial vehicle concepts called "Transport Application based Cost Model" (TACMO) [31] . Configurations of electric powertrains were based on current state-of-the-art electric components. Table 28 summarizes the covered powertrain and fuel options. In the case of ICE powertrains, fossil and renewable fuels were evaluated in parallel. The fuel cell pathway was based on natural gas (EU mix 2016). In the case of EVs, EU's actual power generation mix (low voltage) in 2016 (396 g CO_2/kWh) and the predicted EU mix in 2030 (268 g CO_2/kWh) were used. The hydrogen pathway was based on natural gas (EU mix 2016).

Table 28: Summary of investigated engine and fuel options.

Powertrain:	**Abbreviation and fuels:**
Diesel	Fossil diesel, HVO (waste cooking oil), synthetic diesel (wood waste based)
Spark-ignited LNG	SI-LNG, SI-LBG (manure based)
High Pressure Direction Injection LNG	HPDI-LNG, HPDI-LBG (manure based)
Compression-ignition ethanol	ED95 (Wheat straw based ethanol)
Full Hybrid Electric Vehicle (FHEV)	Fossil diesel and electricity (EU mix 2016 and EU mix 2030)
Fuel Cell Electric Vehicle (FCEV)	Hydrogen (NG based, electricity EU mix 2016)
Battery Electric Vehicle (BEV)	Electricity (EU mix 2016 and EU mix 2030)

30 IEA HEV Task41, Feb 2021, Fact sheet: "Evaluation of powertrain and fuel options for heavy-duty vehicles to meet the EU CO2 emission fleet targets

31 TACMO model

The energy consumption data generated in the project at hand, HDV Performance Evaluation, was used as a starting point. The data indicates that current best-in-class HD diesel engines deliver an efficiency of close to 46% at the crankshaft (break thermal efficiency (BTE)) in typical long-haul driving (average value for the WHVC motorway phase). For heavy-duty SI methane engines the corresponding value is some 37%.

The estimates of the potential for efficiency improvements are based on targets of the US Super Truck II program (55% BTE) and the European H2020 project LONGRUN (50% BTE). In the simulations it was estimated that 50% BTE will be achieved by 2025, and that 53% BTE could be reached by 2030.

The corresponding efficiency improvements in relative terms are some 10% and 15%, respectively. For the SI-LNG engine smaller relative improvements were assumed, around 5% by 2025 and 10% the 2030. For electric powertrains (FHEV, FCEV, BEV), efficiency improvements of 5% by 2025 and 10% by 2030 were assumed. **Table 29** summarizes the assumptions for efficiency improvements.

Table 29: Assumed relative efficiency improvements by 2025 and 2030.

Engine type/powertrain:	Efficiency improvement by 2025	Efficiency improvement by 2030
Compression-ignition	10 %	15 %
Spark-ignition	5 %	10 %
FHEV, FCEV, BEV	5 %	10 %

For the calculation of TTW CO_2 emissions, fuel specific CO_2 emission factors (g CO_2/MJ) from the appendixes of the JEC Well-to-Tank report v5 are used.

The analysis for ICE and electric powertrains was carried out for semi-trailer combinations. In the case of ICE vehicles, starting point was hot start WHVC data for 30 tons. The assumption for the vehicle combination was a 4x2 tractor and a three-axle semitrailer, a configuration quite common in Europe. Two slightly different curb weights for the tractor were used, depending on the fuel. For simplicity for diesel, ED95 and SI-LNG/CNG trucks it was used their average measured curb weight. In the case of electric powertrains, the assumption was a 4x2 tractor combined with a semi-trailer, with a total weight of 40 tons. For the configuration of the electric vehicle concepts, the approach from TACMO was used. The total gross vehicle weight of the combination is the sum from the vehicle curb weight (tractor + trailer) and the maximum permissible payload. The curb weight of the tractor is calculated from the mass of the key powertrain related components and the mass of the glider (rest of the vehicle). The simulated vehicle weight of BEVs is calculated to be significantly higher compared to conventional vehicles.

Table 30 summarizes the vehicle configurations investigated.

Table 30: Summary of investigated vehicle configurations.

	Diesel and ED95	**SI-LNG and HPDI-LNG**	**FHEV**	**FCEV**	**BEV**
Gross vehicle mass rating (GVMR) (kg)	42,000	42,000	40,000	40,000	40,000
Tractor curb weight (kg)	8,100	8,550	9,894	10,083	17,180
Trailer curb weight (kg)	6,800	6,800	4,962	4,962	4,962
Simulated vehicle weight (kg)	14,900	15,350	14,856	15,045	22,142
Simulated payload (kg)	15,100 (56 %)	14,650 (55%)	17,319 (69 %)	17,319 (69 %)	17,319 (97 %)
Simulated combined vehicle mass (kg)	30,000	30,000	32,171	32,360	39,460

The energy consumption was calculated according to the WHVC cycle, which is made up of the three driving sub-cycles urban, rural and motorway cycle. In this work, to represent a typical long-haul driving task, the specific energy consumption was defined with the following split: 80% motorway, 20% rural and 0% urban cycle. This assumption was used for both the data from ICE powertrains and the simulation results for FHEV, FCEV and BEV powertrains. The results regarding energy consumption per kilometer were then multiplied to correspond to the typical daily German long-haul daily service of 698 km[32]. Results are presented in ton (payload) kilometer basis.

For the calculation of the Tank-to-Wheel (TtW) and Well-to-Wheel (WtW) CO_2 emissions, fuel-specific CO_2 emission factors in g CO_2/MJ from the JEC Well-to-Tank report v5[33] are used. When estimating CO_2 reductions, the value for an assumed average 2020 diesel truck operating on fossil fuel was set as the 2020 reference.

[32] https://elib.dlr.de/111576/1/2017_EEVC_Kleiner%20and%20Friedrich.pdf

[33] https://ec.europa.eu/jrc/en/publication/eur-scientific-and-technical-research-reports/jec-well-wheels-report-v5

Results

The simulated CO_2 results are compared to the reduction targets set by EU, -15% by 2025 and -30% by 2030, relative to 2020, and shown as boxes in two shades of green. The reference point is a 2020 diesel truck on conventional fossil diesel.

Figure 131 shows the assessment for TTW (end-use) CO_2 emissions. TTW/tailpipe emissions are the basis for all vehicle CO_2 regulations. The methodology does not take into account renewable fuels in any way, and CO_2 emissions are directly relative to energy consumption and CO_2 intensity of combustion of the fuel. In this context, electric vehicles (both FCEVs and BEVs) are considered zero-emission.

Figure 132 shows results for WTW (overall impact) assessment. In this figure, both upstream (WTT) and end-use (TTW) emissions are taken into account. As stated above, the WTT values stem from the JEC Well-to-Tank report v5 study reference values for each corresponding fuel.

Figure 133 shows WTW energy consumption for daily operations on a WTW basis. Again, the WTT values are from the JEC Well-to-Tank report v5.

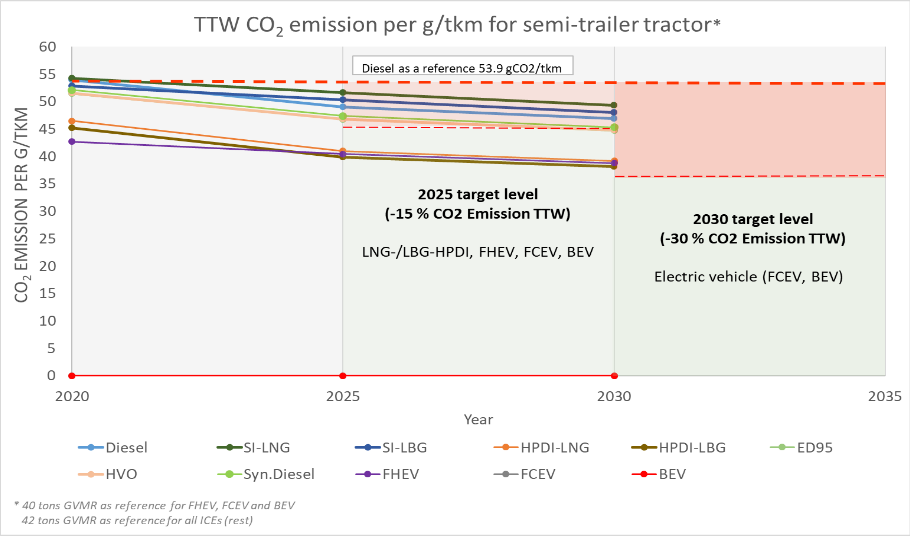

Figure 131: CO_2 emissions in TTW basis per ton-kilometer for different powertrain and fuel options.

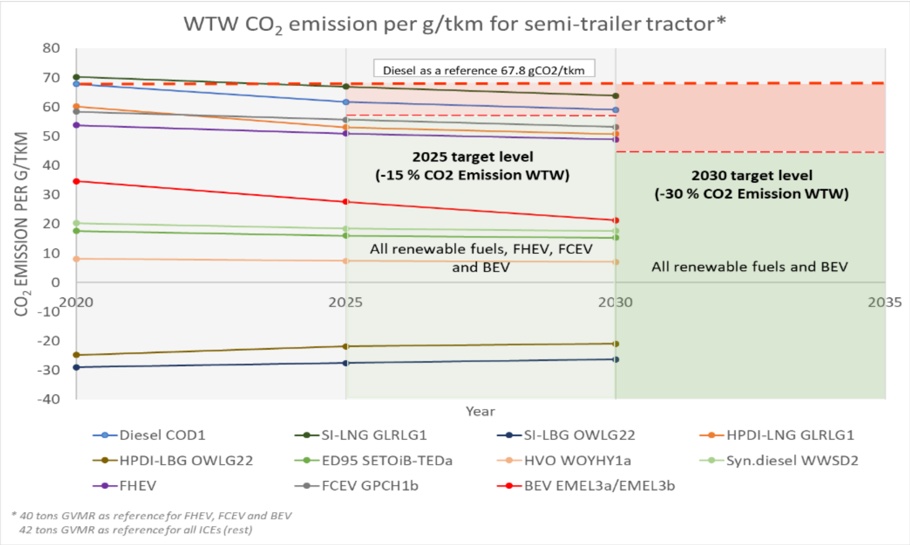

Figure 132: CO_2 emissions in WTW basis per ton-kilometer for different powertrain and fuel options.

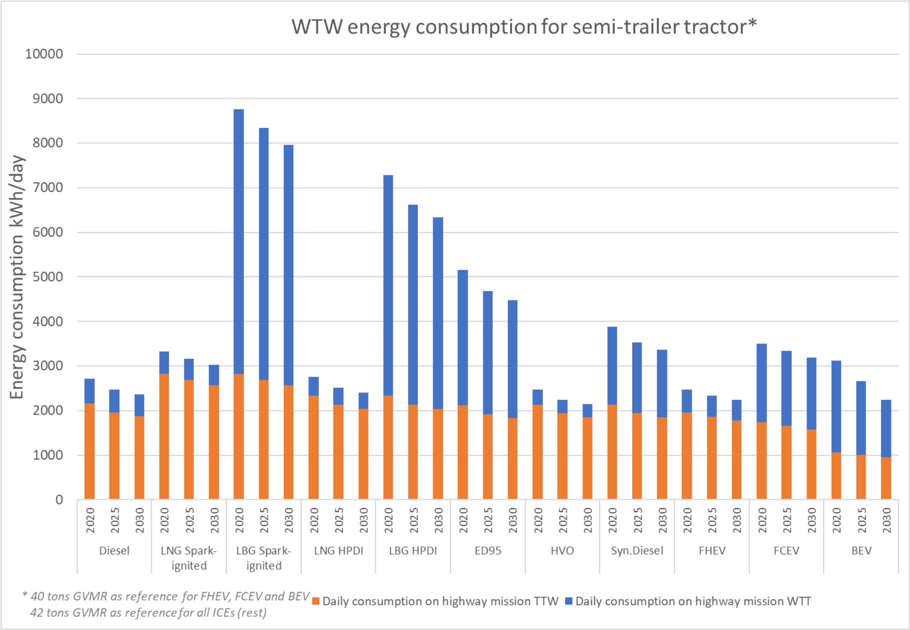

Figure 133: Energy consumption in WTW (WTT+TTW) basis for different powertrain options.

Discussion

Electric vehicles, that is fuel cell electric vehicles (FCEV) and battery electric vehicles (BEV), do not emit tailpipe emissions. Thus, meeting the 2025 and 2030 targets for tailpipe CO_2 emission reductions is a no-issue.

Figure 131 shows small differences between diesel, HVO and synthetic diesel, on one hand, and between LNG and LBG, on the other hand. These differences stem from small differences in fuel CO_2 intensities.

The main message derived from Figure 131 is that ICE vehicles based on diesel, methane spark-ignition or ED95 engines, whether operated on fossil or renewable fuels, will not meet the 2025 tailpipe CO_2 reduction targets with improvements to the engine only, even if relative efficiency improvements of 10% for diesel and 5% for SI engine are assumed. However, in combination with other measures, e.g., reduction of auxiliary losses and measures to the vehicle itself (such as reduced weight and aerodynamic drag) the target is reachable.

The only pure ICE powertrain alternative that has the potential to achieve the 2025 target with a margin and no modifications to the vehicle itself is HPDI LNG/LBG. This is a consequence of diesel-like efficiency and the favorable specific CO_2 emission of methane.

Hybridization (FHEV) alone can also meet the 2025 target with a margin.

The 2030 target of -30% will be challenging. Figure 131 indicates that improved diesel and spark-ignited engines will not be able to provide the required reduction, probably not even combined with improvements on the vehicle level.

However, HPDI LNG/LBG and FHEV come close, each of them estimated to be able to deliver a reduction of about 25% in 2030. Both of them, in combination with some additional measures on the vehicle itself would most probably reach the target (a HPDI LNG/LBG hybrid powertrain most certainly).

The results above highlight the challenge in meeting the 2030 tailpipe CO_2 emission reduction target. Only a few advanced ICE based powertrains can meet this target. This would lead to reduced offering of ICE vehicles and more electric vehicles, a trend that would probably impair functionality in some applications. Most probably there would also be cost implications to the transport industry.

When the CO_2 assessment is carried out on a WTW basis, the picture is totally different (Figure 132). The analysis again assumes that reduction targets are -15 and -30%, relative to 2020 fossil diesel.

The only alternatives that cannot meet the 2025 target of -15% are diesel (fossil) and SI LNG (fossil). HPDI LNG, FHEV and FCEV on hydrogen from fossil natural gas meet the target. All renewable alternatives and BEV on predicted EU 2030 electricity mix meet the 2025 with a wide margin, as they also meet the 2030 target of -30%. Consequently, the fossil alternatives HPDI LNG, FHEV (on diesel) and FCEV (on hydrogen from natural gas) do not meet the 2030 target.

LBG from wet manure is interesting, as the JEC WTW study gives negative WTT values for this option. The explanation is that LBG (or CBG) captures and utilizes methane that otherwise would escape into the atmosphere.

Not shown in Figure 132 are renewable electricity (e.g., hydro, wind and photovoltaic) and renewable hydrogen from renewable electricity. These options would naturally deliver very low WTW CO_2 values. For example, the usage of electricity from wind energy (0 g CO_{2eqv}/MJ) for BEVs or for hydrogen via electrolysis (9.5 g CO_{2eqv}/MJ) in FCEVs would emit zero or close to zero WTT CO2 emissions. In this case, FCEV would also reach the 2030 target level with a wide margin and BEVs would also count as zero-emission according to WTW basis.

There are some discussions going on regarding the possibility to include renewable fuels in vehicle CO_2 legislation. The regulation (EU) 2019/1242 on CO_2 emissions from heavy-duty vehicles is currently under revision. Regarding renewable fuels, the following issues are discussed[34]:

- Assessment of contributions to decarbonization
- CO_2 credits for manufacturers
- Life-cycle assessment of CO_2 emissions

One challenge relates to the question how can it be guaranteed that,

[34] https://ec.europa.eu/jrc/sites/jrcsh/files/dg_clima_ze-hdv-jrc-webinar-2810020_public.pdf

e.g., diesel trucks actually run on renewable diesel. To solve this issue, the German consulting company Frontier in the spring of 2020, in its report to the German Federal Ministry for Economic Affairs and Energy (BMWi), proposed a crediting system for renewable fuels within the EU regulations on transport CO_2 emissions[35]. The basic idea of the system is presented in Figure 134.

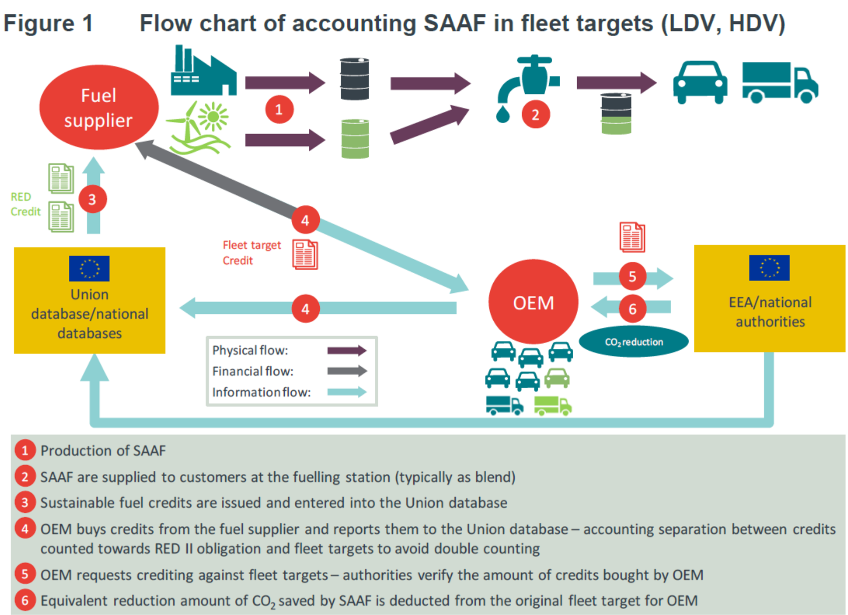

Figure 134: Schematics of a CO_2 crediting system for renewable fuels.

In short, the principle is as follows. Renewable fuels are produced and brought to the market. OEMs buy renewable fuel credits from the fuel suppliers. Credits are reported to a database system, and the OEMs have the possibility to use the credits to lower their fleet average CO_2 values.

The proposed crediting system is voluntary and provides OEMs flexibility

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[35] https://www.bmwi.de/Redaktion/DE/Downloads/C-D/crediting-system-for-renewable-fuels.pdf?__blob=publicationFile&v=4

in meeting their fleet targets. Whether and how OEMs use this option will depend – among other things – on the future price of credits.

Also energy consumption should be assessed on a WTW basis. Figure 133 presents WTW energy use split up in WTT and TTW parts. Values are given for 2020, 2025 and 2030, describing anticipated progress. Such an approach corresponds to the new Japanese fuel efficiency assessment for passenger cars[3].

Regarding TTW energy use it is obvious that BEV is to most efficient alternative, while SI LNG/LBG is the least efficient option. The energy consumption for FCEV is only marginally lower than for diesel. As stated in the experimental part, all engines based on diesel-type combustion (compression ignition) deliver roughly the same energy efficiency. The ratio of energy consumption between least and most efficient option is about 3:1.

The upstream or WTT energy consumption of the fuel or energy produced (mainly electricity) has a huge impact on total energy consumption. The ratio in upstream energy consumption for the least and most efficient pathways studied in this work was as high as 20:1. The explanation for this is the fact that the upstream or WTT parts of fossil diesel and LNG are quite efficient as the oil and gas drilling, transportation and refining are efficient processes. The same applies to waste cooking oil based HVO. Production of synthetic diesel from wood residues, production of hydrogen from natural gas as well as average European power generation consume more energy and are thus these processes are quite high in energy intensity. Highest WTT energy consumption is for biomethane/LBG from wet manure. The anaerobic digestion of wet manure itself is a rather energy efficient process. However, the biogas upgrade process to fulfil the quality requirements of transportation methane is highly energy intensive.

The outcome of all this is that LBG has by far the highest overall WTW energy consumption, whether used in a SI or in a HPDI engine. With the fuel and energy pathways selected, HVO has the lowest overall energy consumption throughout 2020 to 2030. Conventional diesel and HPDI LNG are less energy intensive than BEV on EU electricity mix in 2020 and 2025. However, the ongoing decarburization of the power sector puts BEV slightly below diesel and HPDI LNG in 2030. Naturally, if the reference would be renewable electricity, the overall energy consumption for BEV would be significantly reduced.

Figure 133 shows that the BEV truck would need about 1000 kWh of electricity to cover the daily driving of approximated 700 km, meaning that fast-charging along the route in practice is a necessity. The amount of diesel fuel needed to cover the same distance is only some 200 liters.

Although both low CO_2 emissions and energy consumption should be valued, it should be noted that these two parameters are not interlinked. Biofuels can, despite high overall energy consumption, deliver significant CO_2 reductions.

When approaching 2030, we might see electrofuels (Power-to-X (PtX)), based on captured CO_2 and hydrogen from renewable electricity, in parallel with biofuels. PtX fuels, gaseous or liquid, could deliver very low overall CO_2 emissions.

As a summary, it can be stated that going from a pure tailpipe CO_2 based regulation system to a wider WTW type approach probably would increase flexibility for OEMs as well as truck operators. In the way CO_2 regulations are set up currently, they are in principle mandates for certain technologies. The ideal situation would be that regulations define the targets in a smart and technology neutral way, letting the markets respond to the targets in the most functional and cost effective ways.

Recap of the report

IEA AMF Annex 57 is continuation of a series of projects conducted within IEA AMF assessing energy consumption and emissions of heavy-duty vehicles. Annex 57 tested contemporary heavy-duty on-road trucks representing various technology and fuel options. The main emphasis was in the heaviest vehicle segment, which is tractors. Furthermore, projections on the future potentiality of ICE powered heavy-trucks were carried out. The testing laboratories in the participating countries used a common test methodology, and the results were aggregated in a joint report. The Annex combined measurements on chassis dynamometer and on-road. In addition, simulation was used for analyzing the energy consumption of heavy-duty semi-trailer and full-trailer combinations.

Annex 57 encompassed three different work packages with actual measurements. Chassis dynamometer measurements were carried out in Canada, Chile, Finland and Sweden. On-road measurements with PEMS devices were carried out in Canada, Finland and Sweden. In Finland continuous NO_x concentration monitoring was performed for three trucks (diesel, SI-LNG and HPD-LNG) over a one year period. All in all, two different trucks were investigated in Canada, three in Chile and six in Finland as well as in Sweden.

Modelling activities were carried out in Finland and Korea. In Finland the focus was in modelling of energy consumption for high-capacity transportation. Korea presented a heavy-duty truck CO_2 emissions simulation tool developed for type-approval purposes. In addition, together with Hybrid and Electric Vehicles TCP, work was carried out to investigate the energy consumption and CO_2 emissions of different powertrain options on TTW and WTW basis. In this work, projections towards 2030 were made.

All in all, 17 trucks were tested in the chassis dynamometer. The fuels covered were diesel, B20, renewable diesel, methane and ED95. Each participating laboratory ran the WHVC test cycle according to commonly agreed test procedure. When it was possible, test inertia was set to a value corresponding to half of the maximum payload. An additional test cycle was included in the Finnish test program.

The chassis dynamometer and on-road tests showed that powertrains utilizing the diesel principle, i.e. diesel, ED95 and HPDI-LNG, have roughly equal efficiency. There was some scatter in the results for HPDI-LNG technology, energy consumption was 0 to 10 % higher compared to diesel, depending on the cycle and load.

Powertrains based on SI methane engines have some 15 to 30 % higher energy consumption compered to diesel, depending on the cycle and test inertia. Regarding CO_{2eqv} emissions SI methane engines deliver a reduction from 0 to -9% compared to diesel, depending on the vehicle, driving cycle and load. Due to the diesel-like energy efficiency and methane's favorable carbon intensity, HPDI-LNG trucks showed, in the best case, around 20 % lower CO_2 emissions compared to diesel trucks. However, in the case of CO_{2eqv} emissions the reduction is lower, in average 14 %. ED95 trucks have similar CO_2 emissions compared to diesels due to diesel like efficiency and fuel carbon intensity.

Vehicle weight has a great impact on energy consumption and CO_2 emissions on ton kilometer basis. The higher the combined mass, the lower the specific energy consumption and CO_2 emissions. Thus increased vehicle weight is a great measure to lower CO_2 emissions and reduce energy consumption. This was verified in chassis dynamometer measurements and by simulations. Simulation results up to 92 tons combined weight showed that the CO_2 emissions in relative to effective payload on ton kilometer basis could be reduced up to 40 % compared to 64 ton vehicle combination. Here it should be noted, that the typical GVW of semitrailer combinations in Europe is 40 tons.

In general, pollutant emissions were low for all Euro VI or EPA 2010 certified vehicles tested. Sophisticated diesel type engines (diesel, HPDI-LNG and ED95) are equipped with efficient exhaust after-treatment systems, including DOC, DPF and SCR, which reduce the regulated emissions well below the legislative limit values. Especially when engine and exhaust after-treatment system are fully warmed up, emissions are extremely low.

The CO, THC and PM emissions are close to zero with diesel and ED95 engines, and well below the Euro VI limit values with SI methane and HPDI-LNG engines. Most vehicles also had low NO_x emissions. One of the diesel powertrains (Euro VI D) in fully warmed up conditions showed NO_x emissions even close to 10 mg/kWh in chassis dynamometer and around 20 mg/kWh in on-road. These values are equivalent to a conformity factor of 0.02 and 0.43 compared to the type approval limit value. PN (and PM) emissions are low for powertrains equipped with DPFs. However, the HPDI-LNG Euro VI step D truck showed slightly elevated PN emissions in chassis dynamometer in Sweden and on-road conditions in Finland. The spread in PN emissions for SI methane trucks was high from vehicle to vehicle, from low to very high.

With respect to greenhouse gas emissions, N_2O emissions have to be accounted for. Some SCR systems, depending on the chemistry, can generate high N_2O emissions. This became very clear from the Swedish comparison of Euro VI Step C and Step D vehicles, showing that N_2O emissions were significantly reduced going from Step C to Step D. Notwithstanding, there was still a relatively high portion of N_2O (up to 60 g CO_{2eqv}/kWh) from the Euro VI Step D HPDI-LNG truck. The reason is not the methane fuel in itself, but rather how the SCR chemistry is adapted to the fuel exhaust gas characteristic, and some further development might be needed in this respect. In general, trucks equipped with SCR produced N_2O emissions up to 10 g CO_{2eqv}/kWh. CH_4 emissions seem not to be problem anymore with methane fueled powertrains. Both SI methane and HPDI-LNG engines are capable of levels well below the CH_4 emission limit value.

All in all, one can conclude that state of the art HDV powertrains are highly efficient and capable of delivering low emissions. The best in class diesel engines are capable of delivering 46 % thermal efficiency in long-haul operations and NO_x emissions of around 10 mg/kWh. HPDI-LNG and ED95 powertrains are capable of diesel-like efficiency. Based on the results of previous IEA AMF Annex 49 COMVEC, the state-of-the-art Euro VI diesel powertrains provide close to 17 % lower energy consumption compared to Euro IV diesel powertrains.

The future potentiality of ICE powertrains looks promising with respect to energy efficiency. The US SuperTruck II program has already demonstrated thermal efficiency above 50 %, and in some cases even close to 55 %. The current development trend indicates that by 2030 15% improvement (relative) in engine efficiency can be expected. However, this alone is not enough to meet, e.g., the EU 2030 CO_2 emission reduction target.

Within this Annex 57, AMF and Hybrid and Electric TCP cooperated in estimating the energy consumption and CO_2 emissions of different powertrain options on TTW (tailpipe) and WTW basis. IEA AMF provided data generated within the measurements in this Annex and HEV provided simulation data for trucks equipped with hybrid, fuel cell and battery electric powertrains. Calculations were made for ICE, hybrid, FC and BEV powered semi-trailer combinations in the motorway section of the WHVC cycle, utilizing the typical German daily mileage for a semi-trailer combination of around 700 km. Emission factors from JEC Well-to-Tank report v5 report were used for ICE and BEV powertrains. EU 2016 and estimated EU 2030 electricity mix was assumed for electric powertrains. 15% improvement in ICE thermal efficiency was assumed by 2030.

Investigation showed that on TTW basis, the only ICE powertrain that could meet the EU 2025 CO_2 emission target without major improvements is HPDI-LNG. Other ICE powertrains would need additional measures for achieving the target, for example hybridization, increasing the degree of electrification in various engine auxiliaries and improvements on the vehicle level.

The assessment shows that it is not possible to meet the EU 2030 CO_2 emission target with any ICE powertrain when the evaluation is done TTW basis, as is the current procedure in vehicle regulations. The only options to meet the 2030 target are BEV and fuel cell powertrains.

When the evaluation is done based on the WTW approach, the outcome is rather different. Currently there are renewable fuel options available for all ICE powertrain options covered in the project. These would enable meeting the 2030 CO_2 emission reduction target with a clear margin. Also the BEV option with anticipated EU 2030 power generating mix would meet the 2030 target on a WTW basis. Fuel cell powertrains would require hydrogen produced from renewable electricity.

Regarding energy consumption it should be noticed that even though ICE powertrains are clearly less efficient than battery electric powertrains, the diesel, either with fossil or renewable diesel, ED95 and LNG/LBG all can easily provide ranges of more than 1000 km without refueling. On the other hand, HEV's simulation shows that a BEV semi-trailer combination would need a battery of around 1000 kWh for a daily operation of around 700 km, if not recharged on route. Such a battery would weigh around 10 tons.

If the energy assessment is done on WTW basis it points out a couple of things. Firstly, HDV's powered with fossil fuels are rather energy efficient. Secondly, when using renewable fuels, the spread in overall energy consumption is huge. However, renewable diesel or HVO from waste cooking oil is also energy efficient. The third observation is that only in 2030, with average EU power mix, the BEV is on par with fossil diesel regarding overall energy use.

All in all, including the WTW approach in vehicle CO_2 emission regulations would keep the door into the future open for vehicles capable of running on renewable fuels. Some models for this are already presented. For example, a so called ticket model would enable the vehicle OEM the opportunity to purchase CO_2 reduction tickets from a renewable fuel provider, who would then bring the corresponding amount of renewable fuel into the market. The OEM, for his part, could then deduct the CO_2 avoided from its fleet average value.

As shown in this study, current ICE powertrains are rather energy efficient and deliver low tailpipe emissions. Combined with renewable fuels such as biomethane, ethanol (ED95) or renewable diesel (HVO) they provide an easy and practical way for tackling climate change in applications in which electrification will probably not progress rapidly, e.g., in long-haul heavy-duty trucking operations.

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Appendix A

	Type	Equation	
1	Acceleration	P_acc [kW] = Weight [kg] * acceleration[m/s^2] * velocity [m/s] * 0.001	
2	Load inclination	P_slope [kW] = Weight [kg] * 9.81 [m/s^2] * gradient(sinθ) * velocity [m/s] * 0.001	
3	Air drag	P_air [kW] = 0.5 * density [kg/m^3] * CdA [m ^{2}] * velocity^3 [m/s] * 0.001 * Correction factor	density = 1.188 kg/m^3
4	Rolling resistance	P_roll [kW] = RRC [-] * Weight [kg] * velocity [m/s] * 0.001	
5	Auxiliary	P_aux [kW] = auxiliary power demand[kW]	Default data
6	Engine rotational inertia	P_inertia_engine [kW] = engine inertia [kg*m^2] / tire radius^2 [m] * acceleration[m/s^2] * velocity[m/s] * 0.001	Default data
7	Tire rotational inertia	P_inertia_wheel [kW] = tire inertia [kg*m^2] / tire radius^2 [m] * acceleration[m/s^2] * velocity[m/s] * 0.001	
8	Transmission loss	P_transmission_loss [kW] = Transmission torque loss [Nm] * engine speed [rpm] * $\frac{2\pi}{60}$ * 0.001	Default data
9	Axle loss	P_axle_loss [kW] = Axle Torque loss [Nm] / transmission ratio [-] * engine speed [rpm] * $\frac{2\pi}{60}$ * 0.001	Default data
10	Retarder loss	P_retarder_loss [kW] = Retarder torque loss [Nm] / transmission ratio [-] * engine speed [rpm] * $\frac{2\pi}{60}$ * 0.001	Default data
Sum	Engine power	P_eng [kW] = P_acc [kW] + P_slope [kW] + P_air [kW] + P_roll [kW] + P_aux [kW] + P_inertia_engine [kW] + P_inertia_wheel [kW] + P_transmiss_loss [kW] + P_axle_loss [kW] + P_retarder_loss [kW]	

Appendix B

Chassis dynamometer and on-road tests for Class 5 and Class 7 diesel trucks.

WHVC Emission Rates of CO2, CH4, N2O, CO2-eq and Fuel consumption.

CLASS 7												
Payload	Start Type	Fuel	L/100km FC		g/km CO_2		mg/km CH_4		mg/km N_2O		g/km CO_2-eq	
			Avg	S.D.	Avg	S.D.	Avg	S.D.	Avg	S.D.	Avg	S.D.
Unweighted	Cold	ULSD	20.90	0.08	563.12	2.24	1.41	0.11	27.25	2.90	571.28	3.11
Unweighted	Hot	ULSD	19.41	0.14	523.53	3.88	MQL	-	25.93	0.14	531.26	3.92
Medium	Cold	ULSD	24.73	0.12	666.77	3.18	1.00	0.14	35.78	18.67	677.46	2.38
Medium	Hot	ULSD	23.38	0.03	630.63	0.92	0.00	0.00	31.51	8.49	640.02	1.61
Medium	Cold	B20	24.89	-	671.11	-	0.55	-	26.02	-	678.88	-
Medium	Hot	B20	23.31	-	628.72	-	MQL	-	27.51	-	636.91	-
High	Cold	ULSD	27.62	0.55	744.65	14.85	0.74	0.43	49.27	14.15	759.35	19.07
High	Hot	ULSD	26.23	0.77	707.47	20.89	MQL	-	34.62	0.15	717.79	20.84

CLASS 5												
Payload	Start Type	Fuel	L/100km FC		g/km CO_2		mg/km CH_4		mg/km N_2O		g/km CO_2-eq	
			Avg	S.D.	Avg	S.D.	Avg	S.D.	Avg	S.D.	Avg	S.D.
Unweighted	Cold	ULSD	18.28	0.19	491.21	5.28	1.56	0.25	23.41	0.30	498.22	5.18
Unweighted	Hot	ULSD	16.71	0.08	449.61	1.88	0.22	0.32	26.36	0.67	457.46	2.07
High	Cold	ULSD	20.54	-	552.94	-	1.13	-	31.79	-	562.45	-
High	Hot	ULSD	19.61	-	528.35	-	0.51	-	31.40	-	537.72	-

WHVC Emission Rates of CO, NOx, THC, and PM

Class 7										
Payload	Start Type	Fuel	g/km CO		g/km NOx		g/km THC		g/km PM	
			Avg	S.D.	Avg	S.D.	Avg	S.D.	Avg	S.D.
Unweighted	Cold	ULSD	0.44	0.01	0.74	0.03	0.028	0.004	0.814	0.741
Unweighted	Hot	ULSD	0.01	0.00	0.74	0.01	0.009	0.004	0.225	0.024
Medium	Cold	ULSD	0.17	0.01	0.43	0.01	0.027	0.008	0.403	0.158
Medium	Hot	ULSD	0.01	0.00	0.37	0.01	0.015	0.006	0.177	0.031
Medium	Cold	B20	0.15	-	0.33	-	0.004	-	0.315	-
Medium	Hot	B20	0.01	-	0.34	-	0.001	-	0.201	-
High	Cold	ULSD	0.20	0.05	0.36	0.06	0.025	0.014	0.233	-
High	Hot	ULSD	0.01	0.00	0.25	0.06	0.013	0.002	0.368	-
Class 5										
Payload	Start Type	Fuel	g/km CO		g/km NOx		g/km THC		g/km PM	
			Avg	S.D.	Avg	S.D.	Avg	S.D.	Avg	S.D.
Unweighted	Cold	ULSD	0.14	0.04	0.51	0.03	0.012	0.001	0.78	0.21
Unweighted	Hot	ULSD	0.01	0.00	0.34	0.12	0.007	0.004	0.68	0.34
Medium	Cold	ULSD	0.09	-	0.37	-	0.009	-	0.58	-
Medium	Hot	ULSD	0.06	-	0.22	-	0.003	-	2.87	-

RDE Emission Rates of CO, CO2, NOx, THC, and Fuel Consumption

Class 7										
Test Description	g/km		g/km		g/km		g/km		L/100km	
	CO		CO_2		NOx		THC		FC	
ULSD - Unweighted	Avg	S.D.	Avg	S.D.	Avg	S.D.	Avg	S.D.	Avg	S.D.
Urban	1.07	0.10	832.62	131.53	0.32	0.02	0.0397	0.0203	30.93	4.88
Rural	0.68	0.27	622.01	33.71	0.07	0.03	MQL	-	23.10	1.23
Highway	0.66	0.26	610.96	1.37	0.09	0.08	MQL	-	22.68	0.07
Route	0.77	0.22	671.54	26.74	0.14	0.05	0.0103	0.0053	24.94	1.00
ULSD - High Load	Avg	S.D.	Avg	S.D.	Avg	S.D.	Avg	S.D.	Avg	S.D.
Urban	0.89	0.31	863.07	35.07	0.31	0.04	0.0175	0.0046	32.05	1.30
Rural	0.71	0.19	762.99	40.58	0.04	0.00	0.0008	0.0013	28.32	1.49
Highway	0.59	0.17	672.60	9.45	0.02	0.00	0.0001	0.0002	24.97	0.35
Route	0.71	0.21	747.04	19.86	0.10	0.02	0.0049	0.0014	27.73	0.73
B20 - High Load	Avg	S.D.	Avg	S.D.	Avg	S.D.	Avg	S.D.	Avg	S.D.
Urban	0.50	0.05	886.86	75.29	0.37	0.01	0.0414	0.0664	32.91	2.78
Rural	0.32	0.04	766.75	11.51	0.04	0.00	0.0056	0.0096	28.44	0.42
Highway	0.29	0.04	686.37	0.44	0.02	0.00	0.0002	0.0002	25.46	0.01
Route	0.35	0.02	758.87	22.82	0.11	0.00	0.0123	0.0198	28.15	0.84

Class 5										
Test Description	g/km		g/km		g/km		g/km		L/100km	
	CO		CO_2		NOx		THC		FC	
ULSD - Unweighted	Avg	S.D.	Avg	S.D.	Avg	S.D.	Avg	S.D.	Avg	S.D.
Urban	0.39	0.11	463.57	20.01	0.57	0.09	MQL	-	17.21	0.75
Rural	0.35	0.12	490.85	7.34	0.27	0.08	MQL	-	18.21	0.28
Highway	0.34	0.13	672.95	8.82	0.08	0.01	MQL	-	24.96	0.33
Route	0.36	0.12	563.85	11.59	0.27	0.05	MQL	-	20.92	0.44

Appendix C

Chassis dynamometer and on-road test results performed in Finland.

Chassis dynamometer test results in g per km basis.

Test id and vehicle	Test inertia [kg]	CO2 [g/km]	Fuel energy [MJ/km]	PN [10^11/km]	PM [mg/km]	CO [mg/km]	THC [mg/km]	CH4 [mg/km]	NOx [mg/km]	N2O [g/km]
WHVC hot,Truck A, Special CNG, 30T	30000	1043	18.396	115.8	2.2	2020	586	523	143.0	0.000
WHVC hot,Truck A, Regular CNG, 30T	30000	1025	18.580	84.6	2.1	1764	181	157	198.1	0.000
WHVC hot,Truck B, LNG, 30T	30000	1034	18.662	9.6	3.5	2775	16	8	354.7	0.000
WHVC hot,Truck C, Diesel, 30T	30000	1020	13.869	1.2	2.0	116	9	0	153.2	0.081
WHVC hot,Truck C, HVO, 30T	30000	972	13.653	0.9	1.3	30	11	0	112.2	0.065
WHVC hot,Truck D, LNG, DI, 30T	30000	837	14.588	21.1		42	386	385	14.3	0.285
WHVC hot,Truck E, ED95, 30T	30000	997	13.520	0.8	1.2	0	20	2	476.6	0.022
WHVC hot,Truck F, Diesel, 30T	30000	1034	14.056	1.1	1.1	159	4	0	1.9	0.107
WHVC hot,Truck F, HVO, 30T	30000	1007	13.962	0.6	0.8	80	11	0	1.5	0.108
WHVC hot,Truck A, Regular CNG, 44T	44000	1235	22.380	119.3	2.9	2986	505	453	217.1	0.017
WHVC hot,Truck B, LNG, 44T	44000	1258	22.713	1.0	1.4	2949	21	19	309.0	0.000
WHVC hot,Truck C, Diesel, 44T	44000	1269	17.263	1.2	1.7	0	11	0	47.4	0.071
WHVC hot,Truck D, LNG, DI, 44T	44000	1059	18.588	25.6	2.4	31	449	428	16.5	0.164
WHVC hot,Truck E, ED95, 44T	44000	1239	16.803	1.2	1.3	0	0	3	595.6	0.022
WHVC hot,Truck F, Diesel, 44T	44000	1316	17.899	1.5	3.5	176	22	0	4.8	0.108
HDV PerE,Truck A, Regular CNG, 30T	30000	1054	18.946	36.5	1.8	1096	906	816	148.6	0.000
HDV PerE,Truck B, LNG, 30T	30000	1175	20.520	0.4	2.3	3937	22	20	210.8	0.000
HDV PerE,Truck C, Diesel, 30T	30000	1153	15.685	1.4	2.2	164	1	0	83.2	0.076
HDV PerE,Truck C, HVO, 30T	30000	1100	15.443	1.5	1.9	0	1	0	16.1	0.087
HDV PerE,Truck D, LNG, DI, 30T	30000	956	16.782	27.1	12.5	32	398	392	14.3	0.085
HDV PerE,Truck E, ED95, 30T	30000	1098	14.895	0.8	1.3	0	1	2	315.3	0.016
HDV PerE,Truck F, Diesel, 30T	30000	1160	15.774	1.0	8.0	112	0	0	3.5	0.069
HDV PerE,Truck F, HVO, 30T	30000	1126	15.611	10.1	3.8	49	7	0	3.4	0.076
WHVC cold,Truck A, Special CNG, 30T	30000	1071	19.421	130.0	2.0	19396	1842	1612	163.7	0.047
WHVC warm,Truck A, Special CNG, 30T	30000	1041	18.392	153.8	2.2	2590	744	654	135.5	0.000
WHVC comb.,Truck A, Special CNG, 30T	30000	1046	18.536	150.5	2.2	4943	898	788	139.4	0.007
WHVC cold,Truck B, LNG, 30T	30000	1067	19.381	4.437	6.2	6107	521	445	562.1	0.030
WHVC warm,Truck B, LNG, 30T	30000	1027	18.543	5.903	4.3	2716	8	12	339.3	0.000
WHVC comb.,Truck B, LNG, 30T	30000	1032	18.660	5.698	4.6	3191	80	73	370.5	0.004
WHVC cold,Truck C, Diesel, 30T	30000	1045	14.208	1.305	1.8	374	20	0	1428.5	0.030
WHVC warm,Truck C, Diesel, 30T	30000	1008	13.701	1.061	1.6	5	10	0	30.8	0.029
WHVC comb.,Truck C, Diesel, 30T	30000	1024	13.772	1.095	1.7	224	15	0	648.7	0.029
WHVC cold,Truck D, LNG, DI, 30T	30000	876	15.459	2.498	1.8	3524	579	557	803.9	0.236
WHVC warm,Truck D, LNG, DI, 30T	30000	842	14.712	3.587	1.7	25	414	412	19.9	0.259
WHVC comb.,Truck D, LNG, DI, 30T	30000	847	14.816	3.435	1.7	490	437	432	129.7	0.255
WHVC cold,Truck E, ED95, 30T	30000	1014	13.745	0.685	1.5	73	78	4	1253.2	0.012
WHVC warm,Truck E, ED95, 30T	30000	1006	13.637	0.873	1.0	0	30	3	335.3	0.011
WHVC comb.,Truck E, ED95, 30T	30000	1007	13.652	0.847	1.0	0	36	4	463.8	0.011
WHVC cold,Truck F, Diesel, 30T	30000	1039	14.362	4.8	1.1	255	5	0	5.9	0.078
WHVC warm,Truck F, Diesel, 30T	30000	1041	14.123	1.4	1.2	233	11	0	3.5	0.117
WHVC comb.,Truck F, Diesel, 30T	30000	1041	14.156	1.9	1.2	236	10	0	3.8	0.112

Chassis dynamometer test results in g per kWh (powertrain) basis.

Test id and vehicle	Test inertia [kg]	Powertrain specific CO2 [g/kWh]	Powertrain specific NOx [mg/kWh]	Powertrain specific PM [mg/kWh]	Powertrain specific PN [10^11/kWh]	Powertrain specific NMHC [mg/kWh]	Powertrain specific CO [mg/kWh]	Powertrain specific CH4 [mg/kWh]
WHVC hot,Truck A, Special CNG, 30T	30000	795	109	1.6	88.3	53.9	1.5	398
WHVC hot,Truck A, Regular CNG, 30T	30000	791	150	1.6	64.1	18.3	1.3	119
WHVC hot,Truck B, LNG, 30T	30000	773	265	2.6	7.2	6.9	2.1	6
WHVC hot,Truck C, Diesel, 30T	30000	764	115	1.5	0.9	9.4	0.1	0
WHVC hot,Truck C, HVO, 30T	30000	728	84	1.0	0.7	11.1	0.0	0
WHVC hot,Truck D, LNG, DI, 30T	30000	622	11	-	15.7	37.5	0.0	286
WHVC hot,Truck E, ED95, 30T	30000	769	368	1.0	0.6	14.1	0.0	2
WHVC hot,Truck F, Diesel, 30T	30000	770	1	0.8	0.8	3.9	0.1	0
WHVC hot,Truck F, HVO, 30T	30000	749	1	0.6	0.4	9.3	0.1	0
WHVC hot,Truck A, Regular CNG, 44T	44000	718	184	1.6	57.1	35.9	1.6	276
WHVC hot,Truck B, LNG, 44T	44000	724	178	0.8	0.6	3.3	1.7	11
WHVC hot,Truck C, Diesel, 44T	44000	723	27	1.0	0.7	8.8	0.0	0
WHVC hot,Truck D, LNG, DI, 44T	44000	602	9	1.4	14.5	43.3	0.0	243
WHVC hot,Truck E, ED95, 44T	44000	722	347	0.7	0.7	0.0	0.0	2
WHVC hot,Truck F, Diesel, 44T	44000	741	3	2.0	0.8	14.0	0.1	0
HDV PerE,Truck A, Regular CNG, 30T	30000	671	76	1.1	21.8	35.4	0.8	371
HDV PerE,Truck B, LNG, 30T	30000	703	90	2.7	0.2	1.8	2.6	7
HDV PerE,Truck C, Diesel, 30T	30000	712	51	1.4	0.9	3.4	0.1	0
HDV PerE,Truck C, HVO, 30T	30000	682	10	1.2	0.9	2.4	0.0	0
HDV PerE,Truck D, LNG, DI, 30T	30000	593	9	2.4	16.8	35.0	0.0	244
HDV PerE,Truck E, ED95, 30T	30000	685	197	0.8	0.5	0.0	0.0	1
HDV PerE,Truck F, Diesel, 30T	30000	717	2	5.0	0.6	1.7	0.1	0
HDV PerE,Truck F, HVO, 30T	30000	699	2	2.3	6.3	6.1	0.0	0
WHVC cold,Truck A, Special CNG, 30T	30000	813	124	1.5	98.7	191.8	14730.9	1224
WHVC warm,Truck A, Special CNG, 30T	30000	795	103	1.7	117.5	75.9	1978.0	499
WHVC comb.,Truck A, Special CNG, 30T	30000	798	106	1.7	114.8	92.2	3763.4	601
WHVC cold,Truck B, LNG, 30T	30000	807	425	4.7	3.4	60.6	4622.2	336
WHVC warm,Truck B, LNG, 30T	30000	770	254	3.2	4.4	0.1	2038.2	9
WHVC comb.,Truck B, LNG, 30T	30000	775	278	3.5	4.3	5.5	2400.0	55
WHVC cold,Truck C, Diesel, 30T	30000	790	1080	1.3	1.0	17.3	0.3	0
WHVC warm,Truck C, Diesel, 30T	30000	753	23	1.2	0.8	10.0	0.0	0
WHVC comb.,Truck C, Diesel, 30T	30000	759	171	0.6	0.8	11.0	0.0	0
WHVC cold,Truck D, LNG, DI, 30T	30000	655	601	1.3	1.9	70.1	2.6	416
WHVC warm,Truck D, LNG, DI, 30T	30000	630	15	1.3	2.7	41.5	0.0	308
WHVC comb.,Truck D, LNG, DI, 30T	30000	634	97	1.3	2.6	45.5	0.4	323
WHVC cold,Truck E, ED95, 30T	30000	776	959	1.2	0.5	57.0	0.1	3
WHVC warm,Truck E, ED95, 30T	30000	778	259	0.7	0.7	20.6	0.0	3
WHVC comb.,Truck E, ED95, 30T	30000	777	357	0.8	0.7	25.7	0.0	3
WHVC cold,Truck F, Diesel, 30T	30000	790	484	1.4	3.6	14.2	0.1	0
WHVC warm,Truck F, Diesel, 30T	30000	778	4	0.9	1.0	4.6	0.2	0
WHVC comb.,Truck F, Diesel, 30T	30000	780	72	0.9	1.4	6.0	0.2	0

PEMS test results on-road in g per kWh (engine) basis.

Vehicle and test id	NOx [mg/kWh]	NOx [mg/km/ton]	PM [mg/kWh]	PM [mg/km/ton]	CO2 [g/kWh]	CO2 [g/km/ton]	PN [1*10^11/kWh]	PN [#/km/ton]	Specific energy consumption [MJ/km/ton]
Truck B, 31.2 tons, ISC 1	138	5.13	0.01	0.00	648	24.03	0.69	2.56E+09	0.436
Truck B, 31.2 tons, ISC 2	125	4.55	0.00	0.00	644	23.41	0.77	2.92E+09	0.425
Truck B, 31.2 tons, HDV PerE	193	6.15	0.03	0.00	648	27.49	1.17	3.69E+09	0.499
Truck C, 30.6 tons, ISC 1	153	4.72	0.00	0.00	704	21.76	0.20	6.19E+08	0.297
Truck C, 30.6 tons, HDV PerE	138	5.11	0.01	0.00	712	26.65	0.27	1.02E+09	0.364
Truck D, 31 tons, ISC 1	23	0.76	0.00	0.00	600	20.08	1.10	3.50E+09	0.355
Truck D, 31 tons, ISC 2	35	1.08	0.00	0.02	606	18.88	1.00	3.50E+09	0.334
Truck D, 31 tons, HDV PerE	232	9.05	0.41	0.02	599	23.58	12.53	4.96E+10	0.417