Annex 49




A Report from the IEA Alternative Motor Fuels Technology Collaboration Programme

Fuel and Technology Alternatives for Commercial Vehicles

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ADVANCED MOTOR FUELS
IEA-AMF

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Energy Technology Network
Technology Collaboration Programmes

October 2016

Disclaimer

Abstract

In the "COMVEC" project, eight partners from four continents teamed up to generate new performance data (energy efficiency, exhaust emissions) for commercial vehicles. The work started with the development of a common test procedure. It was decided to use the World Harmonized Vehicle Cycle (WHVC) for vehicle testing and the World Harmonized Transient Cycle (WHTS) for engine testing.

Altogether, 35 different vehicles were tested on chassis dynamometers, with vehicles ranging from light commercial vehicles (vans) to heavy-duty tractors for semi-trailers. In addition, one engine, installed in an engine dynamometer, was tested. The test programme covered several fuel options: diesel, diesel substitute fuels, natural gas, ethanol and even electricity in the category of light commercial vehicles.

With the exception of electricity, the variations in specific energy consumption (relative to vehicle weight) with different fuels were rather small, as were the variations in tailpipe carbon dioxide emissions. There were, however, significant differences in regulated emissions. In the case of regulated emissions, the emission control technology used on the vehicle is decisive for performance, and not primarily the fuel.

The measurements showed that Euro VI vehicles, on an average, deliver really low emissions of nitrogen oxides and particulates, whereas most Euro IV and Euro V vehicles had emissions higher than expected. This leads to the recommendation that countries with less stringent emission legislation in place, when considering tightening requirements, should not go for Euro IV or Euro V, but rather leapfrog to Euro VI, on the condition that high quality fuel is available. The project findings can also be used when setting up requirements for procurement of transport services, such that, whenever possible, they favour services provided by Euro VI (or US 2010) certified vehicles.

Well-to-wheel carbon dioxide emissions depend, first and foremost, on the energy used, not the vehicle itself. Low carbon electricity and the best of biofuels deliver very low well-to-wheel carbon dioxide emissions. A petrol vehicle running on fossil fuel and an electric vehicle running on electricity generated with coal, deliver equally high emissions. In summary, it can be said that vehicle technology determines regulated emissions, whereas overall carbon dioxide emissions are determined by the type of energy carrier (fossil vs. renewable). Euro VI (or US 2010) vehicles, in combination with high quality renewable fuels, are a good choice for local air quality, as well as the climate.

Preface

Commercial goods vehicles, light-, medium- and heavy-duty vehicles together, represent approximately 25 % of the total energy use in transport, and are the second largest segment after passenger cars.

The goals of the "COMVEC" project (Fuel and Technology Alternatives for Commercial Vehicles) were twofold:

1. To agree upon common test procedures for testing and comparing different types of commercial vehicles.

2. To generate performance data specific to commercial vehicles (goods vehicles), thus adding to the information on alternative fuels and vehicle technologies generated in previous AMF activities (Annex 37 on buses, Annexes 38 and 39 on trucks, Annex 43 on passenger cars).

With data covering all road vehicle classes, it will eventually be possible to evaluate the best fit for alternative fuels and new vehicle technologies for road transport, meaning that alternative technologies can be allocated in the most effective way.

The COMVEC project was set up as a task-shared activity within the IEA Technology Collaboration Programme Advanced Motor Fuels. Task-sharing means that all participating countries covered their own contribution and participation costs for the project.

The VTT Technical Research Centre of Finland Ltd acted as the Operating Agent for the project.
The other partners in COMVEC were:

- Canada, through the Environment and Climate Change Canada (ECCC), Transport Canada's ecoTECHNOLOGY for Vehicles Program (eTV) and Natural Resources Canada's Program of Energy Research and Development (PERD) Advanced Fuels and Technologies for Emissions Reduction (AFTER 8).
- Chile, through the Centro Mario Molina Chile (CMMCh).
- China, through the China Automotive Technology and Research Center (CATARC).
- Denmark, through the Danish Technological Institute (DTI).
- Japan, through the Organization for the promotion of low emission vehicles (LEVO).
- Korea, through the Korea Institute of Energy Technology Evaluation and Planning (KETEP).
- Sweden, through the Swedish Transport Administration (STA).
- Thailand, through the PTT Research and Technology Institute.

All in all, COMVEC put together test data from 35 vehicles, ranging from light-duty commercial vehicles (vans) to heavy-duty tractors for semi-trailers, and one test engine. Some tests were carried out, in parallel, with multiple fuel options.

Special thanks go to Debbie Rosenblatt of Environment and Climate Change Canada for technical support and proofreading a major part of the report.

Espoo October 2016

Nils-Olof Nylund, Editor

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Abbreviations

AMF	(IEA) Advanced Motor Fuels Technology Collaboration Programme
BTL	Biomass-to-liquids
Bxx	xx concentration (v/v) of FAME in diesel
CBG	Compressed biogas
CERT	Certification diesel fuel
CH_4	Methane
CLG	Compressed landfill gas
CME	Canola methyl ester
CNG	Compressed natural gas
CO	Carbon monoxide
CO_2	Carbon dioxide
CO_{2eqv}	Carbon dioxide equivalent
DF	Diesel fuel
DME	Di-methyl-ether
DOC	Diesel oxidation catalyst
DPF	Diesel particulate filter
ECCC	Environment and Climate Change Canada
EEV	Enhanced environmentally friendly vehicle
EGR	Exhaust gas recirculation
ENxxx	European fuel standard
EPA	Environmental Protection Agency
ERMS	Emissions Research and Measurement Section (ECCC)
EtOH	Ethanol
EU	European Union
EV (BEV)	Electric vehicle (battery electric vehicle)
Euro II…EEV	Heavy-duty emission certification classes for Europe
ED95	Additive treated hydrous ethanol for diesel operation
E85	High concentration (85 %) ethanol fuel for spark-ignited engines
FAME	Fatty-acid methyl ester
FC	Fuel consumption
FT	Fischer-Tropsch
FTF	Flow-through filter
FTP	Federal Test Procedure
GHG	Greenhouse gases
GTL	Gas-to-liquids
GVW	Gross vehicle weight
GWP	Global warming potential
HC	Hydrocarbons
HD, HDV	Heavy-duty vehicle
HEV (HV)	Hybrid electric vehicle
HP	Horse power
HPDI	High pressure direct injection
HRD	Hydrotreated renewable diesel
HVO	Hydrotreated vegetable oil
HYB	Hybrid
ICE	Internal combustion engine
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
JEC	Joint Research Centre – EUROPIA – CONCAWE
JE05	Japanese vehicle test cycle
JRC	Joint Research Centre
LB	Lean-burn
LCA	Life cycle assessment

LDT	Light-duty truck
LNG	Liquefied natural gas
LPG	Liquefied petroleum gas
MY	Model year
NA	North American
NEDC	New European Test Cycle
NG	Natural gas
NMHC	Non-methane hydrocarbons
NMOG	Non-methane organic gas
NMVOC	Non-methane volatile organic compounds
NO_x	Nitrogen oxides
NO_2	Nitrogen dioxide
NTE	Not-to-exceed
N_2O	Nitrous oxide
OC	Oxidation catalyst
OEM	Original equipment manufacturer
O_2	Oxygen
PAH	Polyaromatic hydrocarbons
p-DPF	Partial diesel particulate filter
PM	Particulate matter
R	Rapeseed
RD	Renewable diesel (HVO)
RED	Renewable Energy Directive
RME	Rapeseed methyl ester
SAE	Society of Automotive Engineers
SCR	Selective catalytic reduction (for NO_x)
SCRT	SCR + CRT
SFC	Specific fuel consumption
SM	Stoichiometric
TCO	Total cost of ownership
THC	Total hydrocarbons
TPM	Total particulate matter
TTW	Tank-to-wheel
TWC	Three-way catalyst
UDDS	Urban dynamometer driving cycle
ULSD	Ultra low sulfur diesel
US	United States
VOC	Volatile organic compounds
VTT	VTT Technical Research Centre of Finland Ltd
WHSC	World harmonized steady cycle
WHTC	World harmonized transient cycle
WHVC	World harmonized vehicle cycle
WTT	Well-to-tank
WTW	Well-to-wheel

Extended summary

General

Commercial goods vehicles, light-, medium- and heavy-duty vehicles together, represent around 25 % of the total energy used in transport, and are the second largest segment after passenger cars. Therefore, this vehicle category is important, not only for its contribution to economic activities, but also for its share of energy use and emissions.

The goals of the "COMVEC" project (Fuel and Technology Alternatives for Commercial Vehicles) were twofold:

1. To agree upon common test procedures for testing and comparing different types of commercial vehicles, and

2. To generate performance data specific to commercial vehicles (goods vehicles), thus adding to the information on alternative fuels and vehicle technologies generated in previous AMF activities (Annex 37 on buses, Annexes 38 and 39 on trucks, Annex 43 on passenger cars).

With data covering all road vehicle classes, it will eventually be possible to evaluate the best fit for alternative fuels and new vehicle technologies for road transport, meaning that alternative technologies can be allocated in the most effective way.

The COMVEC project was set up as a task-shared activity within the IEA Technology Collaboration Programme Advanced Motor Fuels (AMF). Task-sharing means that all participating countries covered their own contribution and participation costs for the project.

In the "COMVEC" project, eight partners from three continents teamed up to generate performance data (energy efficiency, exhaust emissions) for commercial vehicles.

The project plan specified the following main vehicle categories to be measured:

- Category 1: Light-duty commercial vehicles (GVW 2 500 – 5 000 kg)
    - Delivery van type vehicles (vans) and pick-up trucks

- Category 2: Medium heavy-duty trucks (GVW 5 000 – 18 000 kg)
    - Delivery trucks, garbage trucks etc., 2 axles, single unit

- Category 3: Tractors (GVW ~ 40 000 kg)
    - Long-haul semi-trailer tractors.

In the end, Category 2 was expanded to cover all single unit trucks (also vehicles with 3 axles, up to 26 tonnes), and Category 3 to include vehicles for semi- as well as full trailer combinations (up to 60 tonnes).

Altogether, 35 different vehicles were tested on chassis dynamometers, with vehicles ranging from light commercial vehicles (vans) to heavy-duty vehicles for trailer combinations. In addition, one engine, installed in an engine dynamometer, was tested. The test programme covered several fuel options: diesel, diesel substitute fuels, natural gas, ethanol, and even electricity, in the category of light commercial vehicles. The emission certification classes covered were Euro 4, Euro 5 and Tier 2 for light-duty commercial vehicles, and Euro III, Euro IV, Euro V, Euro VI and US 2010 for the heavier vehicles.

The partners contributed with measurements as follows:

Canada:

- Four Category 1 vehicles
    - One vehicle platform, petrol, bi-fuel CNG, bi-fuel LPG, electric
- One Category 3 diesel vehicle

Chile:

- One Category 1 diesel vehicle
- One Category 2 diesel vehicle
- One Category 3 diesel vehicle

China:

- One Category 1 diesel vehicle
- One Category 2 diesel vehicle
- Two Category 3 diesel vehicles

Denmark:

- One Category 2 diesel vehicle
- One Category 2 CNG vehicle

Finland:

- Five Category 1 vehicles
    - Three vehicle platforms, petrol, diesel, bi-fuel CNG, electric
- Nine Category 2 vehicles
    - Including diesel, diesel-hybrid, CNG, dual-fuel CNG, ethanol
- Three Category 3 diesel vehicles

Japan:

- One diesel engine for Category 2 trucks

Sweden:

- One Category 2 diesel truck
- One Category 2 ethanol truck

Thailand:

- Two Category 1 vehicles
    - One vehicle platform, bi-fuel CNG and diesel

Some of the partners also tested multiple substitute fuels, i.e. fuels that can replace conventional petrol and diesel in existing vehicles.

As in the case of IEA AMF Annex 37 on fuel and technology options for buses, COMVEC combines well-to-tank (WTT) data and tank-to-wheel (TTW - actual measurements on the vehicles listed above) data to form well-to-wheel (WTW) data on emissions and energy use.

For COMVEC, it was decided to use WTT data from the JEC - Joint Research Centre-EUCAR-CONCAWE collaboration on WTW. The Joint Research Centre (JRC) is run by the EU Commission. EUCAR is the European Council for Automotive R&D and CONCAWE is the platform for environmental research collaboration of the fuel refining industry. With the participation of JRC, one could state that the JEC work is sanctioned by the European Commission.

The experimental work started with the development of a common test procedure. It was decided to use the World Harmonized Vehicle Cycle (WHVC) for vehicle testing and the World Harmonized Transient Cycle (WHTS) for engine testing. For the chassis dynamometer measurements, the recommended load was set at 50 % of the full load. All tests were carried out with fully warmed-up engines.

The test protocol was a recommendation, and the participants were not forced to follow it exactly. **The individual participants are responsible for the quality and the relevance of the supplied data.**

In the report, the results are presented partner by partner, and then the results are collated. Separate chapters on the effects of substitute fuels, full-fuel-cycle evaluations and cost assessments are presented.

Collated chassis dynamometer results

The results are presented as energy consumption, specific energy consumption (MJ/km/1000 kg of vehicle mass), CO_2 emissions, NO_x emissions and PM emissions versus test weight. Data for all vehicle classes are incorporated in the figures.

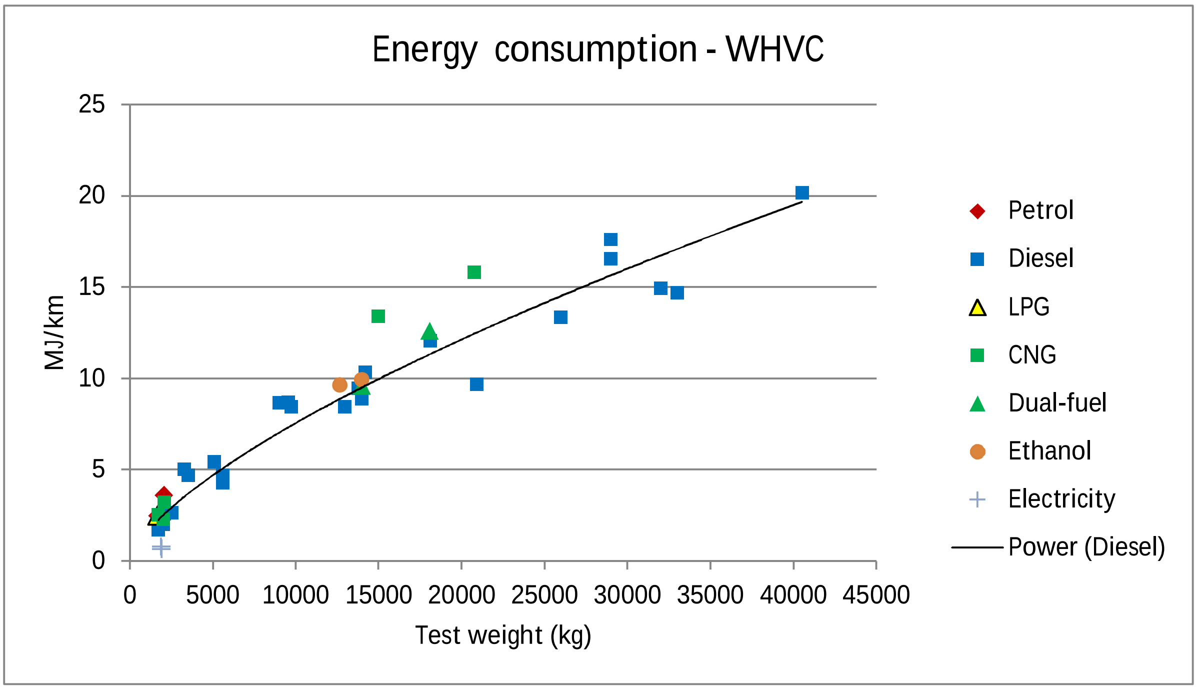

Figure 0.1. Energy consumption by fuel.

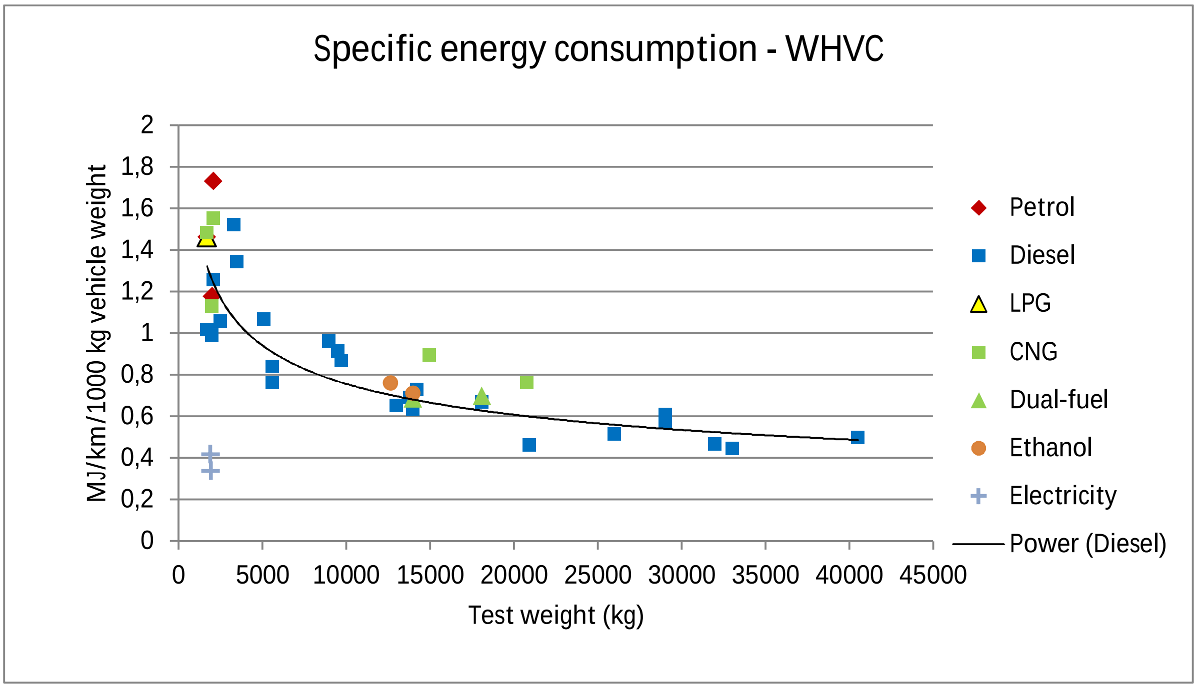

Figure 0.2. Specific energy consumption by fuel.

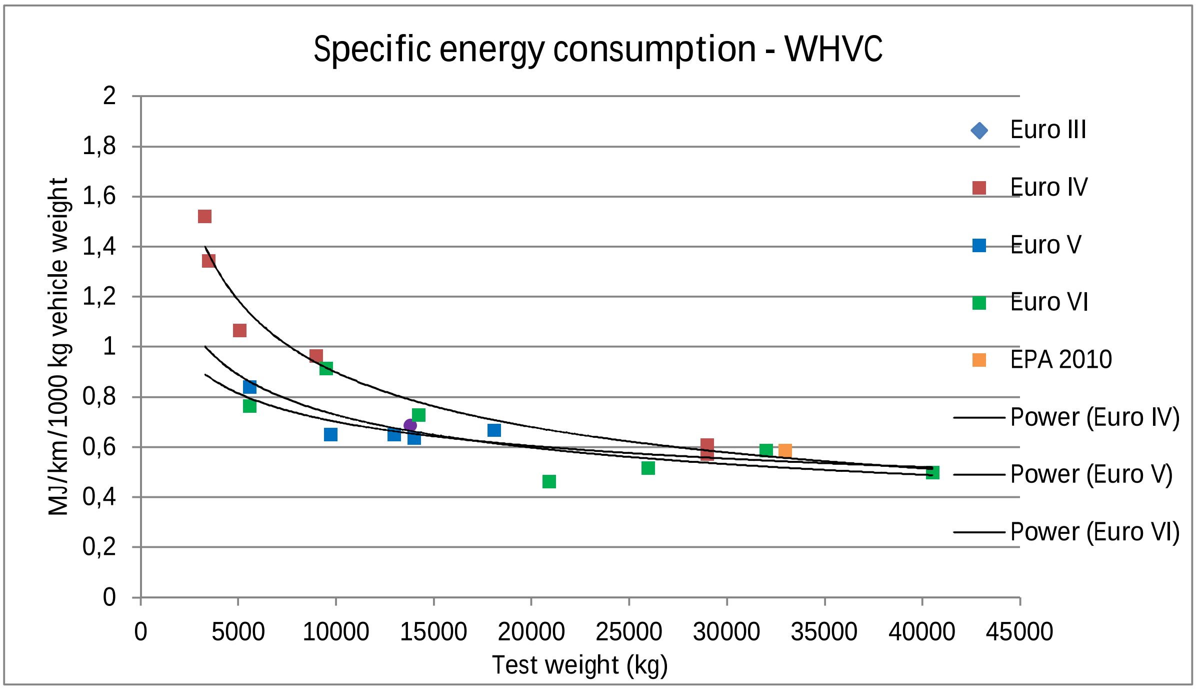

Figure 0.3. Specific energy consumption by emission class (Category 2 & 3 vehicles).

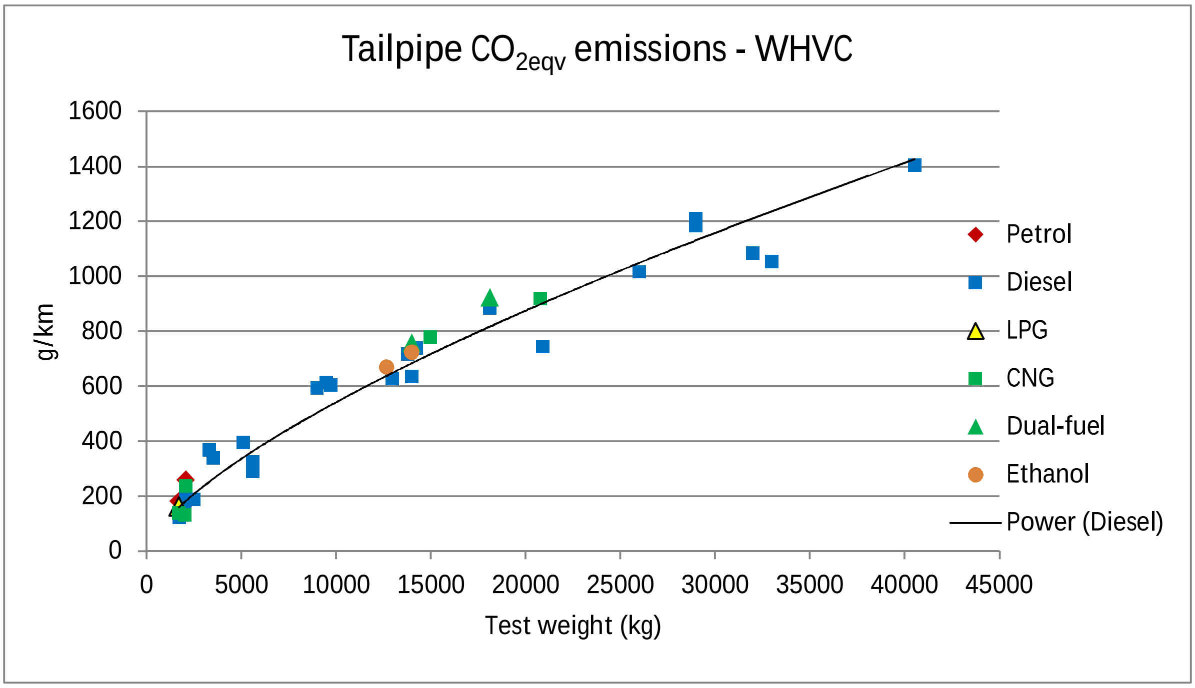

Figure 0.4. CO_{2eqv} emissions by fuel.

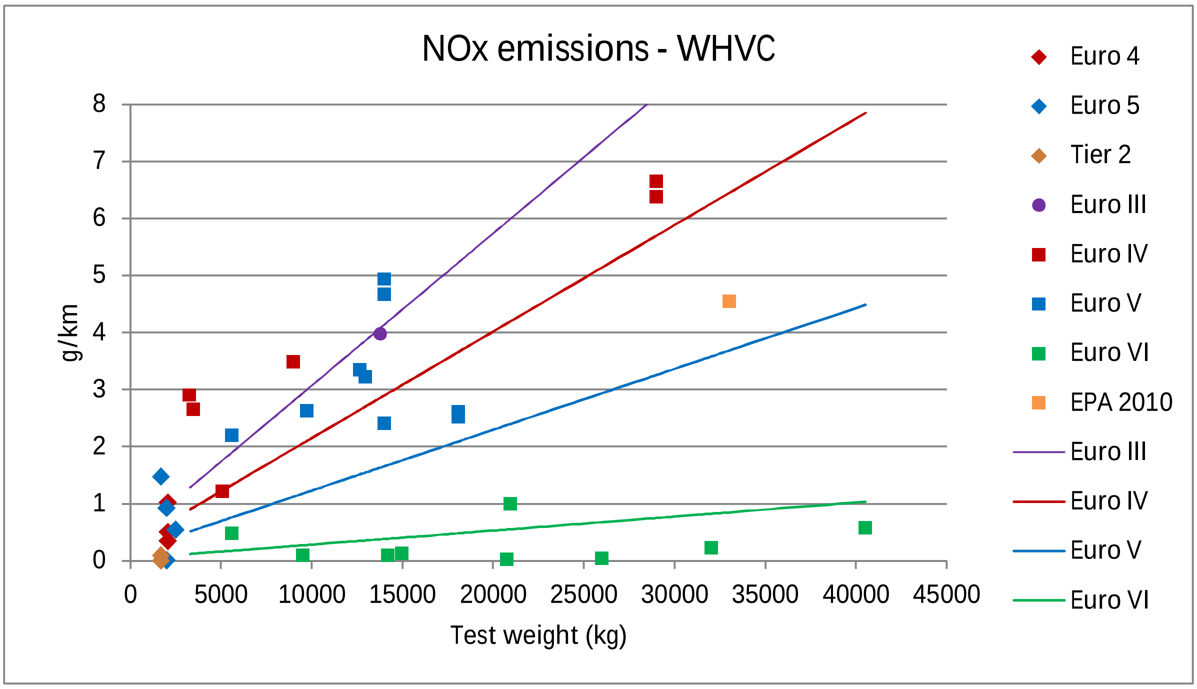

Figure 0.5. NO_x emissions by emission class.

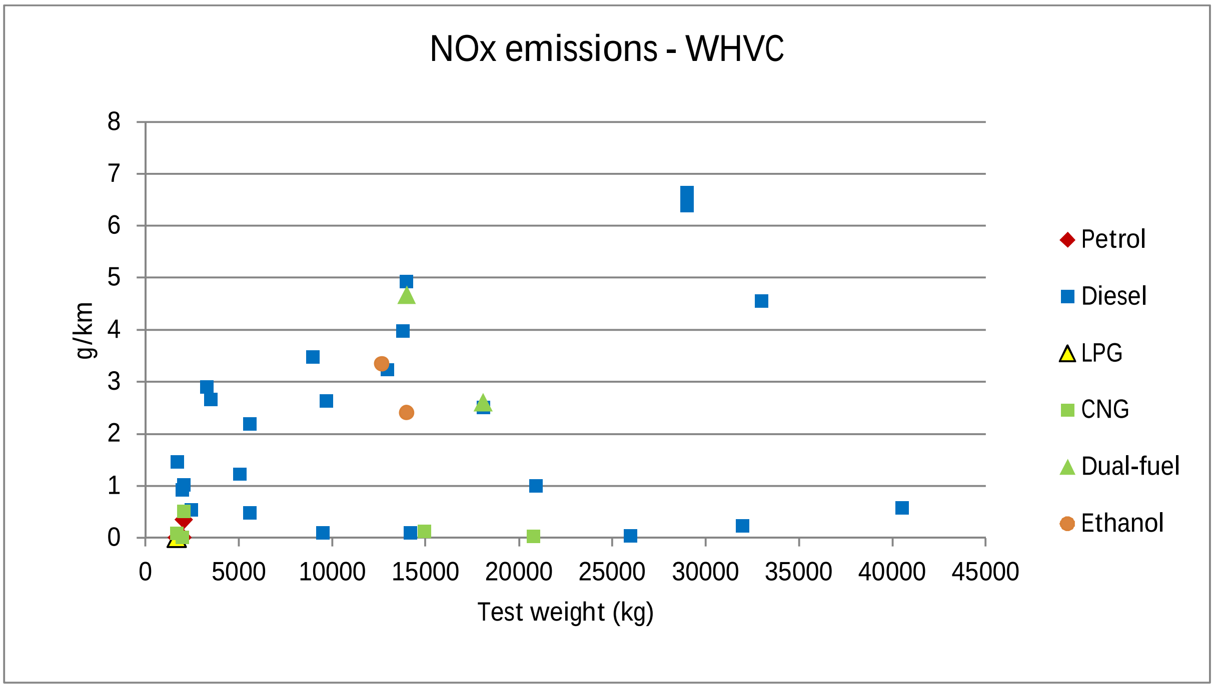

Figure 0.6. NO_x emissions by fuel.

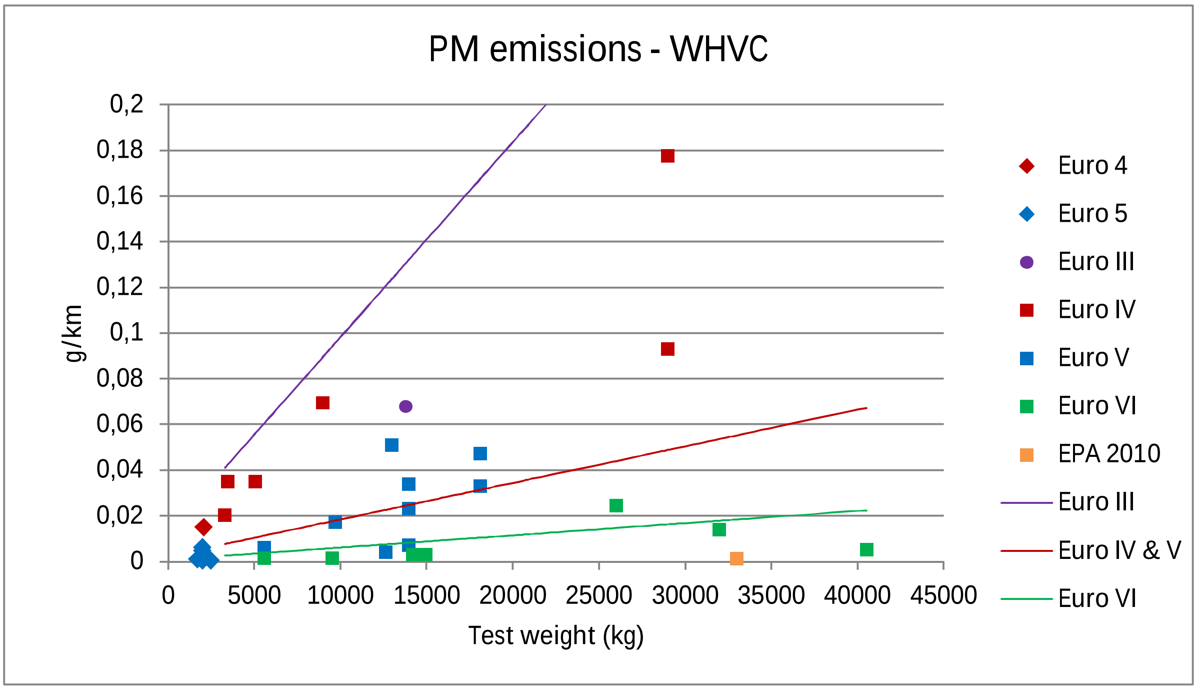

Figure 0.7. PM emissions by emission class.

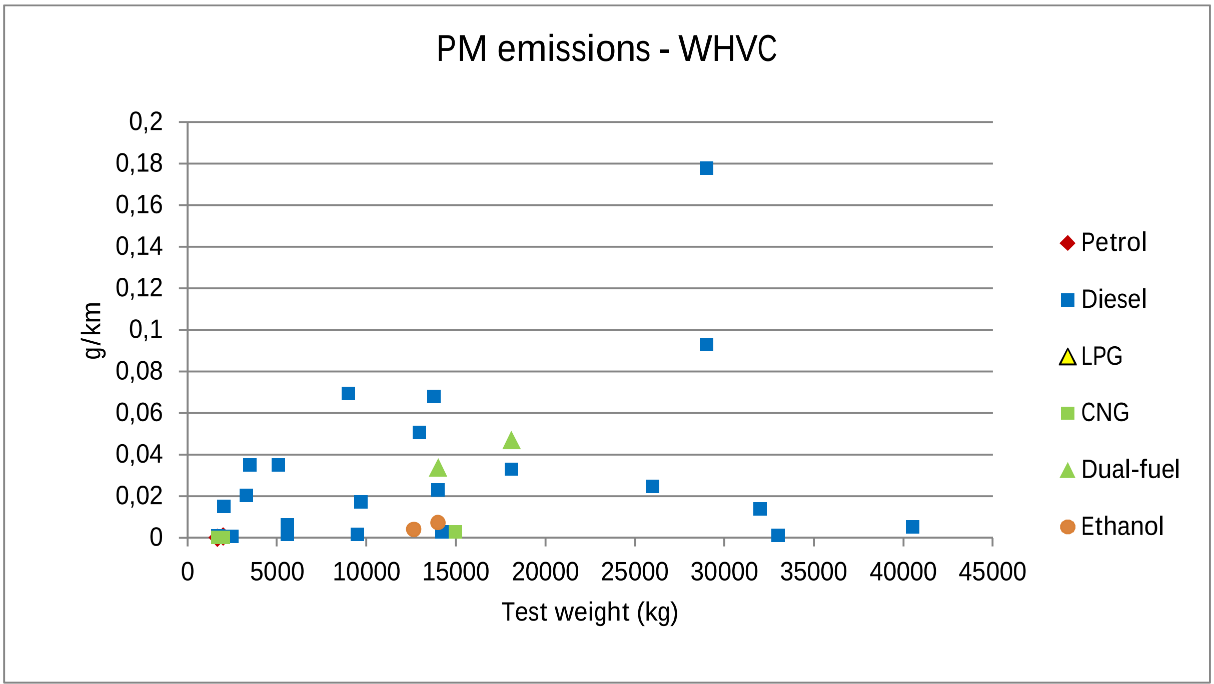

Figure 0.8. PM emissions by fuel.

Relative to mass, larger vehicles are more energy efficient than smaller ones. The most important factor affecting energy consumption is vehicle mass. For diesel powered vehicles, energy consumption per km varied by a factor of 12, from the lightest to the heaviest vehicle tested. However, the type of engine (spark-ignited, diesel, electric) also has an impact on energy consumption. Spark-ignited engines are less efficient than compression ignited (diesel) engines. Thus, spark-ignited gas vehicles have higher energy consumption than their diesel counterparts, independent of vehicle size. New vehicles (particularly Euro VI vehicles) are much cleaner than older ones, showing no fuel consumption penalty, when compared to older vehicles.

In the case of trucks, Euro V and VI diesel vehicles seem to be more fuel efficient than older Euro IV diesel vehicles. Figure 0.3 shows that fuel consumption does not increase, going from Euro V to Euro VI.

As can be seen in Figure 0.4, variations in tailpipe CO_2 emissions are rather small. Electric vehicles are, naturally, an exception, as they emit no local emissions. The values for the ethanol fuelled vehicles are almost identical to average diesel values. In the case of methane fuelled vehicles, favourable fuel chemistry partly compensates for the lower engine efficiency and, on an average, tailpipe CO_2 emissions of CNG vehicles are close to those of diesel vehicles.

Really huge differences can be found for both NO_x and PM emissions. In the case of $NO_{x,}$ specific emission rates varied from less than 0.001 to 0.9 g/km/1000 kg vehicle weight, while for PM, the range is 0.001 to 0.13 g/km/1000 kg vehicle weight.

Seven out of nine Euro VI certified heavy-duty vehicles delivered NO_x emissions below the expected Euro VI reference level. The two remaining vehicles had a NO_x level that was roughly 2–2.5 times higher than the expected Euro VI limit. The highest relative value, estimated at around 1.2 g/kWh on the engine crankshaft, was for a hybrid vehicle. As previously stated, no not-to-exceed factors were applied; but, on the other hand, **the measured data is for fully warmed-up engines.**

Figure 0.5 shows that all Euro IV and Euro V vehicles had higher NO_x emissions than should be expected. Some Euro IV and Euro V vehicles even had NO_x emissions above the Euro III level. The only Euro III vehicle that was measured, delivered true Euro III performance. Only one North-American EPA 2010 heavy-duty truck was measured. The NO_x emission of this vehicle corresponded to the Euro V level.

The conclusion that can be drawn from Figure 0.5 is that, in the case of diesel vehicles, going from Euro III to Euro IV or Euro V does not necessarily bring about reductions in NO_x emissions. Only Euro VI vehicles deliver truly low NO_x emissions.

Figure 0.6 shows NO_x emissions by fuel. The conclusions drawn from this Figure are:

- A huge spread for diesel vehicles.
- Very low emissions for spark-ignited CNG.
- Diesel dual-fuel and ethanol delivered average NO_x emissions.
- Emission class is more decisive than fuel.

Regarding particle emissions, the overall situation is somewhat more positive than in the case of $NO_{x.}$ All vehicles delivered particle emissions lower than the Euro III level. The Euro IV vehicles had PM emissions in between Euro III and the combined Euro IV/V level. On average, the Euro V certified diesel vehicles had PM emissions close to the Euro V level. And, six out of seven Euro VI certified vehicles delivered PM emissions below the Euro VI level. DTI did not measure particle mass emissions; therefore, there were two less results than in the case of NO_x. The EPA 2010 certified North-American truck delivered extremely low PM emissions.

Fuel affects PM emissions. Spark-ignited natural gas delivers very low PM emissions. The two ethanol trucks tested, although Euro V certified and without a particulate filter, delivered Euro VI level particle emissions.

Effects of substitute fuels

Some of the laboratories tested fuels that can replace conventional diesel in existing vehicles and engines.

It is, however, challenging to draw unambiguous conclusions regarding the effects of diesel substitute fuel emission performance. The response will vary from vehicle to vehicle, as well as by vehicle category (light-duty vehicles vs. heavy-duty vehicles). Heavy-duty Euro VI engines are so clean that any effect of the fuel will be dampened by the highly efficient and complex exhaust after-treatment systems. However, high quality fuels with no contaminants are prerequisites to guarantee performance and durability of the exhaust after-treatment systems.

As for pre-Euro VI heavy-duty vehicles, some general conclusions can, notwithstanding, be drawn. Oxygen containing fuels tend to increase NO_x emissions and decrease PM emissions, compared to regular diesel fuel. Paraffinic fuels, on the other hand, may deliver a slight (5–10 %) reduction in NO_x emissions in combination with a decent (up to 30 %) reduction in PM emissions.

In the case of light-duty vehicles, there is no clear trend for fuel effects on emissions. However, substituting regular diesel for 100 % paraffinic fuel seems to have marginal or no benefits for regulated emissions.

The Swedish partner, AVL MTC, carried out in-depth emission analyses. The conclusion is that it is extremely difficult to access the health effects of fuels. Fuel ranking depends on, e.g., what emission component is evaluated, whether it is the filter phase or the semivolatile phase that is being assessed for PAH emission as well as how the vehicle is tested (does testing include a cold start or not).

Going from old Euro I vehicles to Euro VI vehicles will reduce regulated emissions by more than 95 %. It is clear that such a massive reduction in emissions from efficient exhaust after-treatment systems will erase most of the effects of fuel on exhaust emissions. However, in the case of less sophisticated engines, a switch from conventional diesel fuel to chemically simple fuels, such as methane and paraffinic diesel, may still bring about emission benefits.

Full fuel cycle analysis

As previously mentioned, it was decided to use WTT data from the JEC - Joint Research Centre-EUCAR-CONCAWE collaboration on WTW.

The well-to-wheel evaluation is done for two vehicle categories:

- Category 1 vehicles (vans, test weight approximately 2 000 kg)
- Category 2 vehicles (2-axle trucks, test weight approximately 14 000 kg)

The TTW data (energy consumption) is based on VTT's measurements for COMVEC.

Figure 0.9 presents WTW CO_2 emissions (split up into WTT and TTW) and Figure 0.10 WTW energy use for various combinations of vehicle technology and fuel/energy carrier for Category 1 vehicles (vans).

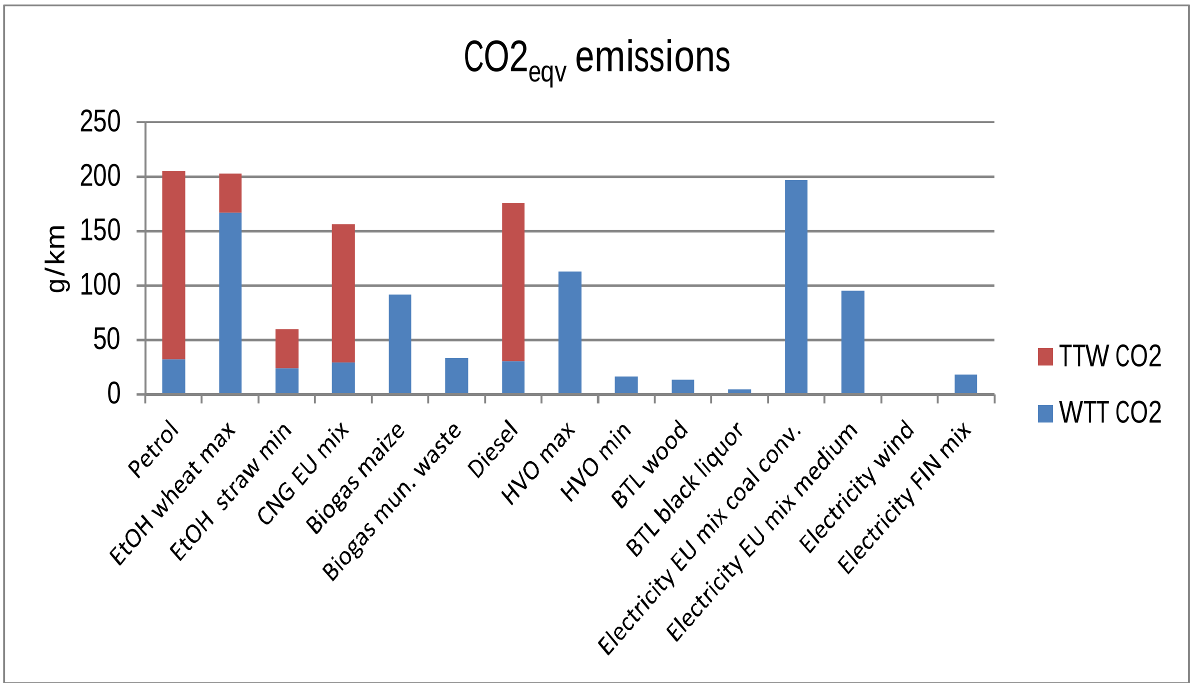

Figure 0.9. WTW CO_{2eqv} emissions for Category 1 vehicles (vans).

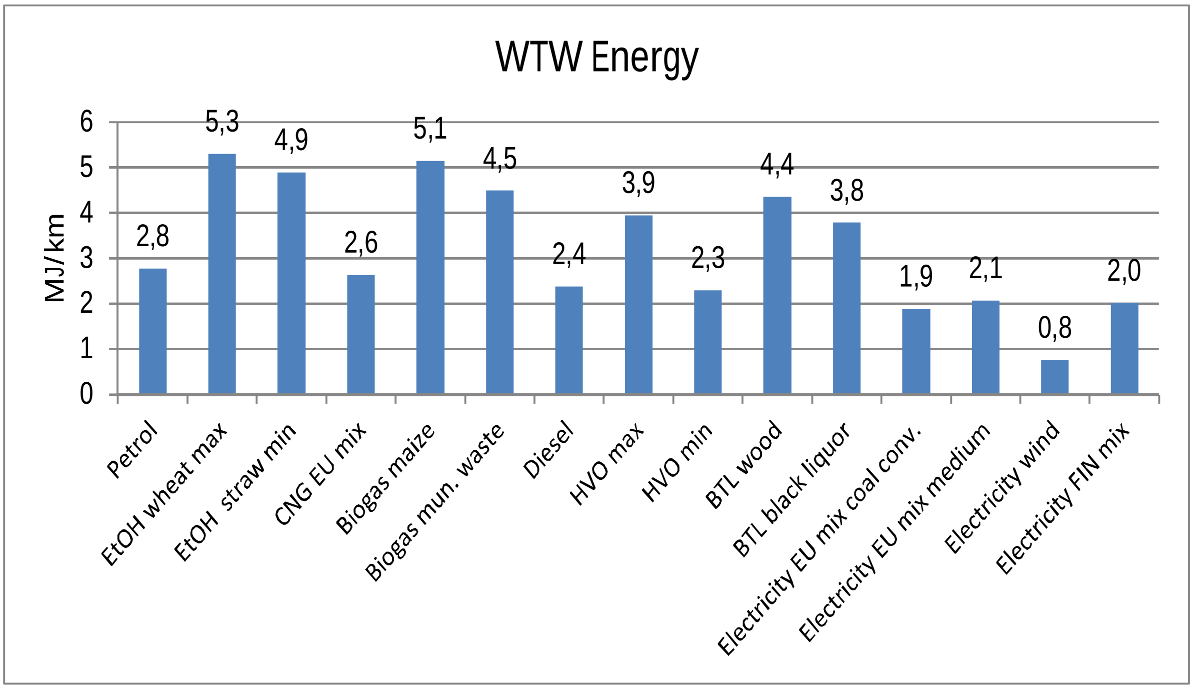

Figure 0.10. WTW energy use for Category 1 vehicles (vans).

In the case of Category 1 vehicles (vans), WTW CO_2 emissions vary from zero to around 200 g/km. Petrol, E85 with ethanol from wheat, CNG, diesel and electricity from coal all deliver values between 150 and 200 g/km. Here, it should be noted that electricity from coal is worse than fossil diesel. Biogas from maize, the HVO worst case and average European electricity all deliver values around 100 g/km. For electricity generated from wind, CO_2 is zero. However, the best of the biofuels also score very well. The WTW CO_2 emission for BTL from black liquor would only be 5 g, a calculatory reduction of 97 %, compared to fossil diesel.

For WTW energy use, electricity from wind is the winner with a value of around 0.8 MJ/km. For fossil diesel and average electricity, WTW energy is around 2–2.5 MJ/km. WTW values for petrol and CNG are slightly higher. As long as the average mix of electricity contains electricity generated through combustion (coal, gas, biomass) and nuclear generation, electric vehicles do not deliver a significant advantage in overall energy use, compared to diesel.

Biofuels, on an average, are more energy intensive, around 4–5 MJ/km. One exception is HVO from waste cooking oil, which is slightly more efficient than conventional diesel.

Electricity was not included for Category 2 vehicles. Fossil fuels and ethanol from wheat deliver WTW CO_2 emissions between 800–900 g/km. Fossil CNG does not deliver an advantage over diesel. Worst case HVO and biogas from maize are around 500 g/km, and the best biofuels fall in the range of 20–200 g/km. In the case of dual-fuel operation with a combination of the best biofuel options, the WTT part is only around 60 g CO_2/km. However, the methane slip, equivalent to around 150 g CO_2/km, is a significant addition to the overall result.

Diesel and HVO from waste cooking oil are the most efficient alternatives for WTW energy use, with around 10 MJ/km. Fossil CNG is around 15 MJ/km. WTW energy use for most biofuels is in the range of around 20–30 MJ/km.

Several conclusions can be drawn:

- Fossil CNG does not deliver significant advantages over diesel for WTW CO_2 and energy use.
- Biofuels are, in general, more energy intensive than fossil fuels.
- Notwithstanding, the best biofuels can deliver significant reductions in WTW CO_2 emissions.
- Renewable electricity (hydro, wind, photovoltaic) is the best option for WTW CO_2 and energy use.
- The average European electricity for EVs is roughly equivalent to fossil diesel for both WTW CO_2 emissions and energy use.

Cost estimates for alternative technologies

In the previous Annex 37 on fuel and technology alternatives for buses, cost assessments were carried out. Crude oil prices, and consequently fuel prices, have been very low in 2016. Therefore, it was decided not to repeat the same kind of detailed cost assessments as those that were carried out in Annex 37. Moving towards the year 2030, with increasingly challenging climate targets and increasing prices on CO_2 emissions, will naturally improve the competitiveness of low-carbon fuels dramatically.

For costs of alternative technologies, the report makes references to two recent studies regarding the costs for CO_2 abatement in road transport, one Finnish (VTT Technical Research Centre of Finland Ltd & VATT Institute for Economic Research, 2015) and one German study (Roland Berger, 2016). Both reports conclude that biofuels seem to be a cost-effective way of reducing CO_2 emissions from road transport, relative to electric vehicles and fuel cell vehicles. Roland Berger found that fossil natural gas is not cost effective for CO_2 emission reductions. The COMVEC measurements show that spark-ignited heavy-duty vehicles deliver tailpipe CO_2 emissions equivalent to those of diesel vehicles.

Key messages

- Going from Euro III to Euro IV or Euro V vehicles does not necessarily deliver real emission benefits, one should leapfrog directly to Euro VI or US 2010 regulations to obtain real-life low emissions.
    - This has implications for those regions that are contemplating more stringent emission regulations, as well as for tendering of transport services.
    - One should keep in mind that Euro VI vehicles require high-quality sulphur-free fuels (S > 15 ppm).
- The regulated emissions of a vehicle are, first and foremost, determined by the emission control technology, not the fuel.
- The response to substitute fuels (fuels that can replace conventional diesel in existing vehicles) varies from vehicle to vehicle, as well as by vehicle category (light-duty vehicles vs. heavy-duty vehicles).
    - Heavy-duty Euro VI engines are so clean that any effect of the fuel will be dampened by the highly efficient and complex exhaust after-treatment systems.
    - Older vehicles, e.g. using paraffinic diesel, can deliver up to a 30 % reduction in regulated emissions, depending on the exhaust component.
- The carbon intensity of the fuel or the energy carrier is decisive for well-to-wheel CO_2 emissions, not vehicle technology.
- CO_2 assessment should be carried out on a well-to-wheel basis, not only by looking at tailpipe CO_2 emissions.
- Electrification, with low-carbon electricity, is a good option for local emissions as well as WTW CO_2 emissions.

    - One should keep in mind that not all applications are suitable for electrification.
- Euro VI (alternatively US 2010) in combination with a renewable fuel is a good option for the local environment, as well as the climate.
- Recent reports conclude that biofuels seem to be a cost-effective way of reducing CO_2 emissions from road transport, relative to electric vehicles and fuel cell vehicles.
    - Fossil natural gas is not a cost-effective option for reducing CO_2 emissions from heavy-duty vehicles.

1. Introduction

1.1 General

Within the IEA Technology Collaboration Programme (formerly Implementing Agreement) on Advanced Motor Fuels (AMF, www.iea-amf.org), fuel and technology options for buses and passenger cars have been evaluated in two previous projects (Annexes), namely:

- Annex 37: Fuel and Technology Alternatives for Buses (http://www.iea-amf.org/app/webroot/files/file/Annex%20Reports/AMF_Annex_37.pdf)
- Annex 43: Performance Evaluation of Passenger Car Fuel and Powerplant Options (http://www.iea-amf.org/content/projects/annexes/43)

Annex 37, which was carried out in cooperation with the IEA Bioenergy Implementing Agreement, generated well-to-wheel assessment of various fuel alternatives for buses. In practise this meant assessing the upfront (well-to-tank) energy use and emissions of fuels using Canadian, European and U.S. methodology, and combining this data with actual measured vehicle data (tank-to-wheel) to produce overall well-to-wheel figures on emissions and energy use.

As a follow-up to Annexes 37 and 43, some members of AMF took the decisions that also commercial vehicles, meaning vehicles from the van category all the way up to heavy-duty combination vehicles, should be addressed.

In addition, two Annexes have looked at specific technologies:

- Annex 38: Evaluation of Environmental Impact of Biodiesel Vehicles in Real Traffic Conditions (http://www.iea-amf.org/app/webroot/files/file/Annex%20Reports/AMF_Annex_38-2.pdf)
- Annex 39: Enhanced emission performance and fuel efficiency for HD methane engines (http://www.iea-amf.org/app/webroot/files/file/Annex%20Reports/AMF_Annex_39-2.pdf)

1.2 Vehicle categories and their share of transport energy

In Europe, road vehicles are split up into four main classes according to Table 1.1. Vehicles for the carriage of goods are again split into three main classes, basically light commercial vehicles (vans), medium-duty trucks and heavy-duty trucks (Table 1.2). Heavy-duty trucks can then be split up into single unit trucks and trucks with trailers. Globally the most common combined goods vehicle is a semi-trailer truck. Finland and Sweden are characterised by a high share of trucks with full trailers and high total weight, in Finland up to 76 metric tonnes.

In Asia, three-wheelers are quite common both in passenger and goods transport, but these vehicles are not covered in this report.

Table 1.1. Main categories of road vehicles according to EU definitions.
http://www.transportpolicy.net/index.php?title=EU:_Vehicle_Definitions

General Vehicle Categories in the European Union

Category	Vehicle type
Category L	Mopeds, Motorcycles, Motor Tricycles and Quadricycles
Category M	Motor vehicles having at least four wheels and for the carriage of passengers
Category N	Power-driven vehicles having at least four wheels and for the carriage of goods
Category O	Trailers (including semitrailers)

Table 1.2. Main categories of Category N road vehicles according to EU definitions.
http://www.transportpolicy.net/index.php?title=EU:_Vehicle_Definitions

Category N – Power-driven vehicles having at least four wheels and for the carriage of goods

Category	Vehicle Description
N1	Vehicles for the carriage of goods and having a maximum mass not exceeding 3.5 tonnes
N2	Vehicles for the carriage of goods and having a maximum mass exceeding 3.5 tonnes but not exceeding 12 tonnes
N3	Vehicles for the carriage of goods and having a maximum mass exceeding 12 tonnes

The breakdown of the energy consumption by various transportation categories in 2010 (WEF 2011) is shown in Figure 1.1.

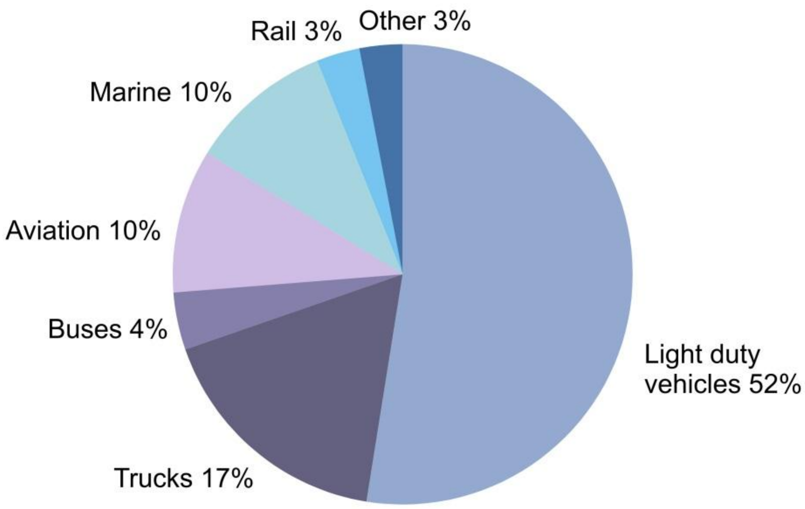

Figure 1.1. Global breakdown of the energy consumption by transportation vehicles (WEF 2011). The 52 % share formed by the light duty vehicles (LDV) contains about 37 %-units of passenger cars and 15 %-units of vans, pick-ups and sport utility vehicles (SUV).

Based on Figure 1.1, one can draw the conclusion that commercial vehicles, light-, medium- and heavy-duty vehicles together, represent some 25 % of total energy use in transport. Figure 1.2 shows the split on energy use in road transport in Finland in 2012. In Finland, vans and trucks together account for 38 % of energy use in road transport. These figures mean that commercial vehicles make up the second largest vehicle category in energy use in transport.

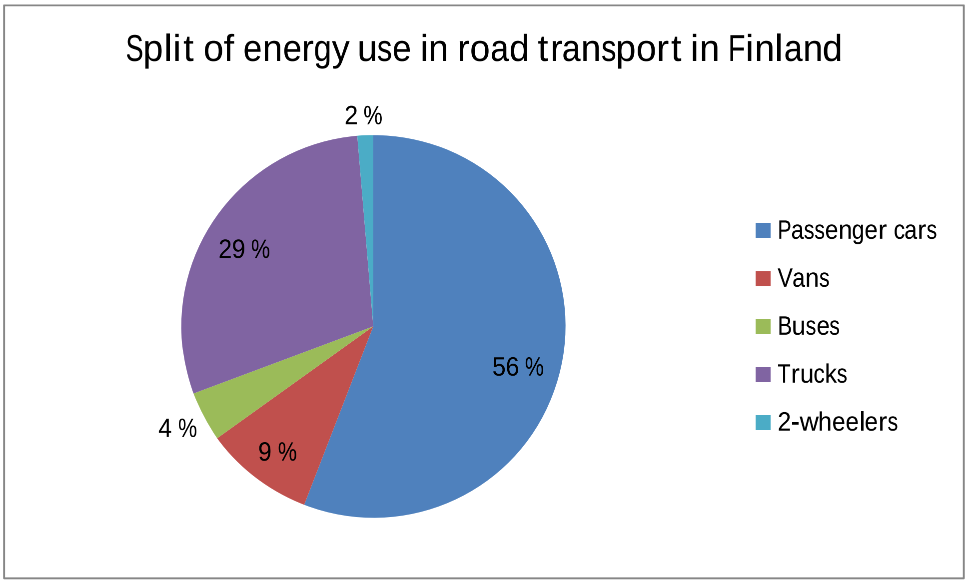

Figure 1.2. Split of energy use in road transport in Finland.
http://www.lipasto.vtt.fi/en/liisa/timeseries.htm

Currently, conventional diesel totally dominates as a fuel option in medium- and heavy-duty trucks. As for light commercial vehicles, vehicles in North-America predominantly run on petrol, whereas vehicles in Europe are mostly fuelled with diesel.

1.3 Technology options for commercial vehicles

The number of available technology options varies by mode of transport and application. Figure 1.3 shows the hierarchy of energy for transport. In commercial transport there are very few options to conventional kerosene, namely synthetic liquid fuels and bio-kerosene, whereas there are several energy options available for light-duty vehicles and vehicles for urban services. This also means that electrification is best suited for applications at the bottom of the pyramid.

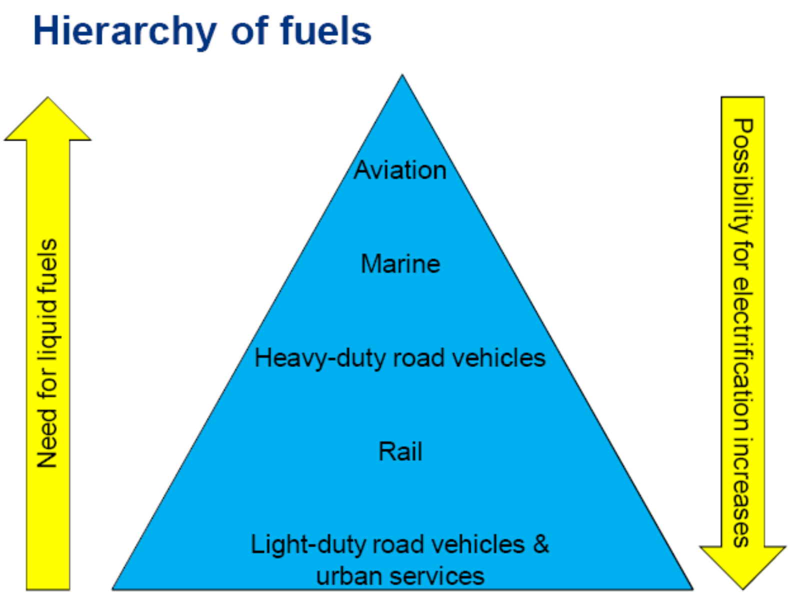

Figure 1.3. Hierarchy of fuels. Based on (Alternative propulsion for the transport of the future 2013).

In 2013, the European Commission developed an alternative fuels strategy for Europe (COM2013(17)). In 2014, a Directive on alternative fuels infrastructure deployment was given, calling the Member States to prepare national implementation plans for alternative fuel infrastructure, mainly electric vehicle recharging and refuelling of compressed natural gas (CNG) and liquefied natural gas (LNG). It is up to the Member states to decide whether they decide to develop hydrogen infrastructure of not (2014/94/EU).

Figure 1.4 shows the applicability of various energy carriers to different modes of transport. It is clear that liquid biofuels (or any other type of liquid fuels such as synthetic fuels) and natural gas (methane) are the most versatile options, with liquid biofuels having the potential of serving all modes of transport.

Spark-ignited petrol engines can be found in light-duty and also to some extent in medium-duty commercial vehicles. It is relatively easy to operate spark-ignition engines also on high-concentration ethanol (E85) and gaseous fuels (methane meaning biogas or natural gas, LPG). In the U.S, flex-fuel vehicles (FFVs) capable of running on any fuel between petrol and high-concentration E85 ethanol fuel as well as bi-fuel vehicles (capable of running on both petrol and gas) are available for these vehicle categories (AFDC 2015).

Figure 1.5 presents biofuel options for diesel substitution in heavy-duty vehicles. Liquid biofuels can be used not only as blending components into diesel, but also as such. Conventional biodiesel (fatty acid methyl ester FAME) is hampered by certain vehicle compatibility issues, even though vehicles approved for the use of 100 % FAME exist. On the other hand, synthetic Fischer-Tropsch diesel (or biomass-to-liquids BTL) and hydrotreated vegetable oil (HVO) are called drop-in fuels (100 % hydrocarbons) and are fully compatible with refuelling infrastructure and vehicles, basically allowing any substitution rate between 0 and 100 %.

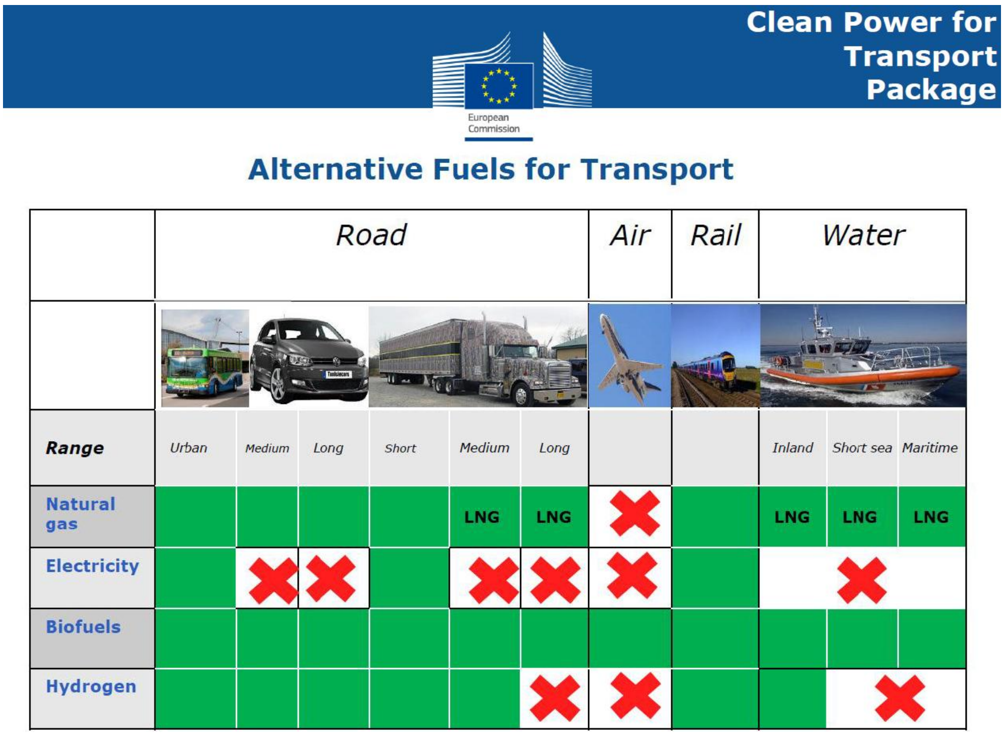

Figure 1.4. Alternative fuels for transport. (Steen 2014)

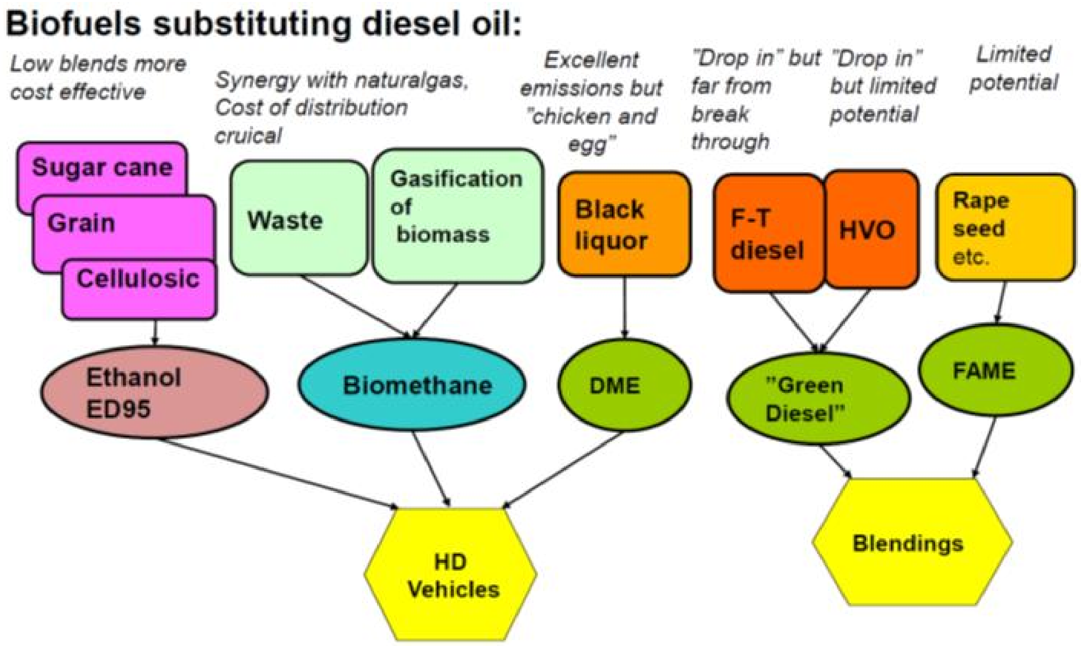

Figure 1.5. Biofuels substituting diesel fuel. (Hådell 2012)

Of the alternatives shown in Figure 1.5, ethanol, methane and di-methyl ether (DME) require dedicated engines and vehicles.

Ethanol as such is not suited as fuel for conventional diesel engines, as the ignitability from compression only is low. In principle this means that either the engine or the fuel has to be modified. In the 1980s and 1990s there were some projects on direct-injection alcohol engines with ignition aid either by diesel pilot injection or by glow plugs. Detroit Diesel had, for a short while, a two-stroke glow-plug assisted alcohol engine available (Toepel et al. 1983).

The only concept that has reached commercial maturity is Scania’s technology with additive treated ethanol. Ethanol buses manufactured by Scania have been in operation in Swedish cities since 1989. More than 600 buses have been supplied. Scania’s ethanol engines are also applied to other areas of transport, e.g., distribution and refuse trucks.

The ethanol engine is an adaptation of Scania's 9-litre diesel engine. The ethanol version features, among other things, 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. Now a Euro VI certified version of the engine is available (Scania Buses & Coaches 2015).

In addition to the light- and medium-duty segments, spark-ignited gas engines are quite common in city-bus applications. Spark-ignited gas engines can also be found in heavy-duty trucks. Maximum power for spark-ignited gas engines is 400 hp or some 300 kW. (Cummins, Lawder 2014)

There has been significant interest in diesel dual-fuel (DDF) engines, with a promise of higher engine efficiency compared to spark-ignited gas engines. Volvo produced limited numbers of Euro V certified DDF engines in two engine sizes, 7 and13 litre (Pilskog 2010).

The idea behind a dual-fuel engine is to ignite the main fuel (methane) with a small amount of pilot fuel (diesel). However, simple DDF systems feeding methane into the intake manifold (premixed DDF) cannot meet stringent emission regulations, mainly due to excessive emissions of unburned methane. The final report of IEA AMF Annex 39 (Enhanced emission performance and fuel efficiency for HD methane engines) states (Annex 39):

"It could be questioned whether dual fuel technology commercial available on the market today (January 2014) can reach emission requirements for Euro V and later emission requirements."

Consequently, there are currently (December 2015) no Euro VI or US 2010 certified engines available. However, there are simple retrofitted dual-fuel technologies on older engines which do not have to meet stringent emission regulations (so-called end-of-life engines).

Direct injection of pilot (diesel) fuel as well as main fuel (gas) has the promise to overcome the problems with excessive emissions. At one point the Canadian technology company Westport point provided a DDF engine with direct injection of gas. Westport called this technology HPDI (high-pressure direct injection). The engine was based on the 15-litre Cummins ISX 15 engine, and the DDF version was claimed to provide equivalent performance compared to the diesel. However, at the end of 2013 the Westport HPDI engine was discontinued (Fleets & Fuels 2013). Afterwards it has been reported that Westport and Volvo Trucks are cooperating to bring the HPDI concept back on the market again (Fleets & Fuels 2015).

Di-methyl-ether (DME) is clean-burning and sulfur-free, with extremely low particulate emissions. DME resembles LPG in many ways. DME, however, has good ignition quality, and is therefore suited for diesel combustion. A dedicated DME vehicle might not require a particulate filter but would need a purpose-designed fuel handling and injection system, as well as a lubricating additive (Green Car Congress 2006).

Originally DME was used as a propellant for aerosols. DME is a rather difficult-to-use motor fuel because of the extremely low viscosity, low lubricity, and high volatility. For a diesel engine, special high-pressure injection systems with anti-leak systems have to be designed. Low lubricity and cavitation in various parts of the fuel system may also cause problems.

At least the following companies have been involved in the development of DME engines or equipment for DME engines: AVL (Austria), Denso, Nissan Diesel (UD Trucks), TNO (Holland), and Volvo. Now an ISO standard on DME for vehicle applications is in place (partly as a result of the activities of IEA AMF Annex 48 (Reconsideration of DME Fuel Specifications for Vehicles, operating agent AIST, Japan)). Volvo has repeatedly stated that DME is its preferred alternative fuel. In 2013, Volvo announced its ambition to launch a DME engine. With its DME development Volvo has been targeting especially the North-American truck market (Alt 2014). Figure 1.6 positions DME versus spark-ignition CNG and LNG with respect to range and need for power/torque.

Hybrid systems are available for passenger cars and buses, as well as for commercial vehicles. However, supply for commercial vehicles is rather limited, focused on medium-duty trucks and heavy-duty trucks without a trailer. Both electric and hydraulic hybrids have been implemented. Figure 1.7 shows the benefits of hybridisation for delivery vehicles.

There has been significant progress in electric vehicles over the past years. According to IEA, the world vehicle fleet at the end of 2014 was some 665 000 units. This is, however, still only 0.08 % of the total world vehicle fleet (EVI 2015). The focus of electric vehicles has been on passenger cars and lately also on urban buses. As for commercial vehicles, with only a few exceptions, the available electric vehicles are light-duty commercial vehicles, i.e. vans.

The focus in fuel cells for vehicles is on passenger cars, buses and mobile machinery, not commercial vehicles.

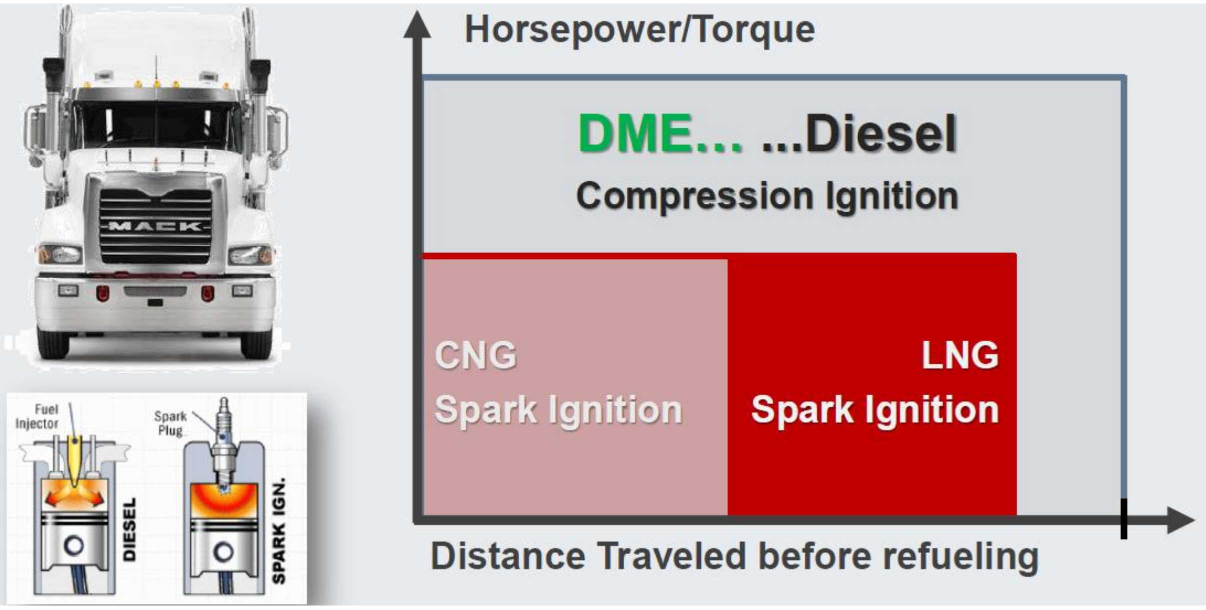

Figure 1.6. DME performance vs. spark-ignited CNG and LNG. (Alt 2014)

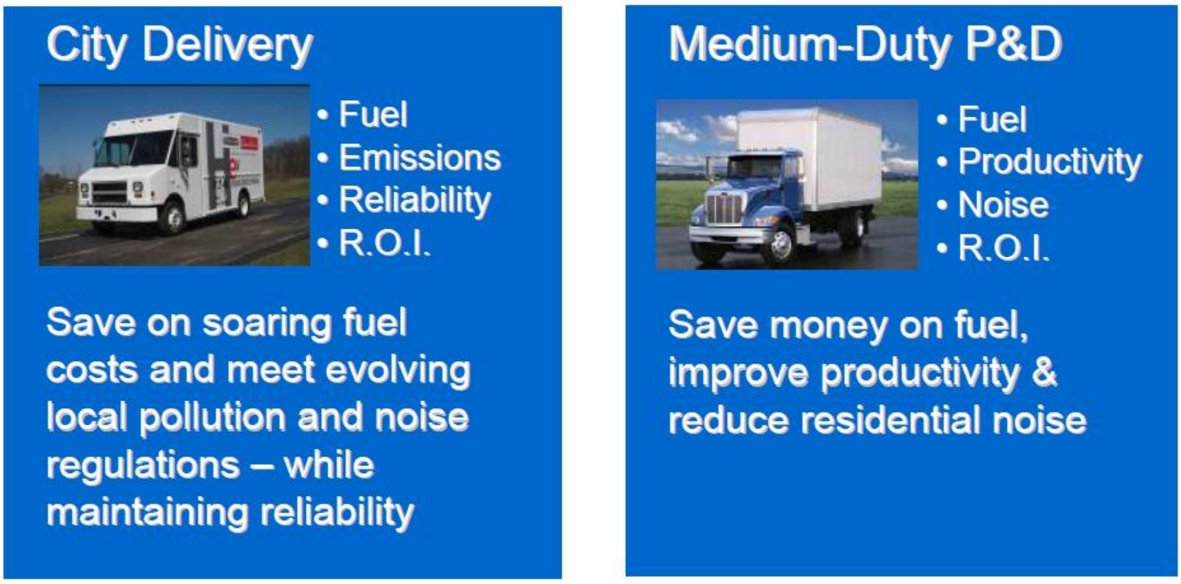

Figure 1.7. Benefits of hybridisation for delivery vehicles. (Eaton 2007)

Table 1.3 summarises the current availability of alternative technologies for commercial vehicles.

Table 1.3. Availability of technology for commercial vehicles. ++= common, += available, -=not available, 0= plausible, D= under development.

	Light commercial vehicles	Medium-duty trucks	Heavy-duty trucks	Long haul heavy-duty trucks with trailers
Petrol	++	0	-	-
Diesel	++	++	++	++
Hybrids	0	+	+	0
Electricity	+	0	-	-
Ethanol SI	+			
CNG SI	+	+	+	-
CNG DDF	-	-	+	-
LNG SI	-	-	0	+
LNG DDF	-	-	D*)	D*)
DME	-	-	D	D
Ethanol CI	-	-	+	0

*) refers to direct-injection DDF technology meeting the most stringent emission regulations

2. Goal

The goals of the “COMVEC” were twofold:

3. To agree upon common test procedures for testing and comparing different types of commercial vehicles. As far as possible, the common methodology shall then be applied by the laboratories contributing test data for COMVEC.

4. Generate performance data specific to commercial vehicles (goods vehicles), thus adding to the information on alternative fuels and vehicle technologies generated in previous AMF activities (Annex 37 on buses, Annexes 38 and 39 on trucks, Annex 43 on passenger cars).

With data covering all road vehicle classes it will eventually be possible to evaluate best fit of alternative fuels and new vehicle technologies road transport, meaning that alternative technologies can be allocated in the most effective way.

3. Partners and sponsors

The COMVEC project was set up as a task shared activity within IEA AMF. Task sharing means that all participating countries covered their own costs for participating and contributing to the project.

VTT Technical Research Centre of Finland Ltd, with the support from Tekes – the Finnish Funding Agency for Innovation, acted as Operating Agent for the project. The COMVEC project also received support from national Finnish projects, i.e. a project called “Pilot study of 2^{nd} generation biofuels for transport (BioPilot)”, and the continuous activity to generate exhaust emission and fuel consumption data for commercial vehicles, supported by the Finnish Transport Safety Agency (Trafi). The partners in the “BioPilot” project include City of Helsinki and Posti (the Finnish postal service) as vehicle operators and the energy companies Gasum, Neste, St1 and UPM.

The other partners in COMVEC were:

- Canada, through Environment and Climate Change Canada (ECCC), Transport Canada’s ecoTECHNOLOGY for Vehicles Program (eTV) and Natural Resources Canada’s Program of Energy Research and Development (PERD) Advanced Fuels and Technologies for Emissions Reduction (AFTER 8)
- Chile, through Centro Mario Molina Chile (CMMCh)
- China, through China Automotive Technology and Research Center (CATARC)
- Denmark, through Danish Technological Institute (DTI)
- Japan, through Organization for the promotion of low emission vehicles (LEVO)
- Korea, through Korea Institute of Energy Technology Evaluation and Planning (KETEP)
- Sweden, through Swedish Transport Administration (STA)
- Thailand, through PTT Research and Technology Institute

Chile was not a member of AMF from the beginning, but joined AMF officially as of November 2015.

The Norwegian Institute of Transport Economics (TØI) contributed to the project by covering the costs of measuring one natural gas truck at VTT.

The institutes that carried out measurements or provided data were:

- Canada: Emissions Research and Measurement Section (ERMS) of ECCC
- Chile: Center for Control and Vehicle Certification (3CV), Ministry of Transport and Telecommunications of Chile
- China: CATARC
- Denmark: DTI
- Finland: VTT
- Japan: National Traffic Safety and Environment Laboratory (NTSEL)
- Sweden: AVL MTC
- Thailand: PTT Research and Technology Institute

Korea Automotive Technology Institute (KATECH) provided general technical support to the project.

4. Structure of the project

In the original plan of the project, in total eight work packages were listed:

- WP 0: Collection and consolidation of the existing data
- WP 1: Development of common test procedures and protocols
- WP 2: Vehicle testing
  - Three different vehicle categories including several alternative fuel and vehicle technologies
  - Parameters to be varied: fuel composition, driving cycle, payload (0, 50 and 100 %), environmental conditions (ambient temperature)
- WP 3: Aggregation of well-to-tank information
  - based on test fuel matrix and information gathered in Annexes 37 and 43
- WP 4: Regional information on transportation sectors energy options
  - Information from project participants on regional challenges and opportunities that drive the development of energy options in transportation sectors and affects the available fuel selection. This regional information will also shed light on various alternative technology options potential in different regions.
- WP 5: Full fuel-cycle evaluation (integration of WP2 & WP3)
  - Well-to-wheel fuel consumption, energy efficiency and emissions
- WP 6: Life-cycle cost analysis
  - How alternative fuel and vehicle technology, together with the operation of the vehicle, influences life-cycle costs. The objective is to find a cost-effective way to reduce emissions and energy consumption in a given vehicle use.
- WP 7: Co-ordination of the project, synthesis and reporting
  - Administrative co-ordination, communication with the IEA AMF ExCo, synthesis of the data, compilation of the Final Report and dissemination of the results

However, during the course of the project some concessions to the scope of the work had to be made. In the end it turned out that it was not possible to obtain coherent regional information on transport energy and technology policies or on fuel and vehicle costs. Therefore the scope of the project changed and focused on three work packages, namely:

- Development of common test procedures and protocols (WP1)
- Vehicle testing (WP2)
- Full fuel-cycle evaluation (WP5, integration of WP2 & WP3)

As for the test programme and testing parameters, most of the tests were carried out using one specific test cycle, 50 % load and normal ambient temperature (25 $\pm$5 ^{o}C).

5. Methods

5.1 General

As in the case of Annex 37 on fuel and technology options for buses, Annex 49 on commercial vehicles (COMVEC) combines well-to-tank (WTT) data and tank-to-wheel (TTW) data to form well-to-wheel (WTW) data on emissions and energy use.

5.2 Well-to-tank data

In Annex 37, three different methodologies to assess the WTT part, namely:

- GREET (United States)
- GHGenius (Canada)
- Renewable Energy Directive (European Union)

For COMVEC, it was decided to use WTT data from the JEC - Joint Research Centre-EUCAR-CONCAWE collaboration on WTW[1]. The Joint Research Centre (JRC) is run by the EU Commission. EUCAR is the European Council for Automotive R&D[2] and CONCAWE is the platform for environmental research collaboration of the fuel refining industry[3]. With the participation of JRC, one could state that the JEC work is sanctioned by the European Commission.

The JEC reports contain data on fuel properties as well as detailed analysis of multiple fuel and energy pathways. Included are fossil petrol and diesel, natural gas, a wide range of biofuels and also electricity. The most recent JEC WTW report (Version 4.a) is from February 2014. The WTT part and its appendices were launched in March 2014:

- WTT Report (Version 4.a)
- WTT Appendix 1 (Version 4.a) – Conversion factors and fuel properties
- WTT Appendix 2 (Version 4.a) – Summary of energy and GHG balance of individual pathways
- WTT Appendix 4 (Version 4.a) – Description, results and input data per pathway

Table 5.1 presents an example of data found in WTT Appendix 2 (case biodiesel and hydrotreated vegetable oil (HVO)).

When needed, the TTW data generated by COMVEC can be combined with other, locally available WTT data.

1 http://iet.jrc.ec.europa.eu/about-jec/downloads
2 http://www.eucar.be/
3 https://www.concawe.eu/

Table 5.1. WTT energy use and greenhosue gas (GHG) emissions for biodiesel-type fuels. (JEC WTT Appendix 2, Version 4.a)

1.4 Biodiesel

Pathway		Energy expended (MJ/MJ final fuel)												WTT GHG emitted (g CO_2eq/MJ final fuel)									%
Code	Description	Total	Fossil	Nuclear	Renewable	Fract renew	Production & conditioning at source	Transformation at source	Transportation to market	Transformation near market	Conditioning & distribution	Range		Total	Production & conditioning at source	Transformation at source	Transportation to market	Transformation near market	Conditioning & distribution	Range		Total GHG inc. combustion	saving
Conventional fossil fuels																							
COD1	Diesel	**0.20**	0.20	0.01	0.00	*0.7%*	0.07		0.01	0.10	0.02	0.18	0.23	**15.4**	4.7		1.0	8.6	1.1	13.8	17.0	88.6	
Biodiesel																							COD1
ROFA1	RME: Meal as AF, glycerine as chem,	**1.12**	0.46	0.02	0.64	*57.2%*	0.35		0.02	0.73	0.02	1.12	1.13	**53.9**	57.6		0.6	-5.6	1.4	46.0	59.8	53.9	39%
ROFA2	RME: Meal and glycerine as AF	**1.18**	0.49	0.04	0.65	*55.0%*	0.35		0.02	0.78	0.02	1.17	1.18	**58.7**	57.6		0.6	-0.8	1.4	51.0	64.4	58.7	34%
ROFA3	RME: Meal as AF, glycerine to biogas	**1.13**	0.45	0.04	0.65	*57.1%*	0.35		0.02	0.74	0.02	1.13	1.14	**57.0**	57.6		0.6	-2.5	1.4	50.4	64.3	57.0	36%
ROFA4	RME: Meal and glycerine to biogas	**0.68**	0.16	-0.09	0.61	*90.0%*	0.35		0.02	0.28	0.02	0.62	0.73	**37.3**	57.6		0.6	-22.1	1.4	29.7	44.3	37.3	58%
ROFA5	RME: Meal as AF, Glycerine to hydrogen	**1.13**	0.44	0.04	0.65	*57.3%*	0.35		0.02	0.73	0.02	1.13	1.14	**56.7**	57.6		0.6	-2.8	1.4	50.1	63.9	56.7	36%
ROFE3	REE: Meal as AF, glycerine to biogas	**1.25**	0.42	0.04	0.79	*63.1%*	0.34		0.02	0.87	0.02	1.24	1.26	**56.6**	55.4		0.5	-0.7	1.3	47.3	60.2	56.6	36%
SOFA3	RME: Meal as AF, glycerine to biogas	**1.08**	0.43	0.04	0.61	*56.3%*	0.32		0.02	0.72	0.02	1.00	1.19	**45.9**	43.8		0.5	0.2	1.4	41.6	49.5	45.9	48%
SYFA3a	SYME: No till, oil import, meal as AF, glycerine to biogas	**2.53**	0.40	0.07	2.07	*81.8%*	0.18	2.13	0.04	0.16	0.02	2.52	2.54	**55.1**	57.4	-14.2	3.3	7.3	1.4	3.8	68.7	55.1	38%
SYFA3b	SYME: No till, beans import, meal as AF, glycerine to biogas	**2.69**	0.57	0.05	2.07	*76.8%*	0.19		0.32	2.16	0.02	2.68	2.70	**59.2**	58.1		23.0	-23.3	1.4	47.7	67.2	59.2	33%
SYFA3c	SYME: Conv. culture, oil import, meal as AF, glycerine to biogas	**2.60**	0.46	0.07	2.07	*79.6%*	0.24	2.13	0.04	0.16	0.02	2.59	2.61	**60.7**	63.0	-14.2	3.3	7.3	1.4	5.0	74.6	60.7	31%
POFA3a	POME: Meal as AF, no CH4 rec., heat credit, glycerine to biogas	**1.18**	0.17	0.03	0.97	*82.5%*	0.16	0.79	0.06	0.15	0.02	1.17	1.18	**50.8**	27.1	11.0	4.3	7.0	1.4	50.3	51.4	50.8	43%
POFA3b	POME: Meal as AF, CH4 rec., heat credit, glycerine to biogas	**1.18**	0.17	0.03	0.97	*82.6%*	0.15	0.79	0.06	0.15	0.02	1.17	1.18	**31.2**	27.0	-8.5	4.3	7.0	1.4	30.6	31.7	31.2	65%
POFA3c	POME: Meal as AF, no CH4 rec., no heat credit, glycerine to biogas	**1.33**	0.33	0.03	0.97	*72.7%*	0.15	0.95	0.06	0.15	0.02	1.33	1.34	**62.6**	27.0	22.8	4.3	7.0	1.4	62.0	63.1	62.6	29%
WOFA3a	FAME: waste cooking oil	**0.28**	0.21	0.01	0.05	*18.4%*				0.25	0.02	0.27	0.28	**13.8**				12.4	1.4	13.6	13.9	13.8	84%
TOFA3a	FAME: tallow oil	**0.48**	0.40	0.04	0.04	*7.6%*		0.30	0.01	0.15	0.02	0.48	0.48	**26.3**		17.5	0.4	7.0	1.4	26.2	26.5	26.3	70%
HVO																							COD1
ROHY1a	HRO (NExBTL), meal as AF	**1.12**	0.45	0.02	0.64	*57.4%*	0.35		0.02	0.72	0.02	1.11	1.12	**56.6**	57.5		0.6	-2.7	1.3	48.9	63.3	56.6	36%
ROHY1b	HRO (UOP), meal as AF	**0.99**	0.50	0.03	0.46	*46.3%*	0.31		0.02	0.64	0.02	0.99	1.00	**57.1**	51.1		0.5	4.2	1.3	50.7	63.5	57.1	36%
ROHY4	HRO (NExBTL), meal to biogas	**0.66**	0.16	-0.11	0.60	*91.4%*	0.35		0.02	0.26	0.02	0.61	0.73	**36.9**	57.5		0.6	-22.4	1.3	30.4	43.4	36.9	58%
SOHY1a	HSO (NExBTL), meal as AF	**1.04**	0.43	0.02	0.59	*56.3%*	0.31		0.02	0.68	0.02	0.95	1.13	**44.8**	43.2		0.5	-0.3	1.3	40.9	48.3	44.8	49%
SYHY1a	HSO (NExBTL), oil imported	**2.51**	0.41	0.04	2.05	*82.0%*	0.18	2.13	0.04	0.14	0.02	2.49	2.52	**55.1**	57.2	-14.1	3.3	7.5	1.3	8.0	68.5	55.1	38%
POY1a	HPO (NExBTL), no CH4 rec.	**1.13**	0.15	0.02	0.96	*85.3%*	0.15	0.79	0.06	0.11	0.02	1.13	1.13	**48.6**	27.0	11.0	4.3	5.1	1.3	48.1	49.2	48.6	45%
WOHY1a	HWO (NExBTL), waste cooking oil	**0.16**	0.13	0.00	0.02	*15.6%*				0.14	0.02	0.15	0.17	**8.1**				6.83	1.3	13.0	13.9	8.1	91%
TOHY1a	HTO (NExBTL), tallow oil	**0.44**	0.38	0.03	0.03	*7.0%*	0.00	0.30	0.01	0.11	0.02	0.44	0.44	**24.5**	0.2	17.3	0.4	5.3	1.3	29.7	30.0	24.5	72%

Note: "% saving" in this table is total GHG including combustion compared to conventional diesel (COD1)

5.3 Vehicle and engine measurements

The recommended test protocol for COMVEC (Appendix 1) was developed in cooperation between the Swedish Transport Administration and VTT within WP1. The basic idea was that the partners in COMVEC should use the common protocol to guarantee comparability of test results.

Eventually one test cycle was recommended, the World Harmonised Transient Cycle (WHTC) and its chassis dynamometer derivate the World Harmonised Vehicle Cycle (WHVC, Figure 5.1). The WHTC cycle is world harmonised. WHTC is the stipulated cycle according to UNECE regulation 49 and can be divided into three sub cycles (Urban, Rural and Motorway). This meant that both engine and vehicle testing was acceptable for COMVEC. However, to be compatible with the previous work on buses (Annex 37), chassis dynamometer measurement was the preferred option.

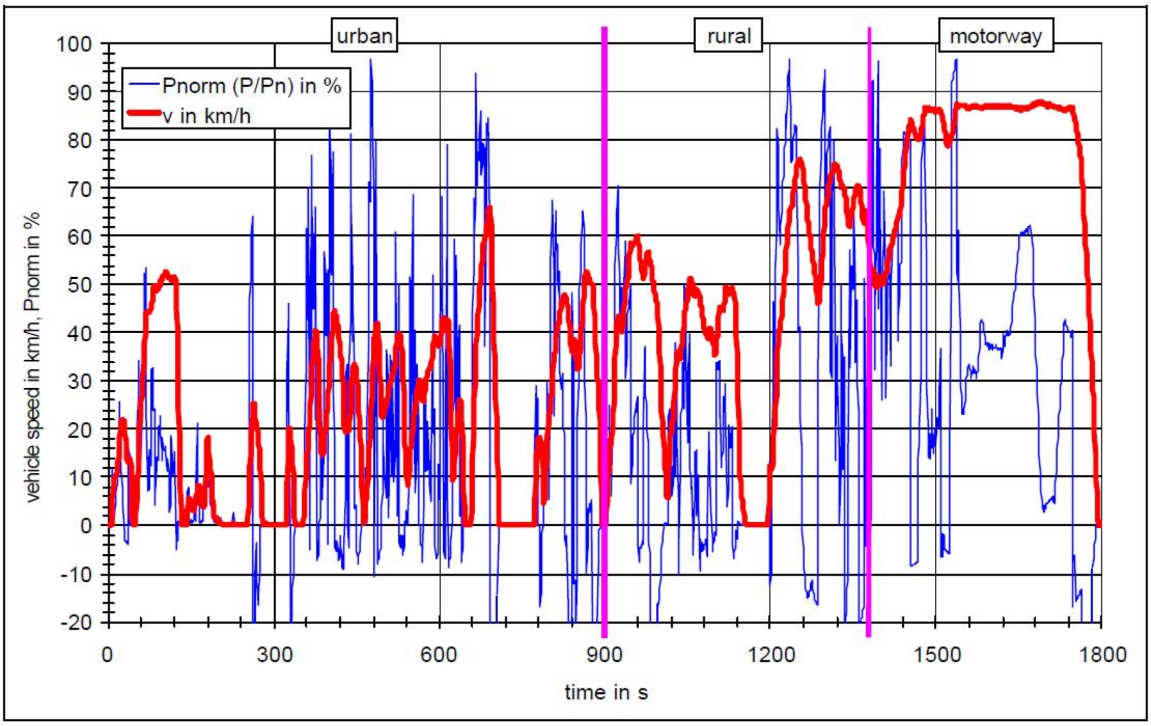

Figure 5.1. The World Harmonised Vehicle Cycle WHVC. (GRPE 2001)

The key parameters of the WHVC are:

- Average speed 40.0 km/h
- Maximum speed 87.8 km/h
- Total time 1800 s
- Total distance 20.0 km

For emission measurements, internationally or nationally recognised standards or regulations are stipulated. When tests are conducted in a chassis dynamometer, measurement procedures according to an engine test should be followed to the maximum extent possible, using good engineering judgement. The test protocol lists the following relevant procedures:

- UNECE R49/GTR no4
- Euro VI (582/2011)
- Japanese “Air Pollution Control Law”
- US EPA part 10.65

- SAE recommended practice, SAE J2711

In addition to defining the test cycle and analytical equipment, the test protocol speaks out on, e.g.:

- Test temperature (25 ±5 °C)
- Preconditioning
- Test fuels
- Vehicle load
- Emission components to be reported
- Vehicle data to be reported

The recommended load was set at 50 % of full load. This was considered to represent average load for commercial vehicles. The participants were free to add additional test cycles and loads.

The test protocol was a recommendation, and the participants were not forced to follow it exactly. **The individual participants are responsible for the quality and the relevance of the supplied data.**

The Euro VI regulation stipulates measurements with both a cold and a warmed-up engine, and a system for calculation of aggregate emission values using weighting factors. However, the results presented in this report are for fully warmed-up engines and vehicles. The COMVEC test protocol stipulates a soak period of maximum 10 minutes between conditioning and actual testing.

5.4 Calculation of energy consumption

Some partners reported values for energy consumption, some fuel consumption in combination with data for the test fuels (e.g. density and heating value) and some only fuel consumption. In the cases where only fuel consumption was reported, fuel consumption was converted into energy consumption using heating values presented in the JEC WTW study. Tables 5.2 (liquid fuels) and 5.3 (gases) present heating values and CO_2 emission factors for various fuels. Alternatively, energy consumption was calculated from measured CO_2 emissions and specific CO_2 emissions. LNG was considered to be pure methane.

Table 5.2. Data for liquid fuels. (JEC WTT Appendix 1, Version 4.a)

Liquids

	Density	LHV				C content	CO_2 emission factor*	
	kg/m³	MJ/kg	GJ/m³	kg/kWh	kWh/kg	% m	g CO_2/MJ	kg CO_2/kg
Crude oil	820	42.0	34.4	0.086	11.67	86.5%	75.5	3.17
Gasoline	745	43.2	32.2	0.083	12.00	86.5%	73.4	3.17
Diesel	832	43.1	35.9	0.084	11.97	86.1%	73.2	3.16
Naphtha	720	43.7	31.5	0.082	12.14	84.9%	71.2	3.11
Heavy fuel oil	970	40.5	39.3	0.089	11.25	89.0%	80.6	3.26
Syn diesel	780	44.0	34.3	0.082	12.22	85.0%	70.8	3.12
Syn naphtha	700	44.5	31.2	0.081	12.36	84.0%	69.2	3.08
Methanol	793	19.9	15.8	0.181	5.53	37.5%	69.1	1.38
DME	670	28.4	19.0	0.127	7.90	52.2%	67.3	1.91
Ethanol	794	26.8	21.3	0.134	7.44	52.2%	71.4	1.91
MTBE	745	35.1	26.1	0.103	9.75	68.2%	71.2	2.50
ETBE	750	36.3	27.2	0.099	10.07	70.6%	71.4	2.59
				Of which renewable		33.3%	23.8	
Plant oil (crude and refined)	920	37.0	34.0	0.097	10.28			
Biodiesel (methyl ester)	890	37.2	33.1	0.097	10.33	77.3%	76.2	2.83
Biodiesel (ethyl ester)	890	37.9	33.7	0.095	10.53	76.5%	74.0	2.81
HVO	780	44.0	34.3	0.082	12.22	85.0%	70.8	3.12
Tallow oil		37.0		0.097				
Glycerine		16.0		0.225	4.44			
Propylene glycol		20.0		0.180	5.56			
n-hexane		45.1		0.225	4.44			

* assuming total combustion

Table 5.3. Data for gaseous fuels. (JEC WTT Appendix 1, Version 4.a)

Gases

	Molar mass	LHV				C content	CO_2 emission factor*		
	g/mol	MJ/kg	MJ/Nm³	kg/kWh	kWh/kg	% m	g CO_2/MJ	kg CO_2/kg	kg CO_2/Nm³
Methane	16.0	50.0	35.7	0.072	13.89	75.0%	55.0	2.75	3.85
NG (EU-mix)	17.7	45.1	35.7	0.080	12.53	69.2%	56.2	2.54	3.21
NG (Russia)	16.3	49.2	35.8	0.073	13.67	73.9%	55.1	2.71	3.72
Hydrogen	2.0	120.1	10.7	0.030	33.36				
LPG	50.0	46.0		0.078	12.78	82.4%	65.7	3.02	1.35
Isobutane		45.6		0.079	12.68				
Isobutene		45.1		0.080	12.52				
Propylene		45.7		0.079	12.70				

* assuming total combustion

6. Test program - vehicle and engine tests

6.1 General

The project plan specified the following main vehicle categories to be measured (Figure 6.1):

- Category 1: Light-duty commercial vehicles (GVW 2 500 – 5 000 kg)
    - Delivery van –type vehicles (vans) and pick-up trucks
- Category 2: Medium heavy-duty trucks (GVW 5 000 – 18 000 kg)
    - Delivery trucks, garbage trucks etc., 2 axles, single unit
- Category 3: Tractors (GVW ~ 40 000 kg)
    - Long haul semi-trailer tractors

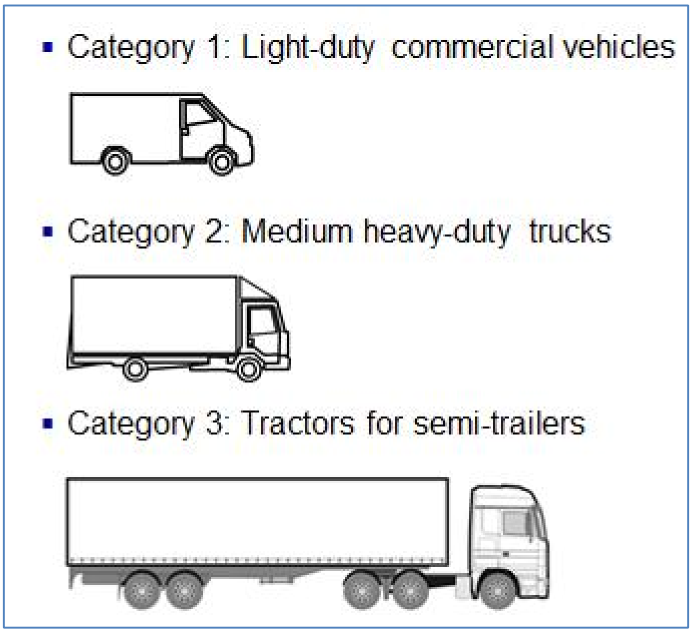

Figure 6.1. Vehicle categories in COMVEC.

This classification differs, e.g., from the EU categorisation shown in Table 1.2 (N1, N2 & N3). The proposed categorisation was considered more relevant for an international project, especially as it better describes the construction of the vehicles (van type vehicles versus real truck type vehicles).

VTT of Finland has data available also for 3-axle trucks (up to 26 ton GVW), as well as for combinations with full trailer (up to 60 ton GVW). When presenting COMVEC results and plotting, e.g., fuel consumption versus vehicle test weight, also data from these vehicles have been included. Category 2 is then expanded to cover all single unit trucks, and Category 3 to include semi- as well as full trailers.

For the various vehicle categories the following energy and technology options were foreseen:

- Category 1:
    - Petrol
    - Diesel
    - CNG, LPG
    - Electricity

- Category 2:
    - Diesel
    - CNG (spark-ignited and dual-fuel)
    - Compression-ignited ethanol (Scania's concept)
    - Hybrid powertrain

- Category 3:
    - Diesel
    - LNG (dual-fuel and HPDI)
    - DME

Drop-in type alternative diesel fuels (e.g. natural gas based GTL or HVO) can substitute conventional diesel in all vehicle categories without any modifications to the vehicle fleet.

6.2 Overview of vehicles and engines measured by the project partners

6.2.1 General

The partners of COMVEC represent four different continents (Asia, Europe, North America, South America). Consequently, the vehicles and engines measured for COMVEC represent a variety of technologies and emission certification classes.

Some partners also provided test data on multiple fuels for individual vehicles. In some cases, the partners added additional test cycles and multiple loads (the test protocol defined baseline as the WHVC cycle at 50 % load).

In addition, some partners also provided performance data on buses. However, although trucks and buses to some extent use similar power trains, it was eventually decided that COMVEC will report on commercial vehicles only, and no results for buses were included.

All in all the partners made data available from 35 different vehicles and three different testbed engines.

The following paragraphs present a short summary of the contributions from the COMVEC partners. Appendix 2 presents key technical data for the tested vehicles and engines.

It was not possible to include HPDI LNG vehicles or DME vehicles in the testing for COMVEC. Data on HPDI LNG can be found in the final report of IEA AMF Annex 39 and on DME in the final report of IEA AMF Annex 37.

6.2.2 Canada

ERMS provided chassis dynamometer data:

- Four Category 1 vehicles
    - One vehicle platform, petrol, bi-fuel CNG, bi-fuel LPG, electric
- One Category 3 diesel vehicle

ERMS tested the vehicles using multiple cycles, and in addition, the Category 1vehicles at multiple temperatures and the Category 3 vehicle on two loads.

6.2.3 Chile

CMM provided chassis dynamometer data:

- One Category 1 diesel vehicle
- One Category 2 diesel vehicle
- One Category 3 diesel vehicle

6.2.4 China

CATARC provided chassis dynamometer data:

- One Category 1 diesel vehicle
- One Category 2 diesel vehicle
- Two Category 3 diesel vehicles

CATARC also provided data for three natural gas buses, but this data is not included in this report.

6.2.5 Denmark

DTI provided chassis dynamometer data:

- One Category 2 diesel vehicle
- One Category 2 CNG vehicle

DTI conducted the testing using multiple driving cycles. In addition DTI provided data on one diesel bus and two natural gas buses, but again, bus data was not included.

6.2.6 Finland

VTT provided chassis dynamometer data:

- Five Category 1 vehicles
    - Three vehicle platforms, petrol, diesel, bi-fuel CNG, electric
- Nine Category 2 vehicles
    - Including diesel, diesel-hybrid, CNG, dual-fuel CNG, ethanol
- Three Category 3 diesel vehicles

VTT tested one dual-fuel CNG truck with several pilot fuels (different diesel qualities).

6.2.7 Japan

NTSEL provided engine dynamometer data:

- One diesel engine for Category 2 trucks

NTSEL ran the engine on three different fuels.

6.2.8 Sweden

AVL MTC provided chassis dynamometer data:

- One Category 2 diesel truck
- One Category 2 ethanol truck

AVL MTC ran the diesel vehicle on five different fuels.

6.2.9 Thailand

PTT provided chassis dynamometer data:

- Two Category 1 vehicles
    - One vehicle platform, bi-fuel CNG and diesel

PTT also provided data from engine testing, from one diesel and one natural gas engine, but this data was not included in this report, as the data could not be fully verified.

7. Results and discussion – vehicle tests

7.1 Presentation of results

The vehicle test results are presented in the following way:

- Results from the individual partners
  - Petrol, diesel, alternative fuel vehicles
  - Diesel vehicles tested on regular diesel fuel

- Collated results
  - Energy consumption and emissions versus vehicle test weight
  - Comparison of results from different laboratories

- Fuel effects
  - Results from "drop-in" fuel substitution (various diesel alternatives, petrol with varying ethanol content)

"Baseline" reporting for the vehicle testing entails regulated exhaust emissions and energy consumption for the WHVC at 50 % load.

CO_2 emissions are, in most cases, reported as direct tailpipe CO_2 emissions only, without considering N_2O or CH_4. However, for methane vehicles, the figures presented include CH_4. CH_4 in included calculation of CO_{2eqv} using a factor of 21 compared to CO_2[4].

When presenting results, focus is on energy consumption, tailpipe CO_2 emissions, NO_x emissions and PM emissions.

7.2 Canada

7.2.1 General

Canada provided test results for four Category 1 vehicles (vans, GVW 2 270 kg, test weights 1 700 – 1 900 kg,) and one Category 3 vehicle (GVW 36 000 kg, test weights 24 000 and 33 000 kg), representing current emission regulations (Tier 2, EPA 2010).

7.2.2 Category 1

<u>General</u>

Four vans of the same vehicle platform (test weight some 1 700 kg for the ICE vehicles and some 1 900 kg for the EV) were tested with the following fuels/propulsion systems:

- Port Fuel Injection (PFI), petrol (Tier 2)
- Vapour Sequential Ignition (VSI) bi-fuel gasoline/LPG (propane), after-market conversion
- Compressed Natural Gas (CNG) bi-fuel, after-market conversion
- Converted electric vehicle

Four test cycles were used representing city driving and cold-start (FTP-75), aggressive high speed driving (US06), free flow highway driving (HWFCT), and the world harmonised vehicle cycle (WHVC). The most extensive testing was carried out using the FTP test cycle. Tests were performed at temperatures of 22°C, with select tests at -7°C and -18°C.

[4] http://unfccc.int/ghg_data/items/3825.php

Test results

In the case of petrol all of the tests done on the petrol vehicle, the LPG bi-fuel vehicle on petrol and the CNG bi-fuel on petrol have been averaged together.

Figure 7.1 presents the effect of test cycle on energy consumption. Figure 7.2 presents relative energy consumption for the test cycles. Figures 7.3 (energy consumption and CO_2 emissions) and 7.4 (gaseous regulated emissions) present data for the WHVC cycle.

Figure 7.5 presents the effects of test cycle on NO_x emissions. Figures 7.6 and 7.7 present the effects of test temperature on energy consumption and emissions. This data is for the FTP cycle. It should be noted that the after-market conversions are not required to meet emission standards in Canada due to low sales volumes. Emissions performance could improve with enhanced emissions calibration.

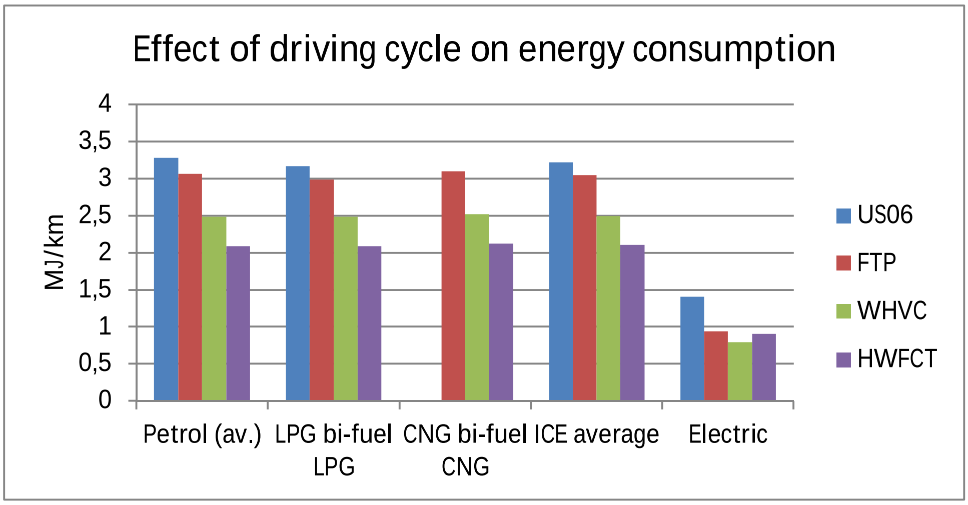

Figure 7.1. The effects of test cycle on energy consumption. Category 1 vans.

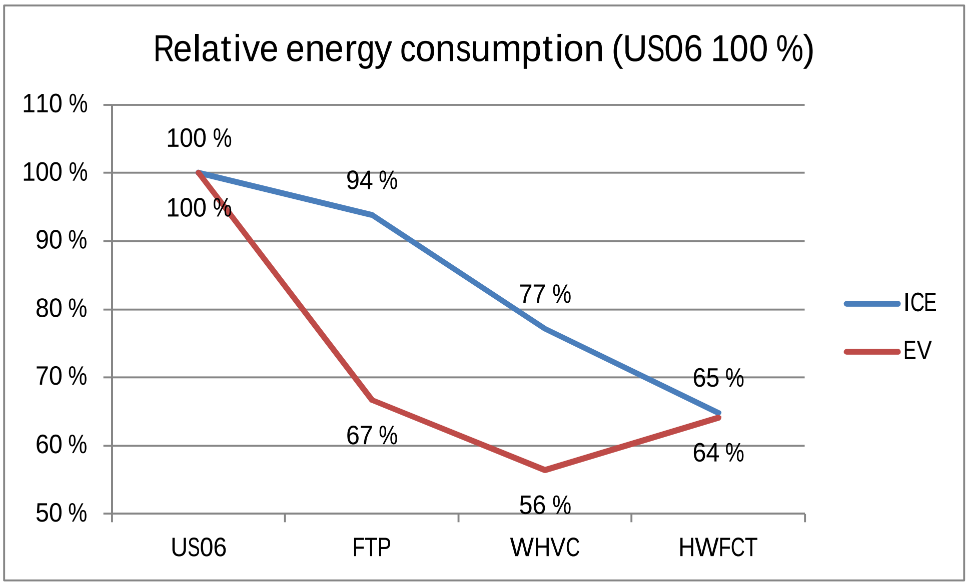

Figure 7.2. Relative energy consumption.

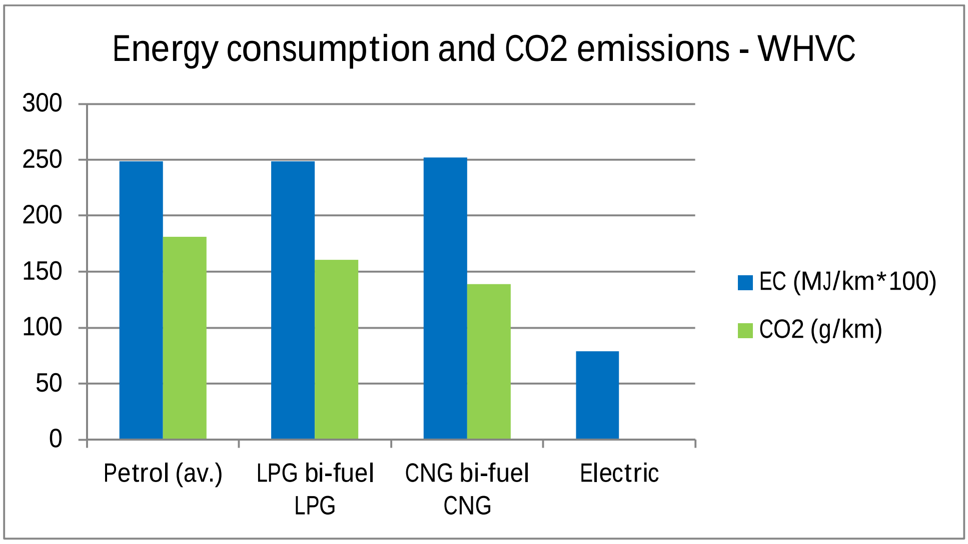

Figure 7.3. Energy consumption and tailpipe CO_{2eqv} emissions. Category 1 vans.

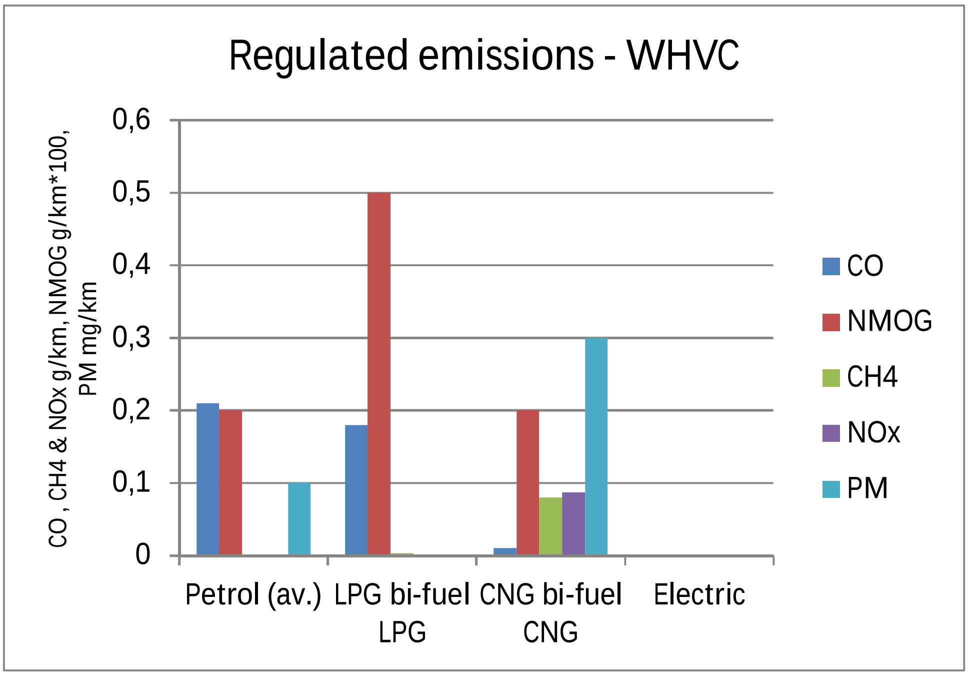

Figure 7.4. Regulated gaseous emissions, Category 1 vans. PM not measured for LPG.

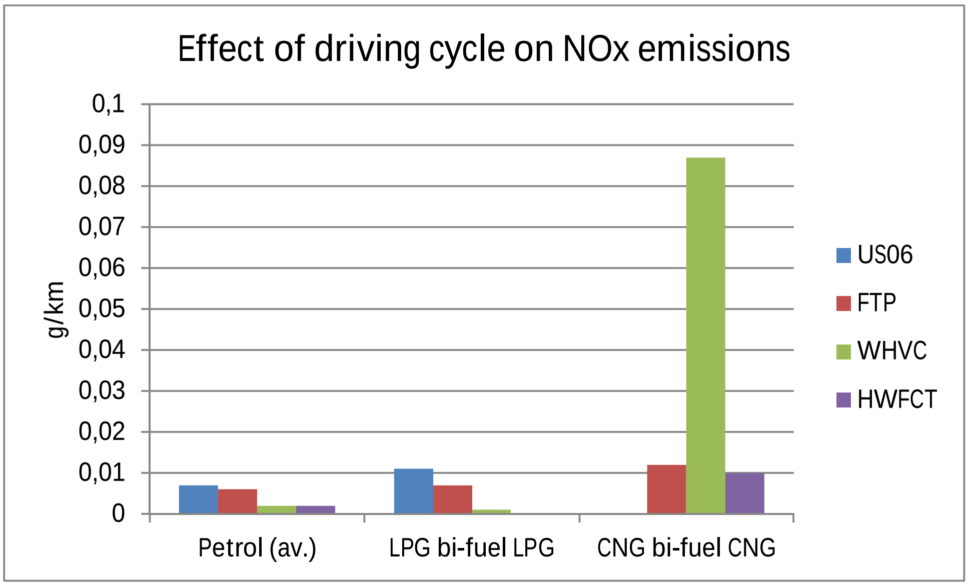

Figure 7.5. The effects of test cycle on NO_x emissions. Category 1 vans.

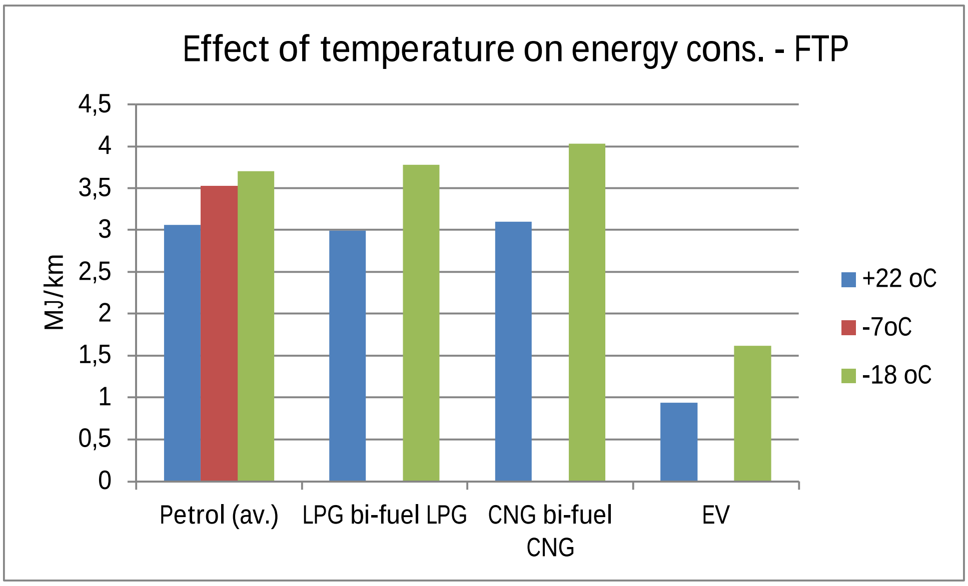

Figure 7.6. The effects of test temperature on energy consumption. Category 1 vans.

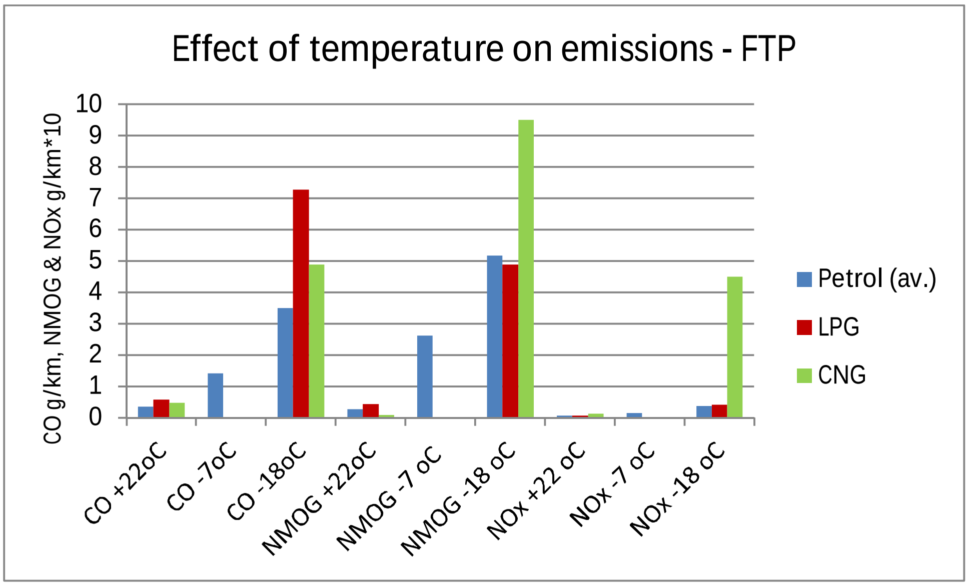

Figure 7.7. The effects of test temperature on emissions. Category 1 vans.

Discussion

Of the test cycles used by ERMS, US06 is the most severe and HWFCT the least severe. The petrol vehicle and the two bi-fuel vehicles show a consistent response on test cycle for energy consumption. The relative energy consumption is (Figure 7.2):

- US06 100 %
- FTP 94 %
- WHVC 77 %
- HWFCT 65 %

The electric vehicle reacts differently, showing a larger variation cycle by cycle. Energy consumption is at minimum for the WHVC, and the relative figures are:

- US06 100 %
- FTP 67 %
- WHVC 56 %
- HWFCT 64 %

Depending on the cycle, the energy consumption of the EV is 31 – 44 % of average ICE vehicle energy consumption.

In the WHVC cycle, petrol, LPG and CNG in practise all deliver same energy efficiency. Energy consumption and fuel carbon intensity determine tailpipe CO_2 emissions. The CO_2 emission factor expressed in g CO_2/MJ is 73 for petrol, 66 for LPG and 56 for natural gas (JEC WTW).

Consequently, with roughly the same energy consumption, LPG delivers 11 % and CNG 23 % lower tailpipe CO_2 emissions compared to petrol (values based on tailpipe emissions, CH_4 accounted for in the case of CNG, CO_{2eqv}).

For the WHVC cycle, the two bi-fuel vehicles deliver roughly the same emission profile when running on petrol. LPG seems to increase hydrocarbon (NMOG) emissions. CNG operation lowers CO emissions but increases NO_x emissions, significantly in the case of the WHVC test cycle. As for end-use, the emissions of the EV are zero. Also when comparing test cycles, the CNG vehicle stands out for high NO_x emissions. The LPG and CNG vehicles are after-market conversions. It is possible that emission reductions could be realized with emission calibration.

Lowering test temperature from 22 to -18 ^{o}C increases energy consumption some 25 % for the ICE vehicles, but surprisingly as much as 70 % for the EV.

Emissions of CO, NMOG and NO_x increase with falling test temperature with petrol, LPG as well as CNG. The increase in NO_x emissions with falling temperature is significant with CNG. The bi-fuel vehicles are normally started on petrol, and this diminishes the potential for reducing CO and HC emissions.

For the studied vehicles, CNG was the best ICE option for tailpipe CO_2 emissions, but the worst for NO_x. The electric vehicle is highly efficient, and has no local emissions. For the local environment, the electric van would be the best option. Overall CO_2 emissions of the EV depend on how the electricity is generated (see Chapter 8). The usability of the electric van may be hampered by limited range, especially in winter conditions. For example, the driving range on the FTP was 118 km at standard temperature, 101 km at -18 ^{o}C, and 86 km at -18^{o}C with cabin heating.

7.2.3 Category 3

General

Canada provided results for one Class 3 diesel vehicle. The truck was model year 2013, with a 15 litre engine equipped with advanced emission control systems and complying with EPA 2010 emission regulations.

The vehicle was tested over the Heavy-Duty Urban Driving Dynamometer Schedule (HD UDDS), the WHVC cycle and two steady-state speed cycles of 89 and 95 km/h at two different test loads. The test weights were 24 000 and 33 000 kg.

Test results

The test results are presented in numerical format in Table 7.1

Table 7.1. Test results for the Class 3 diesel vehicle.

Test Parameters		**Regulated Emissions and FC**							**GHG Emissions**			
		CO	**NO_x**	**THC**	**NMHC**	**TPM**	**FC**	**Energy Efficiency**	**CO_2**	**CH_4**	**N_2O**	**$CO2_e$**
		g/km	g/km	g/km	g/km	mg/km	L/100 km	%	g/km	g/km	mg/km	g/km
587 Diesel 24000 kg	HD UDDS	0.00	5.62	0.00	0.00	0.4	46.8	32	1219	0.00	51.2	1234
	WHVC	0.00	4.55	0.00	0.00	1.2	40.5	32	1054	0.00	38.9	1066
	SS 95 kph	0.00	1.22	0.00	-	1.5	29.7	40	772	0.00	83.5	797
	SS 89 kph	0.00	1.38	0.00	0.00	0.9	28.0	41	728	0.00	77.9	752
587 Diesel 33000 kg	HD UDDS	0.00	5.09	0.00	-	0.8	55.3	33	1484	0.00	117.5	1519
	WHVC	0.00	3.61	0.00	-	1.2	53.2	30	1386	0.00	207.9	1448
	SS 95 kph	0.00	1.16	0.00	-	0.4	33.1	37	889	0.00	135.5	929
	SS 89 kph	0.00	0.77	0.00	-	0.5	31.3	37	838	0.00	266.0	918
HD UDDS (% Difference)												
Diesel 33T vs. 24T		-	-9	-	-	123	18	-	22	-	130	23
WHVC (% Difference)												
Diesel 33T vs. 24T		-	-21	-	-	-	31	-	31	-	434	36
SS 95kph (% Difference)												
Diesel 33T vs. 24T		-	-	-	-	-72	12	-	15	-	62	17
SS 89kph (% Difference)												
Diesel 33T vs. 24T		-	-44	-	-	-	12	-	15	-	241	22

- No value / No statistical differences

Figures 7.8 (energy consumption), 7.9 (CO_2), 7.10 (NO_x) and 7.11 (PM) show results for the different test parameters (two cycles, two steady-state speeds and two test loads).

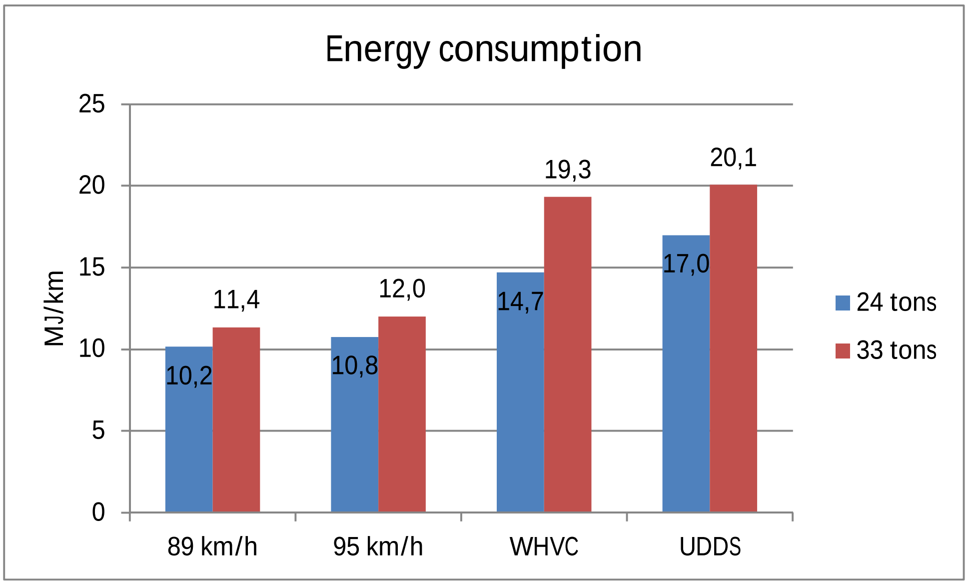

Figure 7.8. Energy consumption. Category 3 truck.

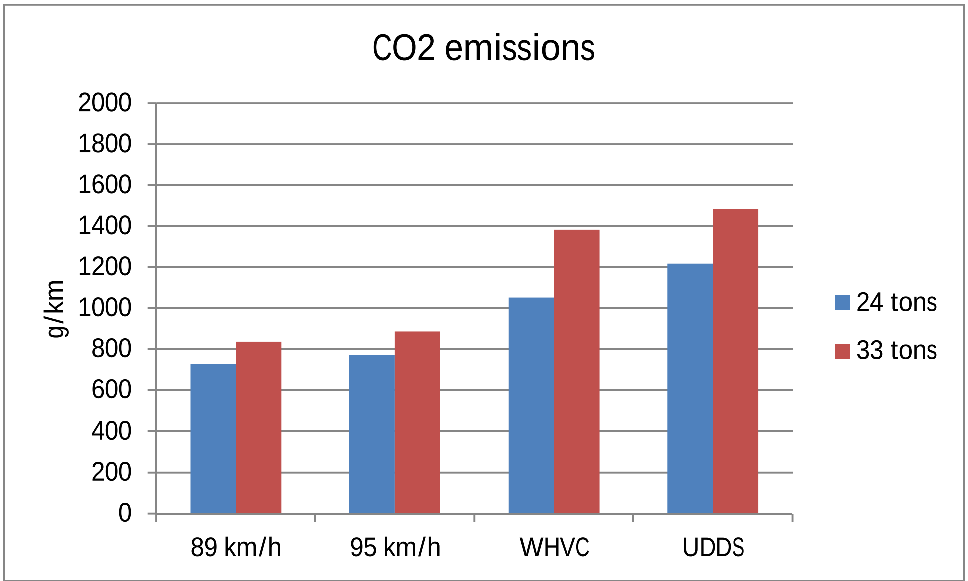

Figure 7.9. CO_2 emissions. Category 3 truck.

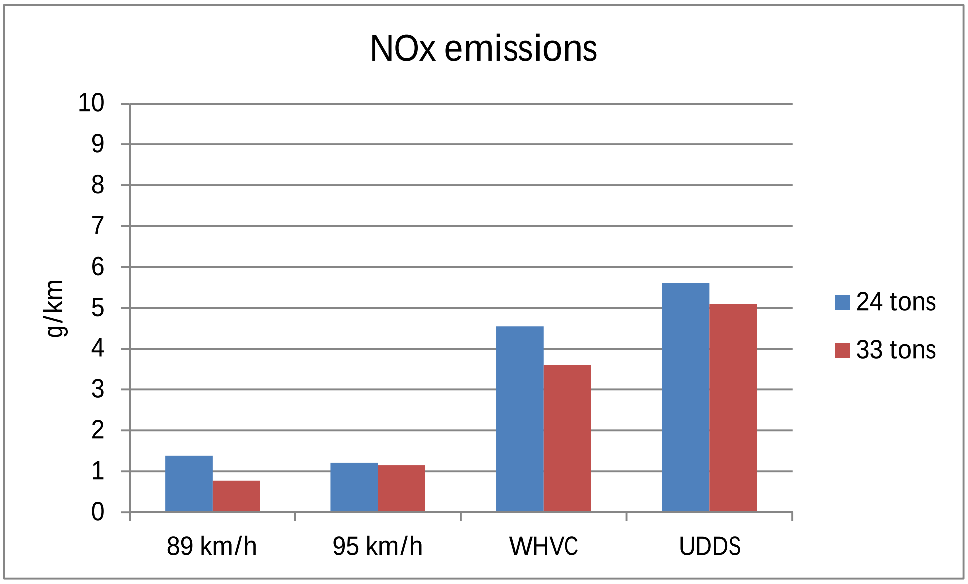

Figure 7.10. NO_x emissions. Category 3 truck.

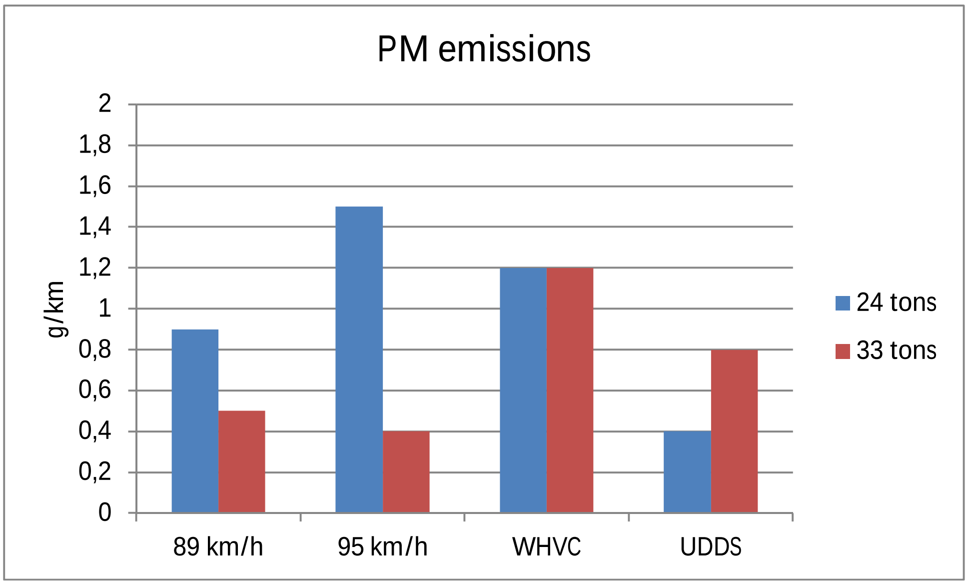

Figure 7.11. PM emissions. Category 3 truck.

<u>Category 3 discussion</u>

Increasing test load from 24 to 33 tons (+37 %) load increases energy consumption and thereby also CO_2 emissions by some 10 – 30 %, with less increase in steady-state operation than in transient operation. The relative energy consumption is (average of the two loads):

- UDDS 100 %
- WHVC 91 %
- 95 km/h steady-state 62 %
- 89 km/h steady-state 58 %

Depending on load and cycle, overall efficiency varies between some 30 and 40 % (from fuel to work on the dynamometer roller).

Higher load results in slightly reduced NO_x emissions, probably due to higher exhaust temperature and more favourable operating conditions for the SCR catalyst. No clear trend can be found for PM emissions, neither for load nor test cycle.

7.3 Chile

7.3.1 General

Chile provided test data for three single truck type vehicles with GVWs of 4 700, 7 500 and 19 500 kg (test weights of 3 300, 5 100 and 12 980 kg). Testing was done using the WHVC cycle. The smallest truck qualified for Category 1 regarding mass but Category 2 regarding its construction. The other two vehicles were Category 2 vehicles.

The biggest truck was of Euro V certification, the smaller ones of Euro IV certification.

7.3.2 Test results

The results are presented as energy consumption (Figure 7.12), CO_2 emissions (Figure 7.13) and NO_x and PM emissions (Figure 7.14) versus test weight.

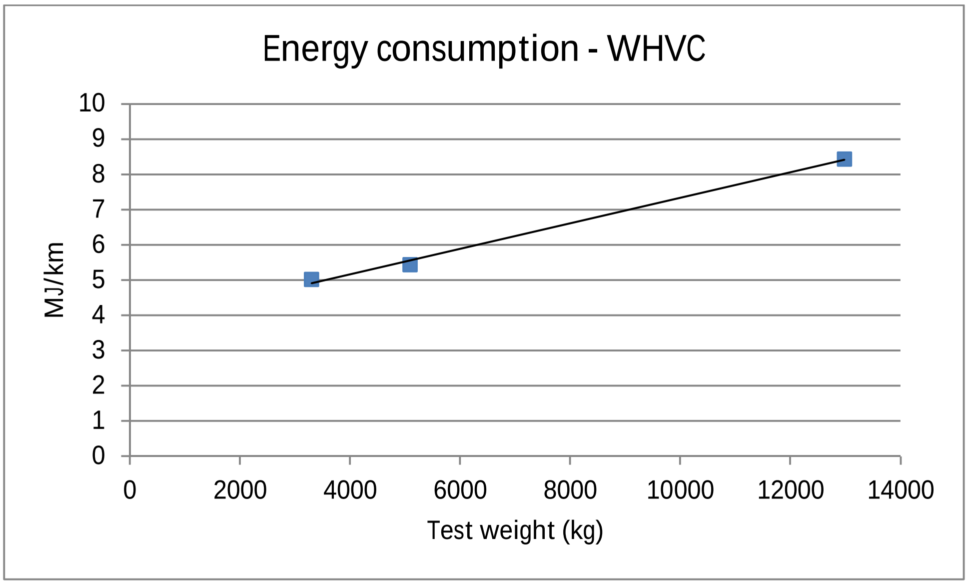

Figure 7.12. Energy consumption vs. test weight.

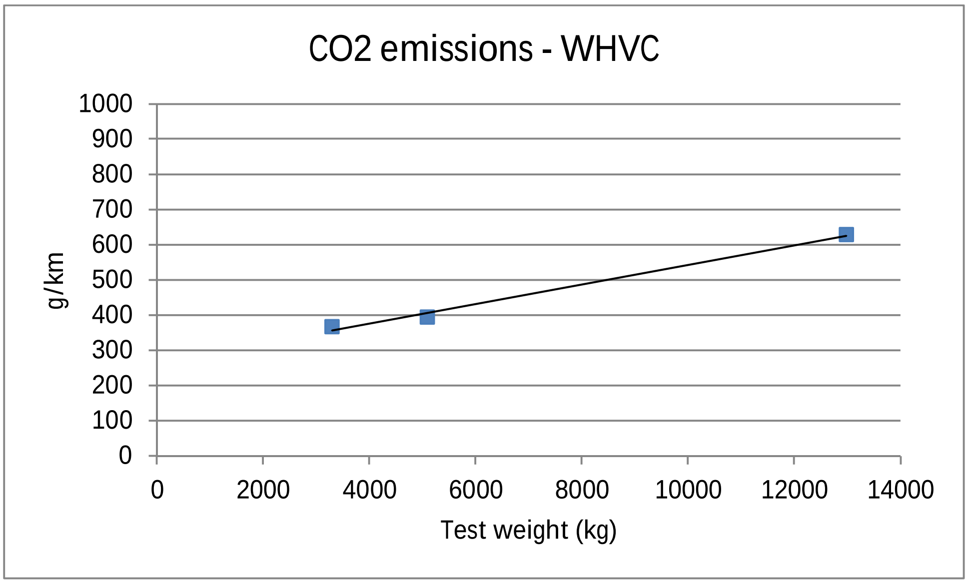

Figure 7.13. CO_2 emissions vs. test weight.

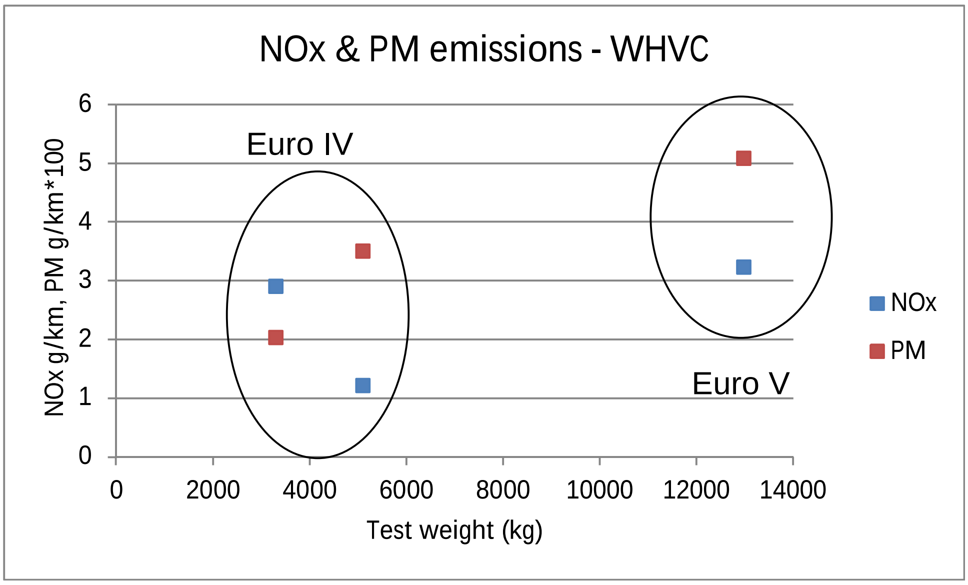

Figure 7.14. NO_x and PM emissions vs. test weight.

7.3.3 Discussion

Figures 7.11 and 7.12 indicate that energy consumption and CO_2 emissions are roughly proportional to vehicle test weight, as can be expected. The scatter in NO_x and PM emissions makes it obvious that regulated emissions cannot be directly attributed to vehicle weight. Emission control technology, vehicle calibration and the functioning of an individual vehicle determine emission levels. Figure 7.13 suggests that the differences in emission performance (relative to weight) are not that significant between the heavier Euro V vehicle and the two lighter Euro IV certified vehicles.

7.4 China

7.4.1 General

China provided data for four Euro IV certified diesel trucks. The GVWs of the trucks were 4 460, 12 005, 48 995 and 49 000 kg (test weights 3 500, 9 000 and 29 000 kg for two vehicles).

7.4.2 Test results

The results are presented as energy consumption (Figure 7.15), CO_2 emissions (Figure 7.16) and NO_x and PM emissions (Figure 7.17) versus test weight. The Figures present data for trucks as well as buses.

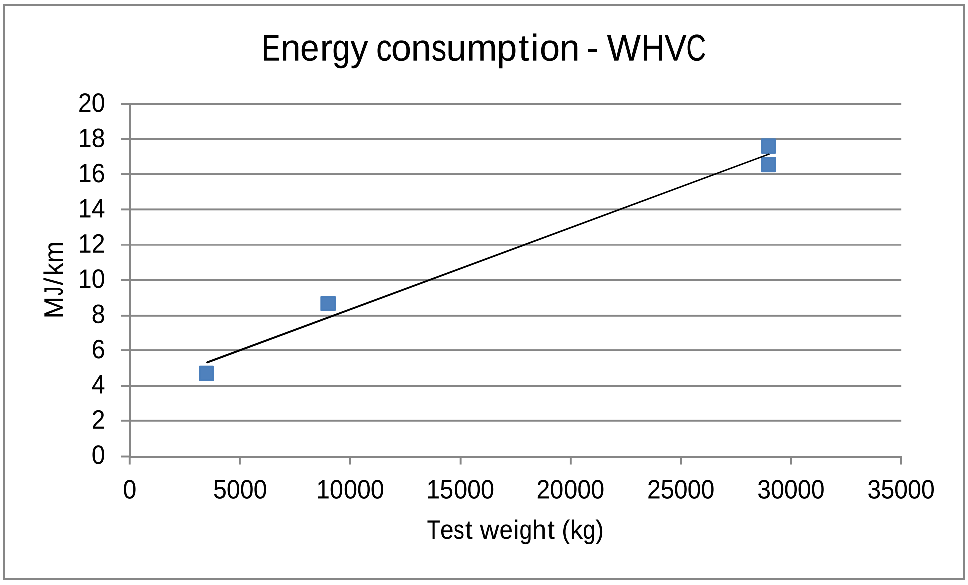

Figure 7.15. Energy consumption vs. test weight.

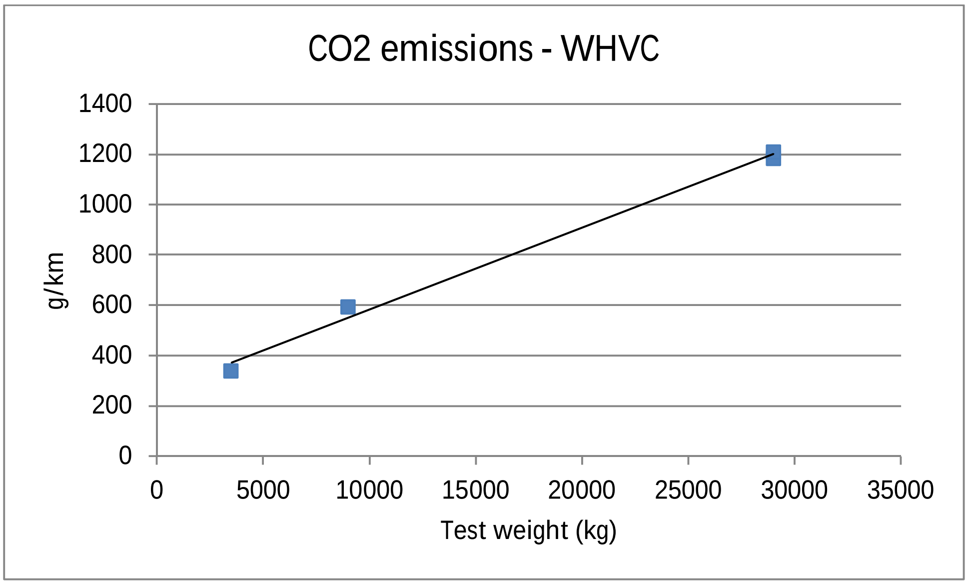

Figure 7.16. CO_2 emission vs. test weight.

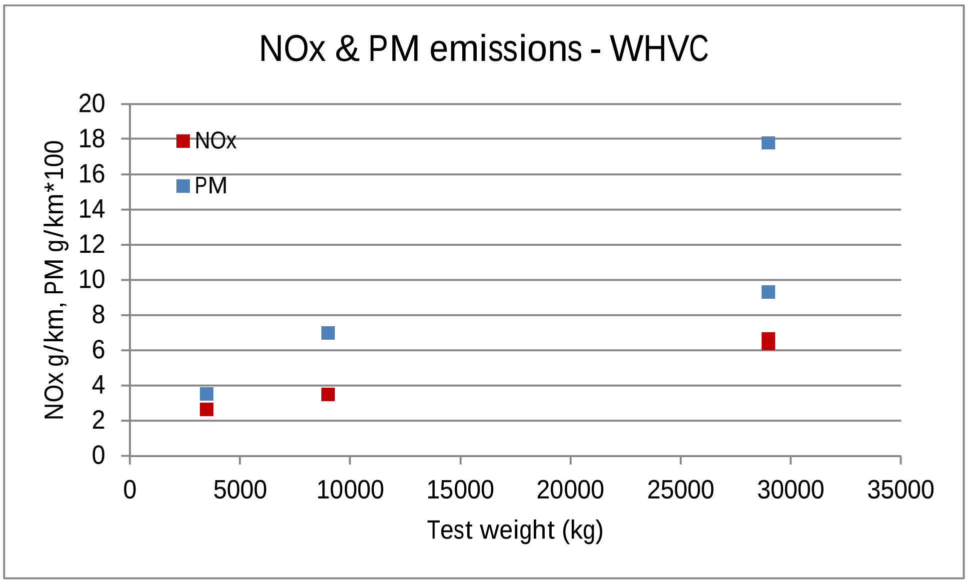

Figure 7.17. NO_x and PM emissions vs. test weight.

7.4.3 Discussion

As in the case of the Chilean results, the energy consumption of the trucks is almost linearly proportional to test weight. In both cases a mass of 10 000 kg corresponds to an energy consumption of some 7.5 - 8 MJ/km.

For the Euro IV certified trucks, also NO_x and PM emissions are almost linearly proportional to test weight. For the lightest truck NO_x reduction is based on exhaust gas recirculation (EGR), whereas the three other trucks are equipped with selective catalytic reduction (SCR) for NO_x control.

7.5 Denmark

7.5.1 General

Denmark provided data for two trucks, diesel and CNG. Both vehicles were Euro VI certified. The GVW of the three-axle trucks was 26 000 kg, and test weights were 20 930 kg (diesel) and 20 780 kg (CNG). The trucks were tested with the WHVC cycle and a neighbourhood refuse truck cycle

7.5.2 Test results

The results for the two test cycles are presented in 7.18 (energy consumption), 7.19 (CO_2 emissions) and 7.20 (NO_x emissions). DTI didn't measure particulate mass. However, DTI provided data on particle number emissions (Figure 7.21).

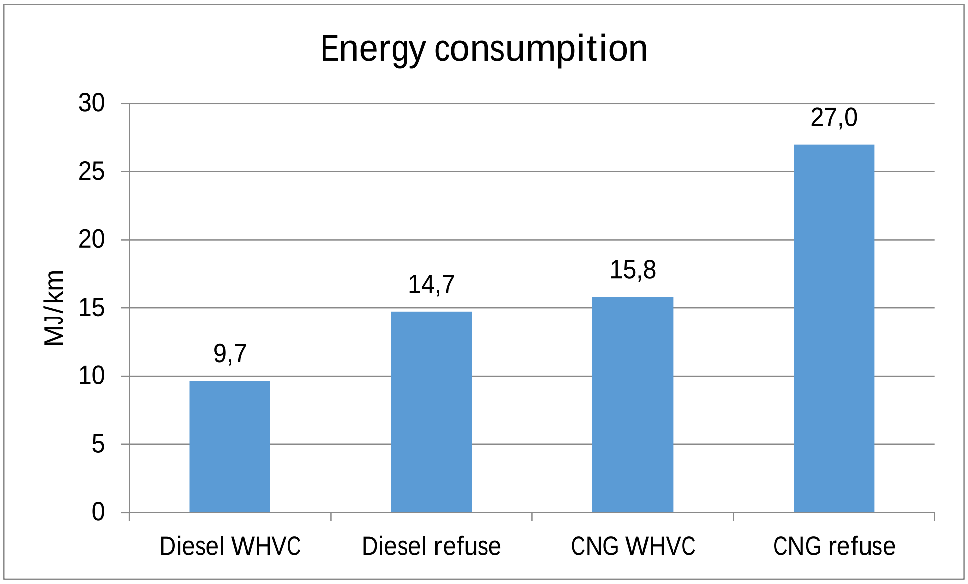

Figure 7.18. Energy consumption for two test cycles.

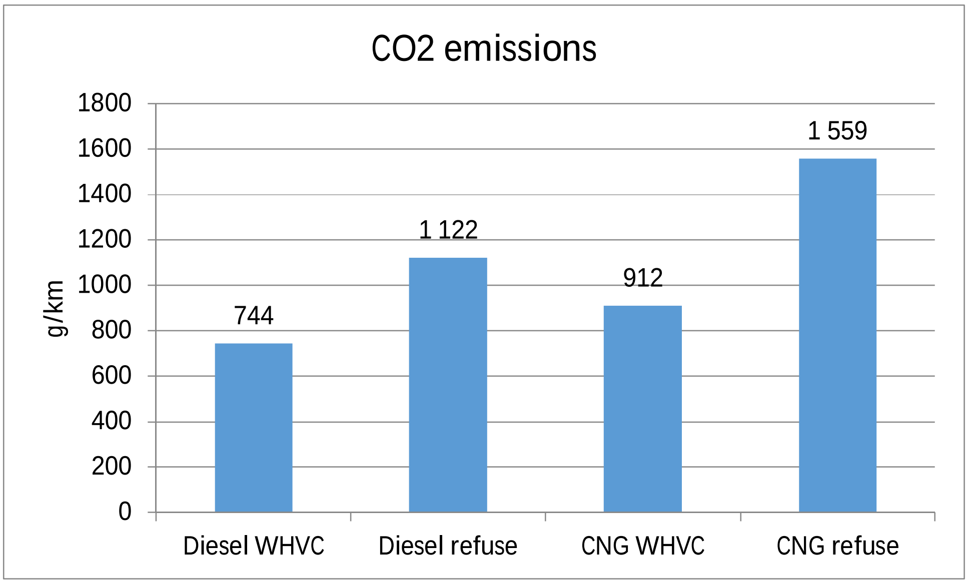

Figure 7.19. CO_2 emission for two test cycles.CH_4 is taken into account for CNG (CO_{2eqv}).

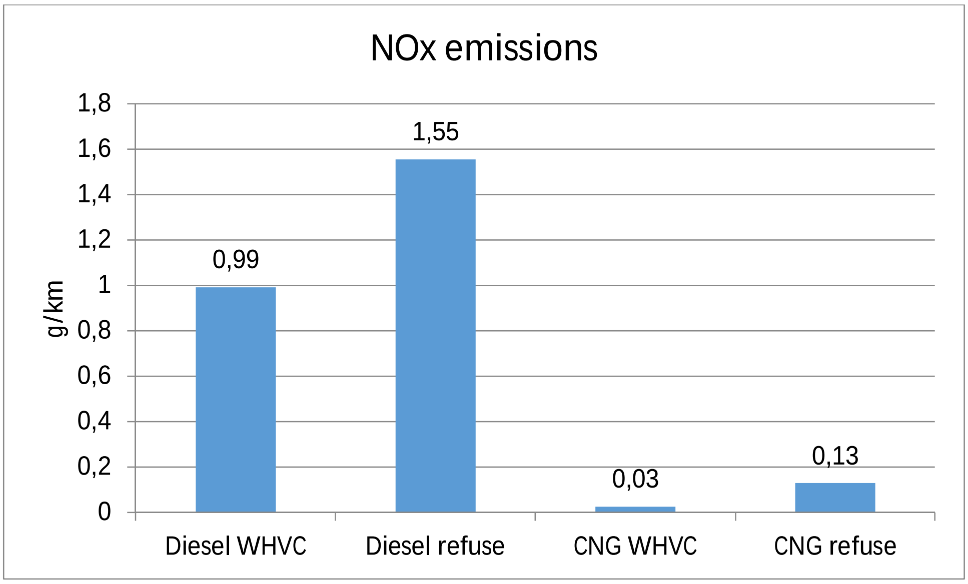

Figure 7.20. NO_x emissions for two test cycles.

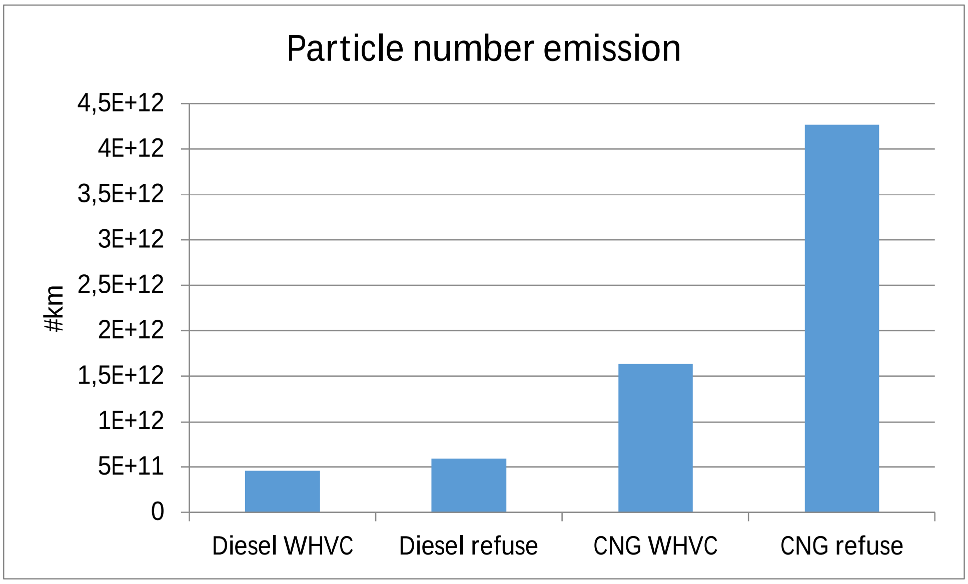

Figure 7.21. Particulate number emissions for two test cycles.

7.5.3 Discussion

The neighbourhood refuse truck cycle used by DTI is significantly more severe than the WHVC cycle. Energy consumption increases some 50 % for the diesel truck and some 70 % for the CNG truck going from the WHVC cycle to the neighbourhood refuse truck cycle.

The Danish results show significantly higher energy consumption, some 65 - 85 %, for CNG compared to diesel. This difference is significantly higher than what is usually reported. It should be noted that the two trucks had different transmission systems. The diesel truck was equipped with an efficient automated mechanical gearbox including an electro-hydraulic controlled clutch compared, whereas the CNG truck was equipped with a conventional automatic gearbox with an integrated hydraulic torque converter.

Due to the high energy consumption tailpipe CO_2 is higher for CNG than for diesel. In this case the methane slip for CNG was very low, below 0.5 g/km, so the contribution of methane to tailpipe CO_{2eqv} emissions is almost negligible.

Both trucks were Euro VI certified. However, there were huge differences in NO_x emissions. In the WHVC, the diesel truck had higher NO_x emission (some 1 g/km) than could be expected for a Euro VI vehicle (see collated results in Chapter 7.9). For the diesel vehicle, going from the WHVC cycle to the neighbourhood refuse truck cycle increased both fuel consumption and NO_x emissions some 50 – 60 %.

The CNG vehicle delivered very low NO_x emissions, below 0.05 g/km for the WHVC cycle. Going from the WHVC cycle to the neighbourhood refuse truck cycle increased fuel consumption some 70 % and NO_x emissions some 400 %. However, also for the neighbourhood refuse truck cycle the CNG truck delivered low NO_x emission in absolute terms, only some 0.15 g/km.

The CNG truck produces higher particle numbers than the wall-flow filter equipped diesel truck. The factor CNG vs. diesel is some 4 in the WHVC and some 7 in the neighbourhood refuse truck cycle. The Euro VI limit value for particle number is $6*10^{11}$ per kWh at the engine crankshaft[5]. For the WHVC cycle DTI estimated the measured particle numbers to be from $5.1*10^{11}$ (diesel) to $1.2*10^{11}$ (CNG) per kWh on the engine crankshaft. Thus the diesel vehicle complies with the Euro VI particle number limit but the CNG vehicle does not.

7.6 Finland

7.6.1 General

Finland provided data for 17 different vehicles:

- Five Category 1 vehicles (vans)
  - Three vehicle platforms
  - Petrol, diesel, CNG, electric (petrol and CNG in the same vehicle)
  - Emission class Euro 5
  - Test weights 1 710 – 2 495 kg
- Nine Category 2 vehicles
  - Eight vehicle platforms
  - Diesel, diesel hybrid, CNG, DDF, ethanol
    - Conventional and hybrid version of one vehicle platform
    - DDF vehicles run both in diesel and DDF mode
  - Emission classes Euro III, Euro V and Euro VI
    - Euro III as a reference of “old technology”
  - Test weights 5 600 – 18 000 kg
- Three Category 3 diesel vehicles
  - Diesel Euro VI
  - Test weights 26 000 – 40 525 kg
  - Tests also with additional loads

Some diesel vehicles were tested with multiple fuels (see Chapter 7.10).

7.6.2 Results

The results are presented as energy consumption (Figure 7.22), specific energy consumption (Figure 7.23, MJ/km/1000 kg of vehicle mass), CO_2 emissions (Figure 7.24), NO_x emissions

[5] https://www.dieselnet.com/standards/eu/hd.php

(Figure 7.25) and PM emissions (Figure 7.26) versus test weight. Data for all vehicle classes are incorporated in the Figures.

Figures 7.27 – 7.30 show “blown-up” data for the Category 1vehicles (vans). Figure 7.31 shows a comparison of diesel and DDF operation of the two DDF vehicles tested (two and three axle versions). Figures 7.32 – 7.36 show the effect of load on the performance of the Category 3 vehicles. Figures 7.37 and 7.38 show how load affects performance expressed as MJ/ton-kilometre and g CO_2/ton-kilometre.

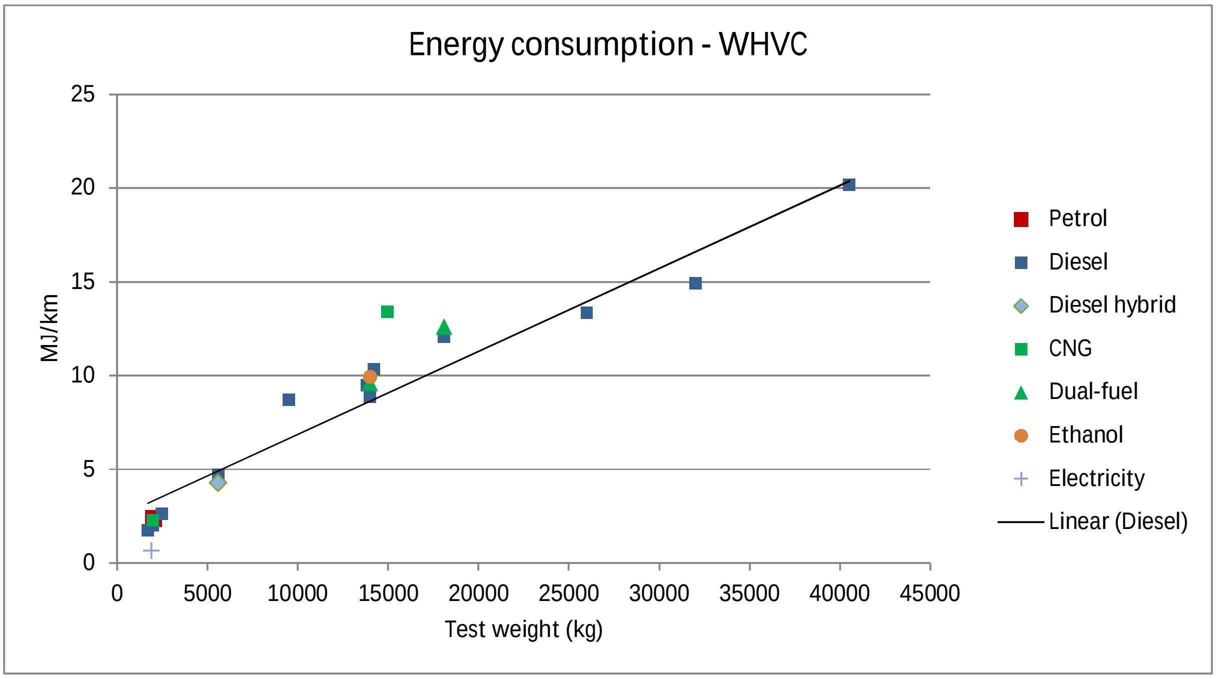

Figure 7.22. Energy consumption vs. test weight.

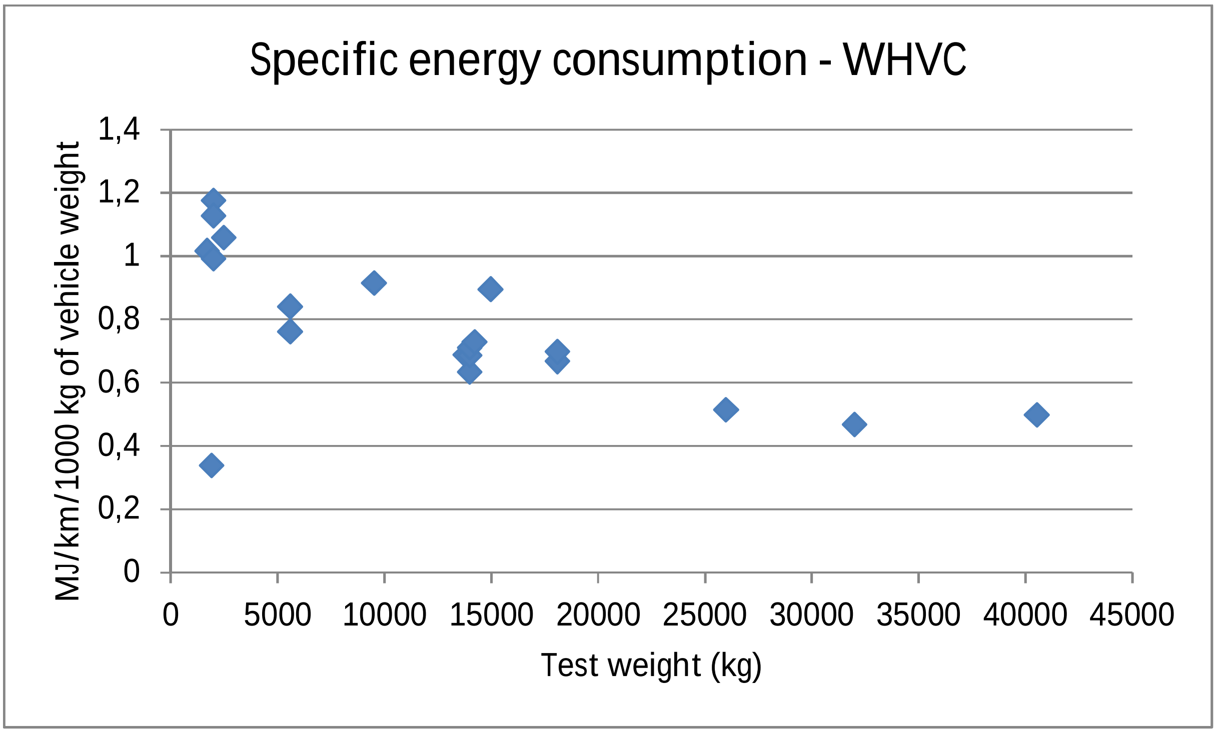

Figure 7.23. Energy consumption vs. test weight.

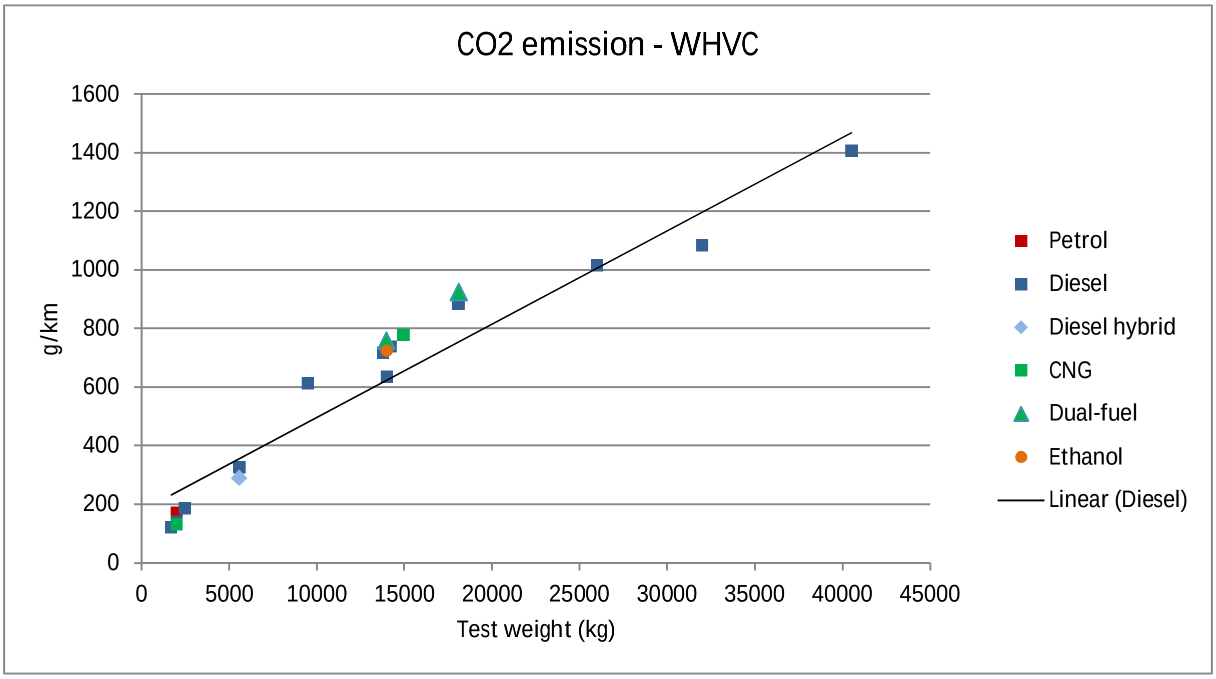

Figure 7.24. CO_2 emission vs. test weight.CH_4 is taken into account for CNG (CO_{2eqv}).

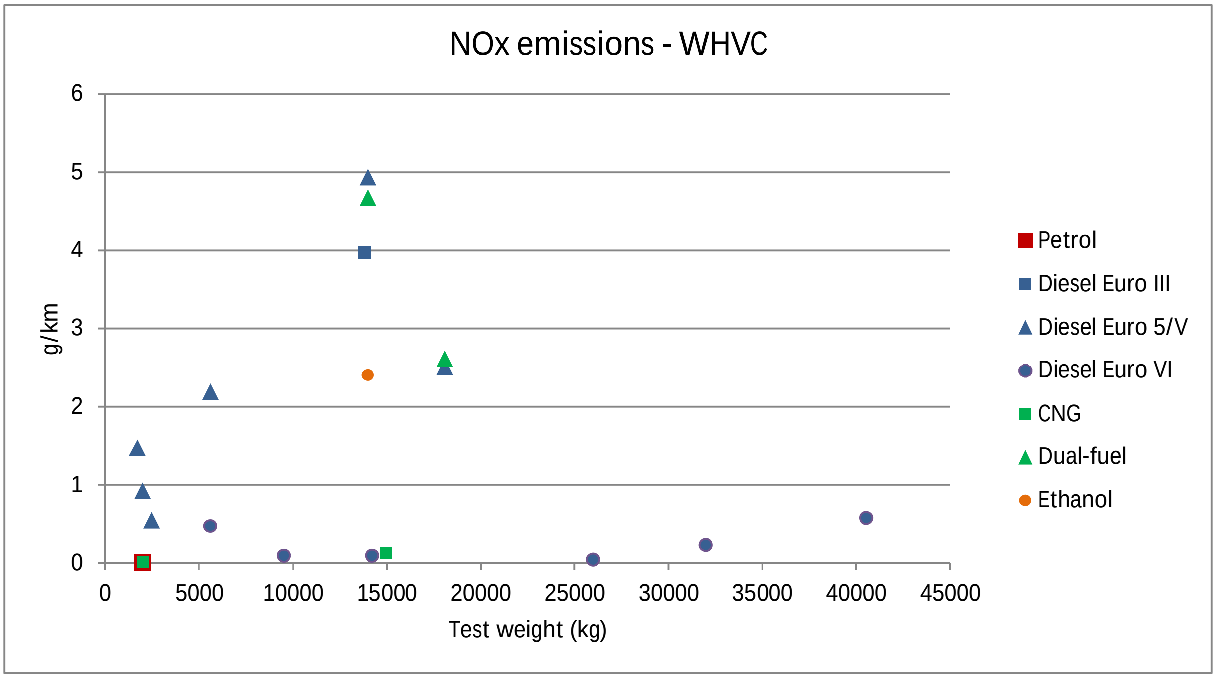

Figure 7.25. NO_x emissions vs. test weight.

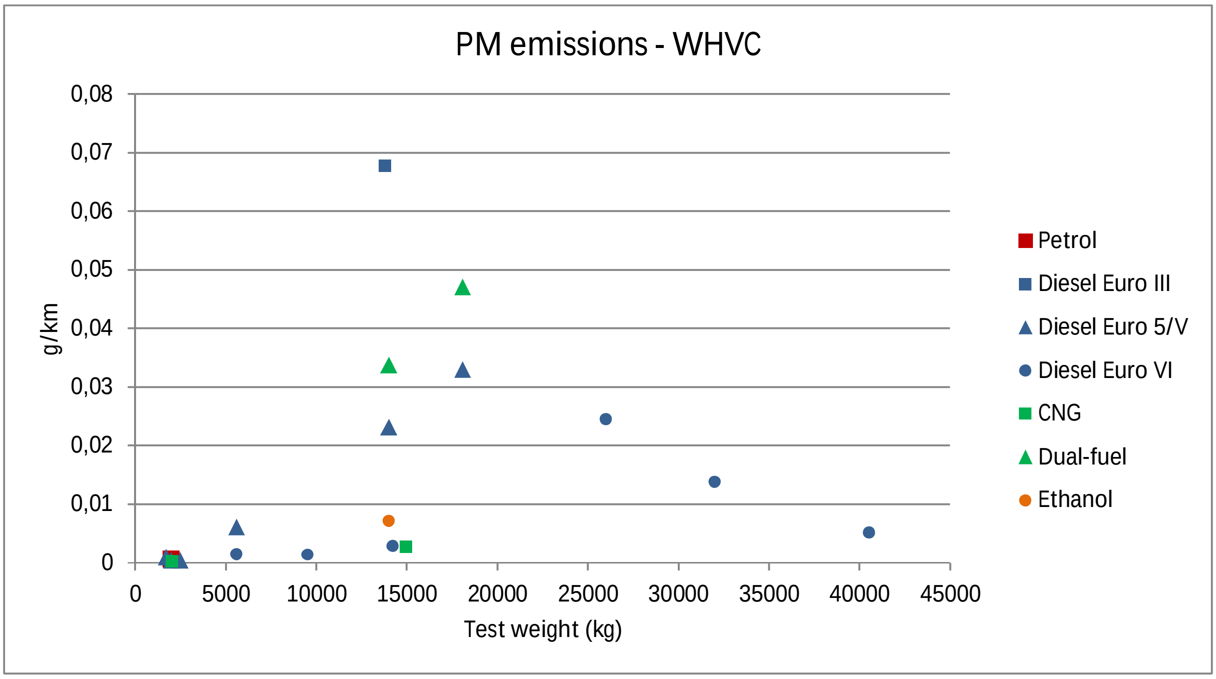

Figure 7.26. PM emissions vs. test weight.

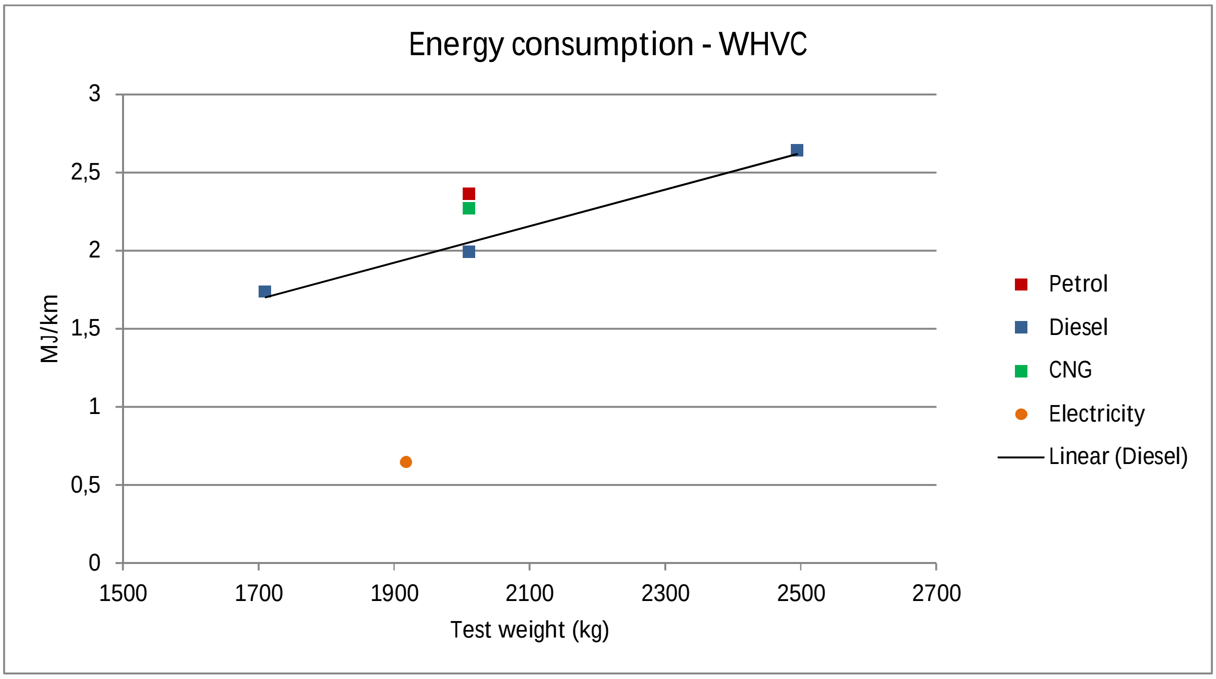

Figure 7.27. Energy consumption vs. test weight. Category 1 vehicles (vans).

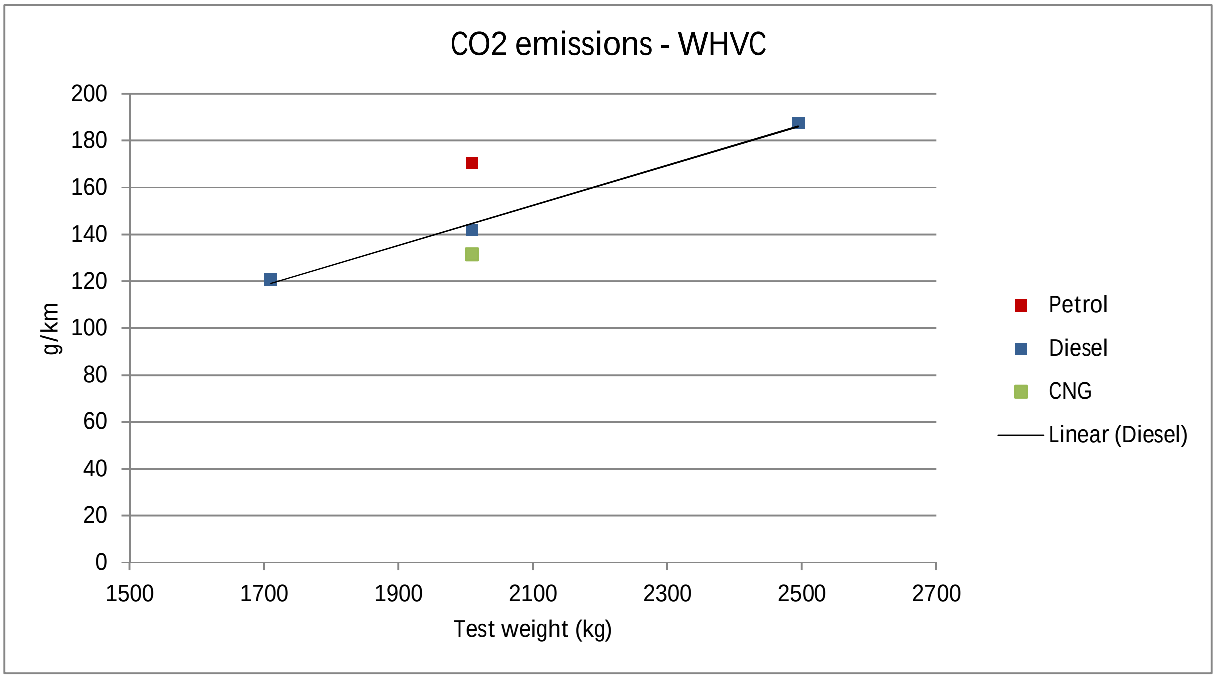

Figure 7.28. CO_2 emission vs. test weight.CH_4 is taken into account for CNG (CO_{2eqv}). Category 1 vehicles (vans).

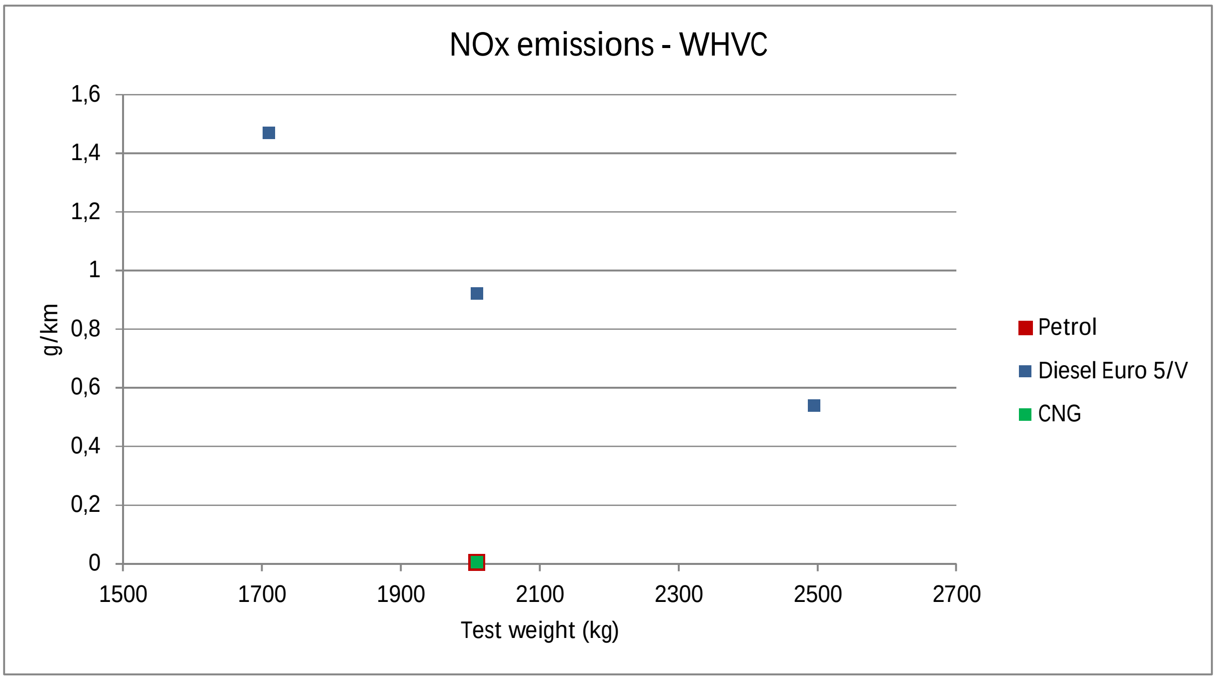

Figure 7.29. NO_x emissions vs. test weight. Category 1 vehicles (vans).

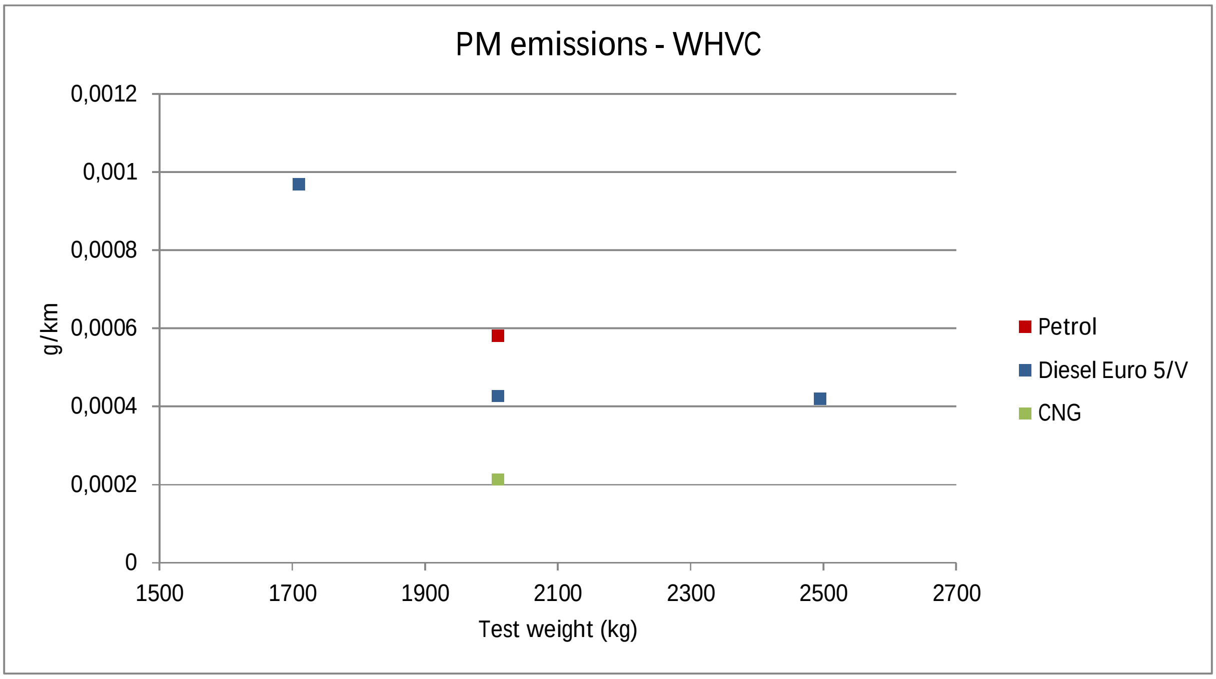

Figure 7.30. PM emissions vs. test weight. Category 1 vehicles (vans).

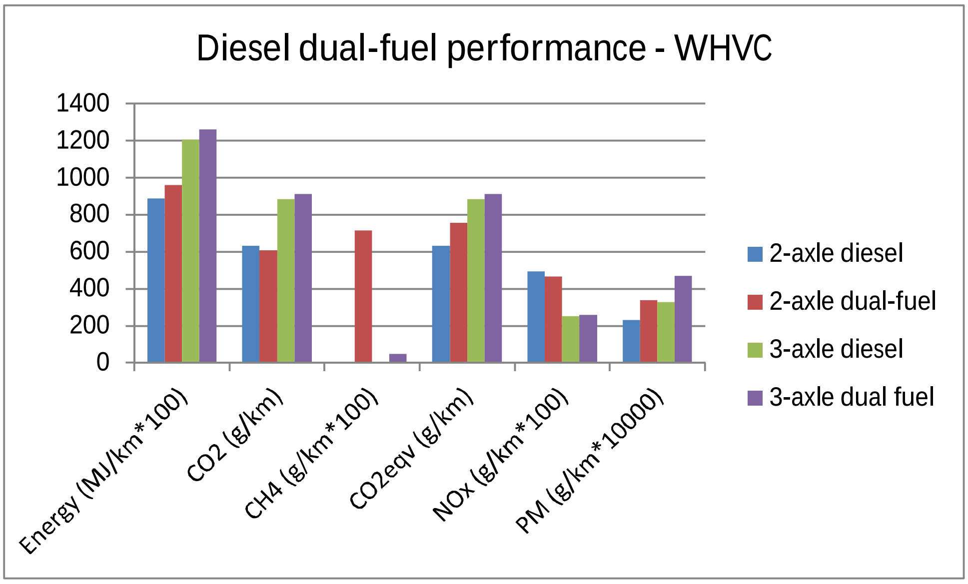

Figure 7.31. Diesel dual-fuel performance. Euro V certified Category 2 vehicles.

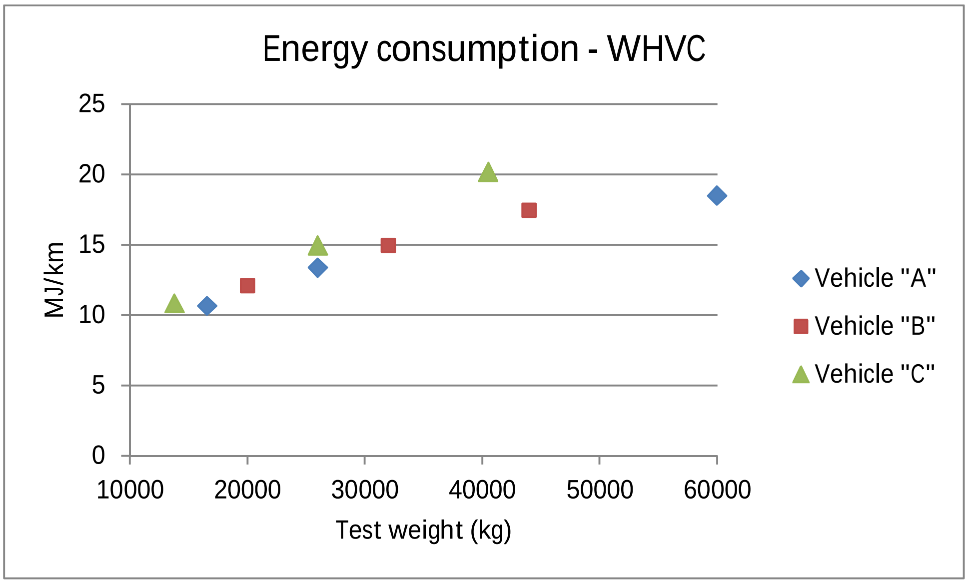

Figure 7.32. Effect of test weight on energy consumption. Euro VI certified Category 3 vehicles.

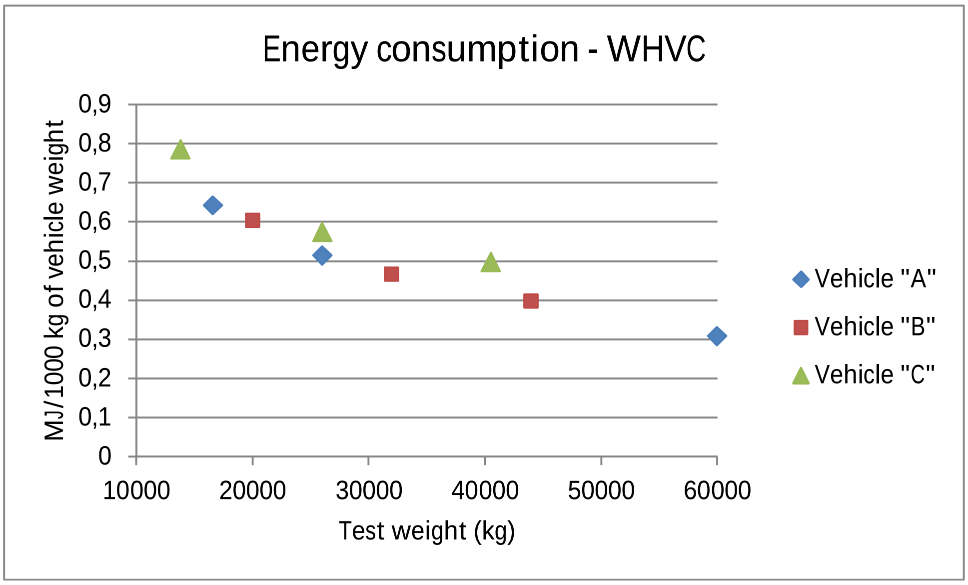

Figure 7.33. Effect of test weight on energy consumption. Euro VI certified Category 3 vehicles. Results presented as MJ per ton of vehicle weight.

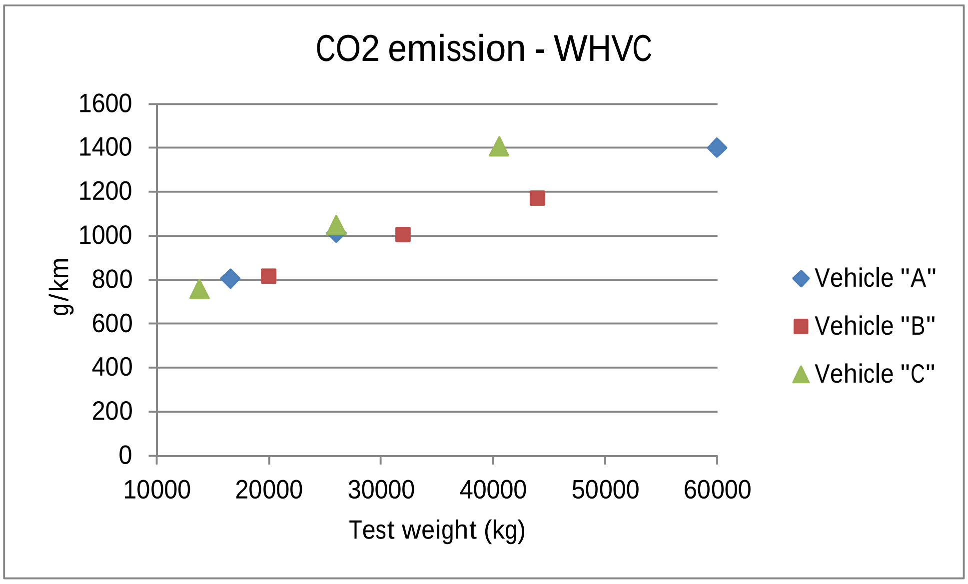

Figure 7.34. Effect of test weight on CO_2 emissions. Euro VI certified Category 3 vehicles.

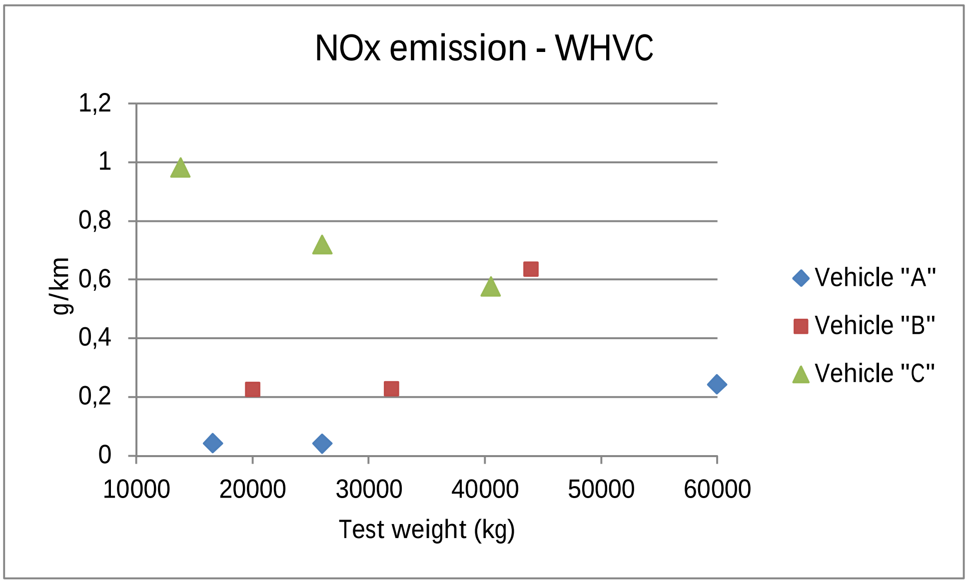

Figure 7.35. Effect of test weight on NO_x emissions. Euro VI certified Category 3 vehicles.

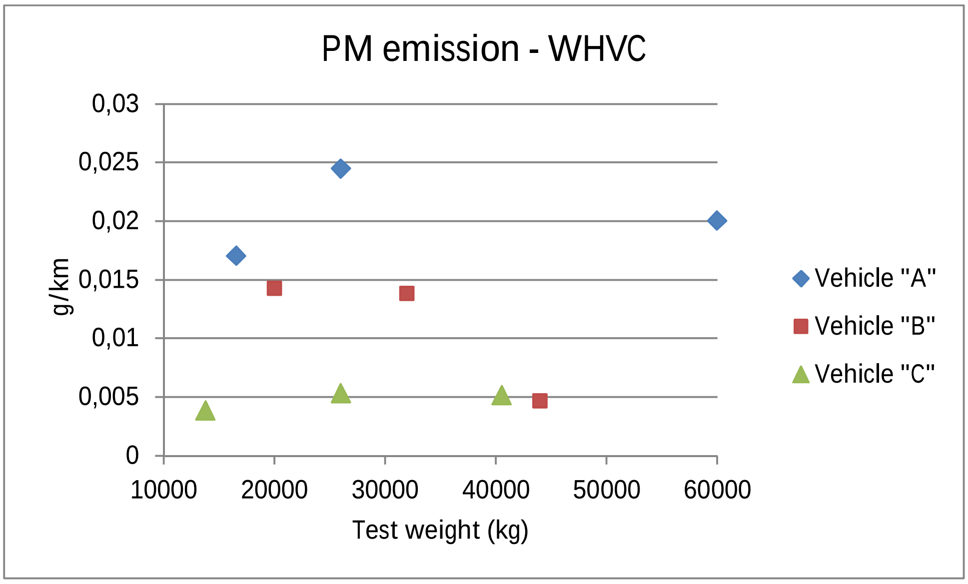

Figure 7.36. Effect of test weight on PM emissions. Euro VI certified Category 3 vehicles.

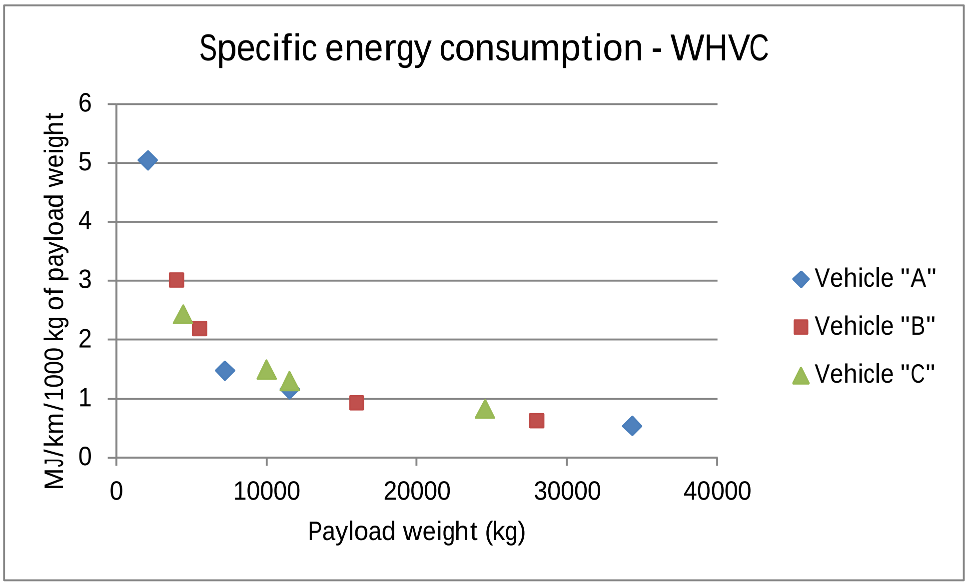

Figure 7.37. The effect of load on specific energy consumption (MJ/1000 kg of payload) for Category 3 vehicles.

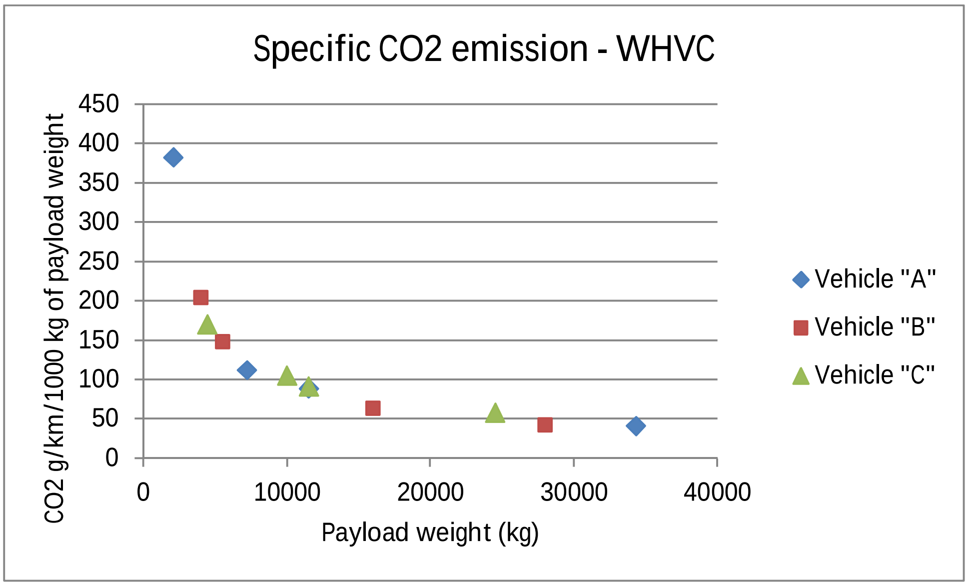

Figure 7.38. The effect of load on specific CO_2 emission (g of CO_2/1000 kg of payload) for Category 3 vehicles.

7.6.3 Discussion

Figure 7.22 includes a trendline (linear) for diesel vehicle energy consumption. It appears that both the Category 1 vehicles (vans) and the Category 3 vehicles are more efficient than the middle sized Category 2 trucks. However, Figure 7.23 clearly demonstrates that the specific energy consumption (energy consumption relative to vehicle weight) is reduced with increasing vehicle weight.

Here it should be noted that Figures 7.22 and 7.23 show energy versus vehicle test weight, not carried load.

Within Category 1 vehicles (vans) petrol and CNG operation consumes some 10 – 15 % more energy than operation on diesel. The energy consumption of the electric van is only some 35 % relative to diesel.

With the diesel vehicles included in the test matrix it is not possible to make a statement regarding Euro V vs. Euro VI fuel efficiency. The baseline assumption is that fuel consumption remains unchanged when going from Euro V to Euro VI.

The tested hybrid truck was Euro VI certified, and its counterpart with conventional driveline was Euro V certified. In the case of this pair the hybrid version saved some 10 % fuel.

Within Category 2 vehicles, the CNG truck shows higher energy consumption than the other trucks, some 25 % higher than the diesel average. Operating the dual-fuel trucks in dual-fuel mode increases energy consumption some 4 – 8 % compared to diesel operation. The share of methane of total energy consumption was modest, approximately 30 % for both DDF vehicles (WHVC cycle, half load). The energy consumption of the ethanol truck corresponds to the diesel average.

The Euro VI certified Category 3 trucks were tested with several loads. Two trucks delivered almost identical energy efficiency, whereas the third truck, which was a pre-series or “incentive Euro VI” vehicle, displayed slightly higher energy consumption (Figures 7.32 and 7.33). Figure 7.33 accentuates how increasing weight decreases specific energy consumption. Relative load has a huge impact on energy consumption and CO_2 emissions per ton-kilometre (Figures 7.37 and 7.38, infinitely high with zero load). With full load energy consumption approaches 0.5 MJ/ton-kilometre and CO_2 emission 40 g/ton-kilometre. For a diesel van at 50 % load the values are some 4 MJ/ton-kilometre and 300 g CO_2/ton-kilometre.

Within Category 1 vehicles CNG delivers the lowest tailpipe CO_{2eqv} emissions, thanks to the favourable carbon/hydrogen ratio of methane. Within Category 2 vehicles, despite the higher energy consumption the CNG truck has a CO_{2eqv} emission rate that is equivalent to the other vehicles.

The two DDF vehicles, of the same brand and using identical technology but with different power ratings, performed differently. The heavier vehicle was better both with respect to methane and NO_x emissions. The lighter vehicle had high methane emissions, some 7 g/km, adding some 25 % to the CO_{2eqv} value (Figure 7.30).

As can be expected, the variations in NO_x and PM emissions are significant. For NO_x, the stoichiometric vehicle (bi-fuel petrol and CNG van), the stoichiometric CNG truck (Euro VI) and most of the Euro VI diesels deliver very low NO_x emissions, basically independent of vehicle weight.

In the case of Euro VI diesel vehicles, the lightest (test weight 5 600 kg) and the heaviest (test weight 40 525 kg) vehicle delivered higher absolute NO_x emissions than the other vehicles, some 0.5 g/km for both vehicles. The lighter one is a hybrid vehicle equipped with a SCR system. Temperature control of the SCR is more challenging with hybrid powertrains than with conventional powertrains.

The lighter DDF vehicle produces the highest NO_x emissions, some 5 g/km in both diesel and DDF mode.

In the case of particulates, the old Euro III diesel truck produced the highest emissions, some 0.07 g/km. The heavier DDF truck in DDF operation has the second highest particulate emissions. For both DDF trucks, DDF operation increases PM emissions some 40 % compared to diesel operation only. The explanation for this is not the fuel itself, as methane should decrease particulate emissions. The reason is that the simple DDF control works on top on the OEM control system without real communication between them, leading to a situation in which the engine actually operates in a different load point than what the original ECU perceives, and therefore, there is a mismatch in control parameters.

All van-type vehicles delivered very low PM emissions (spark-ignition and diesels equipped with particulate filters). Also the CNG and ethanol trucks delivered low PM emissions (without particulate filters). For NO_x, all Euro VI vehicles delivered NO_x levels of some 0.5 g/km or below. For PM, the spread was significantly higher, with values in the range of 0.001 to 0.02 g/km.

7.7 Sweden

7.7.1 General

Sweden provided test results for two Euro V certified Category 2 trucks, one diesel truck and one ethanol truck. Test weights were 9 732 kg (diesel) and 12 670 kg (ethanol). The diesel truck was tested on a number of drop-in type diesel fuels (see Chapter 7.10).

AVL MTC carried out the measurements with both cold and hot start, and reported results for cold start, hot start and also aggregated results. However, only results for hot starts are presented here. The diesel truck was tested with two loads (50 and 100 %) on baseline diesel fuel.

In addition to regulated emissions, ALV MTC also measured unregulated emission components (NO_2, aldehydes, unburned ethanol, PAH components, particulate numbers). The results for unregulated emissions will be presented in Chapter 7.10 on fuel effects.

7.7.2 Results

Figures 7.39 (energy consumption and CO_2 emissions) and 7.40 (regulated emissions) present data for the diesel truck on baseline fuel and for the ethanol truck.

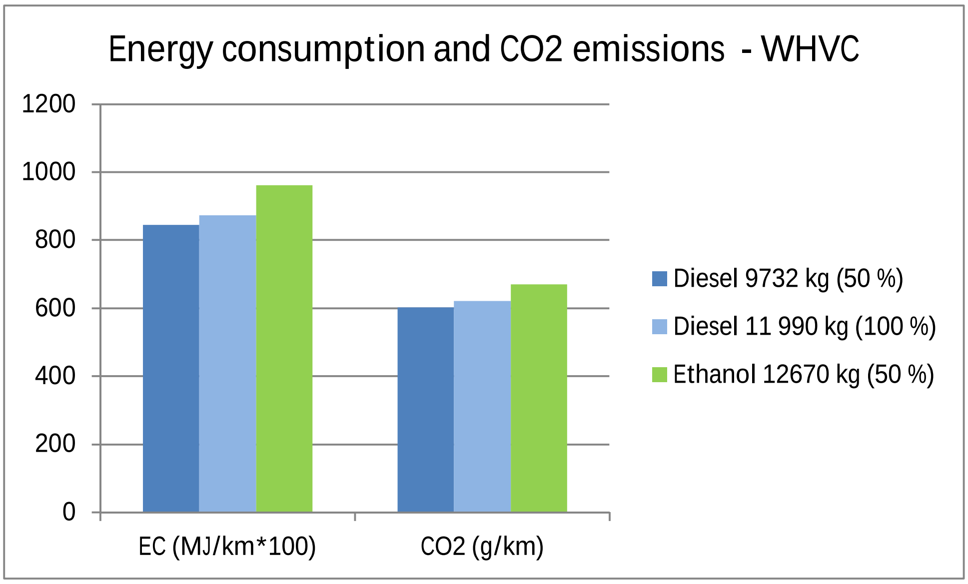

Figure 7.39. Energy consumption and CO_2 emissions. Euro V certified Category 2 trucks.

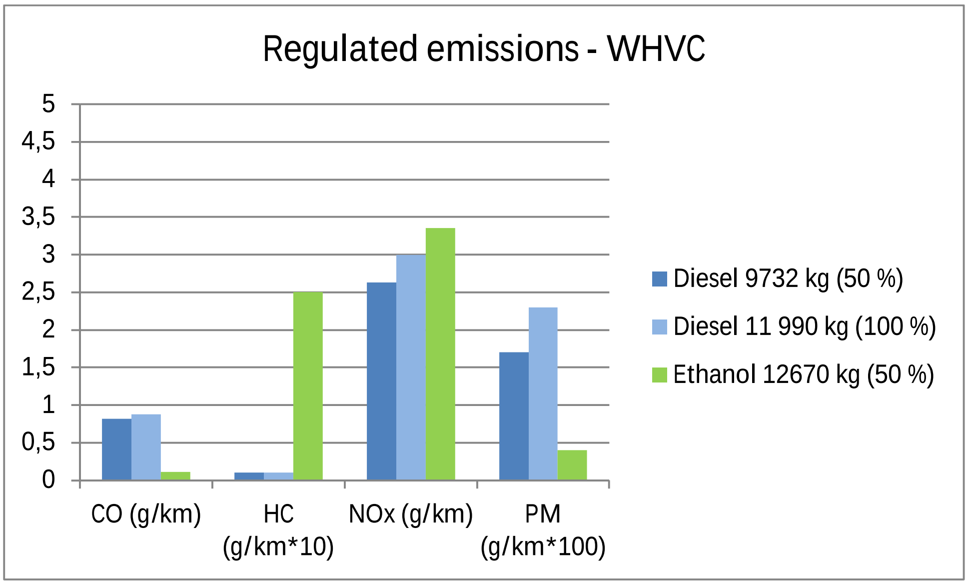

Figure 7.40. Regulated emissions. Euro V certified Category 2 trucks.

7.7.3 Discussion

Diesel and ethanol deliver roughly equivalent performance regarding tailpipe CO_2 emissions and energy consumption. However, regarding regulated emissions there are differences for these Euro V certified vehicles. In comparison with diesel, ethanol reduces CO and PM emissions quite substantially but, on the other hand, increases HC emissions significantly and NOx emissions marginally. Most of the HC emissions registered by the flame ionization detector (FID) type HC instrument are in fact unburned ethanol and aldehydes, not really hydrocarbons.

7.8 Thailand

7.8.1 General

Thailand provided vehicle as well as engine dynamometer results. PTT tested two Category 1 vehicles (pick-ups) in a chassis dynamometer, one diesel vehicle and one bi-fuel petrol-CNG vehicle, both of the same vehicle platform. Both vehicles were Euro 4 certified. Test weight for both vehicles was 2 075 kg (curb weight 1 580 kg for the diesel vehicle and 1 590 kg for the bi-fuel vehicle).

Both vehicles were tested with several fuels (see Chapter 7.10).

7.8.2 Results

Figures 7.41 (energy consumption and CO_2 emissions) and 7.42 (regulated emissions) present data for the diesel pick-up on baseline diesel fuel and for the bi-fuel pick-up on baseline petrol and CNG.

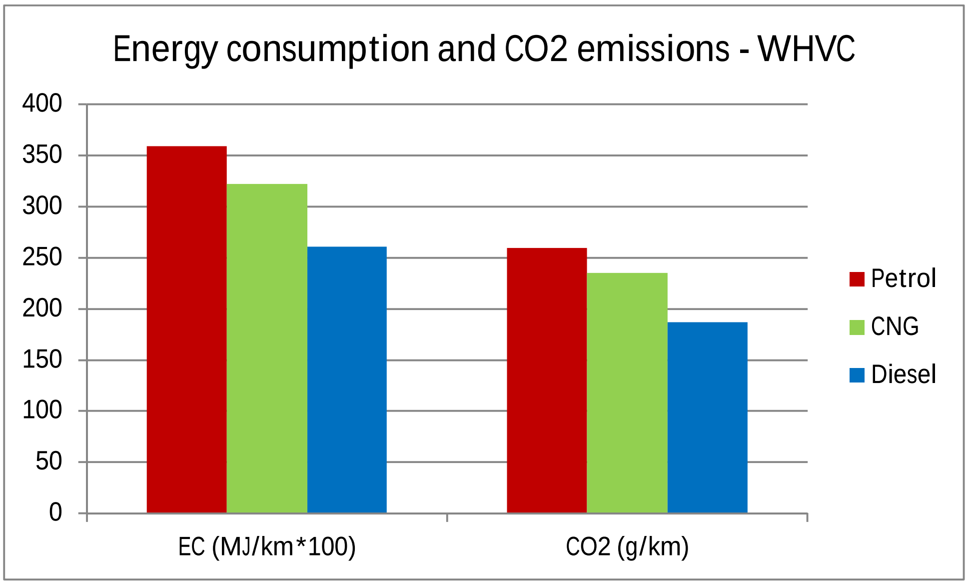

Figure 7.41. Energy consumption and CO_2 emissions. Euro 4 certified Category 1 pick-ups. CH_4 is taken into account for CNG (CO_{2eqv}).

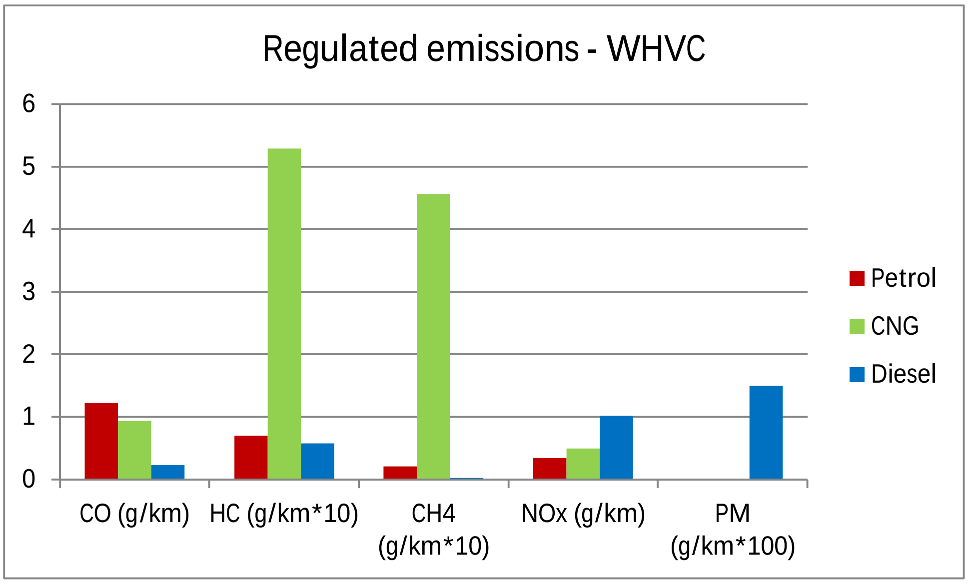

Figure 7.42. Regulated emissions. Euro 4 certified Category 1 pick-ups. PM emissions were not measured for the bi-fuel vehicle.

7.8.3 Discussion

Compared to the Euro V vans measured at VTT, the Thai Euro 4 vehicles show higher fuel consumption and CO_2 emissions. Taking into account the differences in test mass, the Thai values are some 25 % higher.

In contrast to the Canadian and Finnish results, in PTT's measurements CNG delivers lower energy consumption than petrol (approximately 10 % lower). Despite this, CNG only delivers a reduction of some 15 % in tailpipe CO_2 emissions (not taking into account CH_4). In the case of Canada and Finland, CNG delivers, with roughly equivalent energy consumption, a reduction of some 20 % in tailpipe CO_2 emissions. This could be partly explained by differences in gas quality.

The NO_x level of the Thai vehicle is roughly at the same level as of the Euro 5 vans measured by VTT. The bi-fuel vehicle, on the other hand, shows higher NO_x values than the European bi-fuel vehicle.

The Thai diesel vehicle has PM emissions more than an order of magnitude higher than its European counterparts. The ratio of PM limit values between Euro 4 and Euro 5 is eight (0.04 vs. 0.005 g/km, N_1, Class II, reference mass 1305-1760 kg [6]).

7.9 Collated chassis dynamometer results

7.9.1 General

The common test protocol and the common test cycle, WHVC, make it possible to collate and compare results from the different partners. The idea here is not to carry out direct vehicle to vehicle comparisons, but rather to show trends on how vehicle size, emission certification class and fuel affect vehicle performance. The tested vehicles might differ from each other regarding, e.g., driveline configuration, superstructures, auxiliaries and tyres.

In the case of buses and IEA AMF Annex 37 the tested vehicles were far more homogeneous than in this case.

[6] https://www.dieselnet.com/standards/eu/ld.php

For heavy-duty vehicles, the emission limits are presented as grams of pollutants per kWh on the engine crankshaft. In the case of Euro VI engines, the test cycle is the World Harmonised Transient Cycle (WHTC). The World Harmonised Vehicle Cycle (WHVC) is the chassis dynamometer derivative of the WHTC.

For the WHVC, the amount of work accumulated on the rollers of the chassis dynamometer is first and foremost dependent on vehicle mass. In order to translate chassis dynamometer data to engine data and relate the performance to limit values, one has to estimate the losses of the powertrain as well as auxiliary losses.

Figure 7.43 shows an estimation of work accumulated on the engine crankshaft as a function of vehicle test mass. The powertrain and auxiliary losses have been estimated at a total fixed figure of 20 %. It is assumed that accumulated work is linearly proportional to test weight.

As the total driven distance for the WHVC is 20.0 km, the engine of a vehicle with a test weight of 40 000 kg (the highest test weight in the figure) accumulates some 43 kWh over the whole WHVC, or some 2.2 kWh/km. Using this value, it is then be possible to compare the emission performance to the emission limits of various emission classes.

Figure 7.44 shows an estimation of Euro III, IV, V and VI NO_x limit values expressed in the form of g/km plotted against vehicle test mass. The lines are plotted without any consideration of not-to-exceed (NTE) factors (see the IEA AMF Annex 37 report, Chapter 12.3.2). The Figure is indicative, and in addition it should be noted that older engines (Euro III, IV and V) have not originally been certified using the WHTC. As mentioned in 5.3, the Euro VI regulation stipulates measurements with both a cold and a warmed-up engine, and a system for calculation of aggregate emission values using weighting factors. Including the cold start mainly affects the NO_x emissions of SCR equipped diesel engines. All results presented here are for fully warmed-up engines.

Further on in the text, the term “reference value” is used when comparing performance in the WHVC to values derived from emission limit values (vehicles within heavy-duty certification schemes) or WHVC results to limit values for FTP or NEDC testing (vans and pick-ups).

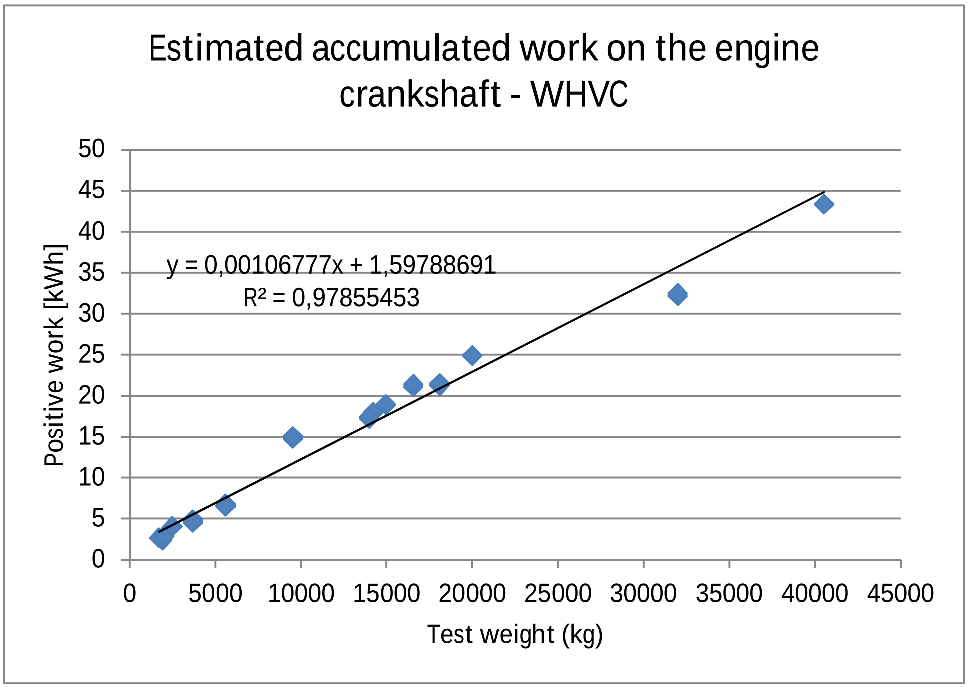

Figure 7.43. Estimated accumulated work on the engine crankshaft in the WHVC test cycle as a function of test mass. Powertrain and auxiliary losses estimated at a total of 20 %.

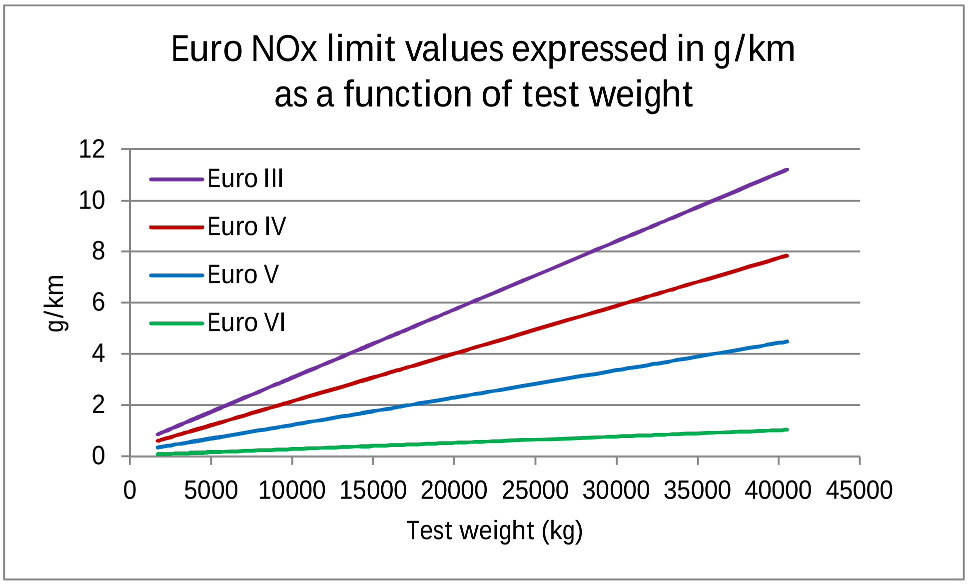

Figure 7.44. Euro III – VI NO_x limit values expressed in g/km as a function of test weight. No NTE-factors. The Figure should be considered indicative.

7.9.2 Collated results

The collated results are presented as follows:

- Figure 7.45: energy consumption by laboratory
- Figure 7.46: specific energy consumption by laboratory
- Figure 7.47: specific energy consumption by emission class (Category 2 & 3 diesel vehicles)
- Figure 7.48: energy consumption by fuel
- Figure 7.49: specific energy consumption by fuel
- Figure 7.50: CO_{2eqv} emission by fuel
- Figure 7.51: NO_x emissions by emission class
- Figure 7.52: NO_x emissions by fuel
- Figure 7.53: PM emissions by emission class
- Figure 7.54: PM emissions by fuel
- Figure 7.55: Specific NO_x and PM emissions (in g/kWh), average values for Euro III, IV, V and VI

"Blown-up" figures for Category 1 vehicles (vans and pick-ups):

- Figure 7.56: specific energy consumption by fuel
- Figure 7.57: NO_x emissions (North-American vehicles)
- Figure 7.58: NO_x emissions (Euro certified vehicles)
- Figure 7.59: PM emissions (Euro certified vehicles)

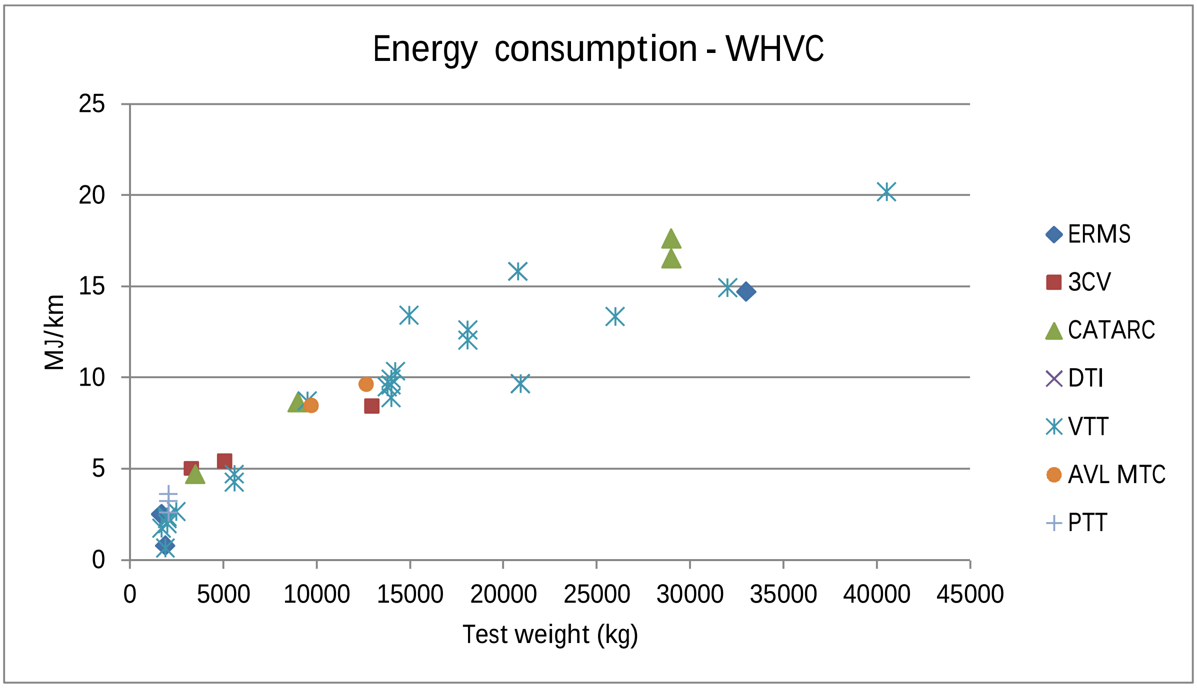

Figure 7.45. Energy consumption by laboratory.

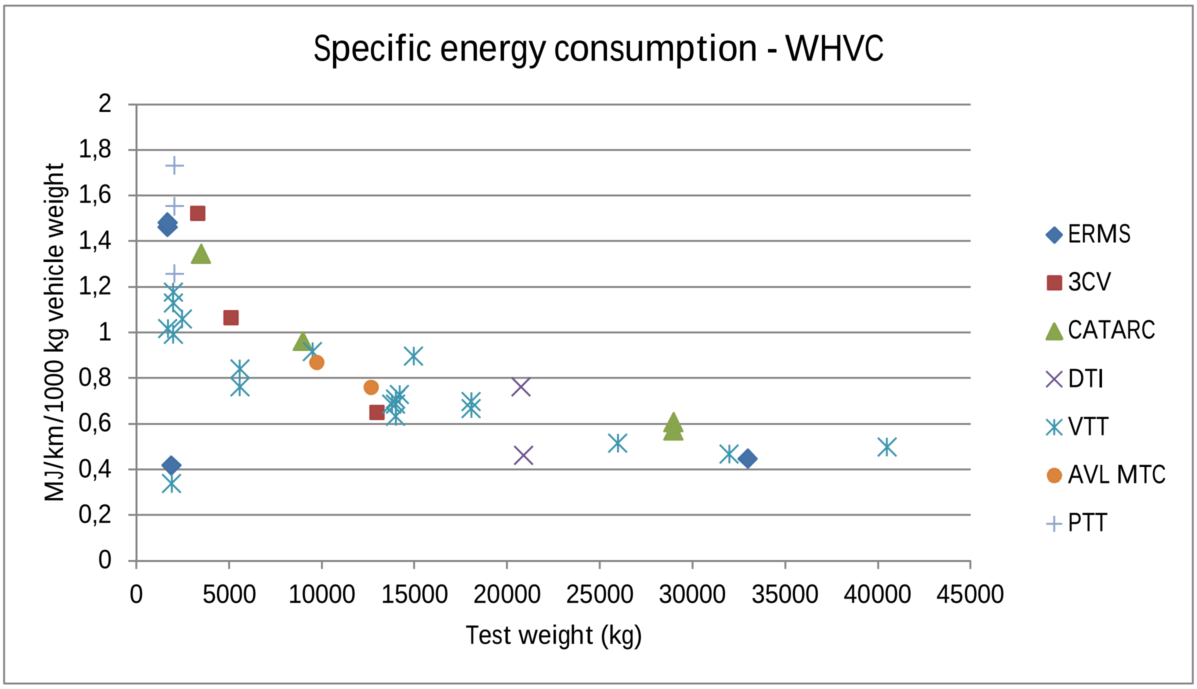

Figure 7.46. Specific energy consumption by laboratory.

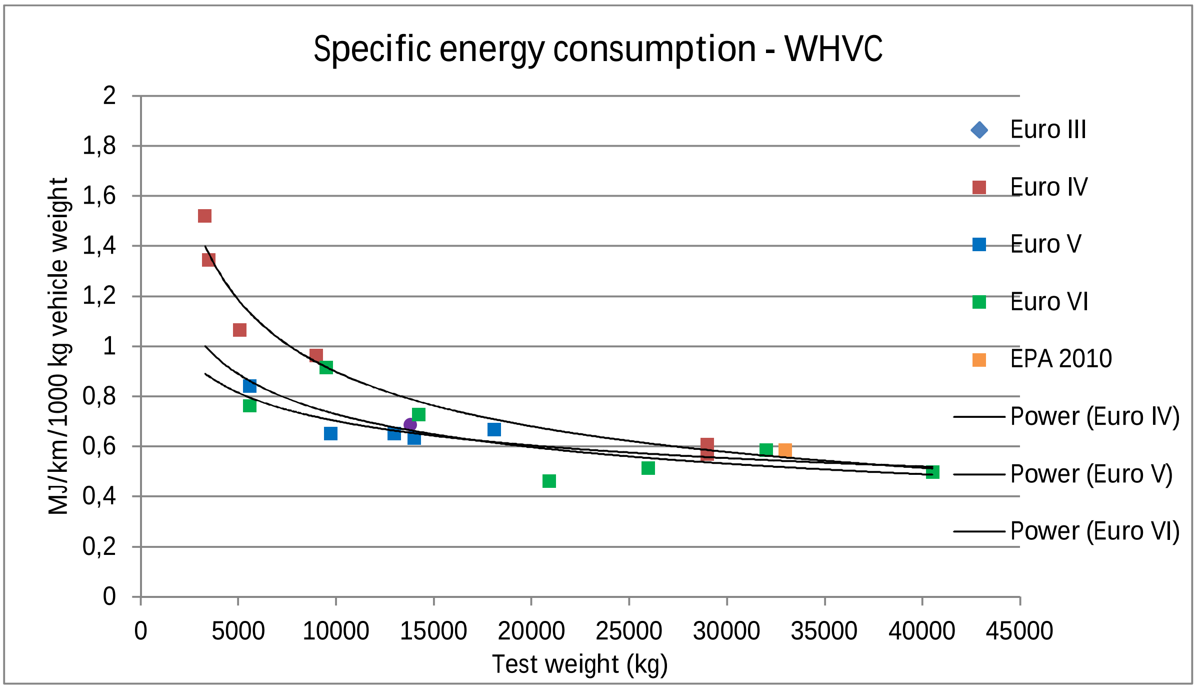

Figure 7.47. Specific energy consumption by emission class (Category 2 & 3 vehicles).

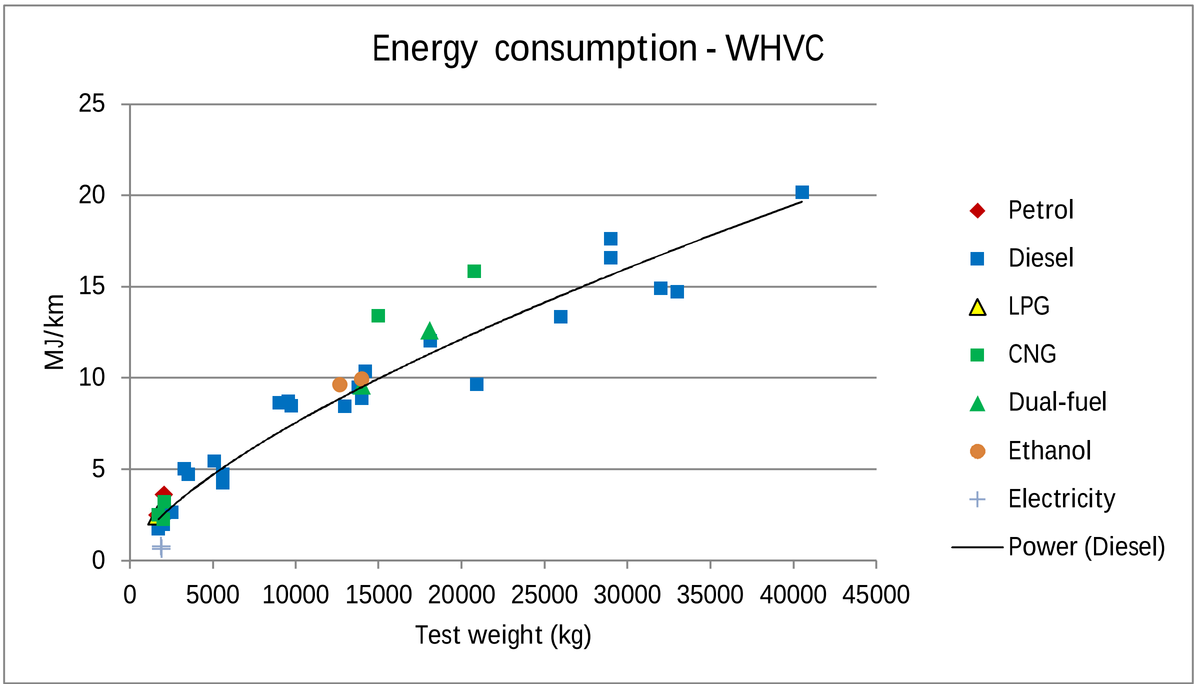

Figure 7.48. Energy consumption by fuel.

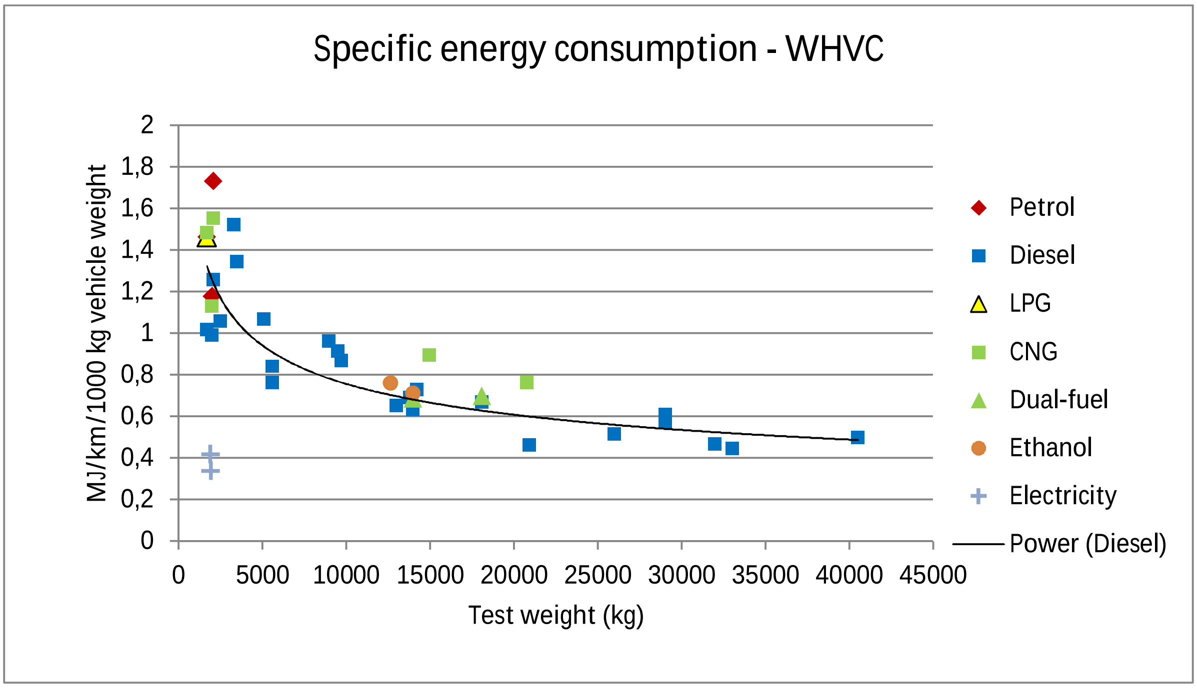

Figure 7.49. Specific energy consumption by fuel.

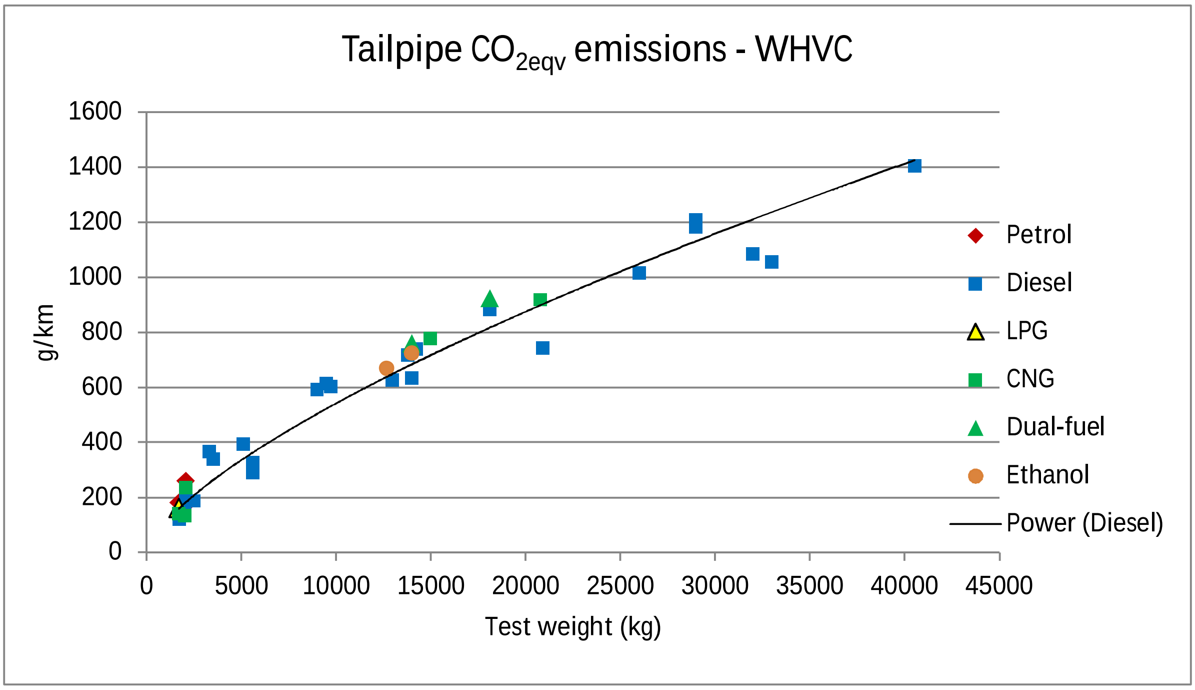

Figure 7.50. CO_{2eqv} emissions by fuel.

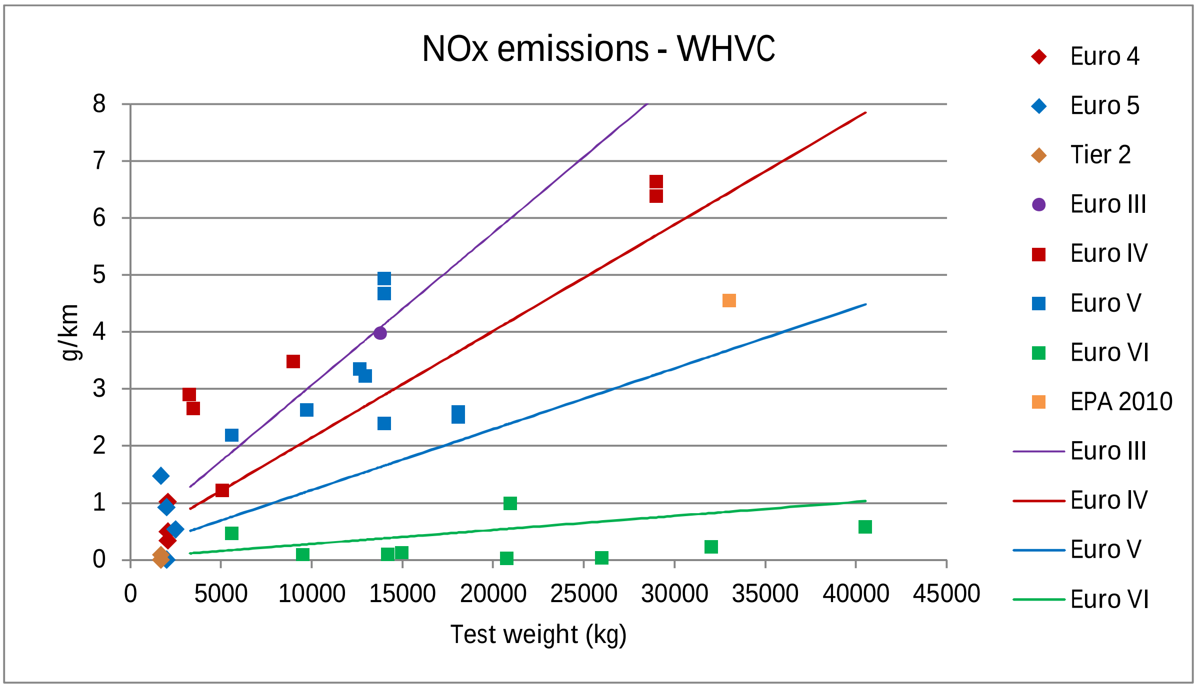

Figure 7.51. NO_x emissions by emission class.

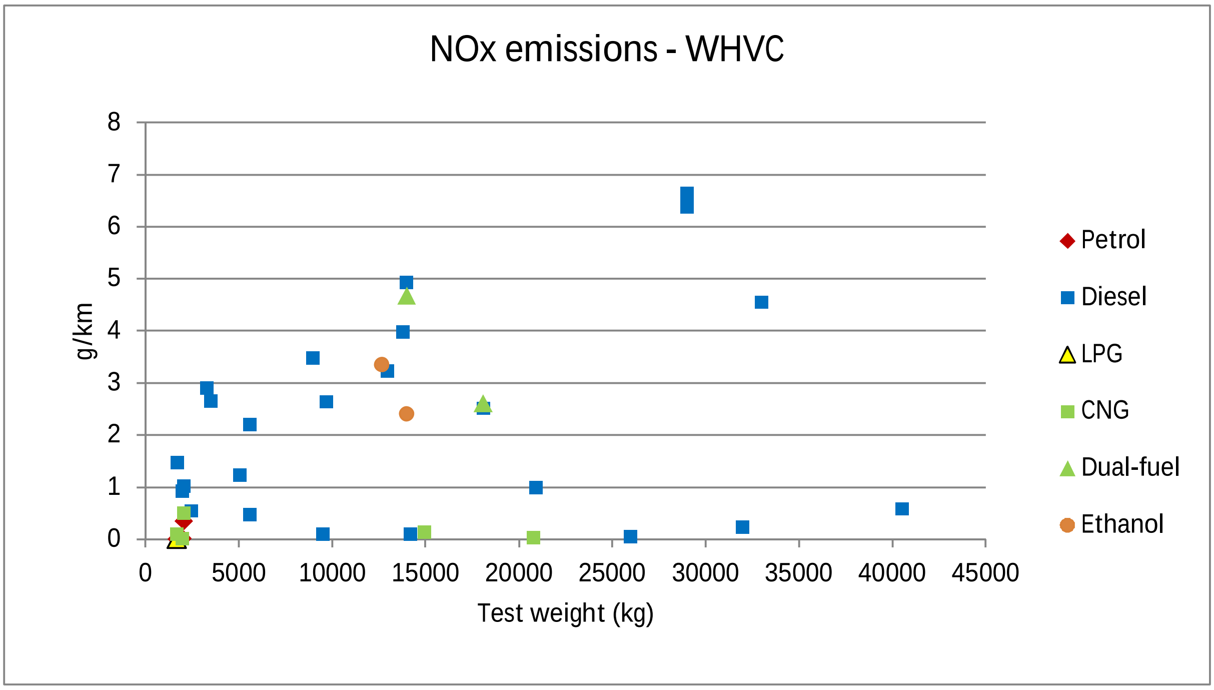

Figure 7.52. NO_x emissions by fuel.

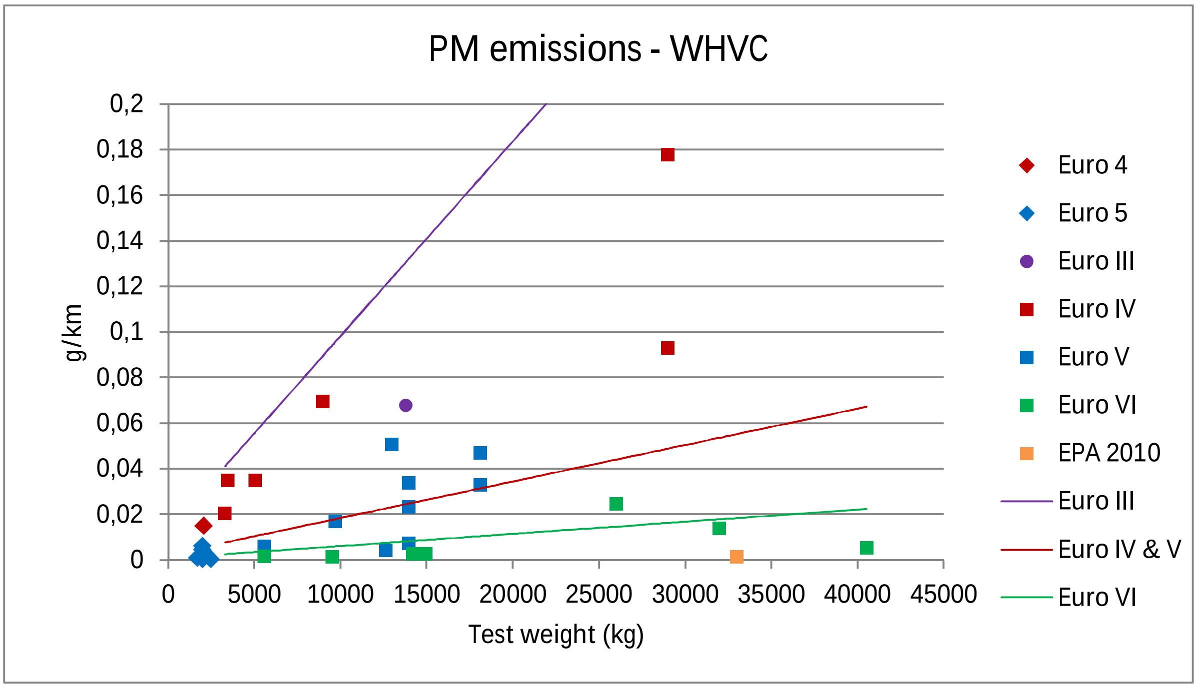

Figure 7.53. PM emissions by emission class.

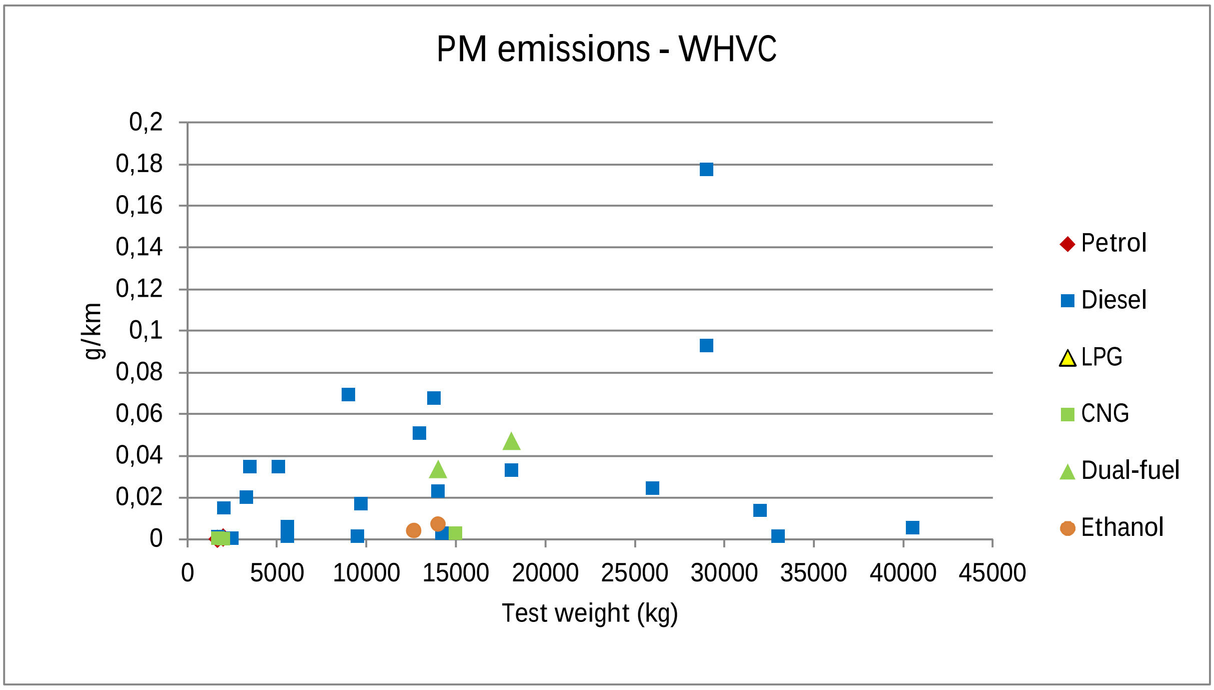

Figure 7.54. PM emissions by fuel.

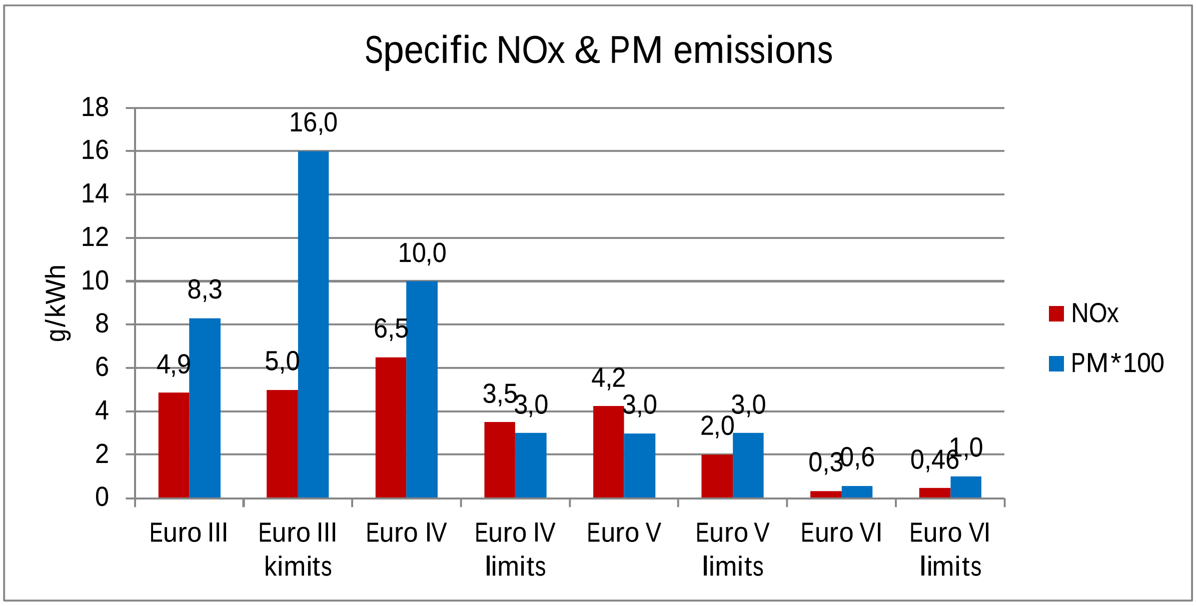

Figure 7.55. Specific NO_x and PM emissions in g/kWh. Emissions estimated relative to work on the engine crankshaft.

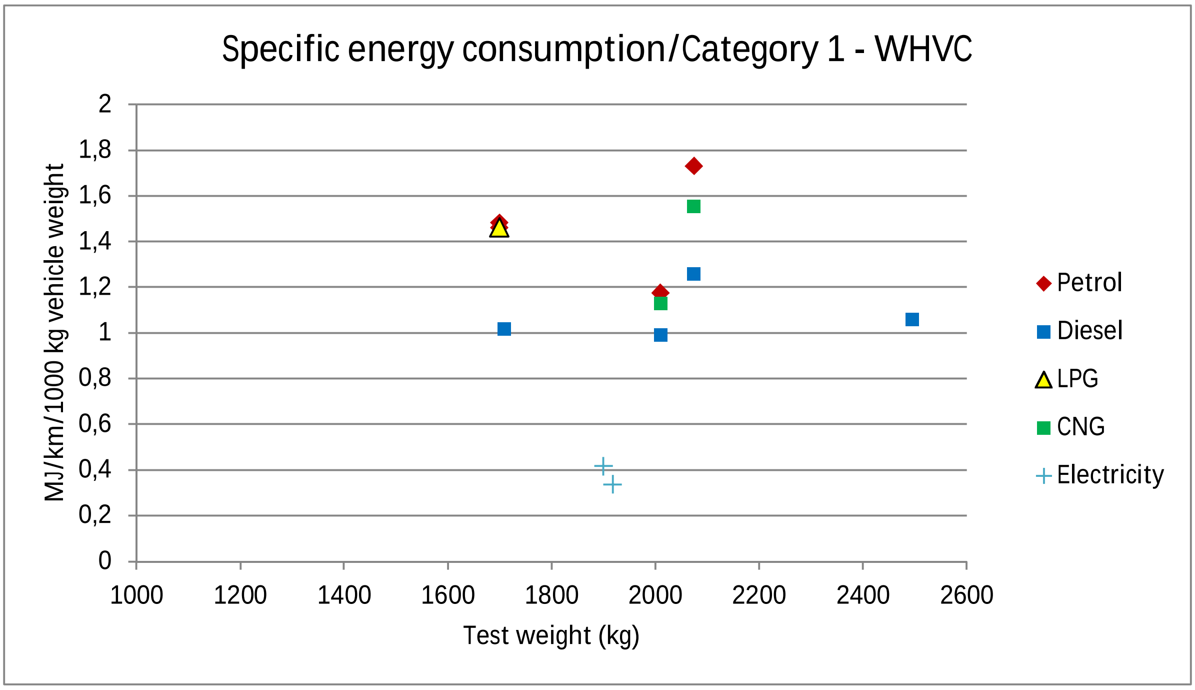

Figure 7.56. Specific energy consumption by fuel. Category 1 vehicles.

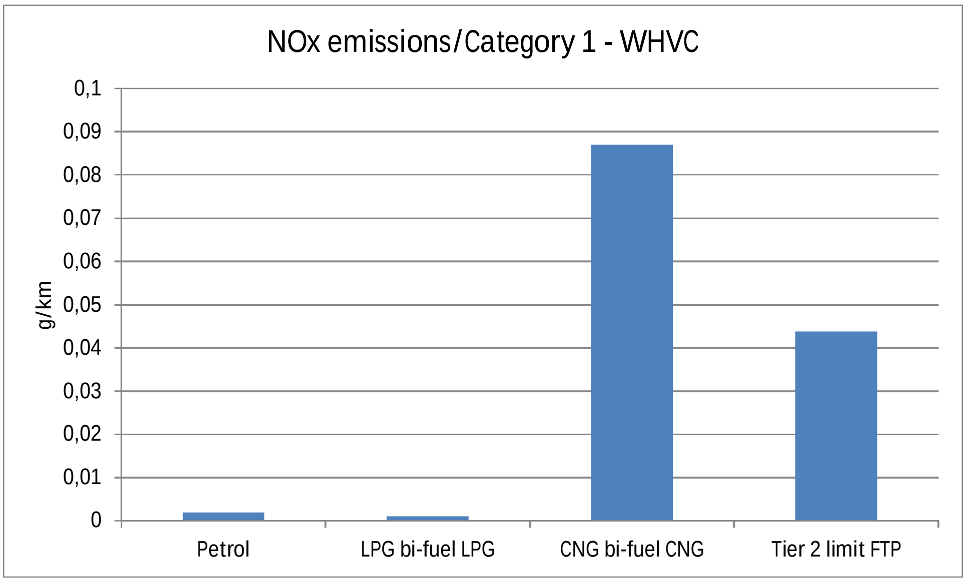

Figure 7.57. NO_x emissions. North-American Category 1 vehicles. The Tier 2 limit for FTP is shown as a reference.

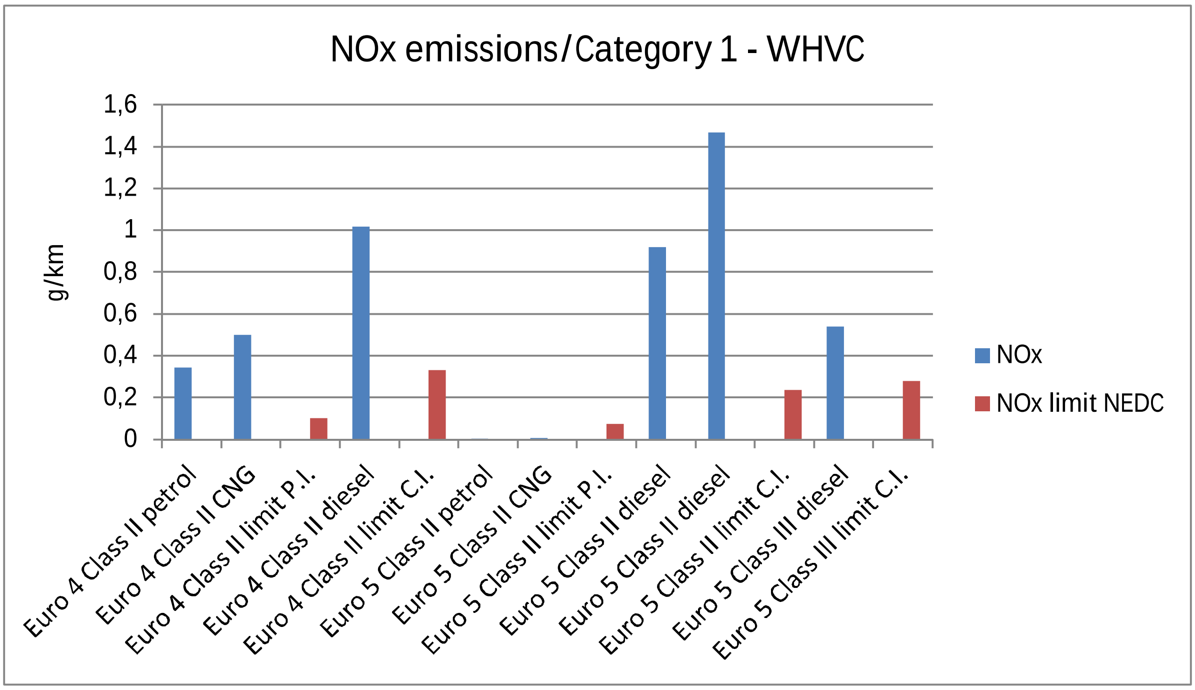

Figure 7.58. NO_x emissions. Euro certified Category 1 vehicles. The NEDC limit is shown as a reference.

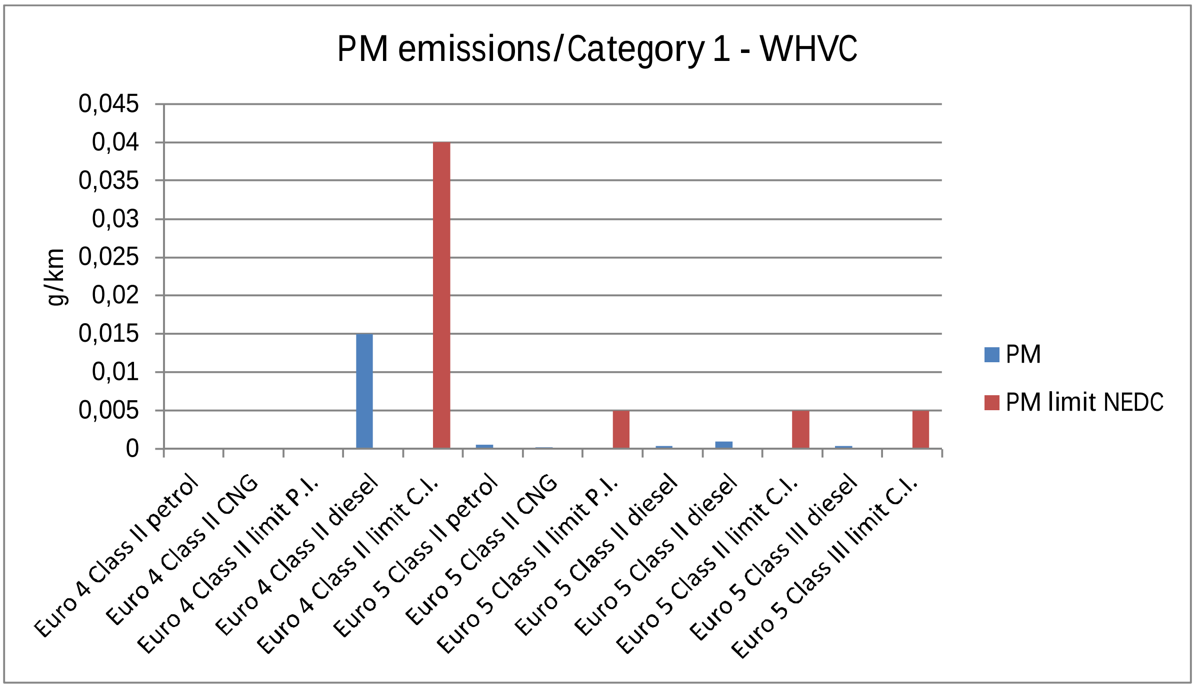

Figure 7.59. PM emissions. Euro certified Category 1 vehicles. The NEDC limit is shown as a reference.

7.9.3 Discussion

General

Overall, the energy consumption figures were quite logical and congruent. Relative to mass, larger vehicles are more energy efficient than smaller ones. The most important factor affecting energy consumption is vehicle mass. For diesel powered vehicles, energy consumption per km varied with a factor of 12 from the lightest to the heaviest vehicle tested. However, the type of engine (spark-ignited, diesel, electric) also has an impact on energy consumption. Spark-ignited engines are less efficient than compression ignited (diesel) engines. Thus spark-ignited gas vehicles have higher energy consumption than their diesel counterparts, independent of vehicle size. New vehicles (particularly Euro VI vehicles) are much cleaner than older ones, without showing a fuel consumption penalty compared to older vehicles.

Class 2 & 3 vehicles

Energy consumption

In the case of trucks, Euro V and VI diesel vehicles seem to be more fuel efficient than older Euro IV diesel vehicles. Figure 7.47 shows that fuel consumption doesn't increase going from Euro V to Euro VI.

For the WHVC, DTI reported 65 % higher energy consumption for a gas truck compared to a corresponding diesel truck. Both 3-axle trucks were of the same brand and were Euro VI certified. One explanation for this huge difference could be the exceptionally low energy consumption measured for the diesel truck (clearly lower than the diesel average, see Figure 7.45, two vehicles with a test weight of some 21 000 kg tested by DTI). It should be noted that the two trucks had different transmission systems. The diesel truck was equipped with an efficient automated mechanical gearbox including an electro-hydraulic controlled clutch compared, whereas the CNG truck was equipped with a conventional automatic gearbox with an integrated hydraulic torque converter.

VTT tested a similar pair of vehicles (same manufacturer as in the case of DTI, Euro VI certification, but in VTT's case two-axle vehicles). According to VTT's measurements, the gas vehicle consumed 23 % more energy than its diesel counterpart.

In VTT's measurements for IEA AMF Annex 37, gas buses consumed 32 – 39 % more energy than their diesel counterparts in the Braunschweig cycle. The Braunschweig cycle is more challenging than the WHVC and accentuates differences between spark-ignition and diesel operation. For COMVEC, CATARC provided data for four diesel trucks and in addition for three gas buses. Average specific energy consumption of the three gas buses tested with 16 000 kg was 0.88 MJ/km/1000 kg vehicle weight. Average value for diesel vehicles at 16 000 kg is 0.65 MJ/km/1000 kg vehicle weight, meaning that the Chinese gas buses on an average consume 35 % more energy in the WHVC than diesel vehicles.

Electric vehicles, on the other hand, are much more efficient than vehicles with internal combustion engines. The energy consumption of EVs is some 30 - 40 % of that of ICE equipped vehicles.

Compression ignited ethanol and diesel dual fuel vehicles deliver energy efficiency that is equivalent to diesel.

Tailpipe CO_2 emissions

As can be seen in Figure 7.50, variations in tailpipe CO_2 emissions are rather small. Electric vehicles are naturally an exception, as they emit no local emissions. The values for the ethanol fuelled vehicles are almost identical to average diesel values. In the case of methane fuelled vehicles, favourable fuel chemistry partly compensates for the lower engine efficiency and, on an average, tailpipe CO_2 emissions of CNG vehicles are close to those of diesel vehicles.

NO_x emissions

Really huge differences can be found for both NO_x and PM emissions. In the case of NO_x, specific emission rates varied from less than 0.001 to 0.9 g/km/1000 kg vehicle weight, for PM the range is 0.001 to 0.13 g/km/1000 kg vehicle weight.

Seven out of nine Euro VI certified heavy-duty vehicles delivered NO_x emissions below the expected Euro VI reference level. The two remaining vehicles had a NO_x level that was roughly 2 – 2.5 higher than the expected Euro VI limit. The highest relative value, estimated at some 1.2 g/kWh on the engine crankshaft, was for a hybrid vehicle. As stated previously, no not-to-exceed factors were applied but, on the other hand, **the measured data is for fully warmed-up engines.**

Figure 7.51 shows that all Euro IV and Euro V vehicles had higher NO_x emissions than should be expected. Some Euro IV and Euro V vehicles even had NO_x emissions above the Euro III level. The only Euro III vehicle that was measured delivered true Euro III performance. Only one North-American EPA 2010 heavy-duty truck was measured. The NO_x emission of this vehicle corresponded to Euro V level.

The conclusion that can be drawn from Figure 7.50 is that in the case of diesel vehicles, going from Euro III to Euro IV or Euro V doesn't necessarily bring about reductions in NO_x emissions. Only Euro VI vehicles deliver truly low NO_x emissions.

Figure 7.52 shows NO_x emissions by fuel. The conclusions drawn from this Figure are:

- Huge spread for diesel vehicles
- Very low emissions for spark-ignited CNG
- Diesel dual-fuel and ethanol delivered average NO_x emissions
- Emission class is more decisive than fuel

Particle emissions

Regarding particle emissions, the overall situation is somewhat more positive than in the case of NO_x. All vehicles delivered particle emissions lower than the Euro III level. The Euro IV vehicles had PM emissions in between Euro III and the combined Euro IV/V level. On an average, the Euro V certified diesel vehicles had PM emissions close to the Euro V level. Six out of seven Euro VI certified vehicles delivered PM emissions below the Euro VI level. DTI didn't measure particle mass emissions, therefore two results less than in the case of NO_x. The EPA 2010 certified North-American truck delivered extremely low PM emissions.

Fuel affects PM emissions. Spark-ignited natural gas delivers very low PM emissions. The two ethanol trucks tested, although Euro V certified and without a particulate filter, delivered Euro VI level particle emissions. As noted in 7.6, for both diesel dual-fuel trucks tested by VTT dual-fuel operation increased particle emissions. This phenomenon can be related to an unsophisticated DDF control system, not the fuel itself.

Summary of NO_x and PM emissions

Figure 7.55 presents average NO_x and PM emissions for Euro III, IV, V and VI relative to work on the engine crankshaft. The only Euro III truck measured delivered NO_x at just below the reference value and PM emissions at some 50 % of the reference value. On an average, the Euro IV trucks measured had a NO_x emission rate roughly two times higher than the reference value and a PM emissions three times higher than the reference value. The average emissions of the Euro IV vehicles were higher than for the old Euro III truck. As stated above for Euro V, the outcome is slightly better. Average NO_x emission rate is still twice the reference values, but average PM emissions, on the other hand, equals the PM reference value. The average NO_x and PM values of the Euro VI certified trucks were, on an average, some 60 - 70 % of the reference values.

Class 1 vehicles

General

The test matrix included four vehicle platforms with multiple fuel options:

- ERMS of Canada tested petrol, LPG, CNG and electricity in the same vehicle platform
- VTT and PTT both tested one vehicle platform each with petrol, CNG and diesel
- In addition, VTT tested one platform with diesel and electricity

Energy consumption

For energy consumption (Figure 7.56) the following observations can be made:

- The energy consumption of electric vehicles is some 30 – 40 % of that of ICE equipped vehicles
- The measurements by ERMS showed equivalent energy consumption for petrol, LPG and CNG
- The measurements by VTT and PTT showed a small efficiency benefit for CNG in comparison with petrol
- Diesel is the most efficient option within ICE vehicles (15 – 30 % lower energy consumption compared to petrol)
- The vehicles for the European market seem to be more energy efficient than the vehicles for the Canadian and the Thai markets

NO_x and PM emissions

In this case, the emission results obtained using the WHVC cycle are compared against Tier 2 (FTP test cycle) and Euro (NEDC test cycle) limit values, which are used as reference cycles. One cannot draw direct conclusions regarding compliance from this comparison. Nevertheless, this gives some reference for the emission levels.

In general, spark-ignited engines deliver very low NO_x and PM emissions. However, the Canadian measurements showed elevated NO_x emissions for CNG operation in a bi-fuel vehicle, roughly two times higher than the Tier 2 limit value.

Thailand uses Euro emission regulations. The pick-ups tested by PTT had Euro 4 certification. Both the spark-ignited bi-fuel pick-up and the diesel pick-up had NO_x emissions surpassing the Euro 4 level. However, the PM emission of the diesel vehicle was rather low, well below the Euro 4 reference level.

In the case of the Euro 5 certified vehicles for the European market, the outcome is divided. The one spark-ignited vehicle tested on both petrol and CNG delivers NO_x values well below the reference value. However, all tested diesel vehicles (three vehicle platforms) have NO_x emissions well above the reference level (six times higher in the worst case). However, the PM emissions of all measured Euro 5 vehicles were well below the reference value.

8. Effects of substitute fuels

8.1 General

Some of the laboratories tested fuels that can replace conventional diesel in existing vehicles and engines.

VTT (Finland) tested one premium diesel fuel quality diesel and 100 % HVO in one van and in one Euro V certified truck. NTSEL (Japan) tested two alternative diesel fuels in a medium-duty truck engine corresponding to the Japanese 2009 emission regulation. AVL MTC (Sweden) tested four alternative diesel fuels in a Euro V certified truck. Also PTT (Thailand) tested four alternative diesel fuels, in a Euro 4 certified pick-up and in a Euro III certified heavy-duty engine. For the engine measurements, both PTT and NTSEL used the WHTC. The WHVC vehicle cycle is derived from the WHTC.

8.2 Finland

VTT tested premium quality diesel fuel, Category 5 according to the World Wide Fuel Charter[7] and 100 % HVO corresponding to the draft European standard FprEN 15940[8] for paraffinic diesel fuel. The fuels are described as follows:

- Category 5 diesel fuel: Markets with highly advanced requirements for emission control and fuel efficiency. Enables sophisticated NO_x and PM after-treatment technologies.
- Paraffinic diesel fuel: Paraffinic diesel is a high quality, clean burning fuel with virtually no sulphur and aromatics. Paraffinic diesel fuel can be used in diesel engines, also to reduce regulated emissions. In order to have the greatest possible emissions reduction, a specific calibration may be necessary. Paraffinic diesel fuel can also offer a meaningful contribution to the target of increased non-petroleum and/or renewable content in transportation fuel pool.

Figure 8.1 shows fuel effects on regulated emissions for a Euro 5 certified Category 1 van and Figure 8.2 results for a Euro V certified Category 2 truck.

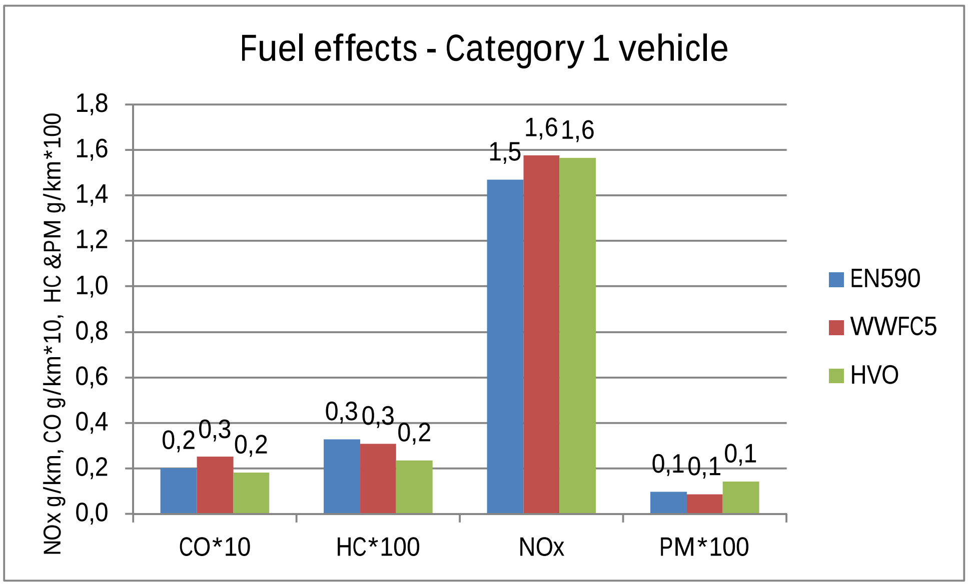

Figure 8.1. Fuel effects on regulated emissions of a Euro 5 certified Category 1 van.

[7] https://www.acea.be/uploads/publications/Worldwide_Fuel_Charter_5ed_2013.pdf
[8] http://www.din.de/en/getting-involved/standards-committees/nmp/projects/wdc-proj:din21:141491694

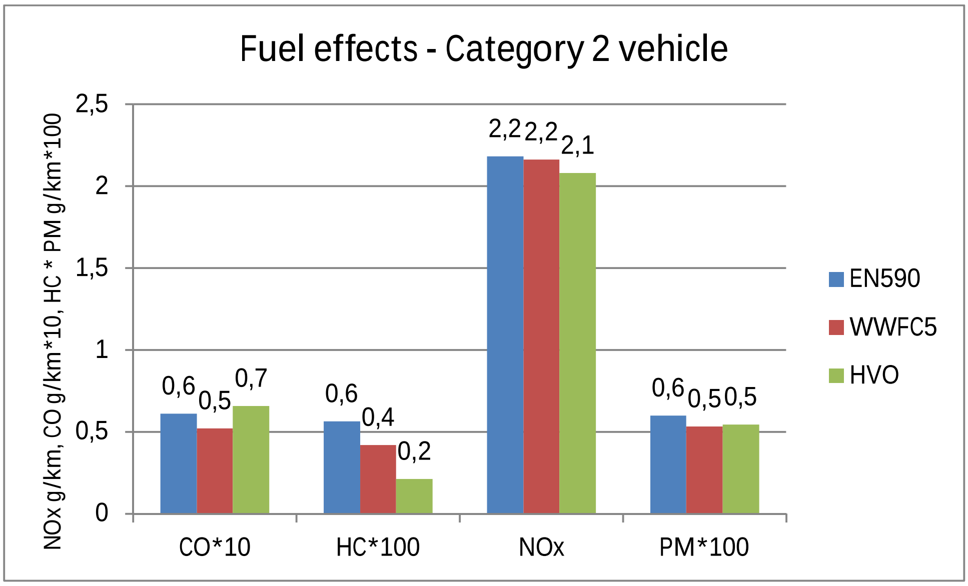

Figure 8.2. Fuel effects on regulated emissions of a Euro V certified Category 2 truck.

In the case of the Euro 5 certified van, the fuel effects on regulated emissions were marginal, and no clear trends could be seen. The vehicle is equipped with a wall-fuel particulate filter, which effectively reduces particulate mass emissions.

The Euro V certified truck shows emission trends for 100 % paraffinic fuel, that is significantly reduced HC emissions (more than 50 %) and slightly reduced NO_x (-5 %) and PM (-10 %) emissions.

8.3 Japan

NTSEL tested ultra-low sulphur diesel, 100 % conventional biodiesel (FAME) and 100 % HVO in a 3 litre medium-heavy duty diesel engine. The engine, with extremely low particulate emissions, was equipped with a diesel oxidation catalyst (DOC) and a wall-flow particulate filter (DPF). Gaseous emission components were sampled both before and after the exhaust after-treatment system. Particulate emissions were sampled after the DPF.

Results for regulated emissions are presented in Figure 8.3.

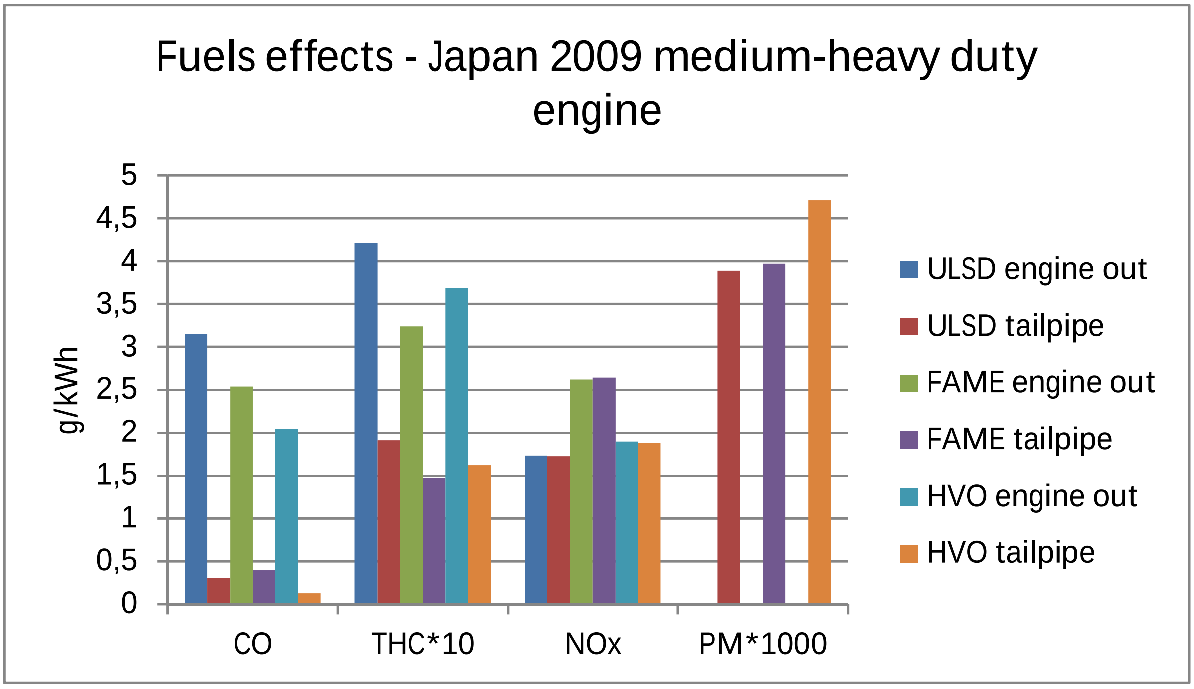

Figure 8.3. Fuel effects on regulated emissions of a Japan 2009 certified medium heavy-duty truck engine.

Both alternative fuels reduced engine out CO and THC emissions somewhat. 100 % FAME increased NO_x emissions as much as 30 %. In this engine, 100 % HVO increased NO_x emissions some 10 % and PM emissions some 20 %. It should be noted that the absolute PM emission level of this engine is low, below 0.005 g/kWh.

8.4 Sweden

AVL MTC tested the following diesel fuels:

- Diesel fuel with 7 % FAME (B7) corresponding to the European diesel fuel standard EN590
- B7 with an addition of 30 % HVO (B7+HVO30)
- 100 % HVO (HVO100)
- Synthetic diesel (GTL)
- 100 % FAME (B100)

The B7+HVO30, HVO100 and the synthetic diesel were so-called drop-in fuels, i.e. fuels that can be used in existing engines. The B100 can be used in existing vehicles with some adjustments. The diesel fuels were tested in a Euro V certified truck without particulate filter. In addition, AVL MTC tested ED95 ethanol fuel in a dedicated vehicle, as reported in Chapter 7.

In addition to regulated emissions and CO_2, AVL MTC also measured some unregulated components:

- Aldehydes: sampled in DNPH-cartridges;
- Ethanol emissions: sampled with FTIR during the tests with the ED95 fuel;
- Particle number: Condensed Particle Counter (CPC);
- Particle size distribution: Electrical Low Pressure Impactor (ELPI);
- Particles: PAH (Polycyclic Aromatic Hydrocarbons) content.

Table 8.1 and Figure 8.4 present results for regulated emissions. The results are for fully warmed-up engines, as the rest of the COMVEC results presented.

Table 8.1. Emission test results in g/km, averaged results from two hot start tests.

		B7 100% load	B7 50% load	B7 + HVO30	HVO100	GTL	B100	ED95
CO	g/km	0,88	0,82	0,80	0,77	0,88	0,66	0,11
HC	g/km	0,01	0,01	0,00	0,00	0,00	0,01	0,25
NOx	g/km	3,00	2,63	2,29	2,51	2,84	3,16	3,35
PM	g/km	0,023	0,017	0,018	0,012	0,018	0,007	0,004

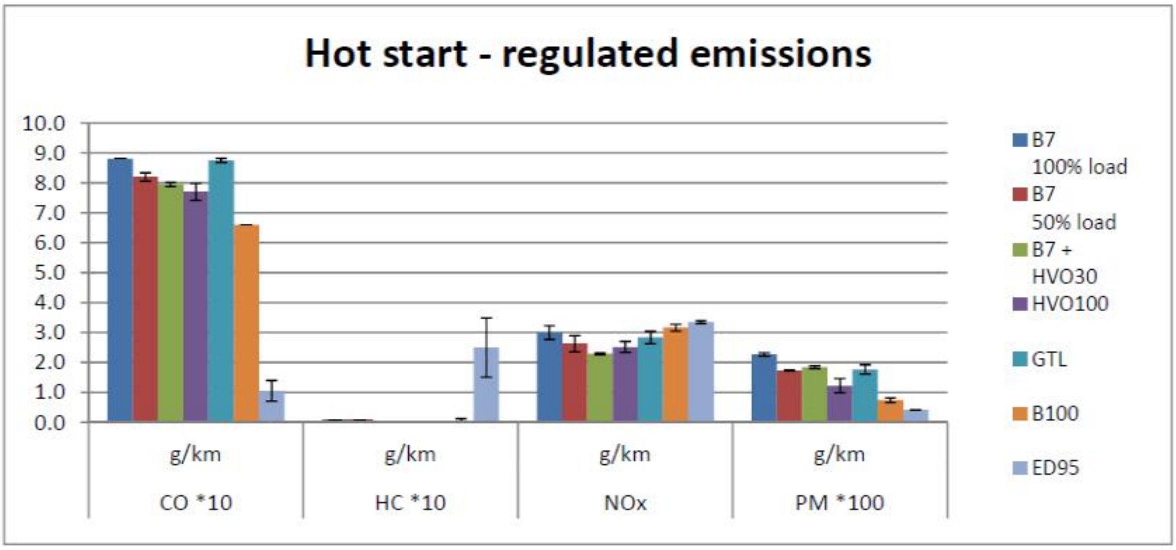

Figure 8.4. Regulated emissions from hot start tests, averaged from two tests.

The PM emissions from B100 are lower compared to the other fuels (with the exception of ED95). This can be explained by the increased amount of oxygen in the fuel, which can lead to more complete combustion and thereby reduce the PM emissions. This explanation could probably also be applicable for the low PM emissions for the ED95 fuel.

The higher NO_x emissions for B100 and ED95 can also be explained by the oxygen content in the fuel. A more complete combustion, in combination with the oxygen present, can lead to higher exhaust emissions of NO_x. For B100, it can also be of relevance that no adaptation had been performed on the fuel system, such as injection timing and fuel pressure adjustments, prior to the tests.

NO_x emissions are at minimum with the B7+HVO30 blend. For the fuels with low or no oxygen content HVO100 delivers lowest PM emissions.

The presumption is that the paraffinic fuels, HVO100 and GTL would deliver more or less identical emission performance. In this case GTL increased both NO_x and PM emissions slightly compared to B7 (some 5 %), whereas HVO100 reduced NO_x emissions slightly (5 %) and PM emissions significantly (30 %).

Figure 8.5 presents results for form- and acetaldehyde, the dominating components for aldehydes. The HVO100 fuel seems to generate lower emissions of formaldehyde. The standard deviation is however large, so this difference cannot be considered as significant. Alcohol fuel produced high aldehyde emissions compared to diesel operation For the ED95 fuel, hot start formaldehyde emission is some 20 mg/km and acetaldehyde emission some 200 mg/km.

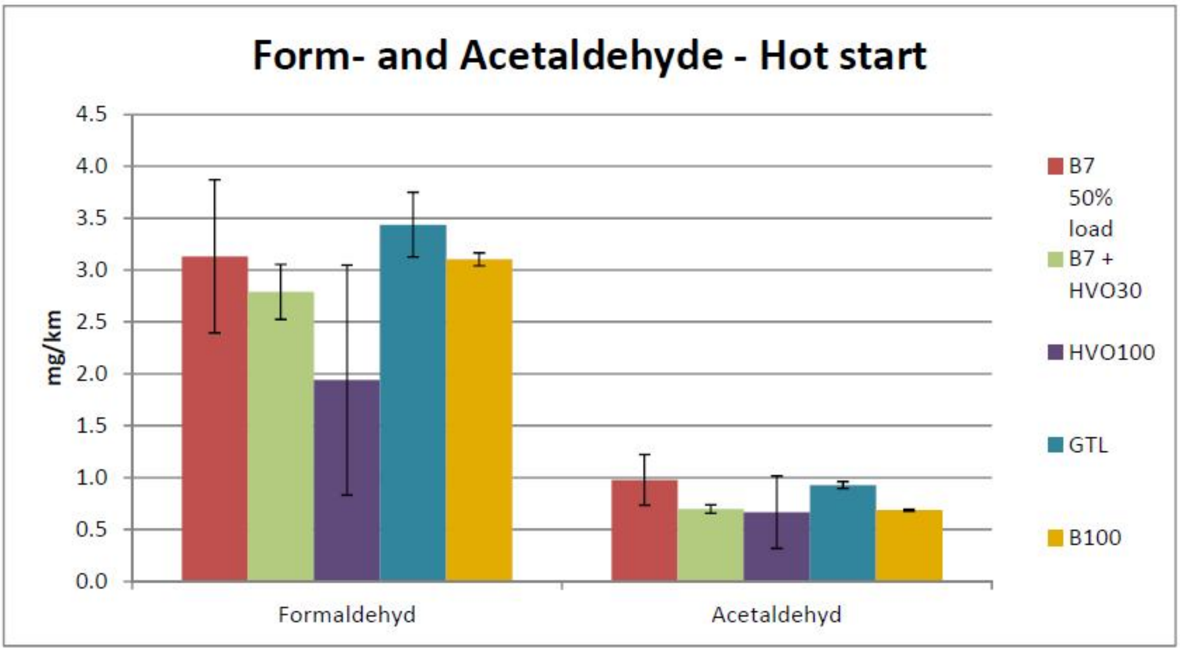

Figure 8.5 Formaldehyde and acetaldehyde emissions, diesel fuels, averaged results from hot start tests.

Figure 8.6 presents particle number emissions for the various fuels. There is little variation between fuels with low or no oxygen contents, whereas the oxygen rich fuels (B100 and ED95) deliver lower particle number emissions. Neither test vehicle (diesel, ED95) was equipped with a particulate filter.

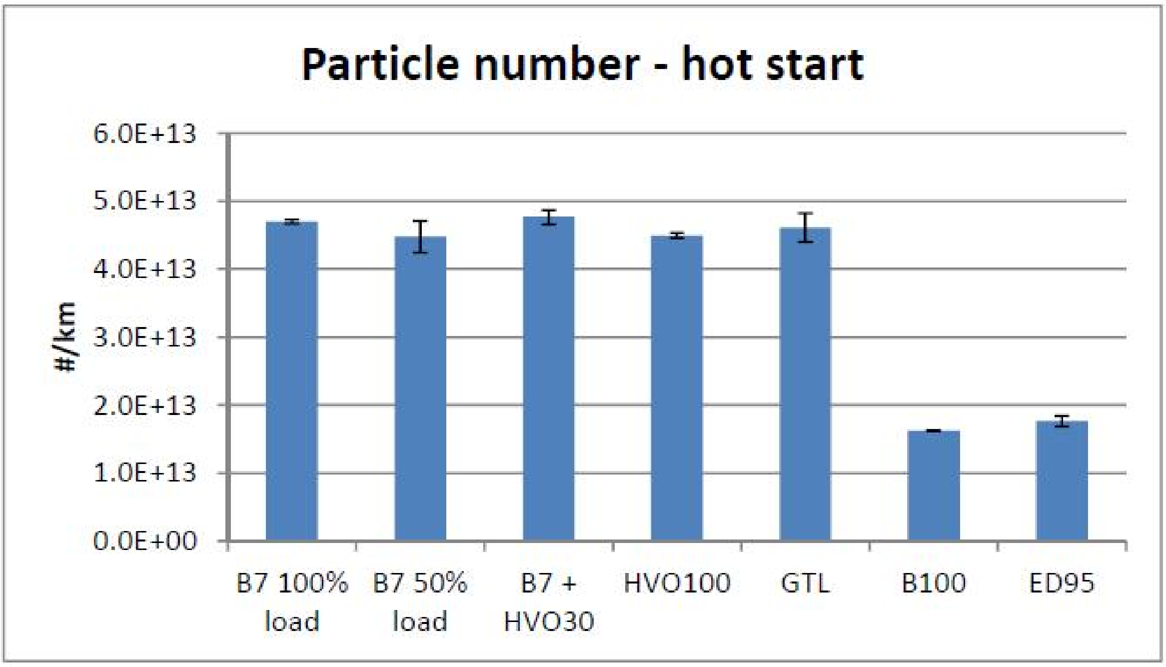

Figure 8.6. Particle number – averaged results from hot start tests.

Particle size distribution is shown in Figure 8.7. For the larger particles sizes, the B100 and ED95 tests are distinguished with lower levels of emitted particles. The reduction of particles for B100 can be explained by the higher amount of oxygen in the fuel, leading to improved combustion and reduction of particle emissions. This explanation could probably also be applicable for the lower particle emissions for the ED95 fuel. When starting from cold, the ED95 fuel had the highest amount of particles in the smallest particle sizes (below 0.1 µm).

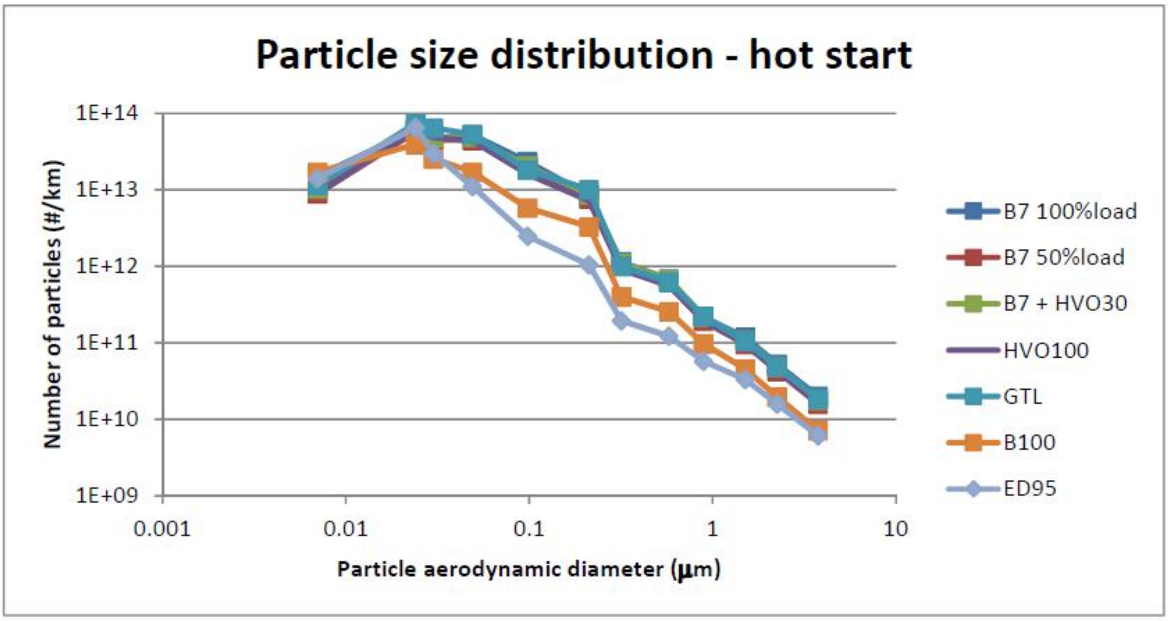

Figure 8.7. Particle number emissions – averaged results from hot start tests.

The PAH in the emissions can be derived from unburned residues of fuel, as a byproduct from the combustion or from the engine oil. According to the fuel specifications, the diesel fuels denoted B7 and B7+HVO30 have higher total aromatic content. This is also reflected in the filter phase of the particle extracts presented in Figure 8.8, with somewhat elevated levels. The difference in the hot start tests is however not significant, due to the high standard deviations. The B100 fuel shows the lowest emissions for summarized PAH in filter phase in the cold start test. With the exception of B100, the summarized PAH emissions in filter phase shows no major differences between the fuels.

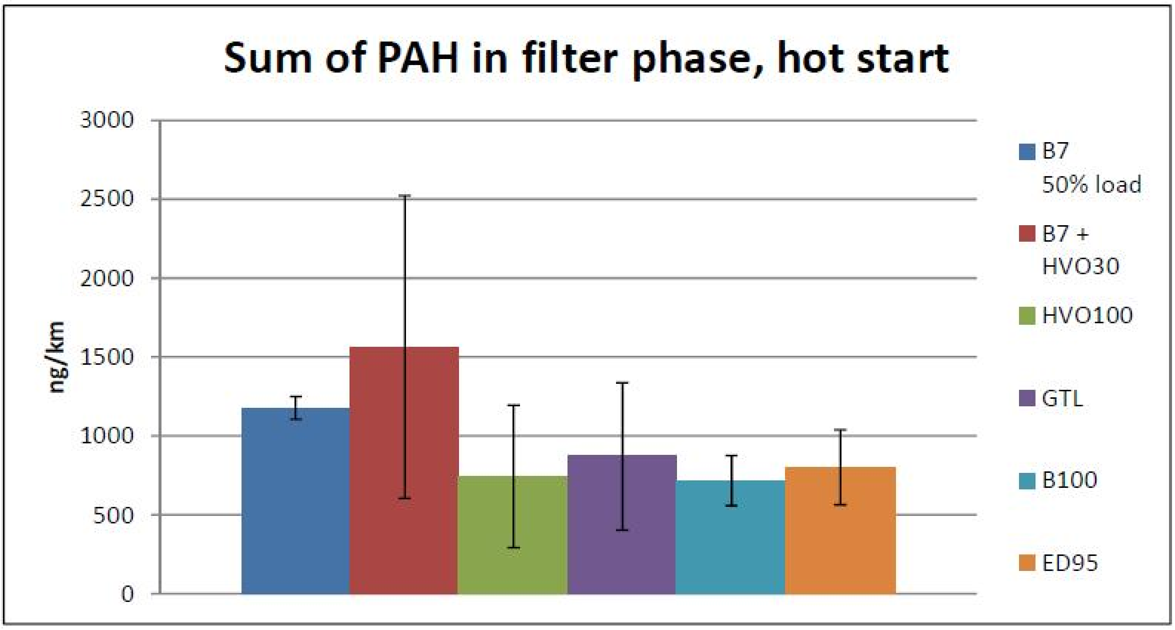

Figure 8.8. Total emissions of analysed PAH in filter phase, averaged results from the hot start tests.

In the hot start tests, the GTL and B7 fuels have the lowest levels of summarized PAH in semivolatile phase (Figure 8.9). In the cold start test, the HVO100 and ED95 fuels show elevated levels compared to the other fuels.

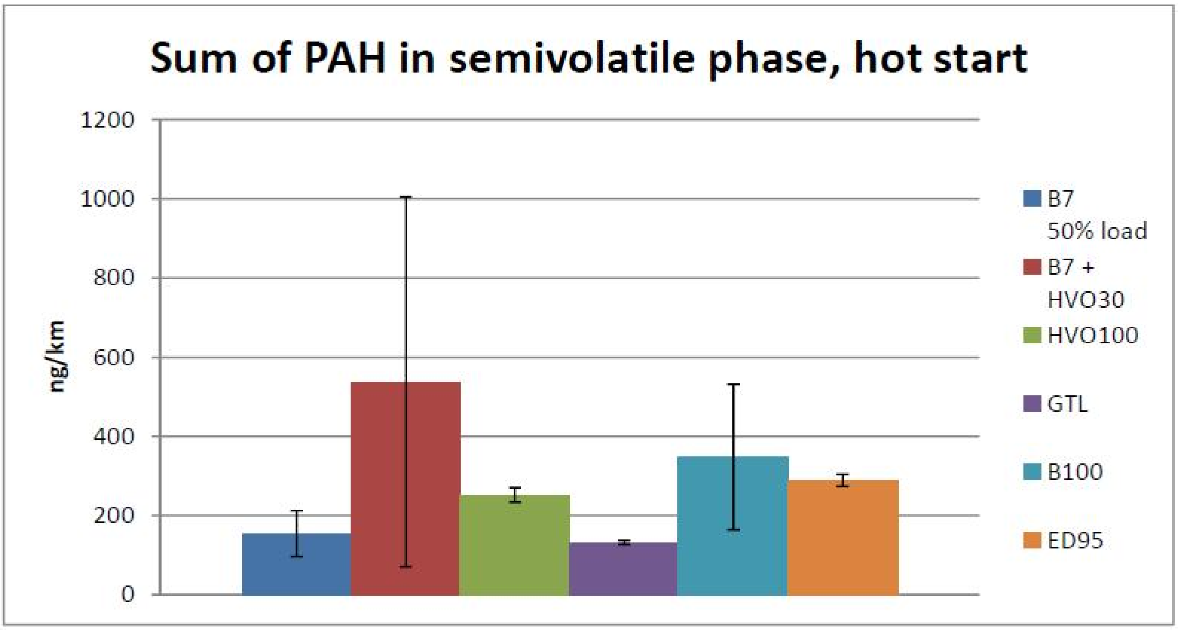

Figure 8.9. Total emissions of analysed PAH in semivolatile phase, averaged results from the hot start tests.

The PAH group consists of many different compounds with varying characteristics. Some PAHs have been more thoroughly investigated regarding health effects. The US EPA uses a theoretical method where the potential effects of some compounds have been translated into Toxic Equivalence Factors (TEF). The factor is established through toxicological studies. This method assumes that compounds have additive effect, and that the effect is linear. Some of the investigated PAHs are presented in Table 8.2 together with their TEF values. Please note that the list is not complete and the TEFs can be updated or changed.

Table 8.2: Toxic Equivalence Factors for some PAH compounds[9].

PAH	TEF
Anthracene	0,01
Benzo(a)pyrene	1
Benzo(b)fluoranthene	0,1
Benzo(k)fluoranthene	0,05
Dibenzo(a,e)pyrene	0,2
Dibenzo(a,h)pyrene	1
Dibenzo(a,i)pyrene	1
Dibenzo(a,l)pyrene	100
Fluoranthene	0,05
Phenanthrene	0,0005
Pyrene	0,001

[9] https://www.epa.gov/risk/documents-recommended-toxicity-equivalency-factors-human-health-risk-assessments-dioxin-and

The TEF can be used to calculate TEQ (Toxic Equivalence) which is described as the potency to induce cancer. The factor for respective compound is multiplied by the emission in ng/km for the specific compound. The products are thereafter summarized to achieve the TEQ value for the emission test.

The TEQ values for the PAH compounds listed in Table 8.2 were calculated, and the results from the filter phase are presented in Figure 8.10 (filter phase) and Figure 8.11 (semivolatile phase).

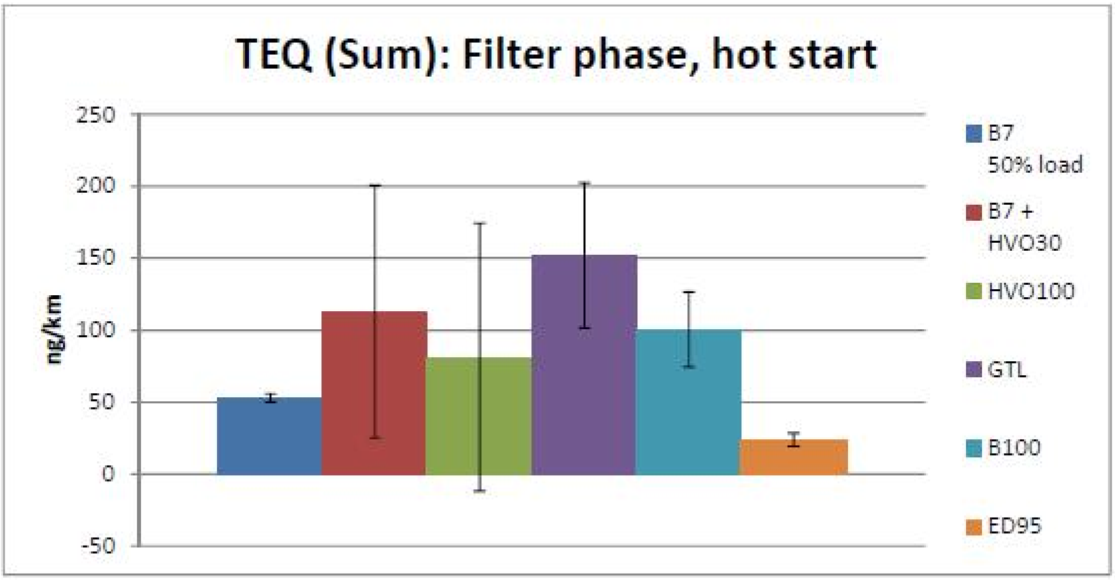

Figure 8.10. Sum of TEQ for filter phase, average of hot start tests.

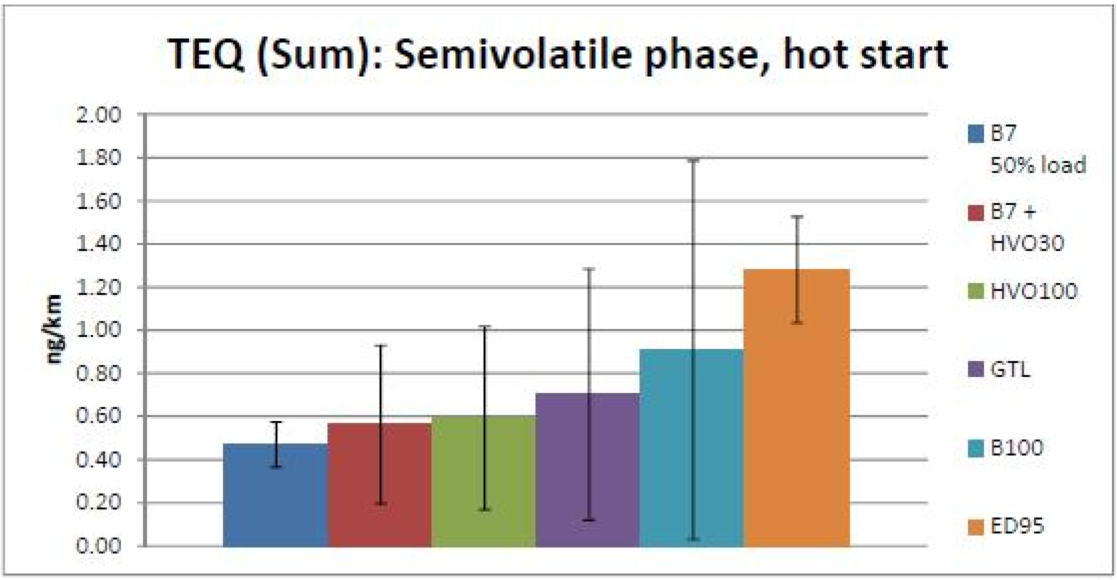

Figure 8.11. Sum of TEQ for semivolatile phase, average of hot start tests.

For the filter phase, the summarized TEQ values in the cold start test are higher for the GTL fuel and lower for the ED95 fuel – compared to the other fuels. For the hot start tests, the ED95 is significantly lower than B7. For the other fuels, the standard deviations are too high to distinguish significant differences.

For the semivolatile phase, consisting of lighter PAHs, the summarized TEQ values are very low for all fuels. The ED95 shows comparatively high TEQ values both at cold start and hot start, and is significantly higher than B7.

Health effect studies are complex, and the results are dependent on the endpoints in the studies. It is not advisable to draw conclusions regarding health effects only from TEQ results, but Toxic Equivalence Factors could be useful as a screening method. High TEQ values for exhaust emissions from a fuel should be followed up with more thorough health effect studies.

8.5 Thailand

In addition to regular diesel, PTT tested four other fuel options in a Euro 4 certified pick-up truck. The fuel codes are:

- HSD (regular diesel)
- B7 (regular diesel with 7 % FAME)
- B100 (100 % FAME)
- BHD20 (regular diesel with 20 % HVO)
- BHD 100 (100 % HVO)

The results for regulated emissions are shown in Figure 8.12.

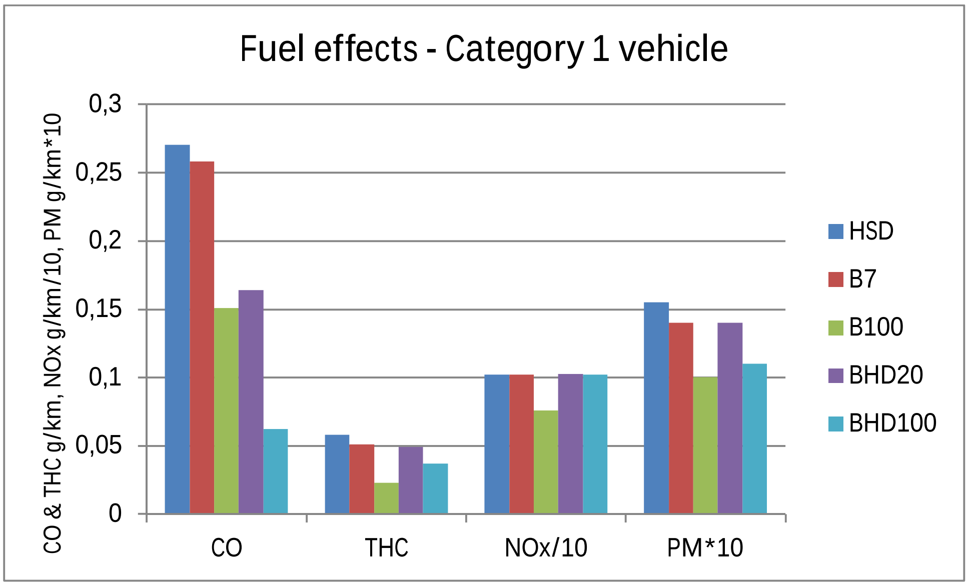

Figure 8.12. Fuel effects on regulated emissions of a Euro 4 certified Category 1 pick-up truck.

According to PTT's measurements, conventional biodiesel B100 delivers best overall performance in the Euro 4 pick-up truck, with lowest emissions for all components but CO. For CO, 100 % HVO delivers the lowest value. In the case of heavy-duty engines, B100 in most cases increases NO_x, but on the other hand reduces PM emissions significantly.

8.6 Discussion

It is challenging to draw unambiguous conclusions regarding the effects of diesel substitute fuels emission performance. The response will vary from vehicle to vehicle, but also by vehicle category (light-duty vehicles vs. heavy-duty vehicles). Heavy-duty Euro VI engines are so clean that any effect of the fuel will be dampened by the highly efficient and complex exhaust after-treatment systems. However, high quality fuels with no contaminants are prerequisites to guarantee performance and durability of the exhaust after-treatment systems.

As for pre-Euro VI heavy-duty vehicles, some general conclusions can notwithstanding be drawn. Oxygen containing fuels tend to increase NO_x emissions and decrease PM emissions compared to regular diesel fuel. Paraffinic fuels, on the other hand, may deliver a slight (5 – 10 %) reduction in NO_x emissions in combination with a decent (up to 30 %) reduction in PM emissions.

In the case of light-duty vehicles, there is no clear trend for fuel effects on emissions. However, substituting regular diesel for 100 % paraffinic fuel seem to have marginal or no benefits for regulated emissions.

The results from AVL MTC highlight that it is extremely difficult to access the health effects of fuels. The ranking of the fuels depend on, e.g., what emission component is evaluated, for PAH emission whether it is the filter phase or the semivolatile phase which is being assessed and in addition how the vehicle is tested, does testing include cold start or not.

Going from old Euro I vehicles to Euro VI vehicles will reduce regulated emissions by more than 95 %. It is clear that such massive reduction in emissions from efficient exhaust after-treatment systems will fade out most of the effects of fuel on exhaust emissions. However, in the case of less sophisticated engines, a switch from conventional diesel fuel to chemically simple fuels like methane and paraffinic diesel may still bring about emission benefits.

9. Full fuel cycle evaluation

9.1 General

As stated in Chapter 5, it was decided to use WTT data from the JEC - Joint Research Centre-EUCAR-CONCAWE collaboration on WTW.

The WTT Appendix 2 (Version 4.a, March 2014) contains numerous alternative energy pathways. The pathways chosen for COMVEC are shown in Table 9.1. CO_2 emission factors are from WTT Appendix 1. In addition to values from JEC, Table 9.1 also includes values for average Finnish electricity, provided by Finnish Energy (average CO_2 intensity 97 g/kWh, MJ/MJ fuel estimated).

Table 9.1. Energy pathways chosen for COMVEC. Codes according to JEC WTT Appendix 2 (Version 4.a, March 2014)

Code	Fuel	WTT energy	WTT CO2	TTW CO2
		MJ/MJ final fuel	g CO2eq/MJ final fuel	g CO2/MJ
COG1	Petrol	0,18	13,8	73,4
WTET3a	EtOH wheat max	1,54	86	
STET1	EtOH straw min	1,32	9,2	
GMCG1	CNG EU mix	0,17	13	56,2
OWCG4	Biogas maize	1,28	40,8	
OWCG1	Biogas mun. waste	0,99	14,8	
COD1	Diesel	0,2	15,4	73,2
ROHY1b	HVO max	0,99	57,1	
WOHY1a	HVO min	0,16	8,1	
WFSD1	BTL wood	1,2	7	
WWSD2	BTL black liquor	0,91	2,5	
KOEL1	Electricity EU mix coal conv.	1,81	292,4	
EMEL2	Electricity EU mix medium	2,07	141,1	
WDEL	Electricity wind	0,12	0	
	Electricity FIN mix (estim.)	2	26,9	

The fuel pathways were chosen to highlight variations in CO_2 intensity. For most pathways maximum and minimum values were chosen. “Best cases” include BTL from black liquor in the case of biofuels as well as electricity from wind in the case of electricity. In the case of fossil fuels (petrol, diesel, natural gas, all without any biocomponents), the values represent average European values.

The well-to-wheel evaluation is done for two vehicle categories:

- Category 1 vehicles (vans, test weight some 2 000 kg)
- Category 2 vehicles (2-axle trucks, test weight some 14 000 kg)

The TTW data (energy consumption) is based on VTT’s measurements for COMVEC. It was not possible to have just one vehicle platform or even one vehicle brand for the two categories.

For Category 1, the vehicles represent one vehicle platform (two vehicles, one bi-fuel petrol/CNG vehicle and one diesel vehicle) from one manufacturer and one vehicle from another manufacturer (electric vehicle).

For Category 2, three vehicles are included, one Euro V dual-fuel vehicle (operated on diesel only and in dual-fuel mode) from one manufacturer and two vehicles (Euro V ethanol and spark-ignited Euro VI CNG) from another manufacturer. The idea here is not to make a direct vehicle-to-vehicle comparison, but rather to demonstrate differences between fuels and combustion technologies.

The comparisons are made for the WHVC test cycle.

The calculation principles are as follows:

- Energy consumption:
  - Starting point specific energy consumption (MJ/km/1000 kg vehicle weight)
  - Calculated back to MJ/km using a vehicle weight of 2 000 kg (vans) or 14 000 kg (trucks)
- CO_2 emissions
  - Calculated from energy consumption using JEC CO_2 intensity data (g CO_2/MJ) for both the upfront WTT part as well as the end-use TTW part
  - The TTW part for biofuels is considered to be zero CO_2 emission, CO_2 emissions are attributed to the WTT part only
- Calculation for dual-fuel operation
  - Energy shares in dual-fuel operation in the WHVC cycle are 72 % diesel and 28 % methane
  - In the case of dual-fuel operation, unburned methane, converted to CO_{2eqv}, is added to the TTW emissions
    - The emission on unburned methane is negligible for stoichiometric three-way catalyst equipped gas engines
- Calculation for ethanol fuels
  - The bi-fuel petrol/CNG vehicle was not tested on high concentration E85 ethanol fuel, however, E85 was included into the WTW assessment assuming equivalent energy consumption for petrol and E85 and assuming the balance of the fuel (15 % hydrocarbons) being fossil petrol
  - The additive treated ED95 diesel ethanol fuel is considered to be 100 % ethanol

9.2 WTW results

Figure 9.1 presents WTW CO_2 emissions (split up into WTT and TTW) and Figure 9.2 WTW energy use for various combinations of vehicle technology and fuel/energy carrier for Category 1 vehicles (vans).

Correspondingly, Figures 9.3 and 9.4 present results for Category 2 vehicles (2-axle trucks).

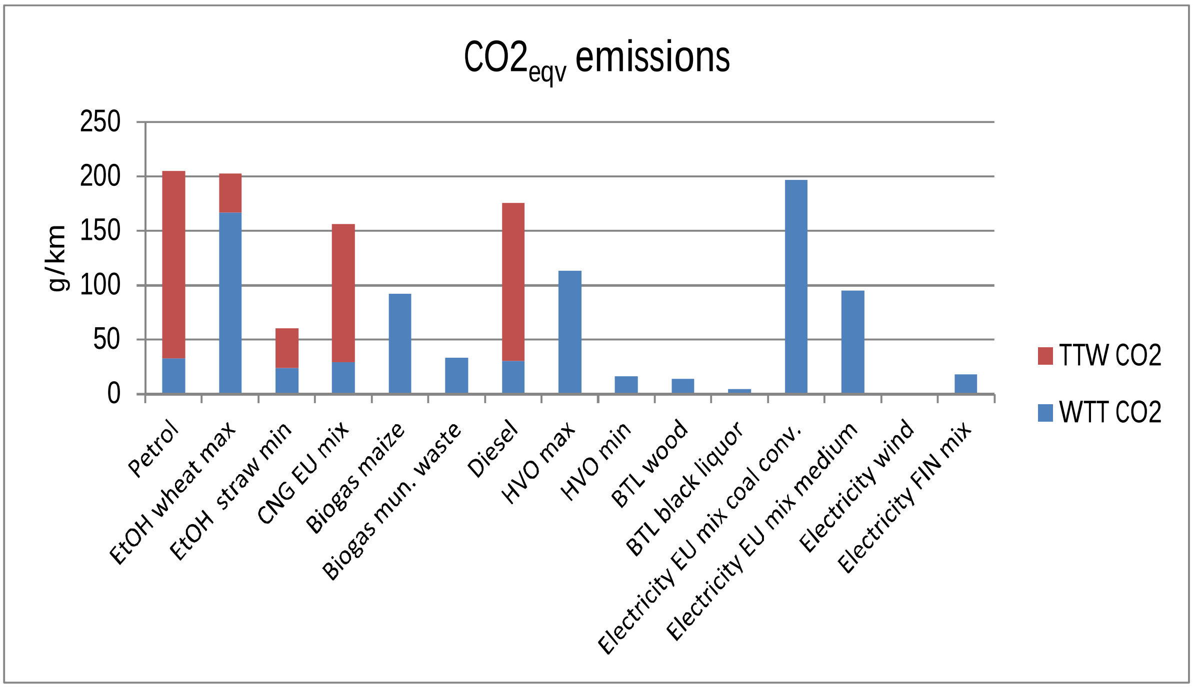

Figure 9.1. WTW CO_{2eqv} emissions for Category 1 vehicles (vans).

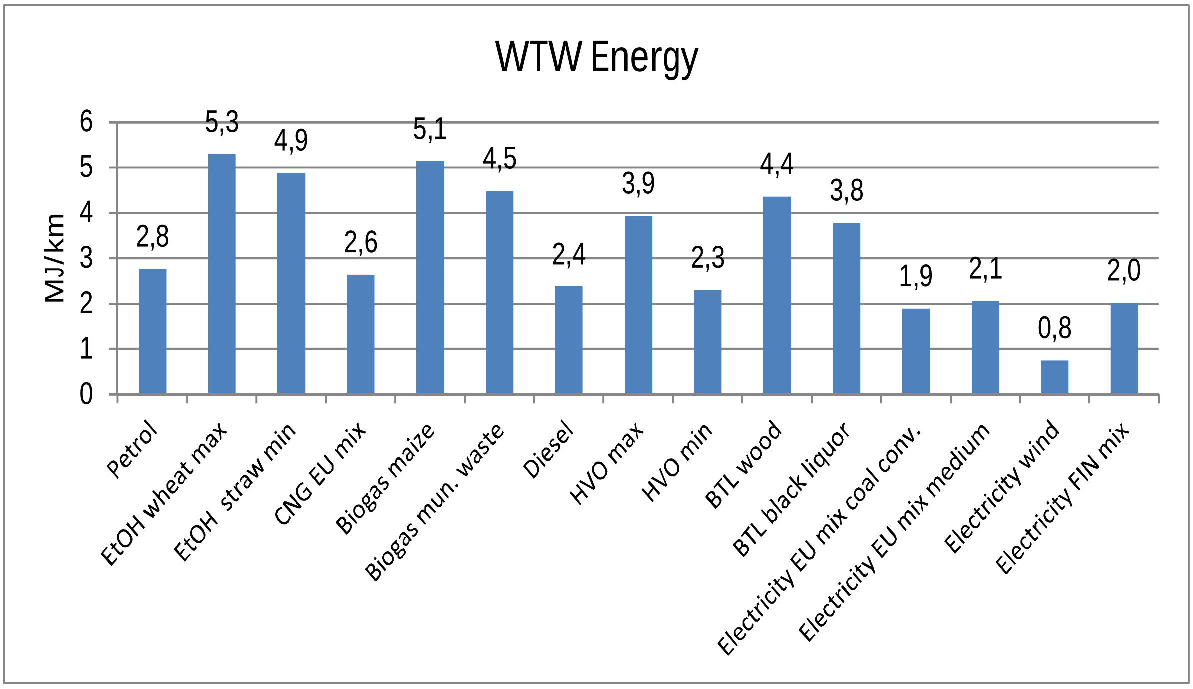

Figure 9.2. WTW energy use for Category 1 vehicles (vans).

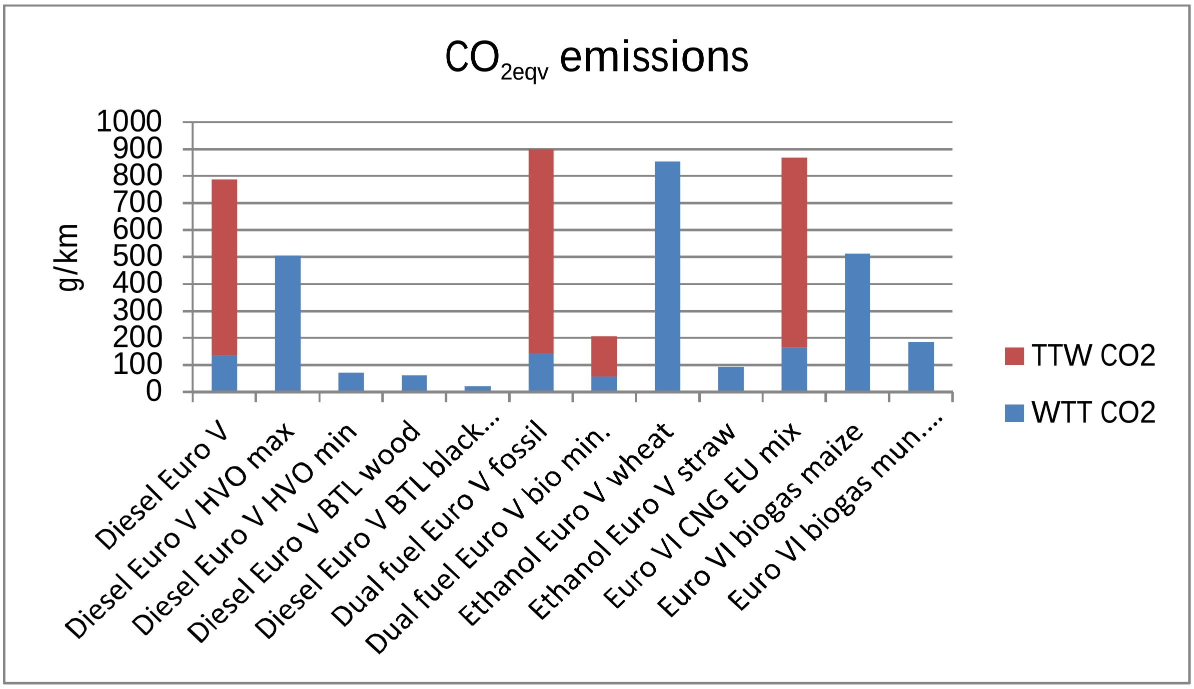

Figure 9.3. WTW CO_{2eqv} emissions for Category 2 vehicles (trucks).

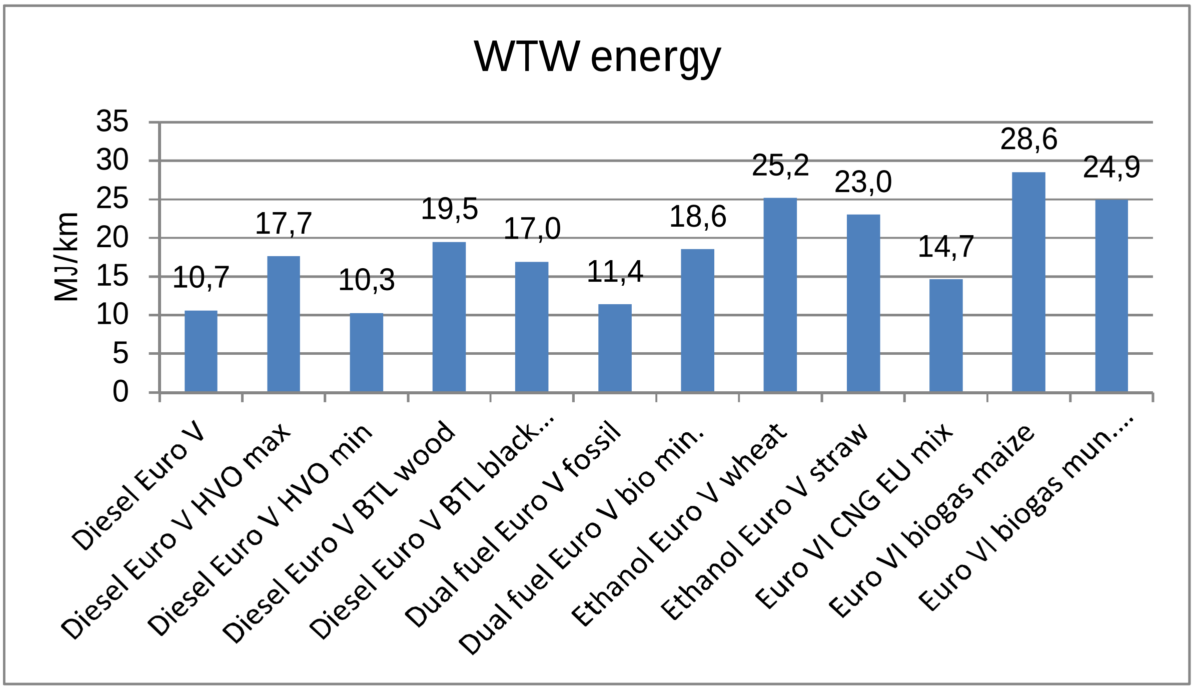

Figure 9.4. WTW energy use for Category 2 vehicles (trucks).

9.3 Discussion

In the case of Category 1 vehicles (vans), WTW CO_2 emissions vary from zero to some 200 g/km. Petrol, E85 with ethanol from wheat, CNG, diesel and electricity from coal all deliver values between 150 and 200 g/km. Here it should be noted that electricity from coal is worse than fossil diesel. Biogas from maize, HVO worst case and average European electricity all deliver values around 100 g/km. For electricity generated from wind CO_2 is zero. However, also the best of biofuels score very well. WTW CO_2 emission for BTL from black liquor would be only 5 g, a calculatory reduction of 97 % compared to fossil diesel.

Also for WTW energy use, electricity from wind is the winner with a value of some 0.8 MJ/km. For fossil diesel and average electricity WTW energy is some 2 – 2.5 MJ/km. WTW values for petrol and CNG are slightly higher. As long as the average mix of electricity contains electricity generated through combustion (coal, gas, biomass) and nuclear generation, electric vehicles do not deliver a significant advantage in overall energy use compared to diesel.

Biofuels, on an average, are more energy intensive, some 4 – 5 MJ/km. One exception is HVO from waste cooking oil, which is slightly more efficient than conventional diesel.

Electricity was not included for Category 2 vehicles. Fossil fuels and ethanol from wheat deliver WTW CO_2 emissions between 800 – 900 g/km. Fossil CNG doesn't deliver advantage over diesel. Worst case HVO and biogas from maize are around 500 g/km, and the best biofuels in the range of 20 – 200 g/km. In the case of dual-fuel operation with a combination of the best biofuel options, the WTT part is only some 60 g CO_2/km. However, the methane slip, equivalent to some 150 g CO_2/km, is a significant addition to the overall result.

Diesel and HVO form waste cooking oil are the most efficient alternatives for WTW energy use, some 10 MJ/km. Fossil CNG is some 15 MJ/km. WTW energy use for most biofuels is in the range of some 20 – 30 MJ/km.

Some conclusions can be drawn:

- Fossil CNG doesn't deliver significant advantages over diesel for WTW CO_2 and energy use
- Biofuels are in general more energy intensive than fossil fuels
- Notwithstanding, the best of biofuels can deliver significant reductions in WTW CO_2 emissions
- Renewable electricity (hydro, wind, photovoltaic) is the best option for WTW CO_2 and energy use
- Average European electricity for EVs is roughly equivalent to fossil diesel for both WTW CO_2 emissions and energy use

10. Cost estimates for alternative technologies

10.1 General

The main costs related to operating commercial vehicles are labour costs of the drivers, capital costs of the vehicle, costs of fuel and liquids (e.g. urea) and vehicle maintenance (including maintenance of the exhaust after-treatment system). In addition, when using non-conventional fuels or electricity, costs for additional refuelling infrastructure have to be taken into account. All these components add up to total cost of ownership, TCO.

Most alternative technologies increase costs in one way or the other. Biofuels are currently more expensive than conventional fossil fuels, and alternative technology vehicles, due to increased complexity, are more expensive than conventional vehicles. Vehicle and fuel technology also can affect labour costs in cases where fuelling up requires extra time, or when additional driving and time are needed to reach refuelling facilities.

On the other hand, taking into account external costs for emissions (local emissions, greenhouse gas emissions) can shift balances in favour of alternative solutions. Annex 37, “Fuel and Technology Alternatives for Buses” (see 1.1), evaluated total cost (direct costs and external/indirect costs aggregated) for a number of technology alternatives.

Crude oil prices, and consequently fuel prices, have been very low in 2016 (Figure 10.1). Therefore it was decided not to repeat the same kind of cost assessments which were carried out in Annex 37. Moving towards the year 2030, with increasingly challenging climate targets and increasing prices on CO_2 emissions will naturally improve the competiveness of low-carbon fuels dramatically.

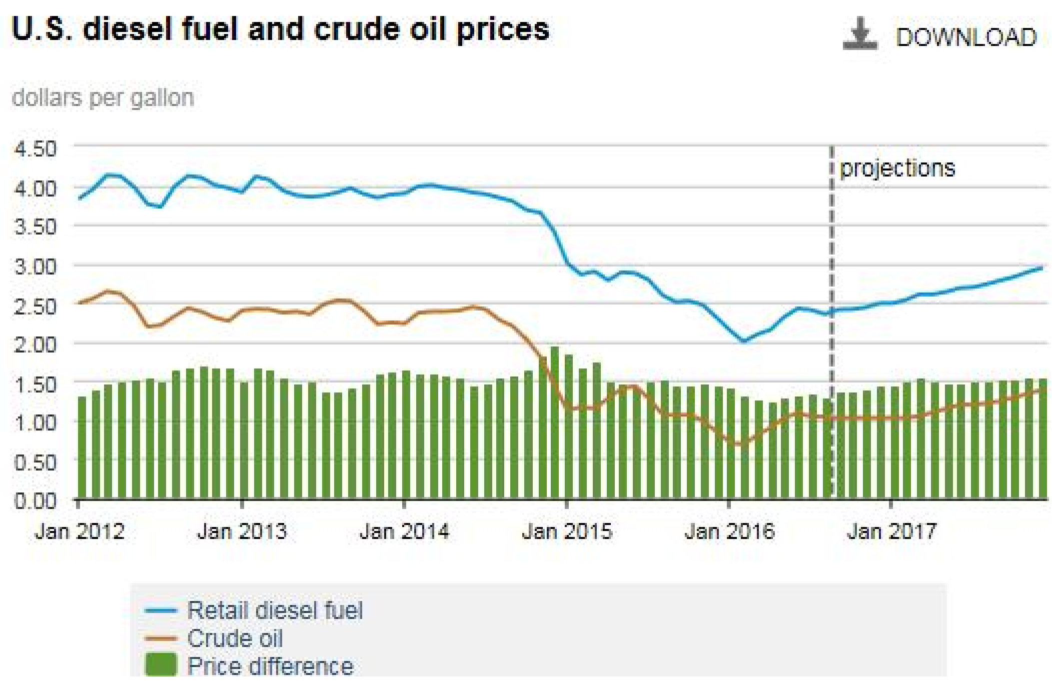

Figure 10.1. Development in U.S. diesel fuel and crude oil prices.
https://www.eia.gov/forecasts/steo/report/prices.cfm

Not only fluctuations in fuel prices make cost estimations and comparisons difficult. Another thing adding to the challenges of making cost comparisons of different technologies is the difficulty to get unambiguous vehicle prices. For passenger cars, the manufacturers and vehicle vendors provide price lists of vehicles. This is also the case for light-duty commercial vehicles such as vans. However, in the case of heavy-duty trucks, price lists are rare, as most vehicles are tailored according to the needs of the individual customers.

In the following text, two studies regarding the costs for CO_2 abatement in road transport are referred to, one Finnish and one German study.

10.2 Finnish study on costs of emission reductions in road transport

In 2015, VTT Technical Research Centre of Finland Ltd and VATT Institute for Economic Research carried out the study "40% Reduction of Carbon Dioxide Emissions from Transport by 2030: Propulsion Options and Their Impacts on National Economy[10]". The study was done with funding from the Finnish Ministry for Employment and the Economy. The report states, among other things:

- *Based on the economic impacts, the most cost-efficient way to reduce emissions is to invest in the production and uptake of domestic, advanced drop-in biofuels. Their use will not require changes in the vehicle fleet or on the fuel distribution system.*
- *Biogas is also a relatively cost-efficient option for reducing transport related CO_2 emissions, but would require a significant increase in the number of gas-powered vehicles. However, it is not possible to set obligations for fleet renewal or powertrain choice.*
- *Because of the high price of electric cars at present, their large-scale uptake will not be cost-effective based on their impact on GDP until technology advancements bring down their price significantly.*

These conclusions are valid for Finland, with its industrial structure (significant pulp and paper industry, no major vehicle industry) and its large biomass resources. The conclusions could be quite different for other countries.

For the study, VTT gathered data in 2013 – 2014 on alternative vehicle prices as well as on refuelling infrastrucure prices. Table 10.1 shows rough estimates for vehicle prices (not all technologies are commercially available) and their development towards 2030.

10 http://www.transsmart.fi/files/297/Tieliikenteen_40_hiilidioksidipaastojen_vahentaminen_vuoteen_2030_Kayttovoimavaihtoehdot_ja_niiden_kansantaloudelliset_vaikutukset._VTT-R-00752-15.pdf (with extended summary in English)

Table 10.1.Estimates for commercial vehicle prices and their development towards 2030. Source VTT.

		€	€	%	€	€	€	€	%
Vehicle type	Technology	Price 2015	Delta/2015	Delta/2015	Delta/2020	Delta/2025	Delta/2030	Price 2030	Delta/2030
Van	Diesel	26000	0	0 %	0	0	0	26000	0 %
Van	CNG/CBG	28828	2828	11 %	2600	2275	1950	27950	8 %
Van	Hybrid	33800	7800	30 %	6500	5200	3900	29900	15 %
Van	PHEV	44200	18200	70 %	14300	117000	9100	35100	35 %
Van	BEV	47450	21450	83 %	18200	15600	13000	39000	50 %
Van	FCEV	71500	45500	175 %	39000	29900	19500	45500	75 %
Single unit truck	Diesel	100000	0	0 %	0	0	0	100000	0 %
Single unit truck	ED95 ethanol	100000	0	0 %	0	0	0	100000	0 %
Single unit truck	Hybrid	140000	40000	40 %	35000	30000	25000	125000	25 %
Single unit truck	CNG/CBG	142500	42500	43 %	40000	37000	35000	135000	35 %
Single unit truck	LNG	150000	50000	50 %	47000	43000	40000	140000	40 %
Single unit truck	BEV	280000	180000	180 %	160000	140000	100000	200000	100 %
Tractor (for trailer)	Diesel	150000	0	0 %	0	0	0	150000	0 %
Tractor (for trailer)	ED95 ethanol	150000	0	0 %	0	0	0	150000	0 %
Tractor (for trailer)	CNG/CBG	200000	50000	33 %	45000	40000	35000	185000	35 %
Tractor (for trailer)	LNG	220000	70000	47 %	65000	60000	50000	200000	50 %

Methane vehicles are commercially available, both as vans and as trucks. In the case of trucks, methane vehicles were estimated to be some 30 – 50 % more expensive than their diesel counterparts. The price differential is due to modified engines, expensive gas storages and limited production numbers. In 2013, the added cost for dual-fuel technology for a medium heavy-duty truck was 35.000 €.

Currently only one manufacturer is offering heavy-duty ethanol vehicles, and only one engine type with a power output of some 300 hp is available. The engine is a slightly modified diesel engine using additive treated ethanol as fuel. VTT estimated the additional costs for the engine itself to be marginal. However, in practice there would be some added costs for ethanol engine technology. In addition, the service interval for ethanol trucks is shorter than for conventional diesel trucks.

In the case of vans, there is currently only a limited supply of battery electric vehicles from major vehicle manufacturers. In the case of trucks, the offering of battery electric trucks from the majors is in practise non-existent, with the exception of some demonstration vehicles. So far fuel cell technology has been demonstrated primarily for passenger cars and buses, not for commercial vehicles. Table 10.1 estimated the added cost for a battery electric van at 83 % over diesel. Currently (October 2016), the Nissan NV200 van is offered in Finland at 24.500 € as diesel and at 33.000 € as battery electric vehicle, a price premium of only 8.500 € or 35 %.

The costs for EV chargers were estimated as follows:

- 50 kW DC fast charger ~ 40,000 €
- 22 kW AC semi-fast charger ~ 6,000 €
- 3,7 kW AC slow charger ~ 2,000 €

The costs for a public CNG refuelling station, including groundwork, gas storage, compressors and dispensers was estimated at 370,000 – 550,000 €. The cost for one LNG refuelling point was estimated at 600,000 €.

10.3 Roland Berger's "Integrated Fuels and Vehicles Roadmap to 2030+"

In April 2016, the German consulting company Roland Berger launched a very comprehensive study, "Integrated Fuels and Vehicles Roadmap to 2030+[11]", on fuel and vehicle technologies for GHG abatement towards 2030, including cost assessments for different technologies. The report states:

The study was commissioned to identify possible reductions in GHG emissions by considering the key elements of technical achievability, infrastructure needs, customer acceptance and which policies, currently being pursued, would lead to greater integration between the automotive and fuel sectors in order to meet the challenging decarbonisation goals set out to 2030 and beyond. This study aims to provide an integrated roadmap taking into account the feasibility of all fuel and vehicle technologies along with infrastructure needs and the recommended policy framework beyond 2020. A key consideration was to identify a roadmap with the lowest, achievable GHG abatement costs to society.

The study covers three main vehicle categories, passenger cars and medium- and heavy-duty vehicles grouped together. The report states that the overall potential for GHG reductions is much bigger for passenger cars (-163 Mt CO_{2eqv}) than for commercial vehicles (-28 Mt CO_{2eqv}, Figure 10.2).

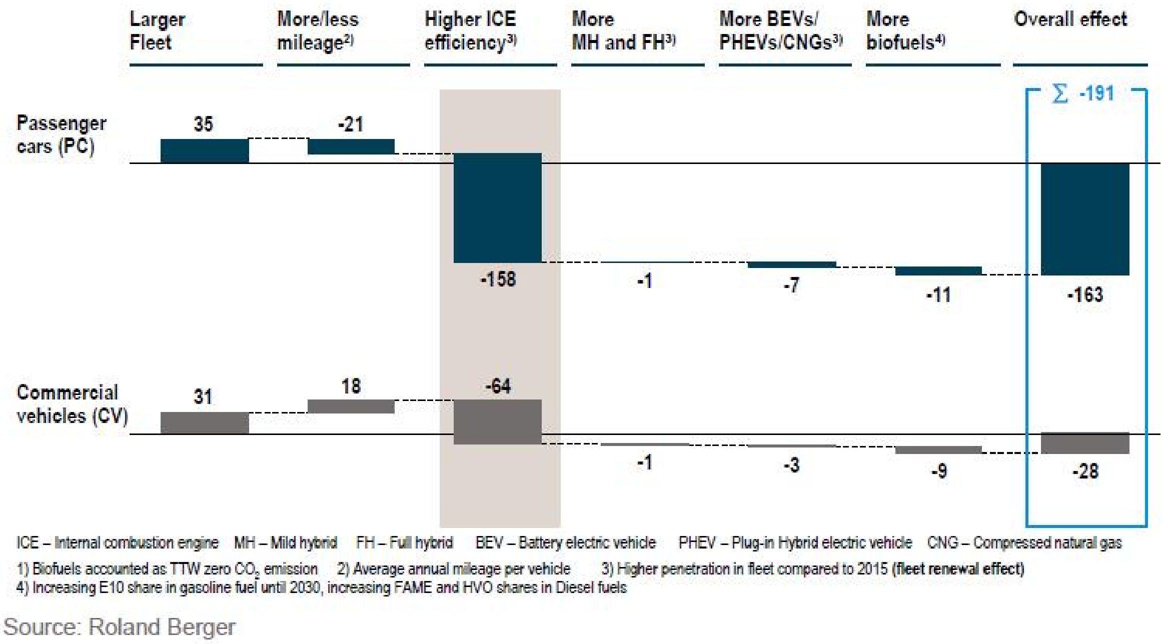

Figure 10.2. Emission reduction potentials for road vehicles in Europe. Source Roland Berger 2016.

The fuel prices used in the Roland Berger study are based on IEA estimates (IEA World Energy Outlook 2015). Table 10.2 summarises price estimates used by Roland Berger. Depending on the oil price scenario, the prices of biofuels are in the range of 101…224 % relative to diesel. The price of CNG is 45…56 % relative to diesel.

11 https://www.rolandberger.com/de/Publications/pub_integrated_fuels_and_vehicles_roadmap_2030.html

Table 10.2. Price (wholesale) estimates for 2030 used by Roland Berger (based on IEA World Energy Outlook 2015).

	Diesel	HVO	Ethanol 1. Gen.	Ethanol 2. Gen.	CNG	CBG
IEA low oil price scenario						
€/MJ	0.0136	0.0268	0.0218	0.0305	0.00767	0.0239
Relative to diesel		197 %	160 %	224 %	56 %	176 %
€/litre, (€/kg)	0.4909	0.9100	0.4579	0.64	(0.3458)	(1.0774)
IEA new policies scenario						
€/MJ	0.0215	0.0285	0.0218	0.0305	0.00957	0.0239
Relative to diesel		133 %	101 %	142 %	45 %	111 %
€/litre, (€/kg)	0.7724	0.9680	0.4579	0.64	(0.4313)	(1.0774)

For passenger cars, Roland Berger carried out TCO calculations for combinations of annual mileage and share of city driving or electrified driving, showing which technologies could be cost effective for certain conditions. However, such assessments were not carried out for commercial vehicles.

The most tangible results of the Roland Berger study are the presentations of CO_2 abatement costs for different technologies in different vehicle categories. Figure 10.3 presents results for medium- and heavy-duty vehicles.

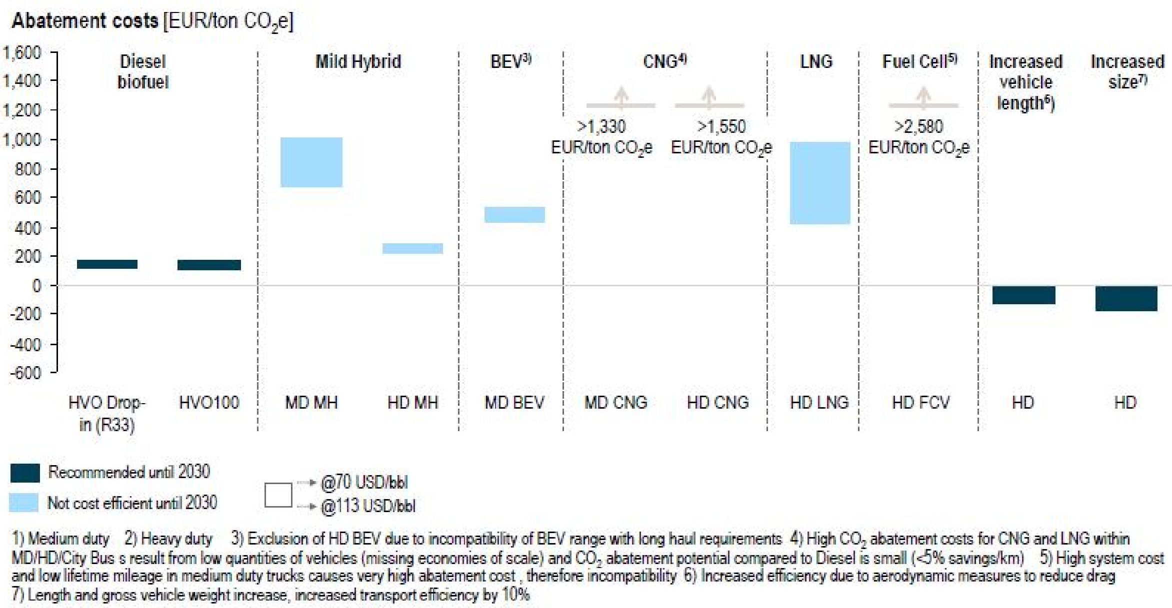

Figure 10.3. CO_{2eqv} abatement costs in €/ton for medium- and heavy-duty vehicles. Source Roland Berger.

Increasing vehicle length and weight are very cost effective measures for CO_2 abatement, as the estimated costs are negative because the fleet operators will actually save both fuel and money for each ton of goods transported.

The cost on emission reduction using biofuels is around 150 €/ton, all other technologies (hybridisation, electrification, natural gas, fuel cells) are more expensive, according to Roland Berger.

Roland Berger makes specific comments regarding paraffinic diesel fuels:

"Paraffinic fuels are totally fungible and can be used as drop-in blending components for conventional diesel fuels.

Advantages of paraffinic fuels:

- *Opportunity to increase the share non-mineral oil based fuels*
- *Positive impact on particulate matter and NO_x emissions compared to conventional diesel fuels*
- *Compatibility with existing conventional diesel engines*
- *CO_2 emission reduction is possible without technical adaptions on vehicles*

Technology maturity to ensure cost competitiveness compared to conventional fuels is a current challenge for paraffinic fuels, in particular for BTL." (Editor's comment: biomass-to-liquids, synthetic fuels from solid biomass).

The CNG vehicles are considered to be equipped with spark-ignition engines. Also the measurements within the COMVEC project show very limited benefits for spark-ignited CNG over diesel regarding CO_{2eqv} emissions, and consequently the abatement costs for this technology are very high, above 1,330 €/ton. LNG is more cost effective than CNG, some 500…1000 €/ton. Roland Berger most probably assumes the LNG vehicles to be equipped with advanced dual-fuel engines, delivering higher engine efficiency than spark-ignited engines. Roland Berger only shows results for fossil natural gas. Biogas would deliver more favourable results, probably close to those of liquid biofuels.

According to Roland Berger, the most expensive technology for CO_2 abatement for 2030 is fuel cell technology, with a cost of more than 2,500 €/ton.

11. Conclusions and key messages

In the "COMVEC" project, eight partners from four continents teamed up to generate performance data (energy efficiency, exhaust emissions) for commercial vehicles. The work started with the development of a common test procedure, The World Harmonized Vehicle Cycle (WHVC) was used for vehicle testing and the World Harmonized Transient Cycle (WHTS) for engine testing.

Altogether, 35 different vehicles were tested on chassis dynamometers, with vehicles ranging from light commercial vehicles (vans) to heavy-duty tractors for semi-trailers. In addition, one engine, installed in an engine dynamometer, was tested. The test programme covered several fuel options: diesel, diesel substitute fuels, natural gas, ethanol and even electricity in the category of light commercial vehicles.

Key messages - overall

- Going from Euro III to Euro IV or Euro V vehicles does not necessarily deliver real emission benefits; one should leapfrog directly to Euro VI or US 2010 regulations to obtain real-life low emissions.
  - This has implications for those regions that are contemplating more stringent emission regulations, as well as for tendering of transport services.
  - One should keep in mind that Euro VI vehicles require high-quality sulphur-free fuels (S > 15 ppm).
- The regulated emissions of a vehicle are, first and foremost, determined by the emission control technology, not the fuel.
- The response to substitute fuels (fuels that can replace conventional diesel in existing vehicles) varies from vehicle to vehicle, as well as by vehicle category (light-duty vehicles vs. heavy-duty vehicles).
  - Heavy-duty Euro VI engines are so clean that any effect of the fuel will be dampened by the highly efficient and complex exhaust after-treatment systems.
  - Older vehicles, e.g. using paraffinic diesel, can deliver reductions in regulated emissions up to 30 %, depending on the exhaust component.
- The carbon intensity of the fuel or the energy carrier is decisive for well-to-wheel CO_2 emissions, not vehicle technology.
- CO_2 assessment should be carried out on a well-to-wheel basis, not only by looking at tailpipe CO_2 emissions.
- Electrification with low-carbon electricity is a good option for local emissions as well as WTW CO_2 emissions.
  - One should keep in mind that not all applications are suitable for electrification.
- Euro VI (alternatively US 2010) in combination with a renewable fuel is a good option for the local environment as well as the climate.
- Recent reports conclude that biofuels seem to be a cost-effective way of reducing CO_2 emissions from road transport; this, relative to electric vehicles and fuel cell vehicles.
  - Fossil natural gas is not a cost-effective option for reducing CO_2 emissions from heavy-duty vehicles.

Key findings – energy consumption

- The most important factor affecting energy consumption is vehicle mass.
  - For diesel powered vehicles, energy consumption per km varied by a factor of 12, from the lightest to the heaviest vehicle tested.
  - Relative to mass, larger vehicles are more energy efficient than smaller ones.
  - Specific energy consumption varied by a factor of 3.

- However, the type of engine (spark-ignited, diesel, electric) also has an impact on energy consumption.
  - Spark-ignited engines are less efficient than compression ignited (diesel) engines.
  - Thus, spark-ignited gas vehicles have higher energy consumption than their diesel counterparts, independent of vehicle size.
  - The energy consumption of electric vehicles is around 30–40 % of that of ICE equipped vehicles.
- New diesel vehicles (particularly Euro VI vehicles) are much cleaner than older ones, showing no fuel consumption penalty, when compared to older vehicles.

Key findings – regulated emissions

- Really huge differences can be found for both NOx and PM emissions.
  - In the case of NO_x, specific emission rates varied from less than 0.001 to 0.9 g/km/1000 kg vehicle weight.
  - For PM, the range is 0.001 to 0.13 g/km/1000 kg vehicle weight.
- All Euro IV and Euro V diesel vehicles had higher NO_x emissions than should be expected.
  - The conclusion that can be drawn is that, in the case of diesel vehicles, going from Euro III to Euro IV or Euro V does not necessarily bring about reductions in NO_x emissions; only Euro VI vehicles deliver truly low NOx emissions.
- Regarding particle emissions, the overall situation is somewhat more positive than in the case of $NO_{x.}$
  - Particulate filters effectively reduce PM emissions.

NO_x emissions by fuel:

- Huge spread for diesel vehicles.
- Very low emissions for spark-ignited CNG.
- Diesel dual-fuel and ethanol delivered average NO_x emissions.
- Emission class is more decisive than fuel.

PM emissions by fuel:

- Fuel type has an impact on PM emissions.
- Spark-ignited natural gas delivers very low PM emissions.
- The two ethanol trucks tested, although Euro V certified and without a particulate filter, delivered Euro VI level particle emissions.
- Dual-fuel operation increased particle emissions, this phenomenon can be related to an unsophisticated DDF control system, not the fuel itself.

Key findings – substitute fuels

- It is challenging to draw unambiguous conclusions regarding the effects of diesel substitute fuels on emission performance.
- The response varies from vehicle to vehicle, as well as by vehicle category (light-duty vehicles vs. heavy-duty vehicles).
  - Heavy-duty Euro VI engines are so clean that any effect of the fuel will be dampened by the highly efficient and complex exhaust after-treatment systems.
  - However, high quality fuels, with no contaminants, are prerequisites to guarantee performance and durability of the exhaust after-treatment systems.

- As for pre-Euro VI heavy-duty vehicles, some general conclusions can, notwithstanding, be drawn:
  - Oxygen containing fuels tend to increase NO_x emissions and decrease PM emissions, compared to regular diesel fuel.
  - Paraffinic fuels, on the other hand, may deliver a slight (5–10 %) reduction in NO_x emissions, in combination with a decent (up to 30 %) reduction in PM emissions.
- In the case of light-duty vehicles, there is no clear trend for fuel effects on emissions.
  - However, substituting regular diesel for 100 % paraffinic fuel seems to have marginal or no benefits for regulated emissions.
- The results from AVL MTC highlight that it is extremely difficult to access the health effects of fuels.
  - Fuel ranking depends on, e.g., what emission component is evaluated, whether it is the filter phase or the semivolatile phase that is being assessed for PAH emission as well as how the vehicle is tested (does testing include a cold start or not).
- Going from old Euro I vehicles to Euro VI vehicles will reduce regulated emissions by more than 95 %.
  - It is clear that such a massive reduction in emissions from efficient exhaust after-treatment systems will erase most of the effects of fuel on exhaust emissions.
  - However, in the case of less sophisticated engines, a switch from conventional diesel fuel to chemically simple fuels, such as methane and paraffinic diesel, may still bring about emission benefits.

Key findings – WTW assessment

  - Fossil CNG does not deliver significant advantages over diesel for WTW CO_2 and energy use.
  - Biofuels are, in general, more energy intensive than fossil fuels.
  - Notwithstanding, the best biofuels can deliver significant reductions in WTW CO_2 emissions.
  - Renewable electricity (hydro, wind, photovoltaic) is the best option for WTW CO_2 and energy use.
  - Average European electricity for EVs is roughly equivalent to fossil diesel for both WTW CO_2 emissions and energy use.