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46

Fuel and Technology Alternatives for Buses

Overall Energy Efficiency and Emission Performance

Nils-Olof Nylund | Kati Koponen

VTT

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Fuel and Technology Alternatives for Buses
Overall Energy Efficiency and Emission Performance

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1. Abstract

In 2009–2011, a comprehensive project on urban buses was carried out in cooperation with IEA's Implementing Agreements on Alternative Motor Fuels and Bioenergy, with input from additional IEA Implementing Agreements. The objective of the project was to generate unbiased and solid data for use by policy- and decision-makers responsible for public transport using buses. The project comprised four major parts: (1) a well-to-tank (WTT) assessment of alternative fuel pathways, (2) an assessment of bus end-use (tank-to-wheel, TTW) performance, (3) combining WTT and TTW data into well-to-wheel (WTW) data and (4) a cost assessment, including indirect as well as direct costs.

Experts at Argonne National Laboratory, Natural Resources Canada and VTT worked on the WTT part. The WTT emissions of various fossil fuels and biofuels were assessed by using GREET model from the United States, GHGenius model from Canada and RED methodology of the European Union. All these models follow the frame work of life cycle assessment.

In the TTW part Environment Canada and VTT generated emission and fuel consumption data by running 21 different buses on chassis dynamometers, generating data for some 180 combinations of vehicle, fuel and driving cycle. The fuels covered included diesel, synthetic diesel, various types of biodiesel fuels, additive treated ethanol, methane and DME. Six different hybrid vehicles were included in the vehicle matrix. The TTW work was topped up by on-road measurements (AVL MTC) as well as some engine dynamometer work (von Thünen Institute).

Based on the findings of the project it is possible to establish the effects of various parameters on bus performance. The largest variations and also uncertainties can be found for WTW CO_{2eqv} emissions, or in fact the WTT part of the CO_{2eqv} emissions. The variation is especially significant for biofuels. The WTT results vary due to the differences in the assessed biofuel chains, the regions of biofuel production, the raw materials used and the technology choices made. In addition, the results of any WTT assessment depend on the calculation assumptions made and are often vulnerable to uncertainties and sensitivities.

Over the last 15 years, tightening emission regulations and improved engine and exhaust after-treatment technology have reduced regulated emissions by a factor of 10:1 and particulate numbers with a factor of 100:1. The most effective way to reduce regulated emissions is to replace old vehicles with new ones. Hybridization or light-weighting reduce fuel consumption 20–30%, but otherwise the improvements in fuel efficiency have not been so spectacular. The driving cycle affects regulated emissions and fuel consumption by a factor of 5:1. The fuel effects are at maximum 2.5:1 for regulated emissions (particulates), but as high as 100:1 for WTW greenhouse emissions. Thus the most effective way to cut greenhouse gas (GHG) emissions is to switch from fossil fuels to efficient biofuels. WTW energy use varies a factor of 2.5:1.

Keywords Urban buses, energy consumption, greenhouse gas emissions, exhaust emissions, costs, alternative fuels, WTT, TTW, WTW

2. Executive summary

City buses are the backbone of many public transport systems, and therefore they constitute a very important element of the transportation system. Procurement of bus services is often handled by municipalities or local governments in a centralized manner.

So far, conventional diesel buses and conventional diesel fuel have dominated the market, with some contribution from natural gas buses. Now we are in a situation in which the technology options are increasing rapidly. This goes for vehicle technology as well as fuels. Advanced diesel vehicles producing very low emissions are entering the market, and hybrids are becoming commercially available. On the fuel side, various biofuels are offered as blending components or to be used as such. Natural gas and biogas can still deliver emission benefits over diesel. Additive treated ethanol is available for captive fleets such as city buses, and DME has progressed into the field testing phase. The diversification in technology increases the challenges in decision making.

In 2009–2011, a comprehensive project on urban buses was carried out in cooperation between IEA's Implementing Agreements on Alternative Motor Fuels (AMF) and Bioenergy, with input from additional IEA Implementing Agreements. The objective of the project was to generate unbiased and solid data for use by policy- and decision-makers responsible for public transport using buses. Within AMF, this was the largest collaborative project so far.

The project comprised four major parts: well-to-tank (WTT) assessment of alternative fuel pathways, assessment of bus end-use (tank-to-wheel, TTW) performance, combining WTT and TTW data into well-to-wheel (WTW) data and cost assessment, including indirect as well as direct costs.

Experts at Argonne National Laboratory, Natural Resources Canada and VTT worked on the WTT part. In the WTT assessment, the total emissions of different fuels were assessed from the raw material production until the distribution of the final product. Argonne National Laboratory calculated the WTT emissions of 5 fossil fuels and 13 biofuels by using the GREET model. Natural Resources Canada calculated the WTT emissions of 6 fossil fuels and 12 biofuels with the GHGenius model. VTT reported the WTT emissions of 4 fossil fuels and 19 biofuels according to the RED methodology, published in the Renewable Energy Directive (2009/28/EC) of the European Union (EU). The fuel chains studied are presented in Table 2.1. In co-operation, the institutes also made a comparison of the different calculation models and methodologies used for the WTT assessment, to better understand their differences and similarities. All these methods are based on life cycle assessment (LCA) approach, which is a commonly used tool for environmental impact assessment of different products. The framework of LCA is presented in two ISO standards, ISO 14040 and ISO 14044.

Table 2.1. The fuel chains studied with the GREET and GHGenius models and the RED methodology. Abbreviations presented are used throughout the report.

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In the TTW part Environment Canada (EC) and VTT generated emission and fuel consumption data by running 21 different buses on chassis dynamometers, generating data for some 180 combinations of vehicle, fuel and driving cycle. The TTW work was topped up by on-road measurements (AVL MTC) as well as some engine dynamometer work (von Thünen Institute).

EC tested altogether 7 vehicles representing EPA 1998, 2007 and 2010 emission regulations. The 1998 vehicle and the three 2010 vehicles had conventional powertrains. Of the three 2007 vehicles one had conventional powertrain and two had hybrid powertrains. EC used 7 test cycles for vehicle evaluation. The fuels tested by EC were three different kinds of ultra-low sulfur diesel ULSD (commercial, oil-sands derived and certification fuel) and biodiesel blends with FAME from canola, soy and tallow. In addition, EC tested HVO as a blending component and as such. The number of combinations evaluated at EC was 68.

Work at **VTT** encompassed 14 vehicle platforms, 6 test cycles and 14 different fuel alternatives, producing a total of 110 different combinations. The emission certification of the vehicles ranged from Euro II (late 90s) to EEV (current regulation).

The vehicle matrix included 10 diesel vehicles, 5 conventional vehicles (Euro II, Euro III, EEV EGR, EEV SCR, EEV SCRT), 4 diesel hybrids (EEV) and one light-weight diesel bus (EEV SCRT). In addition to diesel and diesel replacement fuels (paraffinic GTL and HVO, FAME from Jatropha and rapeseed) VTT also tested natural gas (CNG, Euro V and EEV), additive treated ethanol (EEV) and di-methyl-ether (DME) in dedicated vehicles. The DME vehicle was a prototype heavy-duty truck, simulated as a bus. Therefore the results for DME must be considered indicative, at the most.

Summary of findings

Based on the findings of the project it is possible to establish the effects of various parameters on bus performance. The largest variations and also uncertainties can be found for WTW CO_{2eqv} emissions, or in fact the WTT part of the CO_{2eqv} emissions. The most effective way to reduce regulated emissions is to replace old vehicles with new ones. The most effective way to cut GHG emissions is to switch from fossil fuels to efficient biofuels.

The findings can be summarized and quantified as follows:

Vehicle level

- Old vs. new diesel vehicles
  - 10:1 and even more for regulated emissions
  - 100:1 for particulate numbers
  - close to neutral for fuel efficiency
- Hybridization and light-weighting
  - 20–30% reduction in fuel consumption
  - not automatically beneficial for regulated emissions
  - energy consumption ratio between the least fuel efficient vehicle with conventional power train and the most efficient hybrid 2:1
- Effect of driving cycle
  - 5:1 for fuel consumption and regulated emissions
- Fuel effects on tailpipe emissions (when replacing regular diesel)
  - 2.5:1 at maximum (particulates)
- Alternative fuels (in dedicated vehicles)
  - low PM emissions but not automatically low NO_x emissions
  - fuel efficiency depends on combustion system (compression or spark-ignition)
  - diesel vs. spark-ignited CNG roughly equivalent for tailpipe CO_2

Well-to-wheel level

- Conventional fossil diesel CO_{2eqv}
  - WTT some 20% and TTW some 80% of total WTW
  - 2:1 for WTW for a given fuel (least fuel efficient vehicle with conventional power train and the most efficient hybrid)
- CTL diesel CO_{2eqv}
  - WTT some 60% and TTW some 40% of total WTW
- CTL vs. conventional diesel for CO_{2eqv}
  - 2:1
- CNG, DME, and GTL vs. conventional diesel for CO_{2eqv} (average)
  - ~ +5   +15%
  - CNG equivalent to diesel at its best (local gas)
- Biofuels vs. conventional diesel for CO_{2eqv}[1]
  - relative reduction ~ 30   70% (biofuels from traditional feedstocks)
  - relative reduction ~ 85   95% (biofuels from lignocellulosic feedstocks or waste in vehicles using diesel combustion)
- Conventional biogas vs. CNG for CO_{2eqv}
  - relative reduction ~ 65   90%
- CTL vs. best biofuel for CO_{2eqv}
  - 120:1 (fuel only)
- Biofuels vs. conventional diesel for overall energy
  - 2.5:1   1.75:1
- CNG, DME and GTL from natural gas vs. conventional diesel for overall energy
  - ~1.5:1

Costs

- External costs for NO_x and PM
  - 12:1 variation in unit prices depending on country and region
  - 200:1 in calculatory external costs (including effects of country, region and vehicle, range 0.24   0.001 €/km)
- External costs for CO_{2eqv} (at a price of 40 €/ton of CO_2)
  - 2:1 for vehicle (least fuel efficient vehicle with conventional power train and the most efficient hybrid)
  - 120:1 for fuel (CTL vs. FAME from tallow)
  - 240:1 (fuel and vehicle combined)

[1] Certain GREET values for ethanol resulting in negative GHG values excluded.

- Direct costs (investment, fuel and maintenance), lowest vs. highest
    - ~ +15% (baseline)
    - ~ +20% (high diesel price).

<u>Alternative fuel pathways</u>

The WTT CO_{2eqv} results of biofuels caused the most significant variation for the final WTW results. The WTT results show that the impacts of the region of biofuel production, the raw material used and the technology choices made are crucial to the GHG impacts. In addition, many case specific characteristics, e.g. available energy sources or transportation distances, may cause variation of the results. The results of any GHG emission assessment are vulnerable to uncertainties, and sensitivities. The results may also vary significantly depending on the calculation method used. The models/methodologies used (RED, GREET, GHGenius) have their own calculation assumptions, for example the allocation methods and the consideration of displacement credits for co–products might change between the models.

The WTT GHG emission results are presented in Tables 2.2–2.4. Also other emission components, such as VOC, CO, NO_x, PM, and SO_x emissions were calculated by GREET and GHGenius. The RED only covers GHG emissions.

Table 2.2. GHG emissions of various fuels according to the GREET model.

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Table 2.3. GHG emissions of various fuels according to the GHGenius model.

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Table 2.4. GHG emissions of various fuels according to the RED methodology.

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Vehicle performance

Over the last 15 years, tightening emission regulations and improved engine and exhaust after-treatment technology have reduced regulated emissions dramatically. The most efficient way to reduce regulated emissions is to replace old vehicles with new ones. EC's measurements show that for North America both NO_x and PM have been reduced more than 95% going from EPA 1998 to EPA 2010 (Figure 2.1). For European vehicles, the progress in regulated emissions has not been as remarkable. In round figures NO_x emissions have been cut some 40% and PM emissions some 80% going from Euro II (late 90's) to EEV (current regulation). The oncoming Euro VI emission regulation for Europe roughly corresponds to EPA 2010.

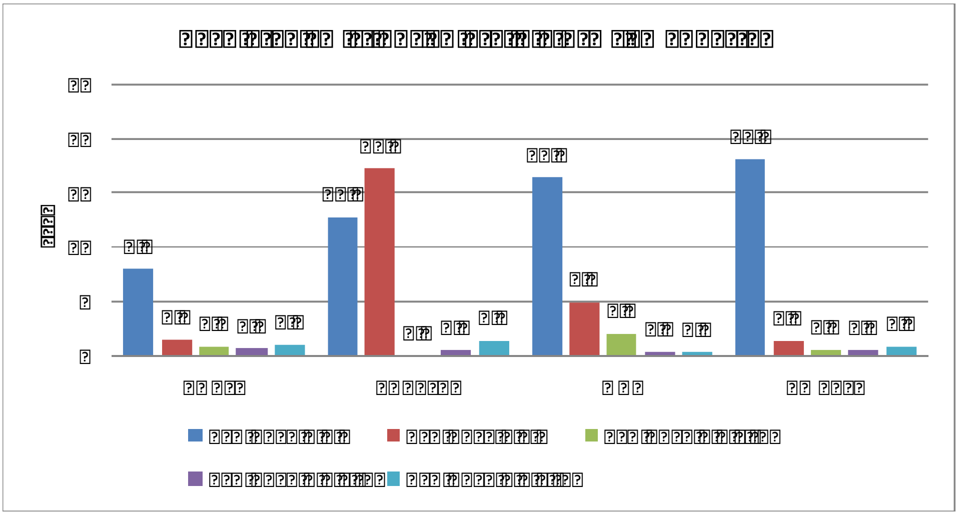


Figure 2.1. Regulated emissions for diesel vehicles with conventional powertrains. North-American vehicles, Manhattan cycle.

Clean burning fuels such as methane, ethanol and DME can still provide some advantages over diesel, but regulated emissions are first and foremost determined by the sophistication of the engine and the exhaust control system. Natural gas in combination with stoichiometric combustion and three-way catalyst delivers low regulated emissions, NO_x and PM. All natural gas engines, independent of combustion system, deliver low particulate emissions, equivalent to particulate filter equipped diesel engines. The drawback of current spark-ignited gas engines is high energy consumption in comparison with diesel engines. Additive treated ethanol as well as DME deliver diesel-like efficiency but with lower engine-out particulate emissions.

Figures 2.2 (NO_x) and 2.3 (PM) show emission results for European vehicles.

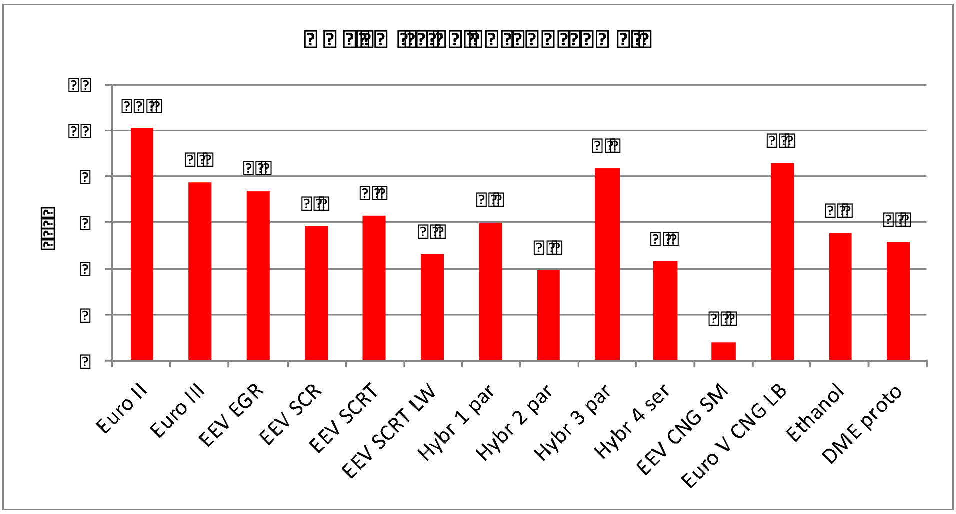


Figure 2.2. NO_x emissions of all tested European vehicles. Braunschweig cycle.

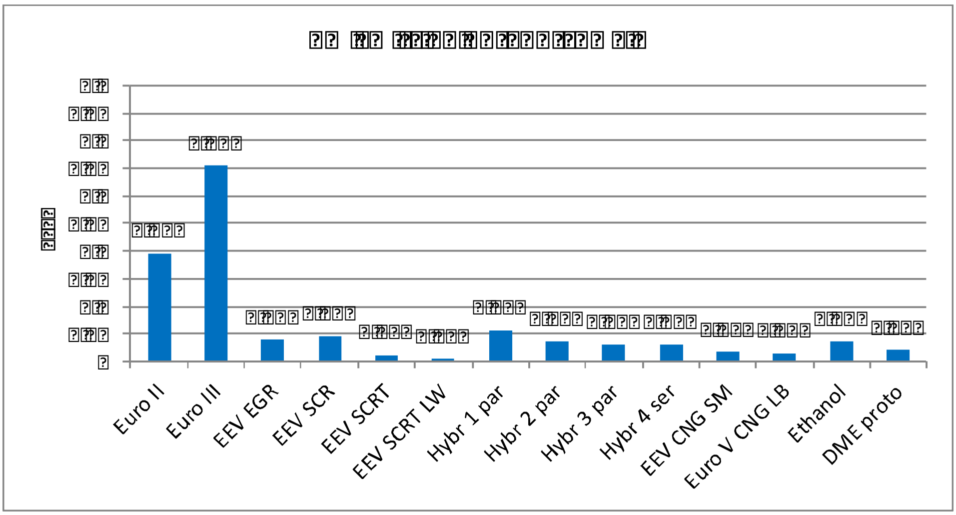


Figure 2.3. PM emissions of all tested European vehicles. Braunschweig cycle.

Hybridization or light-weighting reduce fuel consumption 20–30% on an average, but otherwise the improvements in fuel efficiency have not been so spectacular. In the case of diesel engines sophisticated engine controls and injection systems in principle reduce fuel consumption. Emission control systems such as EGR and particulate filters, on the other hand, tend to increase fuel consumption. As a consequence, at Environment Canada, the US 1998 diesel bus tested had the same fuel consumption as the two US 2010 diesel buses on an average.

For Europe, fuel consumption went down going from mechanically controlled Euro II vehicles towards more sophisticated vehicles, with EEV SCR delivering lowest fuel consumption. The introduction of Euro VI is expected to increase fuel consumption somewhat. Figure 2.4 shows energy consumption for European vehicles. The ratio between highest and lowest value is 2:1.

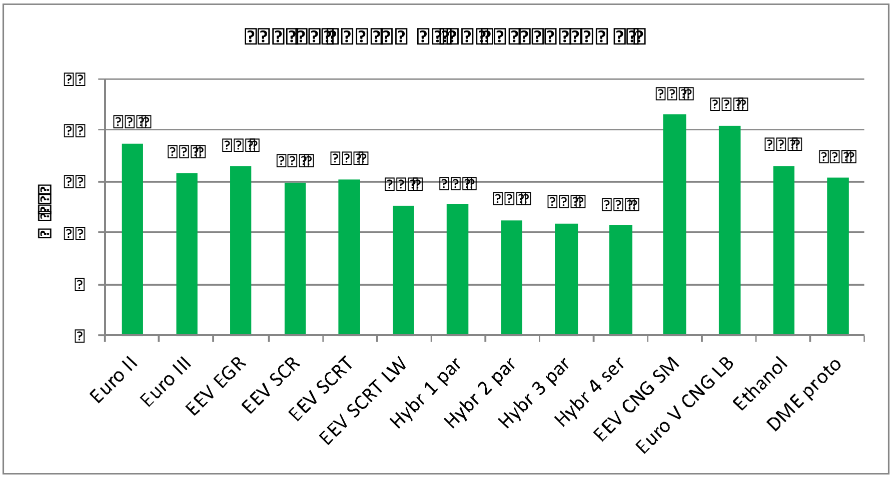


Figure 2.4. Energy consumption of all tested European vehicles. Braunschweig cycle.

Tailpipe CO_2 emissions (Figure 2.5) is a combination of energy consumption and fuel carbon intensity. In the case of CNG, the lower carbon intensity of methane in comparison to diesel basically compensates for the higher energy consumption.

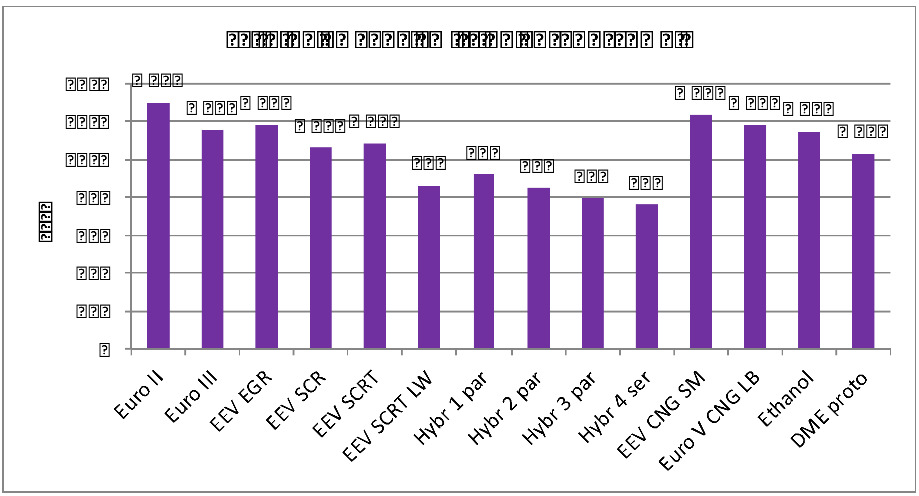


Figure 2.5. Tailpipe CO_{2eqv} emissions of all tested European vehicles. Braunschweig cycle. CH_4 taken into account with a factor of 23 for CNG, ethanol and DME.

The driving cycle affects fuel consumption and in most cases also regulated emissions by a factor of 5:1. The stoichiometric CNG vehicle differs from the other vehicles as it delivers very low NO_x and PM emissions regardless of the cycle (Figure 2.6). The benefits of hybridization depend on the driving cycle. In severe low-speed cycles hybridization saves close to 40% fuel. Figure 2.7 shows an example on the effects of driving cycle and hybridization on fuel consumption.

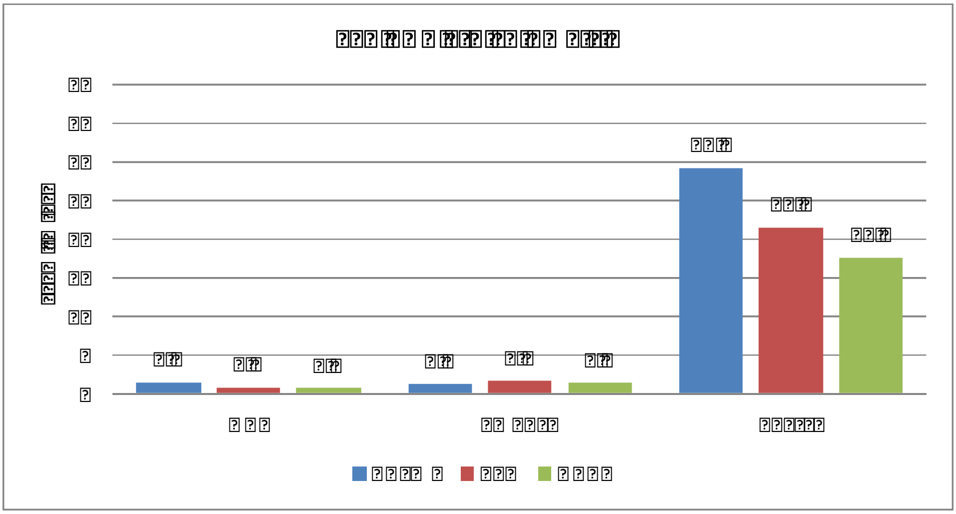


Figure 2.6. The effect of driving cycle on NO_x, PM and fuel consumption. EEV CNG stoichiometric.

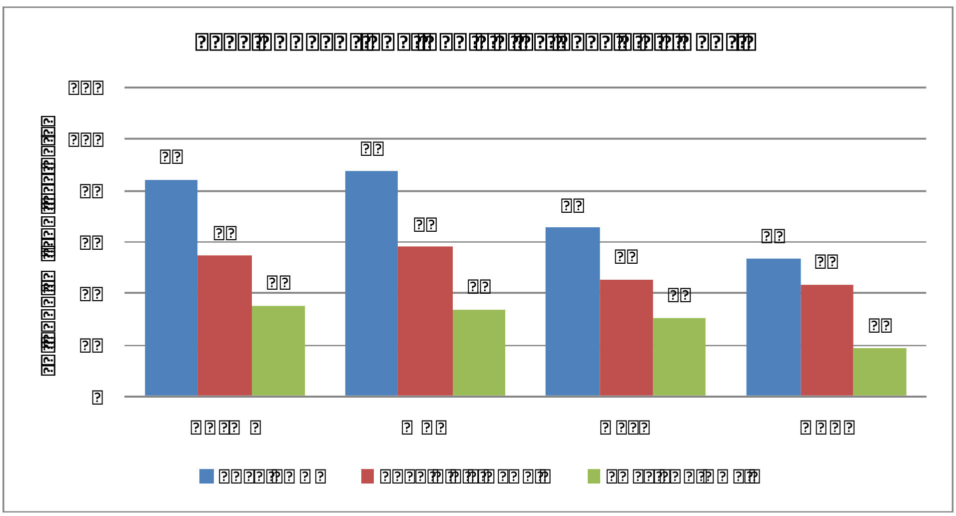


Figure 2.7. An example of driving cycle and hybridization on fuel consumption.

Fuel effects on vehicle emissions

Emission performance and fuel quality are interconnected. Sophisticated diesel engines, especially those equipped with exhaust gas after-treatment require high-quality practically sulfur-free fuels. High aromatic and sulfur content increase exhaust toxicity and/or particulate emissions. In all measurements in this project, the reference fuel was high quality commercial diesel with a sulfur content less than 10 or 15 ppm. If the reference fuel had been low-quality high-sulfur diesel, the effects of fuel replacement would have been more accentuated.

Now the fuel effects for diesel replacement fuels were at maximum 2.5:1 for regulated emissions (particulates, Figure 2.8).

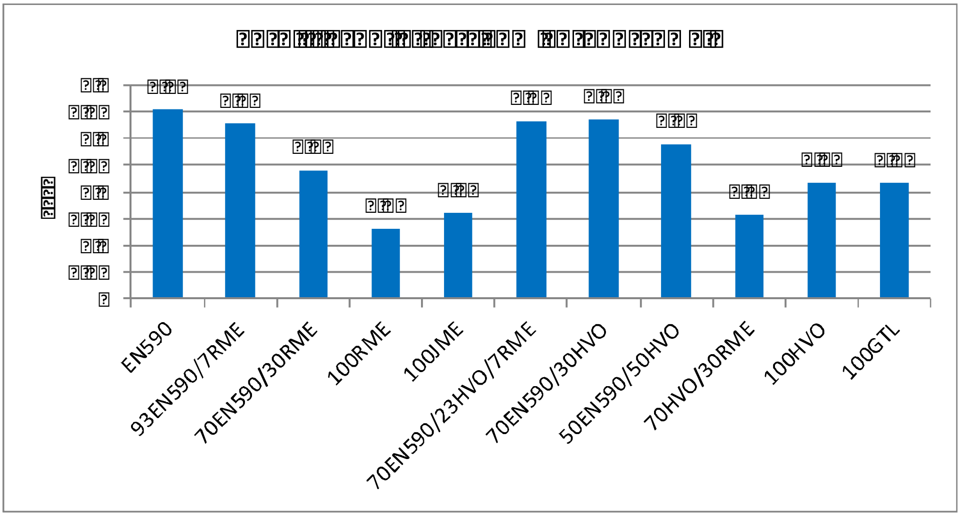


Figure 2.8. Fuel effects on PM emission. Euro III diesel.

FAME type biodiesel is effective for PM reduction, but tends to increase NO_x emission (Figure 2.9). Paraffinic diesel fuels (GTL, HVO) have a potential for simultaneous reductions of NO_x and PM. Paraffinic diesel also delivered significant reductions in exhaust toxicity and mutagenicity (Figure 2.10).

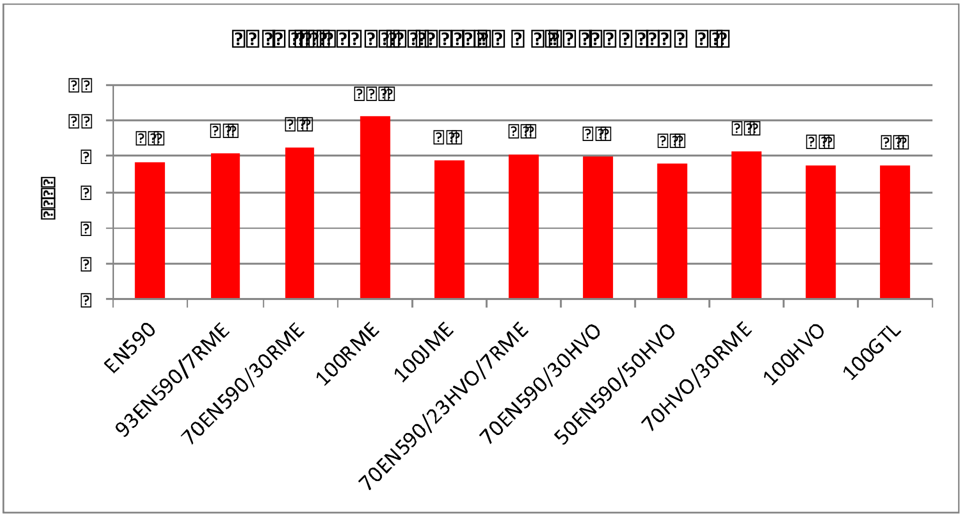


Figure 2.9. Fuel effects on NO_x emission. Euro III diesel.

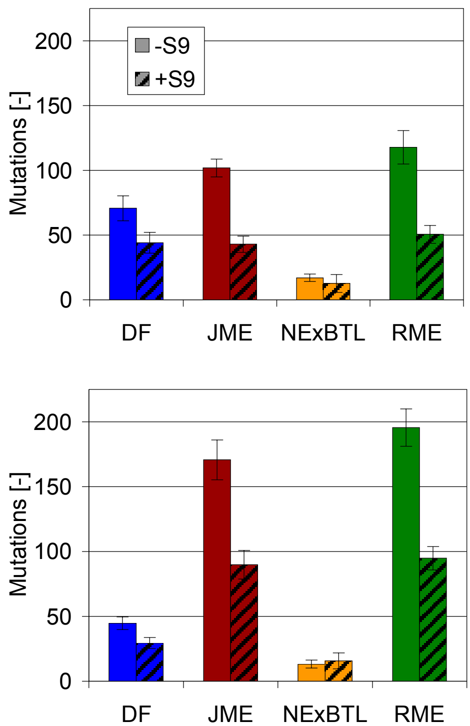


Figure 2.10. Mutagenicity of PM extracts (left) and condensates (right) in strain TA98 (ESC test, OM 906). DF= diesel fuel, NExBTL= HVO.

Some older engines have been approved for 100% FAME type biodiesel. However, most manufacturers do not approve the use of 100% FAME in newer engines with sophisticated exhaust after-treatment systems such as particulate filters. Paraffinic diesel, whether BTL, CTL, GTL or HVO, are drop-in type fuels which in principle can deliver 100% replacement without any modifications to the refueling infrastructure or the vehicles. When applying biofuels, the fuel requirements of the local bus fleet on one hand and the local availability of biofuels on the other hand have to be taken into account. Therefore the optimum solution for Europe and Euro VI vehicles can be a different one compared, e.g., to Thailand and older vehicles.

Well-to-wheel results

Well-to-wheel GHG emissions were calculated using RED, GHGenius and GREET data for the WTT part and combining this data with actual bus performance data. Results were calculated for 8 different vehicle platforms. WTW energy consumption was also calculated.

For fossil fuels, WTW CO_{2eqv} intensity varies with a factor of around 3, between 65 g CO_{2eqv}/MJ (natural gas) and 185 g CO_{2eqv}/MJ (CTL). In the Braunschweig cycle, energy consumption varies from 10 to 22 MJ/km, giving a WTW range of 1000 g CO_{2eqv}/km (European hybrid with conventional diesel) to 4000 g CO_{2eqv}/km (US 2010 diesel bus with CTL).

In the case of biofuels, the extreme WTW CO_{2eqv} intensity values range from nil to close to 2000 g CO_{2eqv}/MJ[2]. The latter value with an energy consumption of 22 MJ/km would mean a figure of some 40,000 g CO_{2eqv}/km. For the biofuels included in the actual WTW assessment in this study the WTW values vary with a factor of 40 (this excludes certain GREET values for ethanol resulting in negative GHG values). In the case of the EEV SCRT vehicle the range is 24 g CO_{2eqv}/km (tallow to FAME/GHGenius) to 943 g CO_{2eqv}/km (palm oil HVO, process not specified/RED). Comparing tallow based FAME to CTL, the factor is some 120 (Figure 2.11). Taking into account vehicle energy consumption (2:1), the ratio for the extreme value is 240:1.

[2] This result is from the literature review made (Chapter 15.2) and presents a worst case scenario of effects due to the indirect land use change that could occur due to biofuel production. Here the assumption is that some tropical forest on peat land would be cut and the methane stored in soil would be released to the atmosphere.

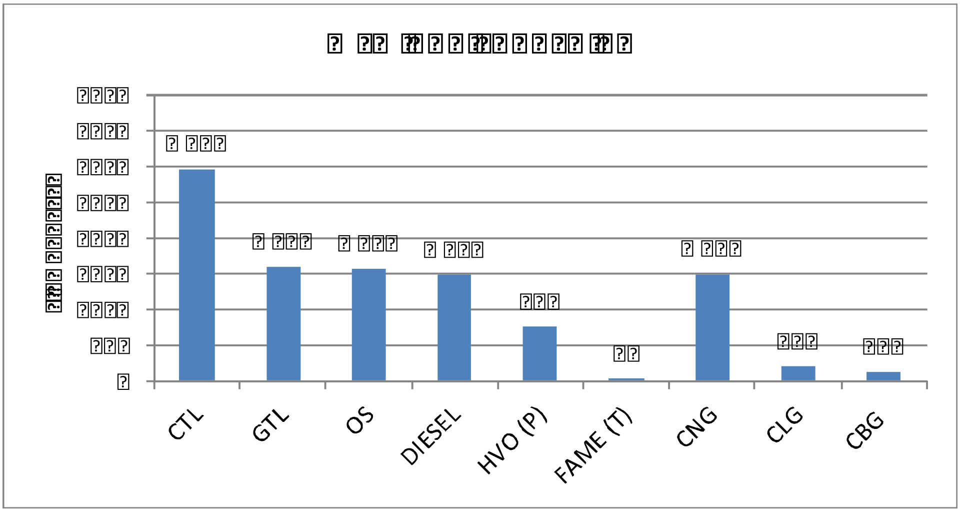


Figure 2.11. WTW GHG emissions for SCRT diesel and alternative fuel vehicles. GHGenius methodology. Braunschweig cycle.

Table 2.5 presents a summary of CO_{2eqv} values. Included are four fossil pathways (GTL, conventional diesel, CNG, natural gas based DME) and the renewable pathways delivering highest and lowest WTW CO_{2eqv}values. Not all biofuels are covered here.

Table 2.5. Summary of CO_{2eqv} values. Highest and lowest value for each category highlighted. According to GREET, some ethanol alternatives result in negative GHG values.

	Diesel fossil		Diesel renewable		GNG	CBG ren.		Ethanol		DME fossil	DME renewable	
	GTL	conv.	max	min		max	min	trad.	lign.		max	min
RED			HVO(P1)	BTL(WW)		OW	WM	WH	ST		FW	WW
	1417	1324	943	61	1693	500	350	764	185	1399	151	120
GHGEN			HVO(P)	FAME(T)		LF	OW					
	1590	1473	751	24	1489	195	124					
GREET			HVO(D)	FAME(D)		CLG	CNG(M)	C	FW			B
	1745	1441	513	75	1794	372	360	1189	-119	1596		41
AVG	1584	1413			1659					1498		
Relative to regular diesel (%)												
	+12	100			+17					+6		

Variations in WTW energy consumption are much smaller than for WTW CHG emissions. Using the European JEC values diesel delivers lowest overall energy consumption and sugarcane ethanol the highest (Figure 2.12). For the EEV SCRT diesel the values are from 18 to 46 MJ/km, a ratio of 1:2.5. In the case of diesel the WTT is some 16% of the total energy use, for ethanol some 64%.

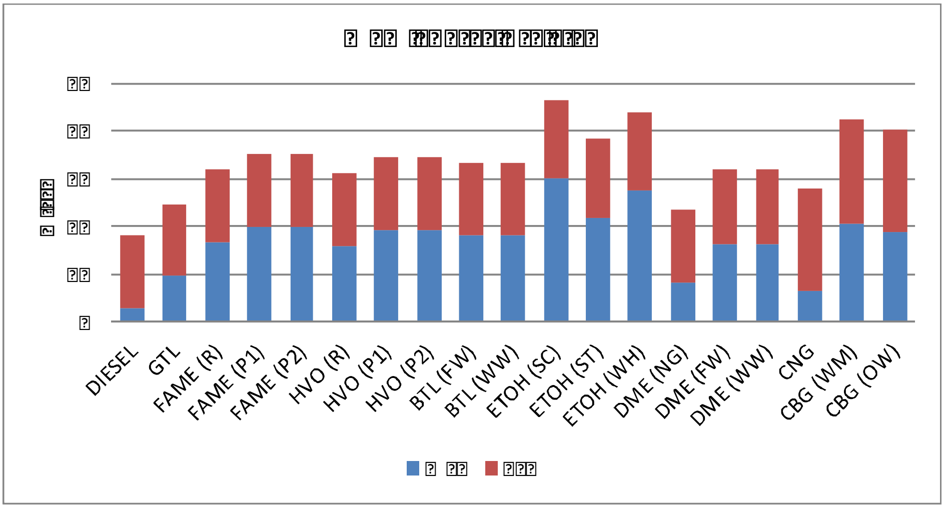


Figure 2.12. WTW energy using JEC values (Europe). Braunschweig cycle.

Cost assessments

Both external (emissions) and direct costs were calculated for the various technology and fuel options. The estimates of external costs were done according to the principles laid out in the European "Handbook on estimation of external cost in the transport sector". The external costs (unit costs) are differentiated by countries and in the case of particulates, also by areas or regions. Most of the calculations were done for the Braunschweig cycle. Calculations were done for three countries, Finland, France and Germany, and for three different population densities (megacity/ADEME cycle, mid-sized city/Braunschweig cycle, outside built-up areas/UDDS cycle).

The **external costs** for regulated emissions vary between 0.001 €/km (stoichiometric CNG, UDDS, Finnish values) and 0.24 €/km (Euro II diesel, ADEME, German values), a factor of some 1:200. The methodology emphasises NO_x emissions, not particulates, so even for the old Euro II vehicle NO_x dominates the emission costs. For the Braunschweig cycle, the emission costs are 0.01–0.12 €/km (German mid-size city values, Figure 2.13). The calculated emission benefit in switching from regular diesel to GTL or HVO is 0.01–0.05 €/km. For the newest vehicles with low emissions the benefit is rather limited.

At a CO_2 price of 40 €/ton, the calculated WTW CO_2 costs is 0–0.12 €/km (Figure 2.14).

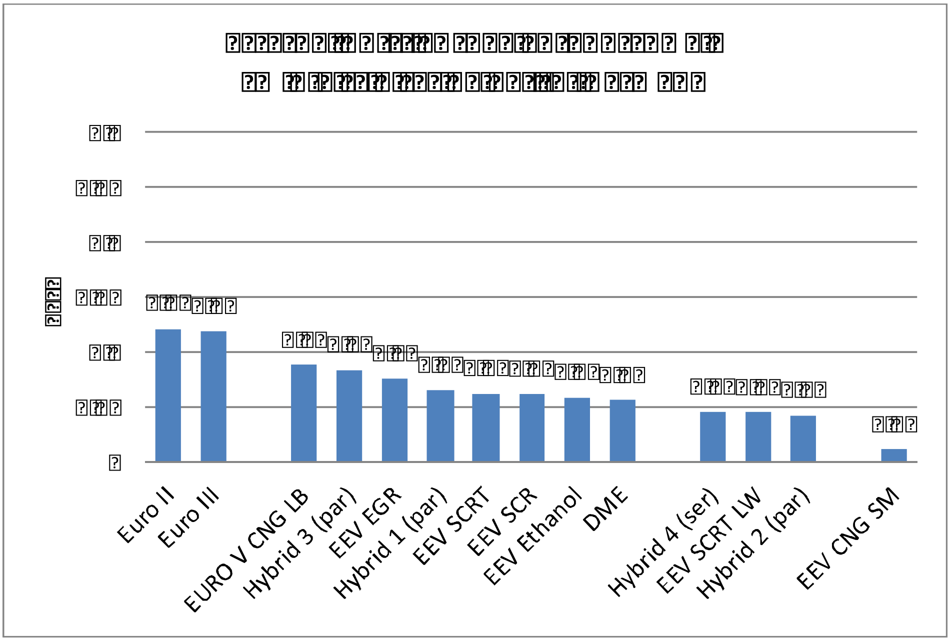


Figure 2.13. External costs. Braunschweig cycle, urban area, using external costs for Germany (maximum case).

Estimates of **direct costs** were calculated taking into account vehicle investment costs, costs for fuel and urea and very rough estimates of maintenance costs. The calculations are indicative, as no fixed price lists are available for buses, nor are there universal price lists for fuels. Taxes and subsidies for fuels and vehicles will vary from market to market. **Please note that no taxes or subsidies are included in the calculations.** Taxes and subsidies might change the competitiveness of certain technologies considerably.

Calculations were made for seven European vehicle platforms, EEV SCRT diesel, light-weight EEV SCRT diesel, Euro VI diesel (imaginary, roughly equivalent to US 2010), hybrid EEV diesel, EEV ethanol, Euro V CNG lean-burn and EEV CNG stoichiometric. DME was left outside this assessment.

The calculation was made for the Braunschweig cycle, using actual measured fuel consumption values with the exception of the imaginary Euro VI diesel vehicle, which is estimated to consume 5% more fuel and 50% more urea that the baseline EEV SCRT diesel vehicle. Fuel prices are based on actual values for diesel and CNG, and IEA estimates for biofuels.

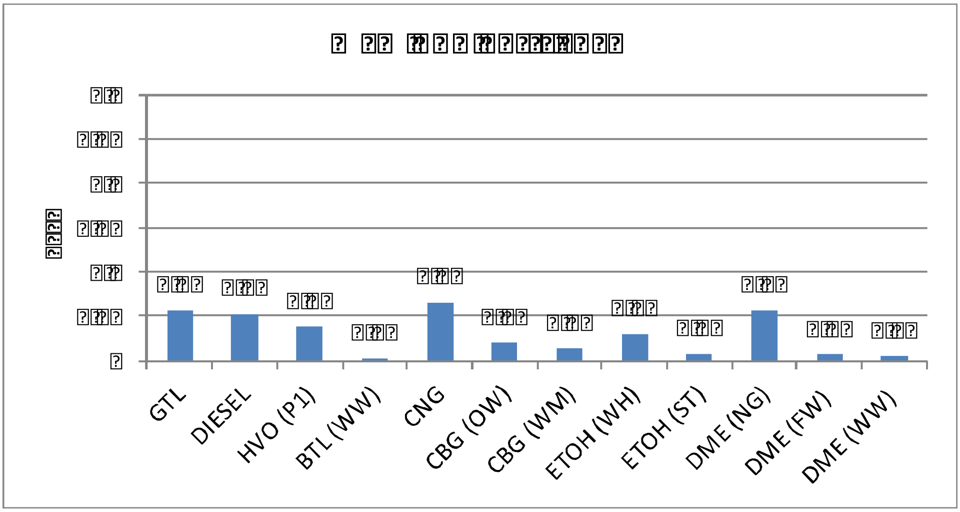


Figure 2.14. WTW GHG costs using RED methodology. Braunschweig cycle. Cost for CO_2 40 €/ton.

Using baseline assumptions (diesel fuel 0.65 €/l, CNG 0.65 €/kg, additive treated ethanol 0.38 €/l), the direct costs, including investment cost for the bus, fuel costs and maintenance costs is 0.63–0.77 €/km. Light-weight diesel and baseline SCRT are at some 0.65 €/km and the rest of the vehicles at some 0.75 €/km (Figure 2.15). On an annual basis, with a mileage of 80,000 km, the difference in operational costs is at maximum some 12,000 €.

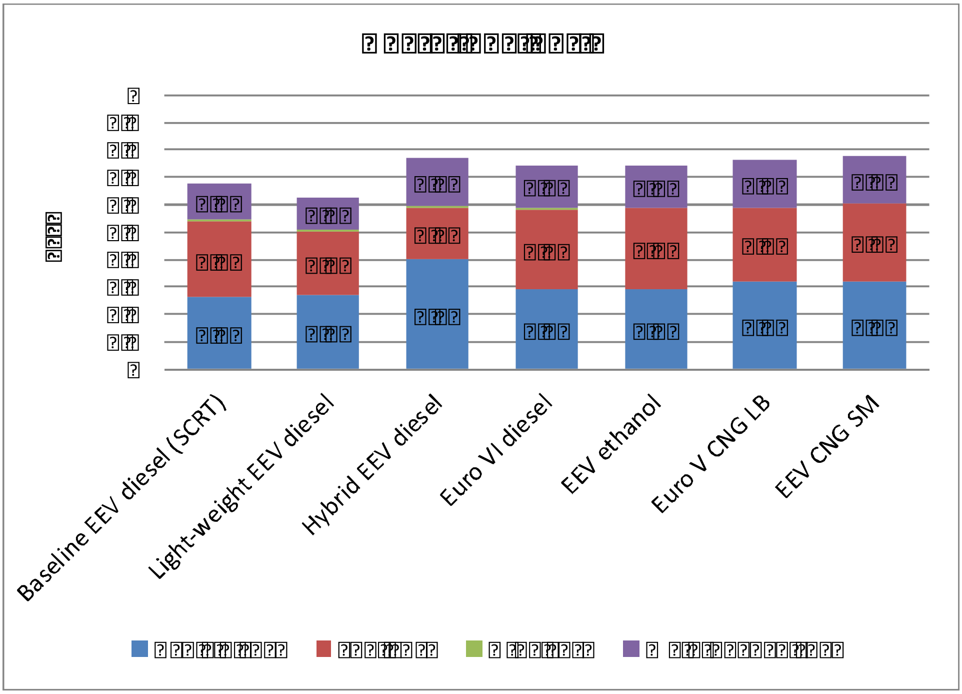


Figure 2.15. Operational costs (indicative) for various vehicle options. Baseline assumptions.

Calculating with a high diesel price of 0.90 €/km would increase the cost of the diesel options some 0.10 €/km. Operational costs are in the range of 0.72–0.85 €/km. Light-weight EEV SCRT diesel is still the cheapest option. Natural gas and ethanol are now competitive with the diesel options, with the exception of the light-weight diesel.

For the baseline case, the additional cost for the hybrid was estimated at some 55%. With a diesel price of 0.60 €/l, the hybrid is not cost competitive. A combination of a diesel price of 0.90 €/l and an additional price of 35% for the hybrid systems makes the hybrid cost competitive.

In the base case going from conventional diesel to BTL would increase operational costs some 20% and going from natural gas to biogas some 10%. Taking into account external costs for regulated emissions and CO_2 would increase the competiveness of the bio-alternatives.

Preface

City buses are the backbone of many public transport systems, and therefore they constitute a very important element of the transportation system. Procurement of bus services is often handled by municipalities or local governments in a centralized manner. So far, conventional diesel buses and conventional diesel fuel have dominated the market, with some contribution from natural gas buses. Now we are in a situation in which the technology options are increasing rapidly. This goes for vehicle technology as well as fuels. Advanced diesel vehicles producing very low emissions are entering the market, and hybrids are becoming commercially available. On the fuel side, various biofuels are offered as blending components or to be used as such. Natural gas and biogas can still deliver emission benefits over diesel. Additive treated ethanol is available for captive fleets such as city buses, and DME has progressed into the field testing phase.

The diversification in technology increases the challenges in decision making. The objective of this project was to generate unbiased and solid data for use by policy- and decision-makers responsible for public transport using buses. To provide a full picture of performance, well-to-tank fuel pathways and vehicle end-use performance were combined to produce figures on well-to-wheel energy consumption and greenhouse gas emissions. However, also tailpipe exhaust emissions and energy efficiency of the vehicle itself were given substantial attention. Finally estimates of direct as well as indirect costs were made for different technology alternatives.

The project was carried out in cooperation with IEA's Implementing Agreements on Advanced Motor Fuels (AMF) and Bioenergy. Within AMF, the project was carried out as Annex XXXVII (37), within Bioenergy as a special operation within Task 41. Other IEA Implementing Agreements contributed with technology outlook reports.

Several countries contributed with actual work to the project: Canada, Finland, France, Germany, Sweden, Thailand and USA. The project combined both task and cost sharing. Contributions in the form of cost sharing were received from the European Commission, Japan and Switzerland. A full listing of partners, contributors and acknowledgements is given later on in the report. The project reported to the Executive Committees of AMF and Bioenergy. VTT, who was responsible for compiling this summary report, wishes thank all involved parties and contributors for good cooperation.

The supporters of this project generously agreed to bring this work into the public domain without any waiting period. This report adds to the long list of original and unique data on vehicle and fuel performance that has been generated within the IEA Implementing Agreement on Advanced Motor Fuels.

Espoo 31.8.2012

Nils-Olof Nylund & Kati Koponen

Contents

List of abbreviations

ADEME	French Environment and Energy Management Agency
ADEME-RATP	Parisian bus cycle
AEZ	Agricultural ecological zone
AFC	(IEA) Advanced Fuel Cells Implementing Agreement
ALL	Energy allocation (GREET)
AMF	(IEA) Advanced Motor Fuels Implementing Agreement
AMT	(IEA) Advanced Materials for Transport Implementing Agreement
ANL	Argonne National Laboratory
B	Biomass
BD	Biodiesel (FAME)
BRA	Braunschweig bus cycle
BTL	Biomass-to-liquids
Bxx	xx concentration (v/v) of FAME in diesel
C	Corn
CA	Carbon content allocation
CARB	California Air Resources Board
CBD	Central business district bus cycle
CBG	Compressed biogas
CCS	Carbon capture and storage
CEN	European Committee for Standardization
CERT	Certification diesel fuel
CFC	Chlorofluorocarbons
CFR	Code of Federal Regulations
CH_4	Methane
CLD	Chemiluminescence detector
CLG	Compressed landfill gas
CME	Canola methyl ester
CNG	Compressed natural gas
CO	Carbon monoxide
COM	Commercial
CO_2	Carbon dioxide
CO_2eq	Carbon dioxide equivalent
CPC	Condensation particle counter

CRT	Continuously regenerating trap (diesel particulate filter)
CS	Corn stover
CTL	Coal-to-liquids
CVS	Constant volume sampler
CWA	CEN Workshop Agreement
D, DISP	Displacement (GREET)
DAD	Diode array detector (HLPC)
DF	Diesel fuel
DGS	Distiller's grains plus solubles
DME	Di-methyl-ether
DNPH	2,4-Dinitrophenylhydrazine (Brady's reagent) for aldehyde sampling
DOC	Diesel oxidation catalyst
DPF	Diesel particulate filter
EA	Energy allocation
EC	Environment Canada
EEPS	Engine exhaust particle sizer
EEV	Enhanced environmentally friendly vehicle
EGR	Exhaust gas recirculation
ELPI	Electrical low pressure impactor
ENxxx	European fuel standard
EPA	Environmental Protection Agency
ERMS	Emissions Research and Measurement Division (EC)
ESC	European steady cycle
ETC	European transient cycle
EtOH	Ethanol
EU	European Union
Euro II	
EEV	Heavy-duty emission certification classes for Europe
FAME	Fatty-acid methyl ester
FC	Fuel cell
FC	Fuel consumption
FID	Flame ionization detector
FLD	Postcolumn fluorescence derivatization (HPLC)
FOB	Free on board/Freight on board
FT	Fischer-Tropsch
FW	Farmed wood
FTF	Flow-through filter
FTIR	Fourier transformation infrared spectroscopy
CG	Gas chromatography
GHG	Greenhouse gases
GTAP	Global Trade Analysis Project
GTL	Gas-to-liquids
GVW	Gross vehicle weight
GWP	Global warming potential
HC	Hydrocarbons
HD, HDV	Heavy-duty vehicle

HEV (HV)	Hybrid electric vehicle
HEV	(IEA) Hybrid and Electric Vehicle Implementing Agreement
HFC	Hydrofluorocarbons
HFID	Heated flame ionization detector
HHV	Higher heating value
HP	Horse power
HPDI	High pressure direct injection
HPLC	High-performance liquid chromatography
HRD	Hydrotreated renewable diesel
HVO	Hydrotreated vegetable oil
HYB	Hybrid
H_2	Hydrogen
ICE	Internal combustion engine
IEA	International Energy Agency
ILUC	Indirect land use change
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
JEC	Joint Research Centre – EUROPIA – CONCAWE
JE05	Japanese vehicle test cycle
JME	Jatropha methyl ester
JRC	Joint Research Centre
LB	Lean-burn
LCA	Life cycle assessment
LCFS	Low carbon fuel standard
LCI	Life cycle inventory
LDT	Light-duty truck
LEM	Lifecycle emissions model
LF	Landfill
LHV	Lower heating value
LLG	Liquefied landfill gas
LNG	Liquefied natural gas
LPG	Liquefied petroleum gas
LUC	Land use change
LW	Light-weight
M	Manure
M	Megacity
MA	Mass allocation
MAN	Manhattan bus cycle
MY	Model year
NA	North American
NDIR	Non-dispersive infrared detector
NDUV	Non-dispersive ultraviolet detector
NG	Natural gas
NMHC	Non-methane hydrocarbons
NMVOC	Non-methane volatile organic compounds
NO_x	Nitrogen oxides

NO_2	Nitrogen dioxide
NRCan	Natural Resources Canada
NTE	Not to exceed
NYBUS	New York bus cycle
N_2O	Nitrous oxide
OC	Oxidation catalyst
OCTA	Orange County Transportation Authority bus cycle
OS	Oil sands
OW	Organic waste
O_2	Oxygen
P	Palm (palm oil)
PAH	Polyaromatic hydrocarbons
PAR	Parallel (hybrid)
PASS	Photo acoustic soot sensor
p-DPF	Partial diesel particulate filter
PEMS	Portable emissions measurement system
PM	Particulate matter
R	Rapeseed
RD	Renewable diesel (HVO)
RED	Renewable Energy Directive
RFS	Renewable fuel standard
RME	Rapeseed methyl ester
S	Outside built-up areas (in external cost calculations)
S	Soy
S	Substitution method (in LCA assessments)
SAE	Society of Automotive Engineers
SC	Sugarcane
SCO	Synthetic crude oil
SCR	Selective catalytic reduction (for NO_x)
SCRT	SCR + CRT
SER	Series (hybrid)
SFC	Specific fuel consumption
SG	Switchgrass
SM	Stoichiometric
SME	Soy methyl ester
SMPS	Scanning mobility particle sizer
SNG (SG)	Synthetic natural gas (methane)
SOF	Soluble organic fraction
SORT	Standardised on-road test cycles
SO_x	Sulfur oxides
ST	Straw
SVO	Straight vegetable oil
T	Tallow
TECA	Total energy cycle analysis
THC	Total hydrocarbons
TME	Tallow methyl ester

TPM	Total particulate matter
toe	ton of oil equivalent
TTW	Tank-to-wheel
TWC	Three-way catalyst
U	Mid-sized city (urban)
UDDS	Urban dynamometer driving cycle
UITP	International Association of Public Transport
ULSD	Ultra low sulfur diesel
US	United States
VA	Value allocation
VAT	Value added tax
VELA	Vehicle laboratory (JRC)
VOC	Volatile organic compounds
vTI	von Thünen Institute
VTT	VTT Technical Research Centre of Finland
WH	Wheat
WHSC	World harmonized steady cycle
WHTC	World harmonized transient cycle
WHVC	World harmonized vehicle cycle
WM	Wet manure
WTT	Well-to-tank
WTW	Well-to-wheel
WW	Waste wood

3. Introduction

City buses, which are the backbone of most public transport systems, are amongst the most uniform vehicle fleets. The baseline bus in most parts of the world is a diesel powered 12 meter or 40 feet long bus. Procurement of bus services is often handled by municipalities or states in a centralized manner. Public transportation using buses has a positive impact overall. However the impact of city buses on urban air quality in many world cities is huge, especially if the vehicles are old. Fuel efficiency, on the other hand, is crucial for operational costs. Whilst these variables and their impacts are routinely evaluated in a local (end use) context, there remains in most such assessments an unmet need when comparing fuels and engine technologies: accounting for the full environmental and energy burdens of the alternatives along a fuel's pathway from raw materials extraction, fuel production, and transportation and distribution to end use. To accomplish this it is necessary to apply "well-to-wheel" analysis methods.

Numerous studies on well-to-wheel greenhouse gas (GHG) emissions and energy use in transportation have been carried out, but most of them related to passenger cars. Studies on heavy-duty vehicle options are rare, partly due to the fact that there are no internationally recognized test procedures to measure distance based fuel consumption or exhaust emissions values for heavy-duty vehicles. In 2005–2007, VTT, Environment Canada and West Virginia University joined forces within IEA Advanced Motor Fuels to evaluate test methods for city buses (Nylund et al. 2007). In addition to describing differences in various test cycles, the study pointed out huge differences in vehicle performance arising from diesel emission control technology, fuel (diesel vs. natural gas) and powertrain configuration (conventional vs. hybrid), all of which redound to the magnitude of energy consumption and total residuals on the fuel pathways.

Well-to-wheel (WTW) thinking about a fuel chain can be broken into two main segments: well-to-tank (WTT) and tank-to-wheel (TTW) (Figure 3.1).

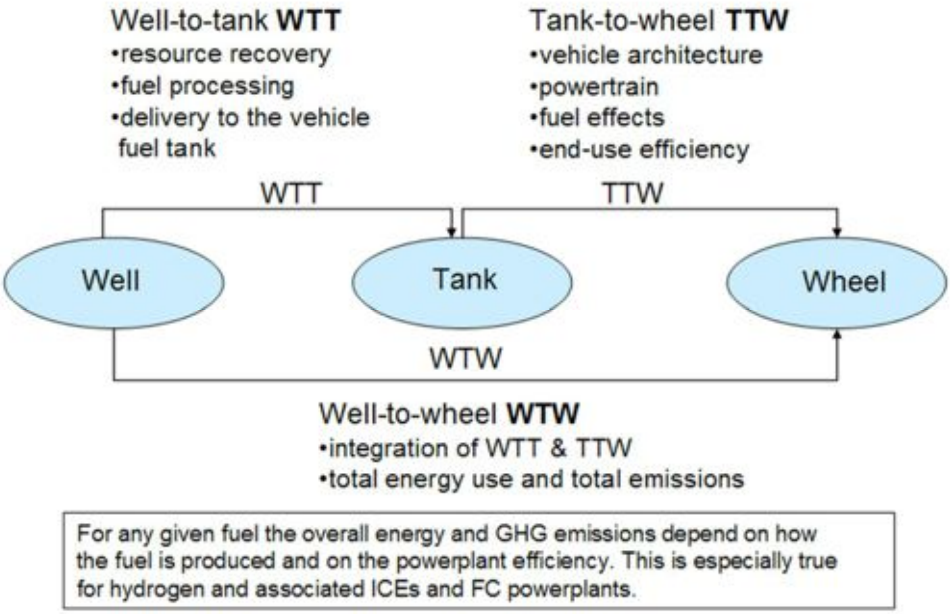


Figure 3.1. The concept of well-to-wheel thinking.

The WTT segment for a given fuel is in principle not dependent on whether the fuel is used in a passenger car or in a bus. Small variations could occur depending on whether the fuel is used in general service or in captive vehicle fleets. On the other hand, for certain processes the end-use performance is not dependent on on the feedstock for the fuel. For example, synthetic diesel fuel from either natural gas or biomass via synthesis gas using Fischer-Tropsch (FT) synthesis should give equivalent end-use performance on the condition that the FT stage and post-processing are identical.

Combining existing WTT data for passenger cars, but capable of generalization over any vehicle, with actual test-based TTW data for buses will enable compilation of city bus-specific data on overall WTW energy efficiency and emissions for alternative vehicle and fuel technologies. What follows is a “best practice manual” designed to assist bus fleet owners and operators in making choices amongst candidate technologies in achieving objectives related to GHG reduction and renewable energy for transport (e.g. Kyoto Accord and the European Union’s Renewable Energy Directive of June 2009). It is not intended as a prescriptive document, for the authors are amply aware that cost and related non-environmental decisions must play a role in the fuel and vehicle choices of a bus fleet. What we intend is that the users of this manual gain a better understanding and appreciation of the comparative benefits and advantages of fuel and technology choices expected to be available to them in the year 2012 and beyond.

Fleets such as city buses are very suitable for the introduction of new fuels. For example, natural gas or biogas is quite commonly used in city buses. At the moment, experts are actively debating the true performance and the sustainability of certain liquid biofuel options. Almost all types of vehicles benefit from hybridization. Efficiency improvements of hybrid (HEV) technology in conjunction with internal combustion engines are due to two major advantages. First, hybrid technology makes it possible to smooth out the operation of the ICE and run the engine only under loads that result in the best fuel efficiency. Secondly, the recuperation of braking energy otherwise lost as heat significantly contributes to improved efficiency. Fuel savings of HEV systems are dependent on duty cycles, and city bus services with their regular stop-and-go driving patterns are ideal for hybrid applications. Fuel savings of more than 30% can be achieved (Chandler & Walkowicz 2006).

4. Goal

It is obvious that the spectrum of vehicle and fuel technologies is widening, not closing in. This poses a challenge to decision makers at all levels; governments, local authorities as well as fleet operators. Both when setting policies and when procuring new vehicles, the following questions must be confronted:

- Which technology or fuel/technology combination gives the best overall energy efficiency?
- Which technology or combination yields the lowest overall greenhouse gas emissions?
- Which technology or combination is best for reduced local emissions and improved urban air quality?
- Which option provides the best overall cost efficiency for reduction of GHG emissions as well as local emissions?
- Which clean fuel options can be implemented for existing vehicle fleets?

The objective of the task is to bring together the expertise of IEA's transport related implementing agreements to access reliable information on overall energy efficiency, emissions, and costs (both direct and indirect) of various technology options for buses. The technology options vary with respect to engine technology, powertrain technology and fuels.

The outcome of the task will be unbiased and solid IEA-sanctioned data for use by policy- and decision-makers responsible for public transport using buses.

5. Partners and sponsors

The project was carried out in cooperation between the IEA Implementing Agreements on Advanced Motor Fuel (AMF) and Bioenergy. The project was carried out as a combination of task and cost sharing. The Implementing Agreement contracting parties and agencies contributing to the project were:

Advanced Motor Fuels:

- Canada (task sharing)
  - Natural Resources Canada
  - Environment Canada
- Finland (task and cost sharing)
  - Tekes – the Finnish Funding Agency for Technology and Innovation
  - Helsinki Region Transport
  - VTT Technical Research Centre of Finland
- France (task and cost sharing)
  - ADEME – French Environment and Energy Management Agency
- Japan (cost sharing)
  - LEVO – Organization for the promotion of low emission vehicles
  - NEDO – New Energy and Industrial Technology Development Organization
- Sweden (cost sharing)
  - The Swedish Transport Administration
- Switzerland (cost sharing)
  - BFE – Swiss federal Office of Energy
- Thailand (task sharing)
  - NSTDA – National Science and Technology Development Agency
- USA (task sharing)
  - US Department of Energy
  - Argonne National Laboratory.

Bioenergy:

- European Commission (cost sharing)
  - DG Energy
- Finland (cost sharing)
  - VTT Technical Research Centre of Finland
- Germany (cost sharing)

- FNR – Agency for Renewable Resources.

The overall budget of the project was some 1.2 M€. The overall project coordination was handled by VTT, who also was responsible for compiling the final report.

The following teams and persons and persons contributed to the tasks of the project:

Well-to-tank assessments:

- Argonne National Laboratory, USA
  - Christopher Saricks
  - Michael Wang
  - Jeongwoo Han
- Natural Resources Canada, Canada
  - Craig Fairbridge
  - Jean-Francois Gagné
  - Derek McCormack
- VTT, Finland
  - Kati Koponen
  - Sampo Soimakallio
  - Kamarat Jermsirisakpong (on exchange from University of California, Riverside, USA, through a scholarship from Honda Motor Company, Japan).

Tank-to-wheel assessments (bus measurements):

- Environment Canada, Canada
  - Eric Meloche
  - Greg Rideout
  - Deborah Rosenblatt
  - Tak Chan
- VTT, Finland
  - Matti Ahtiainen
  - Kimmo Erkkilä
  - Päivi Koponen
  - Petri Laine
  - Timo Murtonen.

Engine dynamometer testing (emission characterization):

- Johann Heinrich von Thünen Institute, Braunschweig, Germany
  - Axel Munack
  - Christoph Pabst
  - Jens Schaak
  - Lasse Schmidt
  - Olaf Schröder
- Coburg University of Applied Sciences
  - Jürgen Krahl
- Steinbeis Transfer Center for Biofuels and Environmental Measurement Technology, Coburg, Germany

  - Jürgen Bünger.

On-road emission measurements:

- AVL MTC, Sweden
  - Lennart Erlandsson
  - Jacob Almén
- VTT, Finland
  - Petri Laine.

Cost assessments:

- ADEME, France
  - Gabriel Plassat
- Veolia Transport Finland, Finland
  - Sami Ojamo
- VTT, Finland
  - Nils-Olof Nylund.

Project coordination and management, WTW synthesis, overall reporting:

- VTT, Finland
  - Nils-Olof Nylund
  - Kimmo Erkkilä
  - Kati Koponen
- Fuels, Engines and Emissions Consulting, USA
  - Ralph McGill.

Additional support to the project:

Additional Canadian support:

- Government of Canada's Program of Energy Research and Development – Advanced Fuels and Technologies for Emissions Reduction (AFTER) Project C21.003 Bus Fuels and Technologies
- Transport Canada –Transportation Development Centre.

Fuel deliveries:

- Neste Oil, Finland
  - HVO fuel
- Petroleum Authority of Thailand (PTT) through the National Metal and Materials Technology Centre of the National Science and Technology Development Agency (NSTDA), Thailand
  - Jatropha FAME fuel
- Shell International Petroleum Company Limited, Shell Technology Centre Thornton, UK
  - GTL fuel
- Shell Canada Limited, Canada
  - commercial ULSD- olisands derived.

Lending of vehicles:

- Daimler Buses North America

- Irisbus, France
- Local bus operators in the Helsinki region
- Société de transport de Montréal
- Volvo Trucks, Sweden
    - prototype DME truck and DME fuel.

Lending of instrumentation:

- JRC VELA, Italy
    - PEMS equipment.

Technology outlook reports by other IEA Implementing Agreements

- Advanced Fuel Cells & Hydrogen Implementing Agreement
    - R. Ahluwalia, X. Wang, and R. Kumar
- Advanced Materials for Transport
    - Stephen Hsu
- Bioenergy/Task 39
    - Jack Saddler
- Combustion/ Collaborative Task on Alternative Fuels in Combustion
    - Martti Larmi, Kalle Lehto, Teemu Sarjovaara
- Hybrid and Electric Vehicles
    - Jussi Suomela (with help from Kimmo Erkkilä/VTT and Sami Ojamo/Veolia Transport Finland).

The contribution of Advanced Motor Fuels in included in the report in the form of Chapter 7.

6. Process and description

The various IEA Implementing Agreements have expertise and knowledge in the following areas:

- Advanced Fuel Cells (AFC): automotive fuel cells
- Advanced Motor Fuels (AMF): alternative fuels in general, and especially fuel end-use
- Advanced Materials for Transport (AMT): light-weight materials
- Bioenergy (specifically Task 39): production of biofuels
- Combustion: new combustion systems
- Hybrid and Electric Vehicles (HEV): hybrid and electric powertrains
- Hydrogen: the use of hydrogen as an energy carrier.

The idea of this cooperative research was to benefit from the cumulative expertise within the IEA Technology Network. Two Implementing Agreements, namely AMF and Bioenergy, were the lead partners in this exercise. These two Implementing Agreements formed projects (Annex of Tasks) to carry out the overall project:

- AMF: Annex 37
- Bioenergy: Task 41/Project 3.

In addition, all transport related Implementing Agreements were asked to submit outlook reports (timeline 2020) of their respective technologies.

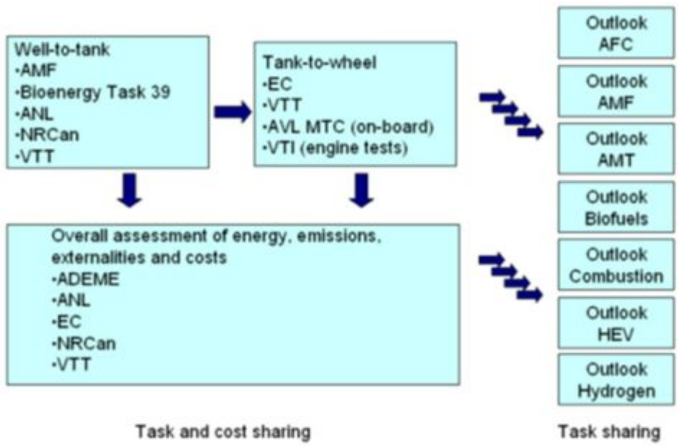
The elements of the projects are shown in Figure 6.1. The basic idea of the project was as follows: use existing well-to-wheel data (most part of the existing data is for passenger cars), extract and process relevant well-to-tank data, generate new IEA data on bus end-use performance (tank-to-wheel), and combine all this data to form bus specific well-to-wheel energy and emission data.

In vehicle and engine testing, the following diesel fuels and diesel substitutes were covered:

- conventional diesel fuel
- diesel fuels from unconventional fossil sources (natural gas, oil sands derived fuels)
- biodiesel fuels (methyl esters as well as hydrotreated vegetable oils).

The fuel matrix contained two types of paraffinic diesel fuels, Fischer-Tropsch GTL (gas-to-liquids) and HVO (hydrotreated vegetable oil). From an end-use perspective, these fuels are considered representative for actual BTL (biomass-to-liquids) fuels.

Figure 6.1. The elements and the actors in the overall project.



The alternative fuels requiring dedicated vehicles covered are:

- methane (biogas/natural gas)
- additive treated ethanol
- di-methyl-ether (DME).

In order to have real international significance, the vehicle matrix consisted of older as well as top-of-the line new buses, and in addition, also some prototype vehicles. The driveline configurations included conventional as well as hybrid drivetrains. As for the hybrid vehicles, the technologies represented were (all with diesel engines):

- parallel and series configuration
- energy storage: batteries and supercapacitors.

The emission certification of the vehicles varied from requirements of the late 90's (US 1998 and Euro II) to current regulations (US 2010, Euro V/EEV). The US 2010 requirements are roughly equivalent to Japan 2009 and the oncoming Euro VI regulation for Europe. By the year 2020, vehicles corresponding to US 2010 and Euro VI regulations, probably with a high share of hybridization, will constitute the bulk of the bus fleets on mature markets.

Full electric powertrains (battery electric or tethered) and fuel cell powertrains were not covered in the experimental part of the project.

As for the WTT part, the spectrum of fuels evaluated was broader than the fuel matrix for actual vehicle and engine testing. The WTT part covered e.g., several options for actual BTL type fuels. GTL and HVO are already in the commercial phase, whereas actual BTL and DME are still in the development phase.

7. Engine, vehicle and fuel technology

7.1 General

The development in engine technology has been tremendous over the last 20 years. Driven by increasingly tightening emission regulations, regulated emissions from heavy-duty diesel vehicles have been reduced by more than 90%. However, improvements in engine technology alone have not been sufficient, also improved fuel qualities and exhaust after-treatment systems have been required for this development.

At the same time as clean diesel vehicles are brought to the market, we see other interesting developments such as introduction of various types of biofuels, alternative fuel vehicles and hybrid power trains. Many of the new technologies find their first applications in urban buses.

Although emissions from traditional vehicles have been reduced, fuels such as synthetic diesel fuel, methane and DME can still provide emission benefits over conventional diesel. The other way round it can be said that clean fuels provide the biggest emission benefits in dirty engines. On the other hand, high quality fuels are needed to reach low emissions both in gasoline and diesel vehicles. Increased emissions due to, e.g., poor quality biofuels is not acceptable.

The technological improvements have mainly been used for the reduction of regulated emissions. In the case of fuel efficiency, progress has been more moderate. Looking at the engine only, the trend for fuel consumption varies from unchanged to a slight reduction. Vehicle technology in the form of hybridization or light-weighting can deliver fuel savings of some 30%. Now regulations for heavy-duty vehicle fuel efficiency are emerging.

At the end of this report there are brief outlook reports provided by IEA Implementing Agreements on various technologies:

- Biofuels for transport (Bioenergy IA/Task 39)
- Fuel cells and hydrogen (Advanced Fuel Cells IA & Hydrogen IA)
- Hybrid and electric vehicles (Hybrid and Electric Vehicles IA)
- Material technology and light-weighting (Advanced Materials for Transport IA)
- Alternative fuels in combustion (Combustion IA/Collaborative Task on Alternative Fuels in Combustion).

The Advanced Motor Fuels Implementing Agreement didn't prepare a separate document as this Chapter (Chapter 7) serves the same purpose.

7.2 Emission regulations

Currently both advanced gasoline vehicles and vehicles fuelled with gaseous fuels reach very low emission levels. Diesel technology has also made good progress. By 2010–2015 increasingly stringent emission regulations (Japan 2009, US 2010, Euro VI in 2013) in developed markets will, in a historic perspective, bring down diesel emissions close to zero. Predicted emission trends for Europe are shown in Figure 7.1. All emissions, except CO_2 are expected to go down.

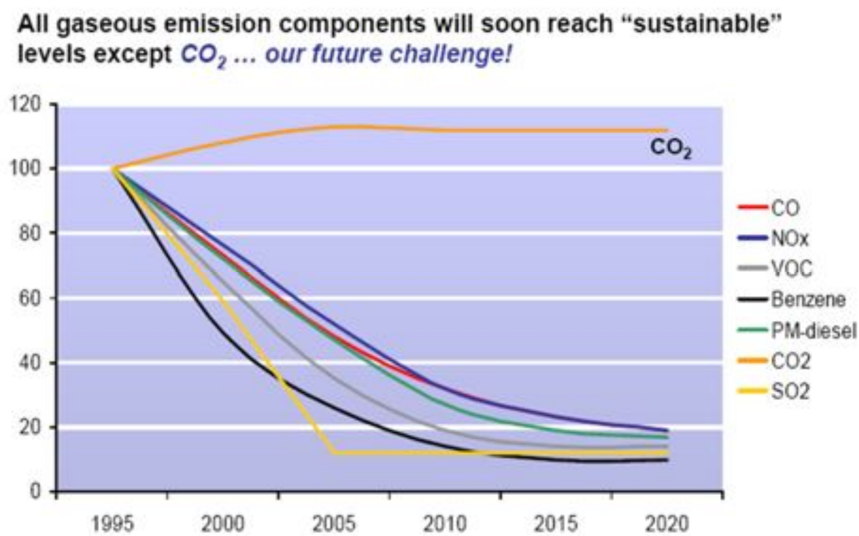


Figure 7.1. Emission trends for Europe (Röj 2006).

Figure 7.2 and Table 7.1 show comparisons of European, Japanese and U.S. emission limits for heavy- duty engines. The emission limits of Japan 2009, US 2010 and Euro VI are in rather good congruence, even though not fully harmonized. NO_x limits are between 0.27 and 0.7 g/kWh, and PM limits between 0.01 and 0.014 g/kWh. The limit values for Japan 2005, US 2007 and Euro V are also quite close to each other.

All current regulations require transient type testing (the European regulations in addition steady-state testing), but the test cycles are different. Going to Euro VI, the test cycles for Europe will be changed from the European Steady Cycle (ESC) and European Transient Cycle (ETC) to World Harmonized Steady Cycle (WHSC) and World Harmonized Transient Cycle (WHTC). Correlation factors have been developed (TNO 2008). In the case of WHTC the results are, for the first time, based on weighted results of a cold start and a warm start.

One should keep in mind that emission regulations are developed for legislative purposes, to determine whether an engine fulfills regulatory requirements or not. Emission certification is always related to a specific test procedure, and doesn't necessarily reflect real world emission performance. The real-life emissions depend on things such as driving patterns, load and also ambient temperature. The efficiency of some exhaust after-treatment systems, e.g. urea-based SCR (selective catalytic reduction) systems, can suffer from low ambient temperature, as well as of low load levels.

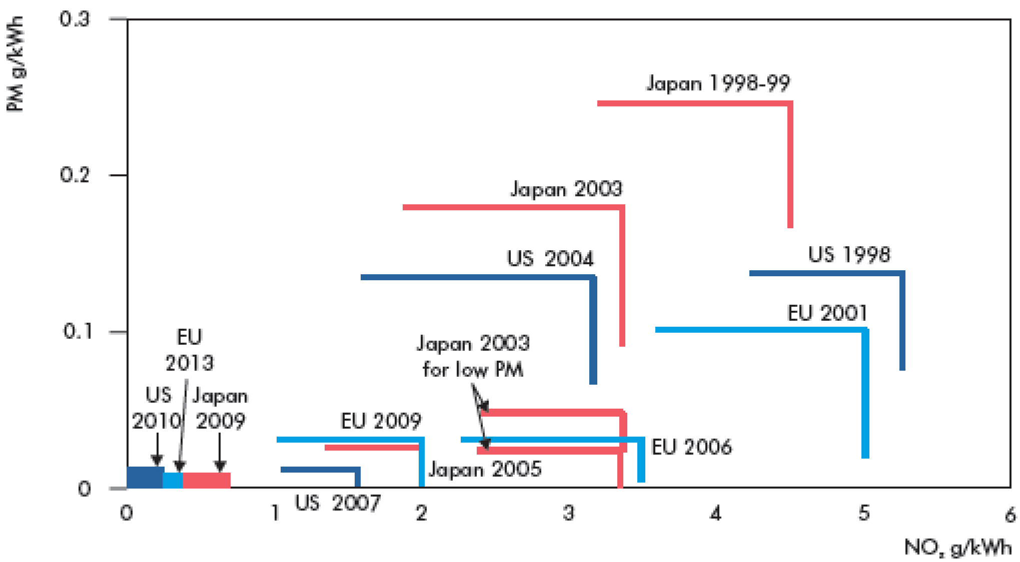


Figure 7.2. Comparison of heavy-duty engine limit values for NOx and PM emissions. (Transport, Energy and CO2 2009)

Table 7.1. Comparison of European, Japanese and US emission regulations. Data from DieselNet and Delphi. (www.dieselnet.com, http://delphi.com/pdf/emissions/Delphi-Heavy-Duty-Emissions-Brochure-2010-2011.pdf)

	NO_x (g/kWh)	PM (g/kWh)	Date
Europe			
Euro II	7	0.15[1)]	1998.10
Euro III	5	0.16	2000.10
Euro IV	3.5	0.03	2005.10

Euro V	2	0.03	2008.10
EEV[2)]	2	0.02	1999.10
Euro VI	0.4	0.01	2013.01
Japan			
2005	2.0	0.027	2007.09
2009	0.7	0.01	2011.09
US			
1998	5.4	0.068	
2007	1.6[3)]	0.014	
2010	0.27	0.014	

1) steady-state
2) voluntary certification class ("Euro V +")
3) phase-in of 2010 values for NO_x between 2007 and 2010, several options for the manufacturers.

The US EPA has introduced not-to-exceed (NTE) emission limits and testing requirements as an additional instrument to assure that heavy-duty engine emissions are controlled over the full range of speed and load combinations commonly experienced in use. The NTE factor is 1.25 or 1.5, depending on the emission certification scheme. (www.dieselnet.com)

7.3 Fuel efficiency

Criteria pollutants from heavy-duty engines are regulated in most parts of the world. For light-duty vehicles there are limits for criteria pollutants as well as CO_2 emissions, alternatively fuel consumption.

Japan was the first country to introduce fuel efficiency standards for heavy-duty vehicles in 2006. For transit buses, the regulation calls for a 12.2% improvement in fuel economy from the year 2002 to the year 2015. For buses with a GVW of more than 14,000 kg the 2015 target is 4.23 km/l, or 23.6 l/100 km. The methodology is based on a combination of engine testing (static engine map for fuel consumption) and modelling the vehicle to produce a simulated fuel efficiency figure (Figure 7.1).

The first US GHG emission and fuel consumption standards for heavy- and medium-duty vehicles were adopted on August 9, 2011 (DieselNet). The standards begin with 2014 model year and increase in stringency through 2018 model year. Vehicles are broken up into three distinct categories with unique approaches for each category (www. epa.gov/otaq/climate/documents/420f11031.pdf):

- Combination tractors
- Heavy-duty pickups and vans
- Vocational vehicles (everything else, buses, refuse trucks, concrete mixers, ambulances, etc.).

The driving cycle used in the simulation is the JE05 cycle.

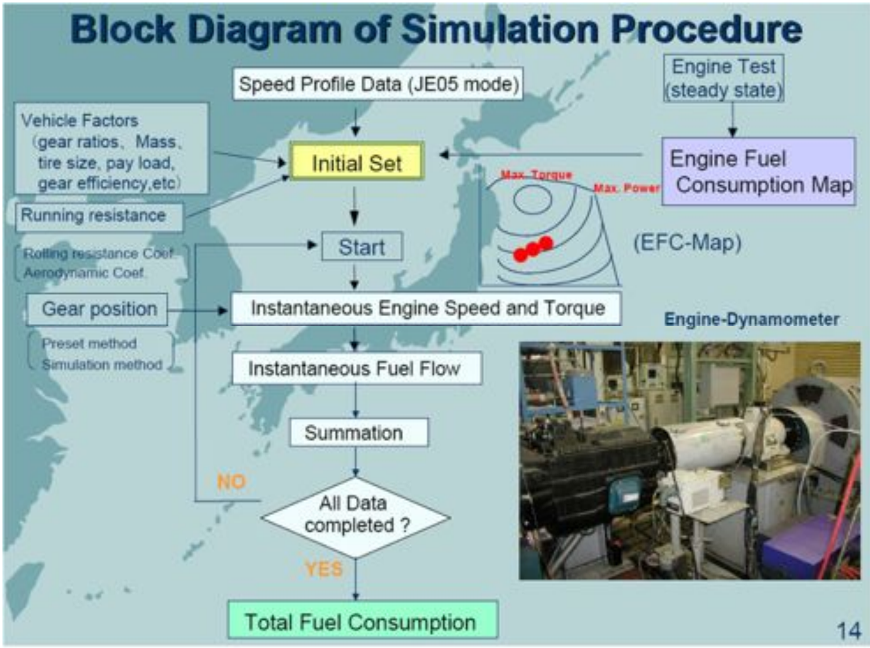


Figure 7.3. The Japanese principle for determining heavy-duty vehicle fuel efficiency. (Wani 2007)

The regulations set separate standards for engines as well as vehicles aiming at ensuring improvements in both vehicles and engines. The regulations provide incentives for early introduction of GHG-reducing technologies and advanced technologies including EVs and hybrids. As in the case of Japan, the methodology is based on measuring the engine and taking into account the specifics of the vehicle by calculatory methods (GEM Simulation Tool v2.0, http://www.epa.gov/otaq/climate/gem.htm).

Tables 7.2 (engine) and 7.3 (vehicle) shows the requirements for vocational vehicles.

Table 7.2. CO_2 standards (in g/hp-hr) for compression ignition engines. (*http://www.epa.gov/otaq/climate/gem.htm*)

Model Years	Light Heavy-Duty	Medium Heavy-Duty – Vocational	Heavy Heavy-Duty –Vocational	Medium Heavy-Duty –Tractor	Heavy Heavy-Duty – Tractor
2014-2016	600	600	567	502	475
2017 and later	576	576	555	487	460

Table 7.3. CO_2 standards (in g/ton-mile) for vocational vehicles.
(http://www.epa.gov/otaq/climate/gem.htm)

GVWR (pounds)	CO_2 Standard (g/ton-mile) for Model Years 2014-2016	CO_2 Standard (g/ton-mile) for Model Year 2017 and later
GVWR ≤ 19,500	388	373
19,500 < GVWR ≤ 33,000	234	225
33,000 < GVWR	226	222

A CO_2 emission of 555 g/hp-hr (Table 7.2, heavy-duty, 2017 and later) or 755 g/kWh corresponds to some 240 g diesel fuel/kWh, or an engine efficiency of some 35%.

With a weight of 33,000 pounds, equivalent to 15,000 kg, the value in Table 7.3 (225 g/ton-mile, 2017 and later) gives a CO_2 value of some 2100 g/km.

Work to develop a CO_2 methodology and standards for heavy-duty vehicles is under way in Europe as well, funded by the European Commission. The first report called "Development and testing of a certification procedure for CO_2 emissions and fuel consumption of HDV" was published in January 2012. The proposed test procedure is based on component testing. The test data of the individual vehicle components is collected in standardised formats and fed into a simulation tool which calculates the engine power necessary to overcome the driving resistances of the vehicle, the losses in the transmission system and the power demand from auxiliaries for defined test cycles. The engine speed course is calculated from the vehicle speed, tire dimensions, the transmission ratios, and a driver model. With the engine power and engine speed in 1 Hz course over the test cycle, the fuel consumption of the entire vehicle is then interpolated from the engine map of the vehicle (TU Graz 2012).

7.4 Diesel engine technology and emission control

The diesel engine is the prime mover for heavy-duty vehicles, including buses, all around the world. It has reached this position thanks to its good fuel efficiency and high reliability. In Europe, the diesel engine has a strong position also in light-duty vehicles. The downside of the conventional diesel engine is high emissions of both particles and nitrogen oxides. Thus, it can be said that the diesel engine faces greater challenges in meeting the future emission regulations than the gasoline engine or engines running on gaseous fuels. The diesel engine is becoming increasingly complex, with several exhaust after-treatment devices added to the engine. Many diesel manufacturers are, therefore, looking for alternative ways such as new combustion schemes utilizing homogenous low-temperature combustion and special synthetic fuels like paraffinic diesel fuel and DME to meet the future challenges. Also, natural gas in fleets such as city buses might become increasingly competitive.

Looking at the engine itself, the diesel engine has gained a lot from electronic controls. Increased injection pressures and accurate injection control have improved performance significantly. Ignition pressures on the order of 2000 bar are now common. The predominant technology in fuel injection today is the common rail system comprising a separate high-pressure pump, a hydraulic accumulator, and a rail connecting the electrically actuated injection nozzles. Very fast actuation makes it possible to divide the injection into several separate phases for optimized engine performance and minimum emissions. With such high injection pressures high quality fuels with no contaminants are required.

Almost all current automotive diesel engines are turbocharged and inter-cooled for enhanced performance. The number of control variables and actuators (variable geometry turbochargers, valve timing, exhaust control devices etc.) is increasing all the time.

For conventional diesel engines, the basic problem is simultaneous reduction of nitrogen oxides and particles, as there is a well-known trade-off effect between NO_x and particles (as well as fuel consumption). The only way to really break this trade-off effect is to implement exhaust after-treatment technology.

Exhaust gas recirculation (EGR) is commonly used to lower combustion temperatures and thus suppress NO_x formation. However, the drawbacks of high EGR ratios are increased particle emissions and increased need for cooling

An alternative technology for NO_x reduction is selective catalytic reduction (SCR). Urea is the most commonly used reducing agent. SCR technology makes it possible to reduce NO_x emissions by more than 80%. The advantage of SCR technology is that engines can be tuned for high engine-out NO_x and low fuel consumption. Drawbacks are that an additional fluid is needed on-board, and that urea cannot be injected and the reduction system doesn’t function when exhaust temperature is low. In addition, SCR systems can generate N_2O emissions.

PM emissions from diesel engines can, to a certain extent, be controlled by improving air handling, injection system performance, and fuel quality. However, exhaust after-treatment devices are needed to achieve significant PM reductions. The main alternatives for PM reduction are simple diesel oxidation catalysts (DOC), flow-through filters (FTF, also called partial diesel particulate filters p-DPF) and actual wall-flow type filters (DPF).

Capturing the particles in actual filters is not a big problem, the problem is rather how to burn the particles (soot) to prevent clogging of the filter. Both active (engine management, fuel injection, actual burners) and passive (catalyzed filters, NO_2, fuel borne catalysts) and combined systems can be used for regeneration. “Overflow” or “slip” of nitrogen dioxide (NO_2) can be a problem with effective oxidation catalysts and catalyzed filters. Slip can occur when production of carbon and NO_2 is not in balance. Direct NO_2 emissions are detrimental for urban air quality.

To reflect the changes in technology, new emission components are under discussion or being introduced in emission legislation, e.g., particulate numbers and NO_2 in Europe and nitrous oxide (N_2O) in the U.S.

EPA 1998 and Euro III emission limits could be met with a simple oxidation catalyst, Euro III in fact without any exhaust after-treatment. The combination of cooled EGR and particulate filter was sufficient to meet the US 2007 on-road heavy-duty emission requirements.

In Europe, the manufacturers use either EGR or SCR technology to meet Euro V and EEV emission requirements. When using EGR technology, for bus applications the manufacturers normally add a FTF device to control emissions. Using SCR technology the EEV requirement for particulates can be met without any additional devices for PM control. However, some European manufacturers add a DPF device for PM reduction.

In most cases EGR alone is not sufficient to reach the very low NO_x levels required by Japan 2009, US 2010 and Euro VI. Earlier on some U.S. manufacturers stated that they will try to meet the 2010 emission regulations with improved combustion systems and without NO_x after-treatment. However, now the mainstream technology to meet the stringent emission regulations is a combination of EGR, SCR and DPF (Figure 7.4).

Figure 7.5 (SCR for Euro V/EEV) and 7.6 (De-NO_x (SCR) plus DPF for US 2010 show different emission control strategies.

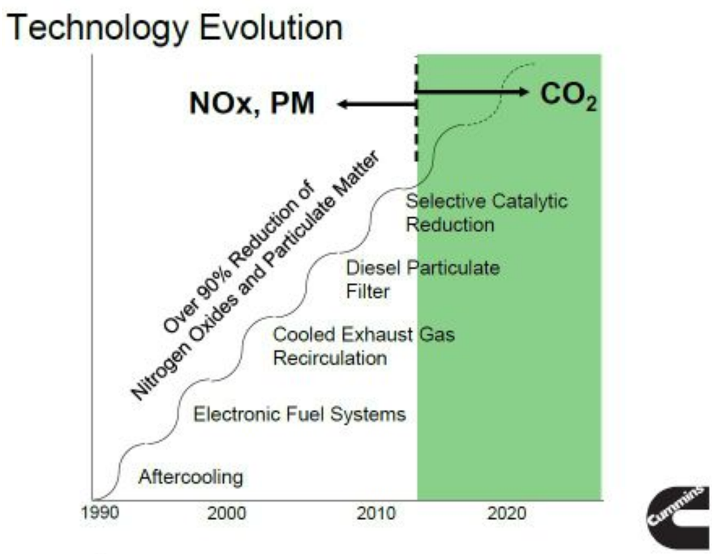


Figure 7.4. Technology pathway for emission reductions of heavy-duty diesel engines. (Mormino 2011)

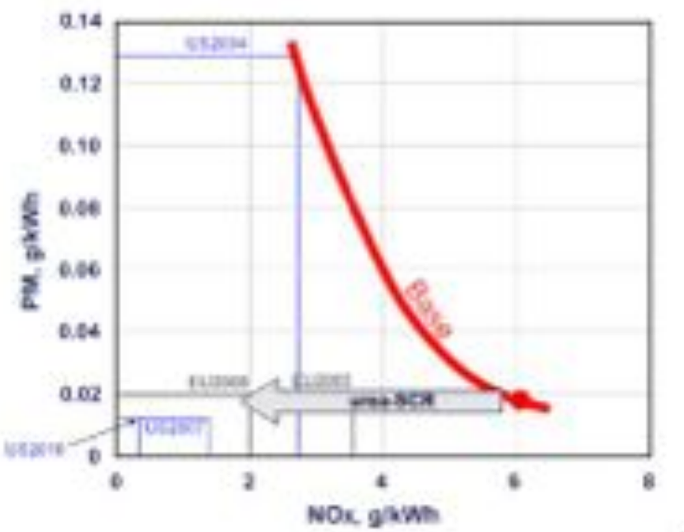


Figure 7.5. One possible emission control strategy for Euro V/EEV. (Majewski/DieselNet 2007)

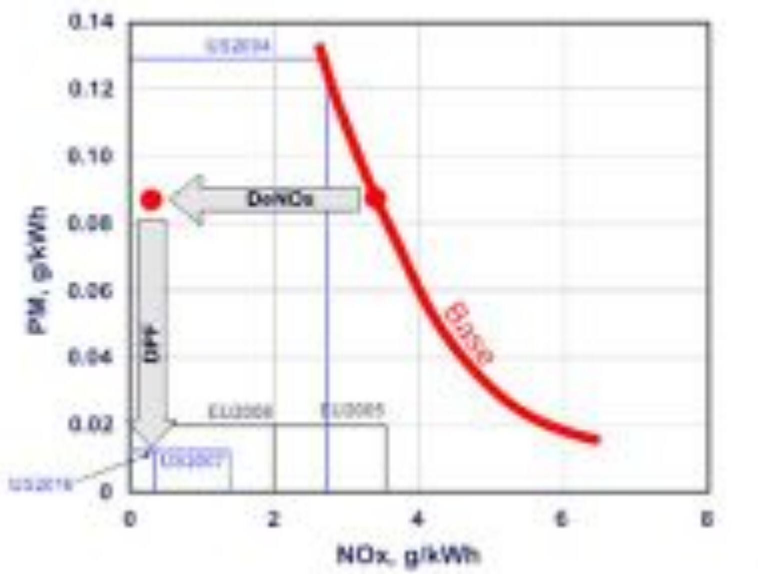


Figure 7.6. Emission control strategy for US 2010. De-NOx most probably a combination of EGR and SCR. (Majewski/DieselNet 2007)

7.5 Fuel alternatives

7.5.1 General

Although alternative fuels and even electricity are entering road transport, oil-based fuels continue to dominate transport energy demand (WEO 2010). As mentioned above, high quality fuels are a prerequisite for achieving low emissions. Figure 7.7 shows development of diesel fuel quality (e.g. sulfur content) in parallel with exhaust emission regulations. Sulfur-free diesel is an enabling fuel for advanced exhaust after-treatment technology such as diesel particulate filters (DPFs).

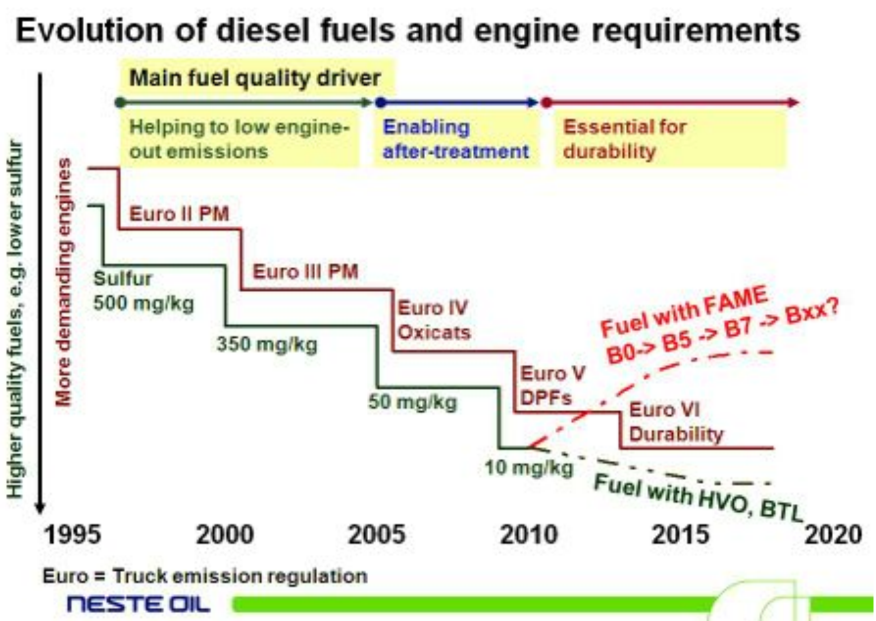


Figure 7.7. Development of diesel fuel quality and emission regulations. (Mikkonen 2012)

Table 7.4 presents fuel and energy alternatives for road transport. Currently the main options for buses are conventional diesel fuel, liquid synthetic fuels (including oil sands derived fuels), biodiesel, compressed natural gas and compressed biogas. The following alternatives are either limited in application or in the development phase:

- additive treated ethanol for diesel engines: commercial, but limited application
- advanced biodiesel (BTL) from biomass: development phase
- DME: development phase
- hydrogen: development phase
- electricity (for buses):
  - tethered vehicles: commercial
  - battery electric vehicles: development phase.

Table 7.4. Fuels and their production processes. (ETP 2010)

Fuel	Feedstock	Process/notes
Liquid petroleum fuels: gasoline, diesel, kerosene, jet fuel	Oil from both conventional sources and non-conventional sources such as heavy crudes and tar sands	Refining
Liquid synthetic fuels	Natural gas, coal	Gasification/Fischer-Tropsch (FT) process (with or without CCS): GTL or CTL
Biodiesel	Oil-seed crops	Esterification, hydrogenation (resulting in fatty acid methyl esters (FAME)) or H_2-treated oils
Ethanol	Grain crops	Saccharification and distillation
Ethanol	Sugar crops (cane)	Distillation
Advanced biodiesel (and other distillate fuels)	Biomass from crops or waste products	Gasification/FT (with or without CCS): biomass-to-liquids (BTL)
Compressed natural gas	Natural gas	Compression to store on vehicle
	Biomass	Methane production from biomass via digestion (biogas) or via gasification and chemical conversion (bio-SG)
Electricity	Coal, gas, oil, nuclear, renewables	Different mixes in different regions, including with or without CCS
H_2	Natural gas	Reforming, compression, centralised with or without CCS, or at point of use
	Electricity	Electrolysis at point of use
	Direct production using e.g. solar, nuclear energy, biomass	High-temperature process or biomass gasification

Table 7.5 presents an estimate of worldwide road transportation use in 2009. The most abundant alternative fuel was ethanol (as gasoline replacement) seconded by natural gas (methane), both with a volume of more than 30 Mtoe/a. Biodiesel, including hydrotreated vegetable oil (HVO), was much smaller, roughly 1/3 of the volume of ethanol. The total share of alternative fuels was some 7.7% of the total fuel use, and the share of biofuels was some 3%.

Table 7.5. Volumes of alternative road transport fuels; data compilation by IEA AMF. (AMF 2011)

ROAD TRANSPORT ALTERNATIVE FUELS	Volumes	
	Mtoe/a	%
Total road transport worldwide[a]	**1.701,00**	**100,00**
Alcohols		
Ethanol[b]	38,7	2,3
Methanol[c]	3,0	0,2
Biodiesel		
FAME biodiesel[b]	10,5	0,6
Hydrotreated biodiesel[d]	2,5	0,1
Other liquid fuels		
GTL[e]	13,0	0,8
CTL[e]	10,0	0,6
Gaseous fuels		
Natural gas and biomethane[f]	33,0	1,9
LPG[g]	21,0	1,2
TOTAL		
Alternative fuels	**131,7**	**7,7**
Biofuels	**51,7**	**3,0**

[a] *Energy Efficiency Indicators in the Transport Sector, Natalie Trudeau. © OECD/IEA, 2011.*
[b] *Volume for 2009. IEA WEO 2010. Volume of hydrotreated biodiesel reduced from total biodiesel of 12.9 toe to represent FAME biodiesel volume.*
[c] *Volume for 2010. Source: Methanol Institute.*
[d] *Volume for 2010. Includes Neste Oil's NExBTL capacity of 1.14 Mtoe (w/o Rotterdam) and capacity of ConocoPhillips, Syntroleum and Eni. Press releases and U.S. DOE's AFDC.*
[e] *Production capacity. IEA ETSAP - Technology Brief S02, May 2010.*
[f] *Volume for 2010. Calculated with general assumptions for the NGV population, which is 12.67 million in 2010 according to IANGV statistics (http://www.iangv.org/tools-resources/statistics.html).*
[g] *Volume for 2008. http://www.worldlpgas.com/gain/key-autogas-data*

BTL = Biomass to Liquids; GTL = Gas to Liquids; CTL = Coal to Liquids; LPG = Liquefied Petroleum Gas

Most new technologies are constrained by some limitations or obstacles. These can relate to resources, conversion technology, sustainability, environmental impacts, infrastructure and vehicle compatibility. Figure 7.8 shows an example of hurdles for various technologies, including electric and fuel cell vehicles.

On the vehicle level, one major divider is compatibility: can the alternative fuel be used in existing vehicles either as a blend or as such, or does the new fuel require dedicated vehicles? Most biodiesel and liquid synthetic fuel options can at least partly replace conventional diesel in existing vehicles.

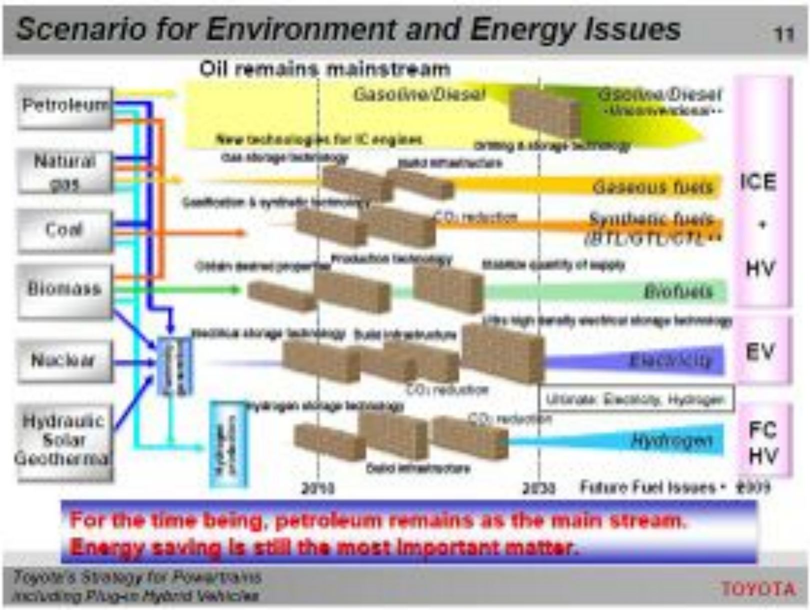


Figure 7.8. Transport energy options and hurdles for individual technologies. (Tanaka 2011)

Today biofuels, especially in the case of biodiesel, is an imprecise word meaning various products with different origins and different end-use properties. Biofuels can, in principle, be used as such or as blending components in conventional fuels. In most cases the use of biofuels as blending components is the most cost-effective approach. Biofuels can be divided into two main categories (Nylund et al. 2008):

- traditional classic biofuels and
- next generation or second generation advanced biofuels.

However, the terminology is not fully established. Reality is such that it is not just "black and white," there are also shades of grey. The criteria could be looked upon from two different angles, from a feedstock and process point of view and from an end-use point of view. From a feedstock and process point of view advanced biofuels should fulfill at least the following criteria, with a focus on sustainability:

- feedstock production should not compete with food production
- feedstock production should not harm the environment (e.g. cause deforestation, ground water pollution etc.)
- feedstock production and fuel processing should be efficient from a GHG point of view.

The criteria from an end-use point of view could be:

- at least equivalent end-use quality compared with traditional mineral oil based fuels
- compatibility with existing refueling infrastructure
- compatibility with existing vehicles
- fuel components that do not only provide heating value but also a possibility for reduced harmful exhaust emissions.

7.5.2 Diesel replacement fuels

There are a number of alternative routes to diesel-type biofuels:

- straight vegetable oil (SVO, not recommended for high speed diesel applications)
- vegetable oil esters (typically methyl esters, FAME, "traditional biodiesel")
- hydrotreated vegetable oil (paraffinic HVO, can also be based on e.g. waste animal fat)
- biomass-to-liquids synthetic diesel (BTL, gasification of any hydrocarbon biomass, e.g. biowaste, followed by Fischer-Tropsch liquefaction).

Two terms that recently have been introduced in the discussions regarding fuels are "blending wall" and "drop-in" fuel.

"Blending wall" means that there is, from a technical viewpoint, a need to limit the concentration of a component. Such limits exist for, e.g., blending ethanol into conventional gasoline and FAME type biodiesel into conventional diesel.

In the United States the term "blend wall" describes the situation in the ethanol market as it nears the saturation point for gasoline with 10-percent ethanol by volume (E10) which is the legal maximum for general use in conventional gasoline-powered vehicles.

The U.S. Environmental Protection Agency (EPA) has partially granted a waiver to allow gasoline that contains greater than 10 volume percent ethanol and up to 15 volume percent ethanol (E15) for use in certain motor vehicles. Partially approving the waiver for allows the introduction into commerce of E15 for use only in model year 2007 and newer light-duty motor vehicles, which includes passenger cars, light-duty trucks and sport utility vehicles (SUV).
(http://www.epa.gov/otaq/regs/fuels/additive/e15/420f10054.htm#e15)

The current European fuel quality Directive 2009/30/EC limits ethanol concentration in gasoline to 10% (volume) and FAME concentration in diesel to 7% (volume). The Directive states (2009/28/EC):

"A limit for the fatty acid methyl ester (FAME) content of diesel is required for technical reasons. However, such a limit is not required for other biofuel components, such as pure diesel-like hydrocarbons made from biomass using the Fischer-Tropsch process or hydro-treated vegetable oil."

The Directive indirectly defines drop-in fuels by stating that a limit is not required for either BTL or HVO. Thus drop-in means that the replacement fuel is fully compatible with existing vehicles and existing infrastructure.

Both hydrotreatment of vegetable oils and animal fats and gasification of biomass combined with a Fischer-Tropsch process render high quality paraffinic diesel fuel. The Fischer-Tropsch synthesis can be used for any hydrocarbon-containing feedstock. When the feedstock is natural gas, the product is called GTL (Gas-to-Liquid); in the case of coal, CTL (Coal-to-Liquid); and in the case of biomass, BTL. Even low-quality heavy oils can be gasified and used as feedstock. Syngas technology can also be used to produce gasoline, methanol, and DME.

Paraffinic diesel has very high cetane number and good combustion properties in general. It is miscible with conventional diesel fuel at any ratio, and if used as such, it can reduce harmful exhaust emissions significantly. As there are no quality or end-use related limitations, synthetic type biofuels can easily contribute to increased use of biofuels in transport.

In 2009, CEN, the European Committee for Standardization launched a pre-standard, a so-called Workshop Agreement, on paraffinic diesel fuel. The CEN Workshop Agreement 15940 states as follows (CEN 2009):

"The Workshop Agreement has been laid down to define a specification for diesel fuel on the basis of synthesis gas (from natural gas, coal or biomass) or of hydrotreated vegetable or animal oils. Its main use is as diesel fuel in dedicated diesel vehicle fleets. Paraffinic diesel fuel does not meet the current diesel fuel specification, EN590. The main differences between paraffinic diesel fuel and automotive diesel fuel are in the areas of distillation, density, sulfur aromatics and cetane. Its low density is outside the regular diesel specification.

From an environmental perspective, paraffinic diesel is a high quality, clean burning fuel with virtually no sulphur and aromatics. Paraffinic diesel fuel can be used in existing diesel engines[3] substantially reducing regulated emissions. In order to have the greatest possible emissions reduction, a specific calibration may be necessary."

[3] Engine warranty may require additional validation steps, dedicated pump marking is recommended.

In the spring of 2011 CEN started work to develop the CWA for paraffinic diesel fuel into an actual European standard. In order to be in congruence with the EN590 standard for regular diesel fuel, the oncoming standard for paraffinic diesel fuel will allow up to 7% (vol.) of FAME.

Earlier on some European manufacturers approved the use of 100% FAME, but in most cases the approvals have been voided for the newest vehicles. On the other hand, Scania, the Swedish heavy-duty vehicle manufacturer, based on a 3.5 year field test in Metropolitan Helsinki Scania approved the use of 100% HVO (NExBTL) in its city and intercity buses with DC9 engines in August 2011 (Nylund et al. 2011).

Hydrocarbon-type fuels can also be derived from unconventional resources such as oil sands and oil shale. Oil sands are a mixture of sand, water and bitumen, from which bitumen must be extracted for further use. Oil sands are primarily concentrated in Canada. According to the U.S. geological service, Canada's estimated technically recoverable resources of bitumen constitute about 80% of the worldwide resources.

Once extracted, oil sands bitumen is either diluted with lighter petroleum products in order to meet pipeline specifications and is sent to refineries, or it is transformed into an upgraded crude oil comparable to a high quality, light, sweet crude oil. The upgrading process is similar to a refining process and upgraded bitumen is known as synthetic crude oil (SCO). Since bitumen is hydrogen deficient, it is upgraded through both carbon removal (coking, which yields petroleum coke, typically burned for energy recovery) and hydrogen addition (hydrocracking). (Transport, Energy and CO_2 2009)

7.6 Engine technology for alternative fuels

7.6.1 General

The internal combustion engine can, in principle, be operated on a variety of fuels and fuel components. Most biofuels – alcohols, biogas and biodiesel – can be used as motor fuels either as blending components or as is. Alcohols and gaseous fuels are suitable for spark-ignited engines, whereas vegetable oil and animal fat derivatives are suitable for diesel engines. Synthetic fuels resemble current fuel qualities and can be used in existing vehicles without modifications. The current production technologies for synthetic fuels emphasize diesel type products.

In reality the options are rather limited. Over the years, engines, fuels and exhaust after-treatment systems have been tuned together for optimum performance. Changing one component, e.g. the fuel, dramatically, necessitates a recalibration of the other components. Compromising reliability, performance, efficiency, exhaust emissions, or safety is not acceptable when introducing a new fuel quality (Figure 7.9). Some alternatives would be highly costly as new production capacity, refueling infrastructure as well as new vehicles would be needed.

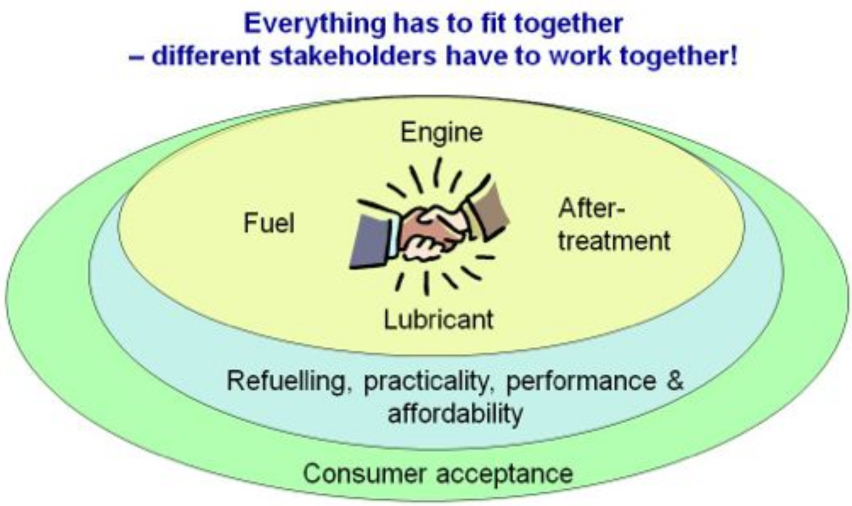


Figure 7.9. Engine, fuel, lubricant and exhaust after-treatment interaction. (Nylund 2011)

Below, the following technologies are briefly described:

- engine technology for methane (natural gas and biogas)
- engine technology for DME
- ethanol for compression ignition engines.

7.6.2 Engine technology for methane

Gaseous fuels like methane, propane, and butane are inherently clean-burning fuels, which in favorable conditions give a soot-free combustion and less harmful exhaust components than conventional liquid hydrocarbon fuels. Gaseous fuels do not provide the same flexibility as liquid fuels. Most engines using gaseous fuels are either dedicated engines optimized for one specific fuel (heavy-duty vehicles) or bi-fuel engines (light-duty vehicles) capable of running on either gasoline or the gaseous fuel.

Methane (and LPG) is well suited for spark-ignition engines. It is relatively easy to convert a gasoline engine to gaseous fuels. The main components of a gaseous fuel system are fuel tanks, pressure regulators, and the gas feed system. However, to achieve low overall exhaust emissions, advanced engine technologies and control systems have to be applied.

Most heavy-duty gas engines of today are based on diesel engines converted to spark-ignition engines. Principally, the conversions are carried out by the engine manufacturers themselves, as mastering thermal loads and securing durability are quite challenging. Spark-ignited heavy-duty engines are quite common in city bus applications all over the world, and several manufacturers can offer natural gas engines.

Two main combustion schemes are applied, either lean-burn combustion in which NO_x formation is controlled in the combustion process by excess air, or stoichiometric combustion in combination with a three-way catalyst. The lean-burn engines are also equipped with catalysts, namely oxidation catalysts to control methane emissions.

At this stage, there is still room for technical improvements to enhance the emission performance, efficiency, and to some extent, even the reliability of natural gas fuelled engines and vehicles. In normal service, current gas engines can consume 25–35% more energy than their diesel counterparts. New engine technologies and electronics like variable valve timing, EGR, skip-fire etc. can help to enhance the performance of gas engines. Ultimately, when the level of technical sophistication of heavy-duty gas engines is at the same level as for the conventional technologies, natural gas engines should have clear advantages from an environmental point of view, both regarding toxic and CO_2 emissions, over conventional fuels.

The Canadian technology company Westport Innovations has actively developed direct injection for natural gas engines to improve fuel efficiency. The direct injection systems for natural gas rely on late-cycle high-pressure injection of gas into the combustion chamber. Natural gas has a higher ignition temperature than diesel, and therefore, an ignition aid (diesel pilot spray) is needed. Basically the engine is operating like a diesel engine, and therefore delivers higher efficiency than spark-ignited gas engines. Westport's HPDI technology has now been commercialized in a 15 liter 400–475 hp engine meant for Class 8 tractors (Westport 2011). However, this technology is not yet available for bus applications.

Methane is normally stored under pressure (typically 200 bar, compressed natural gas CNG). In light-duty vehicles and city buses CNG can provide sufficient cruising range, but CNG is not suited for long-haul trucks. LNG delivers more range, and LNG is used in some trucking operations in the U.S. For energy density, LNG is roughly equivalent to ethanol. International standards are in place to secure safety of high pressure CNG components and installations.

The lack of internationally recognized standards hampers the development of heavy-duty methane engines. Currently it is impossible to certify a dual-fuel engine for Europe.

7.6.3 Engine technology for DME

DME is clean-burning, 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 development of DME engines or equipment for DME engines: AVL (Austria), Denso, Nissan Diesel (UD Trucks), TNO (Holland), and Volvo.

Volvo is now the forerunner in developing DME technology. Within the Bio-DME project, Volvo is running a fleet test with 14 heavy-duty DME trucks in Sweden. The overall project period is 2008 to 2012, and the field test is running from 2010 to 2012. The test vehicles are FH trucks with the 13 liter engine. Maximum power is 440 hp. DME is filled as a liquid via a special nozzle and stored in liquid form in the tanks. A special fuel pump regulates the pressure in the common rail injection system. Special DME injectors have been jointly developed by Volvo and Delphi. The moving parts are identical to those in the diesel variant. The engine management software has been modified to suit the new injection system. (Volvo BIO-DME)

7.6.4 Ethanol for compression ignited engines

Alcohols as such are not suitable for diesel combustion, due to low ignition quality. If high-concentration alcohol is going to be used in compression ignition engines either the engine or the fuel has to be modified. In the past, Detroit Diesel manufactured glow-plug equipped heavy-duty engines to use methanol or ethanol, but due to many problems the production was discontinued.

Ethanol treated with ignition improver and lubricity additive can be used as fuel in conventional diesel engines, although some engine modifications are still needed. Ethanol buses manufactured by Scania have been in operation in Swedish cities since 1989. More than 600 buses have been supplied. Stockholm Public Transport (SL) decided as early as the mid-1980s to start replacing its diesel buses with buses running on renewable fuels on the inner-city lines. Today, ethanol buses complemented with some biogas buses are used on all inner-city routes, and diesel technology is no more in use.

The current 3rd generation ethanol engine is an adaptation of Scania's latest 9-litre diesel engine with air-to-air charge cooling and exhaust gas recirculation, EGR. 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. The engine is available with Euro V and EEV emission certification (Scania 2007). Table 7.6 presents technical data for the engine.

Table 7.6. Technical data for Scania's ethanol engine. (Scania 2007)

Emission levels	Euro V & EEV
Configuration	Charge-cooled in-line 5-cylinder 4-valve cylinder heads Unit injectors, EGR
Displacement	8.9 litres
Comp. ratio	28:1
Power	199 kW (270 hp) at 1900 rpm
Torque	1200 Nm at 1100–1400 rpm

The fuel is hydrous ethanol treated with additives (ignition improver, lubricity). The high compression ratio alone doesn't ensure proper ignition of the ethanol.

7.7 Hybrid powertrains

All types of vehicles benefit from hybridization. In relative terms, the biggest fuel efficiency gains are achieved for gasoline engines and spark-ignited gas engines. In the heavy vehicle sector, hybrid propulsion systems are mostly used in city buses, but hybrid systems are becoming available also for delivery vehicles and small size trucks.

The efficiency improvements with hybrid technology in conjunction with ICEs are due to two major advantages. Firstly, hybrid technology makes it possible to smooth out the operation of the ICE and to run the ICE on loads providing best fuel efficiency. Secondly, recuperating braking energy otherwise lost as heat, significantly contributes to improved efficiency.

Fuel savings using HEV systems are dependent on the duty cycles. City bus services, with regular stop-and-go driving patterns, are ideal for hybrid applications. Fuel savings of more than 30% can be achieved (Chandler & Walkowicz 2006).

As there are several different types of hybrid vehicles, the hybrid-electric drive definition is aggravated by the fact that the technology has many forms and different labels to describe them. The highest level distinction can be made based on the power flow in the powertrain. This divides the vehicle designs into two categories – series and parallel hybrid designs. Both of them are currently commercialized, and each has its advantages.

In the series hybrid system the ICE and the electric motor provide equivalent amounts of work. In the parallel hybrid system the ICE dominates while the electric motor provides assistance. In mixed systems the ratio is variable (Figure 7.10).

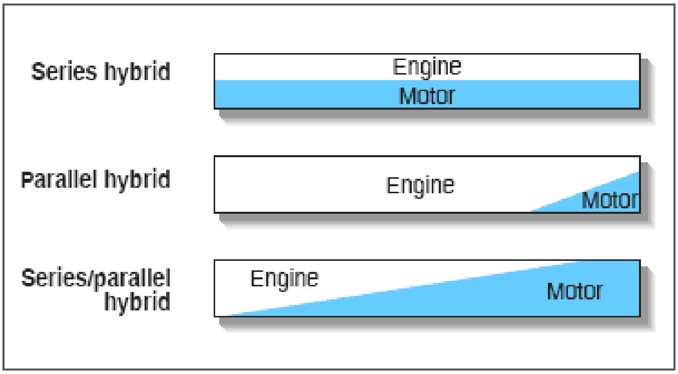


Figure 7.10. Contribution of ICE and electric motor in different hybrid systems (Toyota 2003).

The best known hybrid vehicle Toyota Prius utilizes a rather complicated mixed system. The system comprises a battery pack, two inverters, two electric motors/generators, and a mechanical power-split device based on planetary gears. The smaller electric motor on the crankshaft acts as starter and generator. The second electric motor is the actual traction motor. The power of the ICE is 57 kW and the power of the traction motor 50 kW. (http://www.toyota.com/prius/index.html)

The systems used in buses are either parallel or series type systems, not mixed systems.

A hybrid vehicle is more complicated and more difficult to manufacture compared with conventional vehicles. The battery and battery recycling are of crucial importance in the whole process. Lead-acid batteries have been replaced by more advanced battery types such as Ni-MH and Li-ion batteries. Figure 7.11 presents the characteristics for various types of batteries. In hybrid applications, emphasis is on high power density, whereas emphasis for pure battery electric vehicles is on energy density. Li-ion batteries can be tuned for different types of applications.

Super-capacitors may be a solution for energy storage when high power density and high cycle numbers are needed rather than high energy density. Capacitors store energy in an electrostatic field rather than as a chemical state as in batteries. Super-capacitors, or ultra-capacitors as they are also called, look very much like batteries. They have a low energy density of less than 15 Wh/kg but a very high power density of 4,000 W/kg. They are very fast in charge and discharge, and can be charged and discharged in seconds. Expected life is more than 500,000 cycles. (mpower)

In the experimental part of this project several types of hybrids were tested. The variants included parallel and series configuration, and energy storage in NiMh batteries, Li-ion batteries or supercapacitors.

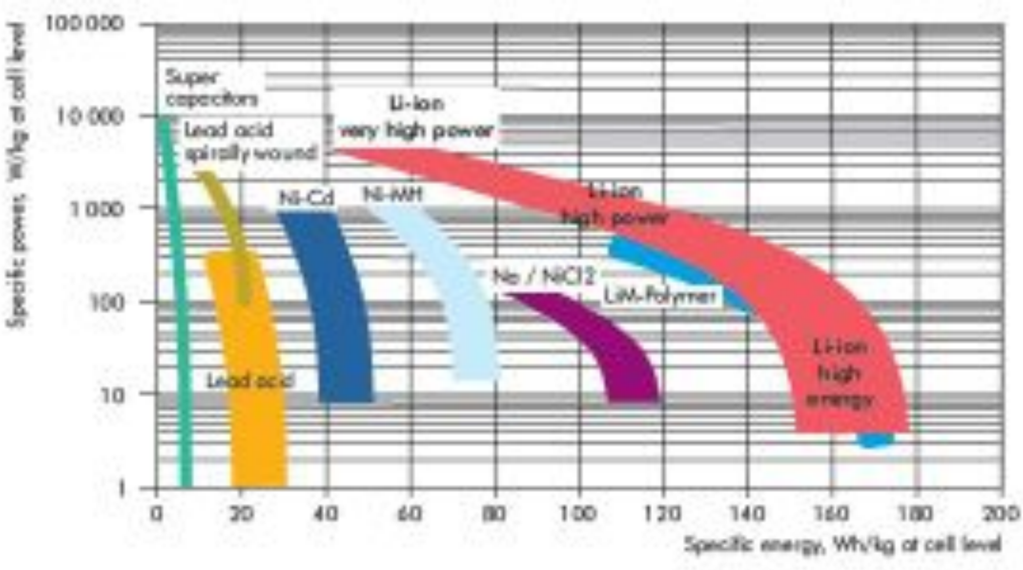


Figure 7.11. Specific energy and specific power of different battery types. (Transport, Energy and CO_2 2009)

Allison Transmissions, which is a part of the GM group, has been one of the forerunners in supplying hybrid systems for buses. Two parallel systems are available, H 40 EP and H 50 EP. For accelerations, maximum power output (ICE + electric motor) is 261 kW and 298 kW, respectively. Allison does not state the power of the electric motor directly, but the power rating of the inverter unit is 160 kW (Allison 2011). Several independent bus manufacturers use Allison's hybrid systems. In Europe, several manufacturers including Mercedes-Benz and Volvo are now offering hybrid buses.

Hybrids but more specifically battery electric vehicles are discussed in one of the Annexes to this report.

8. Methods

8.1 General

As described in the previous Chapter, the work was split up in three main parts:

- Well-to-Tank (fuel production, upstream)
- Tank-to-Wheel (end-use)
- Well-to-Wheel (Assessment of overall energy use, environmental impacts and costs).

8.2 WTT assessment methods

8.2.1 Life cycle assessment (LCA)

Life cycle assessment (LCA) is a commonly used tool for environmental impact assessment of different products (and services). The framework of LCA is presented in two ISO standards, ISO 14040 and ISO 14044. LCA considers the entire life cycle of a product, from raw material extraction and acquisition, via energy and material production and manufacturing, to use and end of life treatment and final disposal (ISO 14040, 2006). An LCA study includes several phases. The first phase is to define the goal and scope of the study. It is followed by inventory analysis (LCI), where data is collected and calculation procedures are made to quantify relevant inputs and outputs of a product system. The results of the inventory analysis might already be sufficient at this point and the results of the inventory may be directly interpreted and used (LCI study), but to complete the LCA, an impact assessment needs to be performed, meaning that the results of the LCI are used to evaluate the significance of potential environmental impacts. LCA is an iterative process: as data and information are collected, various aspects of the scope may require modification in order to meet the original goal of the study. (ISO 14040, 2006)

LCA is commonly used to assess the environmental impacts of fuel products. The assessment of a complete life cycle of a fuel product includes all the phases from raw material production and extraction, processing, transportation, manufacturing, storage and distribution until use of final product. Over the past twenty years, several transportation LCA models have been developed to address transportation fuels and vehicle technologies (such models include GREET, GHGenius, and the E3 Database). The life cycle of a fuel product can be studied in phases (see Figure 3.1). In this report, the life cycle of fuel products studied is divided into well-to-tank (WTT) phase and tank-to-wheel phase (TTW). These phases are later combined to well-to-wheel (WTW) phase, meaning the whole life cycle of a fuel product. The WTT phase is assessed by applying the LCA approach and different LCA methodologies from, respectively, the USA, Canada and the EU. This study may not be considered a complete LCA as analysis because it assesses only the fuel life cycle instead of both the fuel cycle and vehicle cycle, and it does not include the impact assessment which is required in the ISO standard. However, the LCA approach has been applied as the basis of the WTT calculations. In this report the GREET model (http://greet.es.anl.gov/publications) is used to assess the WTT emissions of fuels in the US context. The GHGenius model (www.GHGenius.ca) is used for WTT emissions in the Canadian context. In the EU context the methodology for GHG assessment of biofuels presented in the EU renewable energy directive (RED, 2009) is used. Contrary to GREET and GHGenius, the RED is not a modeling tool for GHG assessment of biofuels, but a simple calculation methodology. These models and methodologies are presented briefly in chapters 8.2.2 - 8.2.4 and in more detail in Appendix 1.

When defining the goal and scope of an LCA or LCI study the main questions are: *what is compared with what*, and *why*, and *for whom is the study performed*? In this study, the goal is to compare the life cycle emissions of different biofuels and fossil fuels, both natural and synthetic, in order to inform decision makers and fleet operators about how these fuels compare across various properties of interest in the context of energy policy, performance, and cost. It is critical to define initially the functional unit, that is, the quantitative unit of reference to define the performance of a product system under study (ISO 14040, 2006), including its emissions. Using a common functional unit makes it possible to compare the emissions of the studied product with the emissions of reference products. When assessing fuels the functional unit at end use is often *residuals/effluents/energy per km driven* or *MJ of energy input per MJ of fuel used*, or both. For example, greenhouse gas emissions may be expressed as grams of carbon dioxide (GWP) equivalent per kilometer driven (gCO_2-eq./km) or per mega joule of energy (gCO_2-eq./MJ), which may be defined as total energy use, fossil energy only, or petroleum energy only. In this study, the WTT results are expressed as gCO_2-eq./MJ of final product and the WTW results as gCO_2-eq./km driven.

To be able to start an LCA study, the system boundary of the assessment must be defined. The system boundary is delineated by a set of criteria specifying which unit processes are part of a product system (ISO 14040, 2006). In other words, it defines which factors are included in or excluded from the assessment. The setting of the system boundary can have significant impacts on LCA results, so it must be clearly stated at the beginning (Cherubini et al. 2009). The choice of system boundary is challenging, for choosing a very inclusive/relaxed system boundary can result in a lack of data and knowledge; however, if a very limited system boundary is chosen, relevant information may be excluded (Soimakallio et al. 2009).

In product systems there are often several products and side effects produced (main product, intermediate products, co-products and effluents). In these cases LCA must define how it allocates emissions and effluents percentage-wise to the products and co-products. Allocation of emissions is often based on physical relations among the products, such as the mass or energy content of each. It can also be based on the economic value of the products. If the process can be divided initially into sub-processes, or the system boundary can be expanded (ISO 14040, 2006), it may be possible to avoid this allocation. Expanding the system boundary will include parts of other life cycles affected (Finnveden et al. 2009). This means, for example, that if in a bioethanol process animal feed is produced as a co-product, animal feed production elsewhere that would otherwise occur using another process may be avoided. This avoided animal feed production may result in a net reduction of emissions, and emission reduction credit can be assigned to the bioethanol produced. This kind of approach is often referred as substitution or replacement (displacement) method. In this study, the GREET model offers a selection from among several methods (co-product displacement, production energy use allocation, market value), depending on the importance and variety of fuel co-products and by-product. The GHGenius model uses both displacement and allocation methods and EU RED methodology requires the use of energy allocation, based on lower heating value (LHV) of the products. The choice of the allocation method can have a significant impact on the LCA results (Wang et al. 2011, Cherubini et al. 2009) and unfortunately there is no universally accepted method to generate reliable LCA results for biofuels (Wang et al. 2011).

8.2.2 GREET (US)

GREET was developed with support from the U.S. Department of Energy. This public domain model is available free of charge for anyone to use. The first version of GREET was released in 1996. Since then, Argonne National Laboratory, which developed the model, has continued to update and expand it. The most recent GREET version is GREET1.2011 (http://greet.es.anl.gov/).

For a given vehicle and fuel system, GREET separately calculates the following:

- Consumption of total energy (energy in non-renewable and renewable sources), fossil fuels (petroleum, natural gas, and coal together), petroleum, coal and natural gas.
- Emissions of CO_2-equivalent greenhouse gases – primarily carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O).
- Emissions of six criteria pollutants: volatile organic compounds (VOCs), carbon monoxide (CO), nitrogen oxide (NO_x), particulate matter with size smaller than 10 micron (PM_{10}), particulate matter with size smaller than 2.5

micron ($PM_{2.5}$),and sulfur oxides (SO_x). These emissions are separated into total and urban emissions.

GREET includes more than 100 fuel production pathways and more than 70 vehicle/fuel systems. General fuel production pathways are shown in Figure 8.1.

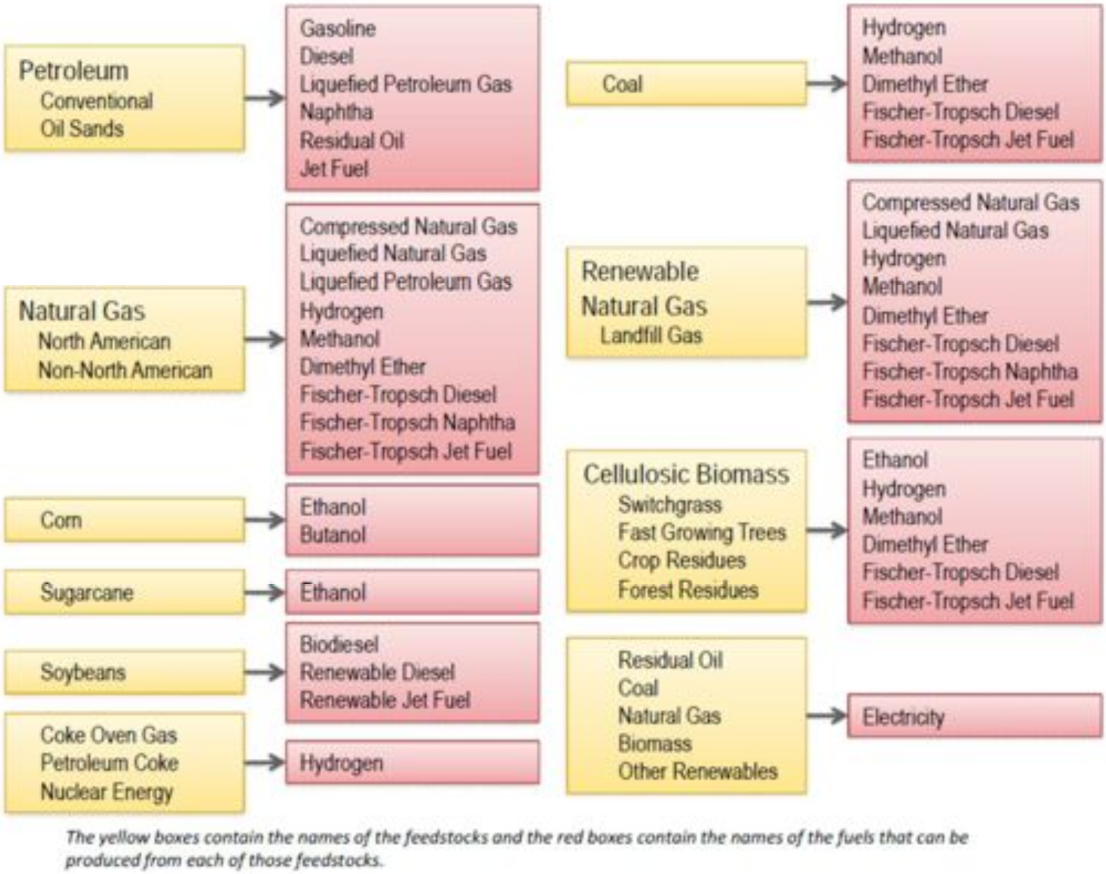


Figure 8.1. General fuel production pathways of the GREET model.

GREET covers the following vehicle technologies:

- Conventional spark-ignition engines
- Direct-injection, spark-ignition engines
- Direct injection, compression-ignition engines
- Grid-independent hybrid electric vehicles
- Grid-connected (or plug-in) hybrid electric vehicles
- Battery-powered electric vehicles
- Fuel-cell vehicles.

When biofuels cycles are analyzed in GREET, the carbon emitted from biofuel combustion (carbon in carbon dioxide, methane, volatile organic compounds, etc.) is considered to be the carbon uptaken during biomass growth. In general, this is a "break even" proposition, which means that, in GREET, the net carbon emission generated from the biofuel combustion itself is zero (it is all fully recycled). On the other hand, the entire fuel cycle of biofuels requires chemical inputs and fossil energy use, which produce anthropogenic GHG emissions that must be accounted for in biofuel fuel cycles. Besides these anthropogenic emissions, the current GREET version incorporates a module to estimate GHG emissions from direct and indirect land use changes for U.S. corn ethanol production (see below, Paragraph 9.1.1). This is based on recent modeling of land use changes within economic models.

8.2.3 GHGenius (Canada)

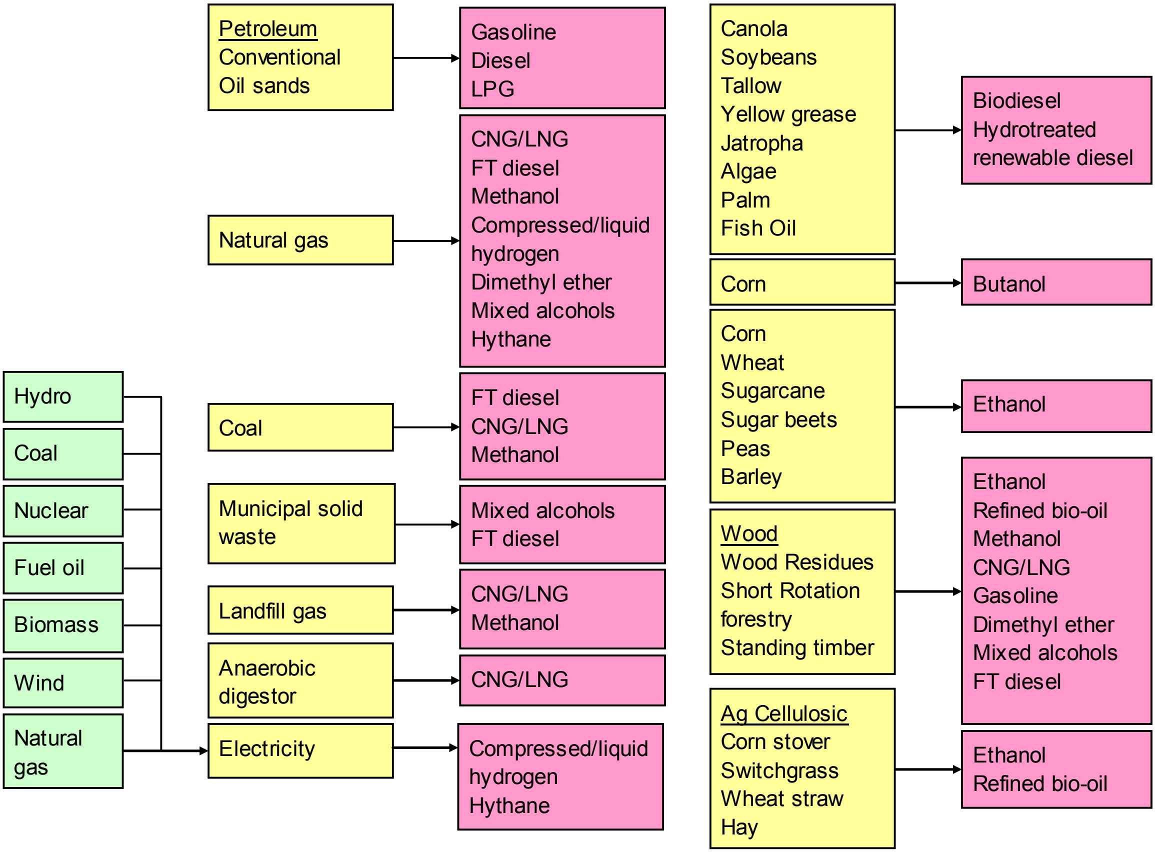
GHGenius has been developed by Natural Resources Canada since 1999. It was originally based on the Lifecycle Emissions Model (LEM) created at University of California, Davis. It has since been populated with Canadian data and converted to an Excel spreadsheet. Many new fuel pathways and functionalities have been added, along with the ability to analyze lifecycle emissions of fuels for Mexico and India, as well as for individual regions of Canada and the U.S. GHGenius is available free of charge for anyone to use. The version of GHGenius used in this report is version 3.20. (http://www.ghgenius.ca/).

For a given vehicle and fuel system, GHGenius separately calculates the following:

- Consumption of total energy (fossil and non-fossil) to produce the fuel
- Emissions of CO_2-equivalent greenhouse gases (carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), chlorofluorocarbons and hydrofluorocarbons(CFCs & HFCs) separately for vehicle operation, fuel production stages, and vehicle materials
- Emissions of five other criteria air pollutants: carbon monoxide (CO), nitrogen oxides (NO_x), sulfur oxides (SO_x), volatile organic compounds (VOC), and particulate matter (PM).

GHGenius covers numerous fuel and vehicle technology combinations. New fuels are added as they become relevant or as data becomes available. The following figure represents the feedstock and fuel combinations that GHGenius includes. (Many of the fuels also have fuel cell applications in GHGenius.)

Figure 8.2 presents the fuel pathways covered by GHGenius.



The yellow boxes contain the names of the feedstocks, and the red boxes contain the names of the fuels that can be produced from each of these feedstocks. The green boxes are energy sources for electricity generation.

Figure 8.2. General fuel production pathways of GHGenius.

GHGenius covers the following vehicle technologies in light and heavy duty cases:

- Conventional spark-ignition engines
- Compression ignition engines
- Hybrid vehicles
- Plug-in hybrid vehicles
- Battery powered electric vehicles
- Fuel cell vehicles.

Vehicle operation parameters such as fuel consumption can easily be changed by the user.

The carbon emitted from the combustion of biofuels (carbon in carbon dioxide, methane, volatile organic compounds, etc.) is considered to be the carbon absorbed during biomass growth, which is treated as a credit. However, combustion emissions may not be zero since there is expected to be a certain amount of methane or other GHGs produced from incomplete combustion. The balance of the fuel cycle emissions includes the emissions from producing the feedstock and other chemical inputs and the renewable and non-renewable energy used to produce the fuel.

8.2.4 Renewable Energy Directive (EU)

The WTT assessment in the European context is done by following the guidelines given in the European Union Renewable Energy Directive 2009/28/EC (RED). The EU Directive on the promotion of the use of energy from renewable sources was published in the Official Journal of the European Union on 5 June 2009. It establishes an overall binding target of a 20% share of energy from renewable sources in gross final energy consumption in the EU, as well as binding national targets in line with the overall EU target of 20%. It also sets a 10% binding minimum target for renewable energy (including biofuels) in transport, to be achieved by each member state by 2020.

The RED introduces environmental sustainability criteria for transportation biofuels and other bioliquids. Only biofuels and bioliquids in compliance with these criteria may benefit from national support systems and can be counted in the targets presented in the RED.[4] There are two types of sustainability criteria in the RED. Firstly, there are limitations concerning the areas of origin of the raw materials for the biofuel production. Secondly, there are limitations concerning the greenhouse gas emissions produced during the life cycle of the biofuels. The greenhouse gas emission saving from the use of biofuels compared to the use of fossil fuel shall be at least 35% for current biofuels and at least 50% from 1 January 2017. From 1 January 2018 the emission saving shall be at least 60% for biofuels produced in installations in which production started on or after 1 January 2017. The RED provides a list of default values of the emissions saving results for certain biofuels. It also introduces a methodology for calculating the greenhouse gas emissions of a biofuel production chain. This methodology is presented in detail in the Appendix 1. The RED does not introduce any criteria for other pollutants than greenhouse gas emissions.

In this report, the RED default values for studied biofuels were chosen to present the European values of the greenhouse gas emissions. However, these default values are based on assumptions, and might not present the real greenhouse gas emissions of any biofuel chain. The RED default values are presented in the

[4] The focus of this report is on transportation biofuels, but the RED criteria presented apply also for other bioliquids even though they are no more mentioned.

annex V of the directive. The assumptions behind these default values are currently clarified in a project called Biograce and this data can be downloaded from: http://www.biograce.net/content/ghgcalculationtools/excelghgcalculations.

The default values originally based on a research made by Joint Research Centre, EUCAR and CONCAWE (Edwards et al. 2008), so called JEC-study. To get the RED default values, the results of the JEC-study are adapted to the RED calculation methodology. The main difference between the RED and JEC-study is that in the RED methodology the emissions are allocated between the main product and co-products based on energy allocation when in the JEC-study the substitution method is used.

8.2.5 Comparison of the different models and methods used

The WTT results always depend on the calculation methodology used, the system boundary set and the assumptions made for the calculation parameters. The models and calculation methodologies presented in this study differ from each other. We made a simple comparison of the GREET and GHGenius models and the RED methodology by comparing some calculation principles and assumptions used in each model. The results are presented in Table 8.1. Also the calculation methodology used in the JEC-Study (Edwards et al. 2008) is included in the comparison, as the results of this study are linked with the RED default values.

There is one important difference between the GREET model and the RED methodology, which is crucial to understand in order to interpret the WTT results in this report. In the RED methodology, the emission due to combustion of a biofuel is considered to be zero. This is due to the assumption that the amount of carbon absorbed in the growing biomass used as biofuel raw material, is similar to the carbon released when biofuel is combusted. On the contrary, in the GREET model the carbon absorption of growing biomass is taken into account and consequently the WTT emission may be negative, if more CO_2 is absorbed than released during the biofuel production. However, the GREET model takes into account the real emission of the biofuel combustion and does not consider it as zero, as the RED methodology does. This means, that **the RED results should be compared with the sum of WTT and TTW results of the GREET-model.** The GHGenius considers the CO_2 emissions due to biofuel combustion as zero (as the RED), but calculates the CH_4 and N_2O emissions for combustion. The RED does not consider CH_4 and N_2O emissions of combustion as it is assumed that they are similar for biofuels and fossil fuels. The GREET model considers the CH_4 and N_2O emissions of biofuel combustion.

Also, an important difference is that the allocation method may vary between the models. The GREET lets the user to choose between co-product displacement, or energy / market value allocation, the GHGenius uses system expansion and displacement for biofuels and process allocation for petroleum fuels, and the RED requires the use of energy allocation based on lower heating value of products.

Table 8.1. Comparison of the models and methods used in the WTT assessment.

Comparison of:	**RED (European Union calculation methodology)**	**JEC 2007 (JRC, CONCAWE, EUCAR)**	**GREET-model**	**GHGenius**
Greenhouse gas saving calculated as:	SAVING=(Ef-Eb)/Ef Ef=emission of fossil fuel Eb=emission of biofuel	SAVING=(Ef-Eb)/Ef Ef=emission of fossil fuel Eb=emission of biofuel	Results given as emission factors: WTT: grams/mmBtu (or MJ) fuel available at pump station WTW: grams/mile Savings are calculated the same way as RED (bottom of the Results Sheet)	Results given as gCO_{2eq}/km (WTW), gCO_{2eq}/GJ (WTT), gCO_{2eq}/fuel unit WTW). Also, savings per unit of fuel basis (WTW).
GHGs taken into account and values for calculating CO2-eq:	CO_2: 1 N_2O: 296 CH_4: 23 (IPCC 2001)	CO_2: 1 N_2O: 296 CH_4: 23 (IPCC 2001)	CO_2: 1 N_2O: 298 CH_4: 25 (IPCC 2007)	CO_2: 1, N_2O: 298, CH_4: 25 (IPCC 2007) (IPCC 1995 and 2001 also available)
Emissions of production of chemicals and fertilizers:	Should be Included	Partly included	Included (the Agri-Inputs Sheet)	Included
Emissions of production of farming equipment:	Excluded	Excluded	Can be included or excluded	Included
Emissions from construction of processing plants, buildings, infrastructure	Excluded	Excluded	Some facilities included	
CO_2 emissions from biofuel combustion considered as zero	Yes	Yes	No	No
CO_2 credits from absorption of C in growing biomass:	**Excluded**	**Excluded**	**Included as separate line**	**Included as separate line**
Land Use Change (status change):	el=(CSR-CSA) x 3,664 x 1/20 x 1/P-eB (iLUC is excluded)	Excluded	Included (direct LUC and iLUC for corn ethanol, and will have LUC for cellulosic biomass)	Included (net capture/release estimated based on region) (ILUC is excluded) Uses IPCC methodology.

Time period for LUC:	20 years	Excluded	20-100 years (default 30 years)	Selected by user, default is 20 years
Soil carbon stock changes due to biomass cultivation or harvesting	Excluded?	Excluded	Capable of inclusion	
Reference land use	Not specified	The alternative use of the land under set-aside (fallow or sown with a green cover crop)	Part of LUC modeling framework	
Nitrogen emissions:	Emission factor not specified	DNDS soils model (direct + indirect compared to reference scenario)	N content of above and below ground biomass + N2O of fertilizers	N content of above and below ground biomass + N2O of fertilizers. Full IPCC methodology (direct plus indirect)
Bonus of using degraded land for raw-material cultivation:	29 gCO_{2eq}/MJ	Not considered	Not included directly, indirectly in LUC modeling	Not included, but could be captured in land use change calculation.
Emissions of processing:	Actual values should be used	Typical average values relevant for the EU	Default values are based on industry averages. Can be overridden by the user with actual values.	Default values are based on industry averages. Can be overridden by the user with actual values.
Emissions of electricity:	Average value of the region or average value of the process	Average value of the EU (447 or average value of the process?	Average value of the region or average value of the process	Average value for a region.
Emissions of raw material, intermediate product or final product transportation:	Not specified	Specific assumptions for different fuel pathways	Model offers several well defined choices	Model offers default values for several different modes. User may modify.
Carbon capture and storage:	CCR: only for carbon originating from biomass and if fossil-derived carbon replaced CCS: geological storage → for all carbon	Not considered as an option for biofuel pathways	Included for coal and biomass gasification and combustion	May be included for several different stages (power generation, fuel production, refineries)

Allocation method:	Energy content	System expansion and displacement for biofuels. Process allocation for petroleum fuels	Energy content, Displacement, Market value, Hybrid, User can choose	System expansion and displacement for biofuels. Process allocation for petroleum fuels
Excess electricity credit:	Credits from primary energy efficiency improvement considered if excess electricity from co-generation is produced by agricultural crop residue	Credits from primary energy efficiency improvement considered	Depends on the allocation method used	Displacement. User can select displaced power mix.
Waste/residue raw materials:	Lifecycle starts at point of collection of waste/residue	Lifecycle starts at point of collection of waste/residue	Lifecycle starts at point of collection of waste/residue and supplement fertilizer is considered	Lifecycle starts at point of collection of waste/residue
Comparator:	Fossil fuel comparator: 83,8 gCO_{2eq}/MJ		Petroleum gasoline comparator: 97 gCO_{2eq}/MJ (LHV)	Petro gasoline: 88 g/MJ (HHV) (~93.9 g/MJ LHV)

8.3 TTW assessment methods

8.3.1 General

As described above, the WTT figures are based on a number of assumptions, and cannot be measured in an exact way. Engine and vehicle performance i.e. TTW, on the other hand, can be measured objectively and with good accuracy applying methodology used for engine and vehicle type approval. However, these methods are basically designed to evaluate whether an engine or a vehicle meets certain limit values for emissions when running on a standardized test fuel according to a certain test cycle.

The emission regulations typically require the following components to be measured:

- Carbon monoxide (CO)
- Total hydrocarbons or non-methane hydrocarbons (THC/NMHC)
- Oxides of nitrogen (NO_x)
- Particulate matter (PM, gravimetrically)
- Carbon dioxide (CO_2, for light-duty vehicles).

When evaluating alternative fuels there is often a need to carry out more comprehensive measurements, including unregulated components as well as particle size measurements.

Type approvals for light-duty vehicles are carried out by running complete vehicles on a chassis dynamometer. Thus the results will depict the performance of the total vehicle, not only the engine. Parameters are typically reported in the form of g/km, i.e. relative to driven distance.

The situation for heavy-duty on-road engines is different, as homologation is done for the engine only. The rationale for this is that a particular engine can be applied in different kinds of vehicles, i.e. city buses, intercity buses and trucks.

However, this leads to a situation in which the emission results do not correspond well to the real world operation of the total vehicle. To determine the actual emissions of the complete vehicle, e.g. a city bus, the vehicle can be measured on a chassis dynamometer in the same way as the type approval for light-duty vehicles is done.

Although there is no universal methodology or standard for chassis dynamometer measurements of heavy-duty vehicles, several laboratories around the world are producing emission results for complete heavy-duty vehicles. One widely recognized guideline for this kind of measurements is SAE J2711, SAE Recommended Practice for Measuring Fuel Economy and Emissions of Hybrid-Electric and Conventional Heavy-Duty Vehicles.

In general, measurements are focused on new types of vehicles, i.e. vehicles using newest exhaust clean-up technology, advanced power-trains and/or alternative fuels. To include the specifics of the vehicle itself is a must when evaluating new vehicle technologies. Natural gas buses and hybrid buses are heavier than conventional diesel vehicles, and this must be taken into account when evaluating overall performance. Testing the internal combustion engine (ICE) only will not depict the performance of a hybrid powertrain, as the testing methodology doesn't account for recuperated kinetic energy or an alternative strategy to utilize the ICE, changing the load pattern significantly.

However, engine testing is usable when evaluating, e.g., interchangeable fuels. On-road or on-board measurements again can be used to account for real traffic conditions and varying ambient temperature.

Regarding accuracy, engine testing provides the best accuracy, chassis dynamometer measurements second best and on-road measurements lowest accuracy and repeatability.

All three types of testing were applied in the IEA Bus Project. The bulk of the testing was carried out with complete vehicles on chassis dynamometers. Detailed emission analyses for selected fuels were carried out running a heavy-duty diesel engine installed in an engine dynamometer. Some on-road measurements were carried out as well, mostly to study the impact of ambient temperature.

A complete emission measurement system consists of a power absorption unit (chassis dynamometer or engine dynamometer, in on-road measurements the vehicle itself), a system for exhaust collection and sampling to determine exhaust volume flow and an analytical system to determine component concentrations.

8.3.2 Chassis dynamometer testing

In the IEA Bus Project, both Environment Canada (EC) and VTT carried out chassis dynamometer measurements. Both laboratories use standardized equipment, i.e., a chassis dynamometer allowing transient-type driving, a full-flow constant volume sampler (CVS) system for handling exhaust sampling and an analytical system, and also an array of city bus driving cycles. As mentioned before, the laboratories cooperated, together with West Virginia University (USA), within an IEA AMF project in 2005–2007 to evaluate test cycles for city buses (Nylund et al. 2007).

For the measurements, the laboratories basically followed the practices and recommendations of SAE J2711 (SAE Recommended Practice for Measuring Fuel Economy and Emissions of Hybrid-Electric and Conventional Heavy-Duty Vehicles).

<u>Chassis dynamometers</u>

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

At Environment Canada a single axle dynamometer system, designed and assembled by the Emissions Research and Measurement Section (ERMS), was used in this project (Figure 8.3). The system consists of a single roll which has a diameter of 61 cm. The inertia weight and road loads were simulated during testing using a 300 kW General Electric direct current motor/generator working as a power absorber. The system simulates inertia and the road load (rolling resistance and the air drag forces) of tested vehicle. All the power generated by the dynamometer is regenerated and is returned to the electric grid. The system has the capability of testing vehicles from 7,700 to 35,000 kg, simulating the appropriate road load at all vehicle speeds. The dynamometer also has the ability to compensate for the system’s internal power losses, so the vehicle behaves similarly as it was being driven on the actual road.

The rotating speed of the dynamometer rolls during a vehicle emissions test is measured by an optical pulse counter (1500 pulses per revolution), which communicates this information to a microprocessor controller. The controller translates the pulses into the linear speed of the vehicle and it is displayed on a video screen as a cursor. The vehicle driver then uses the cursor to follow a preselected speed versus time trace. In this way, the vehicle may be operated over a selected transient operation or driving cycle. Dynamometer parameters are recorded continuously, including distance, speed, acceleration, torque, simulated road load force, and simulated inertia force. A fixed speed fan which meets the requirements of 40CFR Part 86.107-96 (d) was used to provide engine cooling air.

Figure 8.3. A test bus on Environment Canada's chassis dynamometer.

For measurements of heavy-duty vehicles, **VTT** uses a single-roller, 2.5 meter diameter chassis dynamometer with electric inertia simulation. The system has the capability of testing vehicles from 2,500 to 60,000 kilograms. Maximum power absorbed power (continuous) is 300 kW. Figure 7.4 presents the schematic of VTT test facility.

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

CVS and analytical systems

For emission measurements, both laboratories used full-flow CVS dilution systems. In the case of EC, the instrumentation conforms with United States Code of Federal Regulations (CFR) Title 40, Subpart B & N of Part 86. In the case of VTT, the analytical equipment (Pierburg CVS-120-WT CVS and analyzer set Pierburg AMA 4000) is compliant with Directive 1999/96/EC.

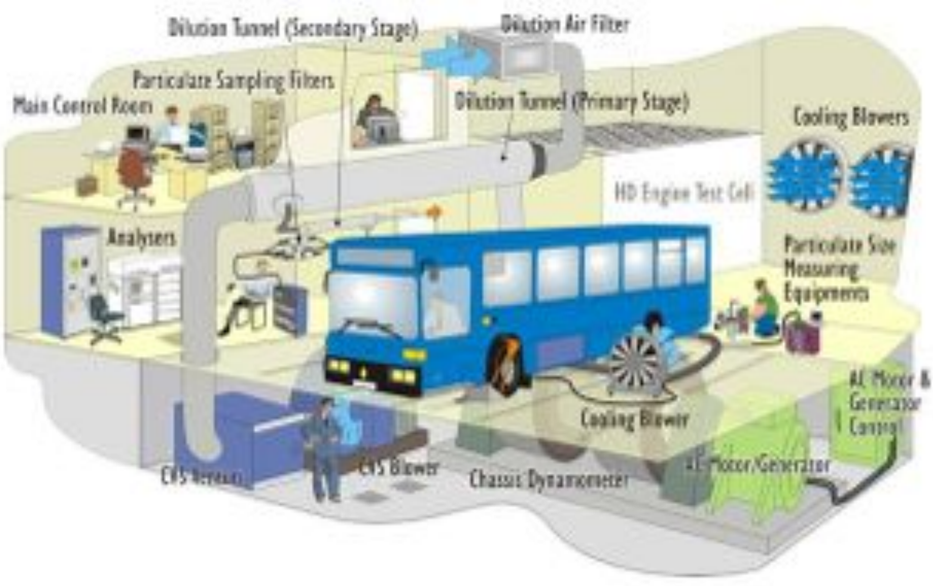


Figure 8.4. Schematic of VTT's heavy-duty test facility.

The total exhaust stream produced by the bus was collected and diluted using the CVS dilution system. The raw exhaust was then diluted with filtrated laboratory background air and the mixture drawn through a critical flow venturi. During the exhaust emissions tests, continuously proportioned samples of the dilute exhaust mixture and the dilution air were collected and stored in Tedlar^{TM} sample bags for analysis. In addition, for some components continuous sampling was also undertaken through heated probe, filter, and sample line systems. Table 8.2 presents a summary of sample collection and analysis in the two labs.

Table 8.2. Summary of sample collection and analysis.

Compound	Analysis method		Sample collection	
	EC	VTT	EC	VTT
Regulated components				
Carbon dioxide (CO_2)	NDIR	<-	Tedlar™ bag	<-
Carbon monoxide (CO)	NDIR	<-	Tedlar™ bag	<-
Oxides of nitrogen (NO_x)	CLD	<-	Continuous collection	Tedlar™ bag
Total hydrocarbons (THC)	FID	<-	Continuous collection	<-
Particulate mass (TPM/PM)	Gravimetric	<-	47 mm filter	70 mm filter
Unregulated components				
Methane (CH_4)	GC	FID splitter[2)]	Tedlar™ bag	Tedlar™ bag
Nitric oxide (NO)/ Nitrogen dioxide (NO_2) balance	CLD[3)]	CLD[3)]	Continuous collection	Continuous collection
Nitrous oxide (N_2O)	GC[1)]	FTIR[3)]	Tedlar™ bag	Continuous collection
Particulate numbers (#)	CPC/EEPS	ELPI[3)]	Continuous collection	Continuous collection
Aldehydes	HPLC	HPLC[4)]	DNPH car-tridges	DNPH car-tridges
Unburned ethanol	n/a	HPLC[4)]	n/a	Water imping-er

CLD: Chemiluminescence Detection (heated)
CPC: Condensation Particle Counter
DNPH: 2,4-Dinitrophenylhydrazine (Brady's agent)
EEPS: Engine Exhaust Particle Sizer
ELPI: Electrical Low Pressure Impactor
FID: Flame Ionization Detection (heated)
GC: Gas Chromatography
HPLC: High Performance Liquid Chromatography
NDIR: Non-Dispersive Infrared Detection
[1)]: with Electron Capture Detection
[2)]: CNG vehicles
[3]): selected vehicles
[4)]: ethanol vehicle

Fuel consumption

Environment Canada calculated fuel consumption from an industry standard method based on carbon balance of the exhaust gases. VTT used this method only for the di-methyl-ether (DME) vehicle, but measured fuel consumption gravimetrically for the other vehicles. A special gas meter calibration system, consisting of a compressed natural gas (CNG) cylinder and a special balance, on loan from the Finnish Centre for Metrology and Accreditation, was used to measure the fuel consumption of the CNG vehicles. At VTT, all liquid fuels were measured using VTT's standard protocol of fuel handling, including fuel temperature control, flushing in conjunction of fuel change etc.

Dynamometer settings

The chassis dynamometer testing procedures followed for this type of emissions testing are outlined in a US EPA report entitled "Recommended Practice for Determining Exhaust Emissions from Heavy Duty Vehicles under Transient Conditions"[5]. The electronic programming feature of the dynamometer controller allows for a speed-power curve[6] for each test vehicle.

At EC, the dynamometer settings were determined using data from on-road coast down tests. The test weight was used simulated the weight of half of the passengers at 68 kg per passenger. Target coefficients were derived using the SAE J1263 coast down technique. Based on these target coefficients, dynamometer set coefficients were obtained by performing a chassis dynamometer coast down procedure according to SAE J2264§3.12.

For all test buses, at EC, it was not possible to perform on-road vehicle coastdowns, and therefore some of the test buses were tested with road load simulations which were derived from a similar vehicle.

VTT used a road-load model for a typical two-axle city bus, based on coastdown measurements on the road. To determine the dynamometer settings (F0, F1, F2), the rolling resistances of the rear tires and the rear axle were deducted from the total resistance values, a common practice in setting up the chassis dynamometer. For a bus running a typical transient city cycle, the mass of the vehicle is decisive for driving resistances. The aerodynamics and the front area of city buses are practically constant. The bus which was tested on the road was used as a gauging rod for the other vehicles. For the other vehicles, the settings were adjusted by taking into account vehicle mass. Vehicle mass affects inertia as well as rolling resistance. The simulated load at VTT was half load, approximately 3000 kg. When testing vehicles on the chassis dynamometer, VTT used special sets of tires with longitudinal grooves only to normalize the effects of tires.

For each driving cycle and vehicle the theoretical amount of work on the perimeter of the chassis dynamometer drum can be calculated. The driving cycles are defined as speed versus time. If a vehicle cannot follow the stipulated speed versus time trace, either due to limited power or limited maximum speed, the work performed over the test cycle will not amount to the correct value. Hence, the engine output will also remain lower, with due influence on fuel consumption and emissions. Therefore, at VTT, the actual measured emission and fuel consumption values for each individual vehicle were scaled to correspond to the correct amount of work, derived from the weight of the vehicle.

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

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

Vehicle conditioning

At EC the test buses were warmed at a steady state conditions for 15 minutes at a constant speed of 65 km/h, then the a warm-up test cycle was driven; followed by three additional test cycles. The final results were calculated as an average of the last three drive cycles.

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

Driving cycles

When assessing vehicle emissions performance and energy consumption, it is customary to use fixed, prearranged driving schedules that reflect the duty-cycle of the vehicle in the given application and operating environment. In the 2005–2007 joint study (Nylund et al. 2007) altogether 20 different cycles for heavy-duty vehicles were evaluated. This time the number of test cycles was lower. Three cycles, ADEME (describing driving in Paris), Braunschweig bus cycle and Heavy-Duty Urban Dynamometer Driving Schedule (UDDS) were the common drive cycles used by both EC and VTT. The idea was that when possible, all vehicles and fuels should be tested at least using these cycles. This was, however, not possible in all cases, due to technical, financial or even time schedule reasons.

These three cycles represent driving in different conditions:

- ADEME: European megacity
- Braunschweig: mid-size city
- UDDS: suburban driving pattern.

When estimating external costs of emissions, especially the costs for particulate emissions vary with population density: the bigger and more densely populated city, the higher the number of people exposed to particulates and thus the higher the calculatory external costs (Handbook on estimation of external costs 2008).

In addition, the testing partners added cycles of special interest. At EC, the additional cycles were:

- Central Business District (CBD)
- Japanese JE05
- Manhattan
- Orange County Transportation Authority (OCTA).

VTT selected the following additional cycles:

- Japanese JE05
- New York Bus (NYBUS)
- World Transient Vehicle Cycle (WTVC).

Data on all test cycles is given in Table 8.3. Four of these cycles are those identified in SAE J2711: CBD, Manhattan, OCTA and UDDC. All cycles are presented in graphic form in Appendix 2.

Table 8.3. Relevant properties of drive cycles, in order of ascending average speed.

Cycle	Code	Time (sec)	Distance (km)	Av. speed (km/h)	Idle (%)	Stops per km
New York Bus	NYBUS	600	0.98	5.94	66	12.4
ADEME-RATP	ADEME	1897	5.68	10.7	33	7.52
Manhattan	MAN	1099	3.33	10.9	37	6.00
Orange County	OCTA	1950	10.5	19.4	24	2.95
Central Business District	CBD	568	3.23	19.9	22	4.33
Braunschweig	BRA	1750	10.9	22.6	26	2.65
Japanese HD cycle	JE05	1800	13.9	30.0	25	1.08
Urban Dynamometer Driving Cycle	UDDS	1060	8.91	30.3	33	1.46
World Transient Vehicle Cycle	WTVC	1800	20.1	40.1	14	0.50

When running a vehicle test on a chassis dynamometer these prearranged driving schedules are usually fed into a system called “driver’s aid”.

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

8.3.3 Engine dynamometer testing

The Institute of Agricultural Technology and Biosystems Engineering at the Johann Heinrich von Thünen Institute (vTI) in Braunschweig carried out fuel evaluation for the IEA Bus project using a heavy-duty diesel engine installed on an engine dynamometer test stand. Data for the Mercedes-Benz OM 906 LA engine with turbocharger and intercooler is presented in Table 8.4.

This engine was well suited for fuel evaluation. Euro III was applicable in Europe until 2005/2006, and as the engine has no exhaust after-treatment devices, it accentuates differences in exhaust emissions arising from variations in the fuel.

The engine was installed in an automated eddy-current brake (Froude Hoffmann AG 250). The fuel testing for the IEA Bus project was mainly carried out in accordance with the European Stationary Cycle (ESC) test procedure defined in

Directive 1999/96/EC. Figure 8.5 presents the load points (relative speed and load) of the ESC test cycle. The running order as well as the weighting of the individual points are also shown in the Figure. Figure 8.6 presents an example of the speed and torque traces of an actual test at vTI.

Table 8.4. Technical data of the test engine OM 906 LA.

Stroke	130 mm
Bore	102 mm
Number of cylinders	6
Swept volume	6370 cm^3
Rated speed	2300 min^{-1}
Rated power	205 kW
Maximum torque	1100 Nm at 1300 min^{-1}
Fuel injection system	In-line injector pump
Exhaust emission certification	Euro III
Exhaust after-treatment	None

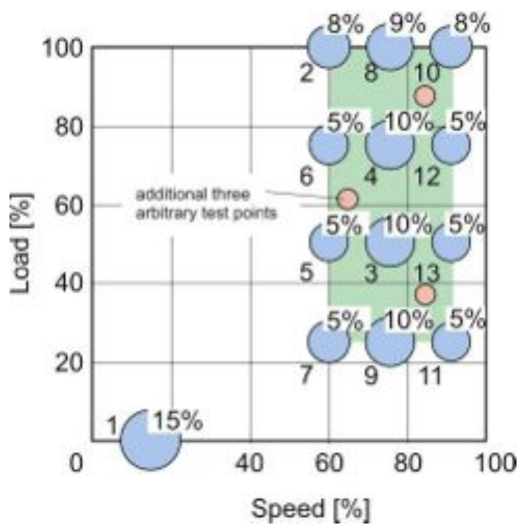

Figure 8.5. The ESC test cycle. (1999/96/EC)

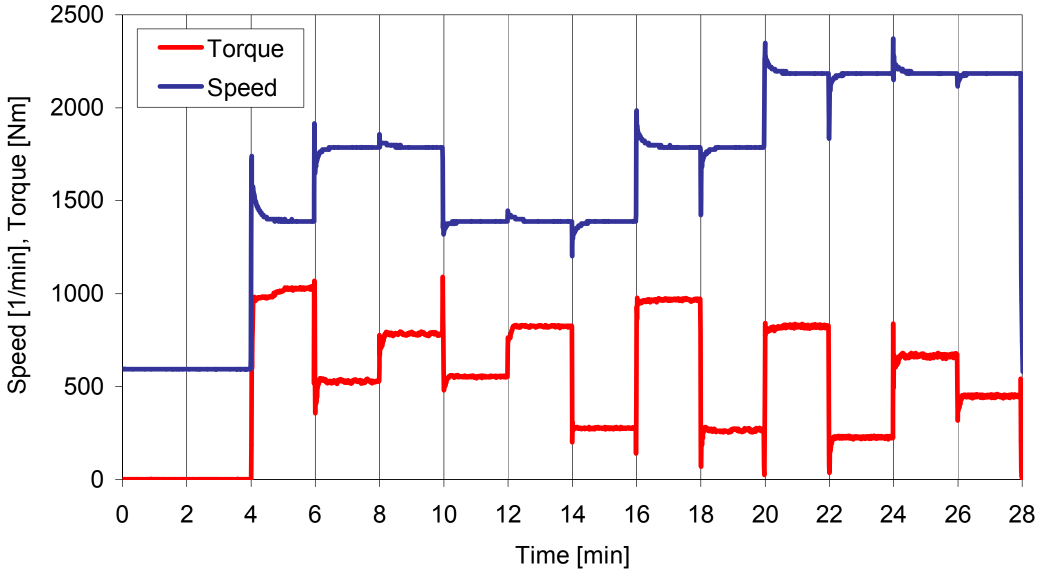

Figure 8.6. Example of actual speed and torque traces during testing.

In the case of ESC testing, a full-flow dilution tunnel is not required. Therefore vTI used a partial dilution system shown in Figure 8.7.

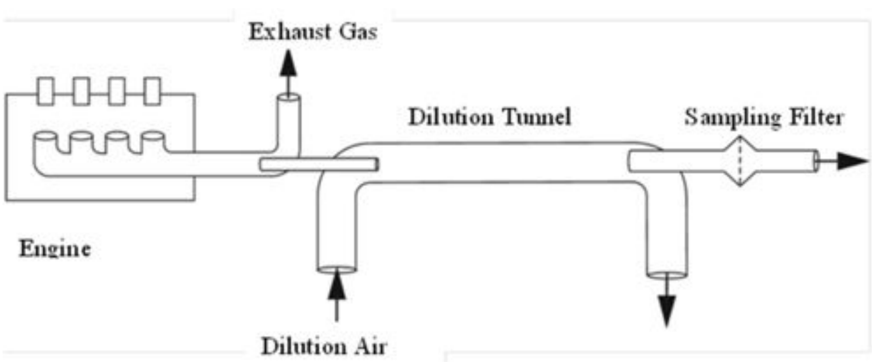

Figure 8.7. Schematic presentation of the exhaust gas dilution tunnel.

The regulated gaseous components (CO, THC, NO_x) were determined in the undiluted exhaust gas using commercial gas analyzers (NDIR, FID, CLD) with a sampling rate of 1 second. To achieve the desired weighting for the individual load points in the particulate measurement (PM), the sampling flow rate was controlled in proportion to the weight factor of the load point.

vTI carried out a comprehensive set of measurements for unregulated emission components. Table 8.5 presents the compounds and parameters analyzed and the methodology.

Ames et al. (1975) developed the *Salmonella typhimurium*/mammalian microsome assay that detects mutagenic properties of single compounds as well as of complex mixtures by reverse mutation of a series of *Salmonella typhimurium* tester strains, bearing mutations in the histidine operon. Depending on the tester strain different types of mutations can be detected.

Table 8.5. Unregulated components and parameters analyzed by vTI.

Component or parameter	Analysis method
Number of Particles and Particle Size Distribution	SMPS & ELPI
Mutagenicity of the Soluble Organic Fraction of the Particles	Ames testing with *Salmonella typhimurium* tester strains TA98 and TA100 (Maron & Ames 1983)
Carbonyl compounds	DNPH sampling + HPLC-DAD
Polyaromatic hydrocarbons (PAH)	Toluene extraction + HPLC-FLD

SMPS: Scanning Mobility Particle Sizer

In this study tester strains TA98 and TA100 were used, detecting mutagens that cause frameshift mutations and base-pair substitutions. These strains were shown to be most sensitive to mutagens of organic extracts of diesel engine particles (DEP). The samples were tested both for direct (without metabolic activation) and indirect (with metabolic activation) mutagenicity. When the direct (-S9) mutagenicity is higher than the indirect (+S9) after metabolic activation of extracts by rat liver enzymes, this speaks for the theory that the largest part of the mutagenicity is caused by substituted PAH (for example, nitro-PAH). These are mostly direct mutagens while the native PAH require a metabolic activation through the formation of epoxides.

vTI analysed all in all 11 carbonyl compounds. Table 8.6 presents the PAH compounds analyzed by vTI.

Table 8.6. 16 PAH compounds measured by vTI.(EPA method 610)

Name	Number of rings	Abbreviation
Naphthalene	2	Nap
Acenaphthylene	3	non fluorescent
Acenaphthene	3	Ace
Fluorene	3	Flu
Phenanthrene	3	Phe
Anthracene	3	Ant

Fluoranthene	4	Fla
Pyrene	4	Pyr
Benz[a]anthracene	4	BaA
Chrysene	4	Chr
Benzo[b]fluoranthene	5	BbFla
Benzo[k]fluoranthene	5	BkFla
Benzo[a]pyrene	5	BaPyr
Dibenz[a,h]anthracen	5	DBAnt
Benzo[ghi]perylene	6	BPer
Indeno[1,2,3-cd]pyrene	6	IPyr

8.3.4 On-road measurements

Two on-road measurement campaigns were performed. Early in 2009 AVL together with VTT tested three city buses, two diesel vehicles and one CNG vehicle, on actual bus lines in Helsinki area. In 2011, VTT, in cooperation with JRC VELA, organised a second on-road session, comprising three diesel buses, at Varkaus airport. The second campaign was aimed at studying the start-up performance of the emission control systems. In both campaigns, emissions were measured using a Portable Emission Measurement System (PEMS). For both campaigns, ambient temperature was around zero degree Celsius or below.

Instrumentation of the first campaign

For the first campaign, a system from Sensors was used. The Semtech-DS system is developed for testing all classes of diesel and gas-powered vehicles and equipment under real-world operating conditions. The instrument is an on-board emissions analyzer which enables tailpipe emissions to be measured and recorded simultaneously while the vehicle is in operation.

The following measurement subsystems are included in the Semtech-DS emission system:

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

The instrument is operated in combination with an electronic vehicle exhaust flow meter, Semtech ExFM. The Semtech-DS instrument uses the flow data together with exhaust component concentrations to calculate instantaneous and total mass emissions. The flow meter is available in different sizes depending on engine size. A 4” flow meter was used, which is suitable for the engine size of the tested buses.

Soot was measured using the AVL 483 Micro Soot Sensor (Photo Acoustic Soot Sensor PASS), which is a system for continuous measurement of soot concentration internal combustion engines. In contrast to an opacimeter instrument, the soot concentration is determined directly from primary measurement quantity. The AVL 483 Micro Soot Sensor works on a photo-acoustic principle and the cell design chosen (called the "resonant measuring cell") allows a detection limit of $\leq$10 µg/m³, (typically ~ 5 µg/m³).

Test program of the first campaign

The three buses tested in the first campaign were (same individuals as in the chassis dynamometer measurements):

- Euro III diesel
- EEV EGR diesel
- EEV CNG stoichiometric.

The buses were tested during urban, suburban and highway driving conditions.

Three test runs were carried out on each test vehicle. The vehicles were loaded with ballast corresponding to approximately 26 passengers i.e. 1800 kg. In addition, some test runs were carried out without any ballast. The on-road testing and calculation was basically performed in accordance with the PEMS protocol. The PEMS protocol uses a work-based moving window or a CO_2 based moving window to sort out certain data points. However, in this case all data points second by second were included.

According to the PEMS protocol, the driving routes should include urban, suburban, and highway driving. Where possible, the trips should include:

- Hill climbs
- Segments with cruising at constant speed and segments that is highly transient in their character
- Different altitudes
- Typical driving for the vehicle type.

The test route was selected by VTT to represent urban, sub-urban and to some extent, highway driving. The test route consisted basically of three Helsinki city bus lines, 194, 63 and 550. The test routes are denoted Part 1, 2 and 3 in Tables and Charts. All tests were carried out at an ambient temperature ranging from -5 to +2 ^{o}C. Table 8.7 presents data for the bus lines, and Figures 8.8–8.10 present the speed vs. time profiles.

Table 8.7. Test route data.

	Line 194 (1)	Line 63 (2)	Line 550 (3)
Trip duration (s)	1620	1800	1475
Trip distance (km)	10.1	14.3	9.5
Average speed (km/h)	23	30	23

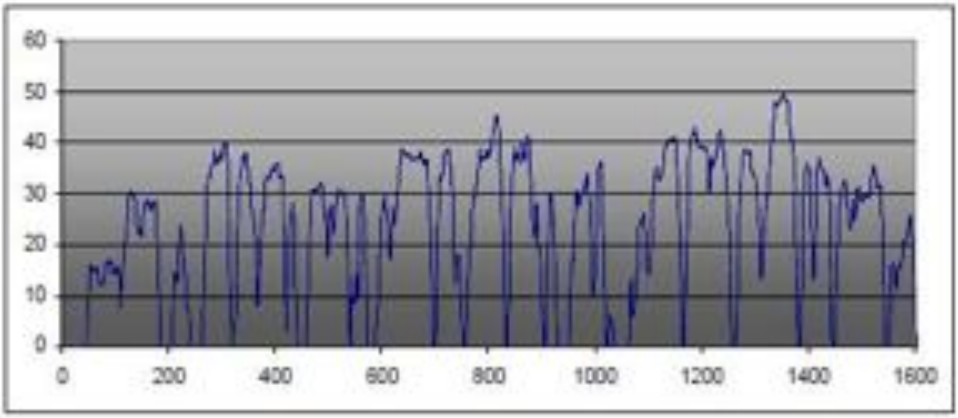

Figure 8.8. Line 194 profile, speed vs. time.

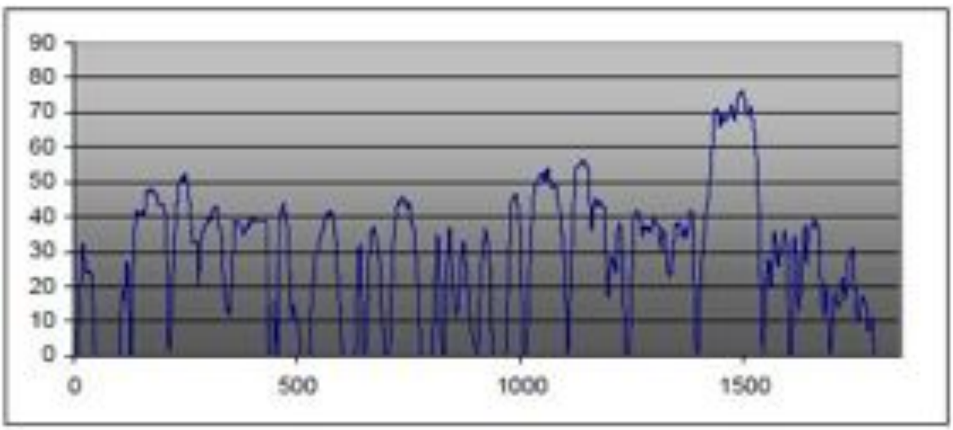

Figure 8.9. Line 63 profile, speed vs. time.

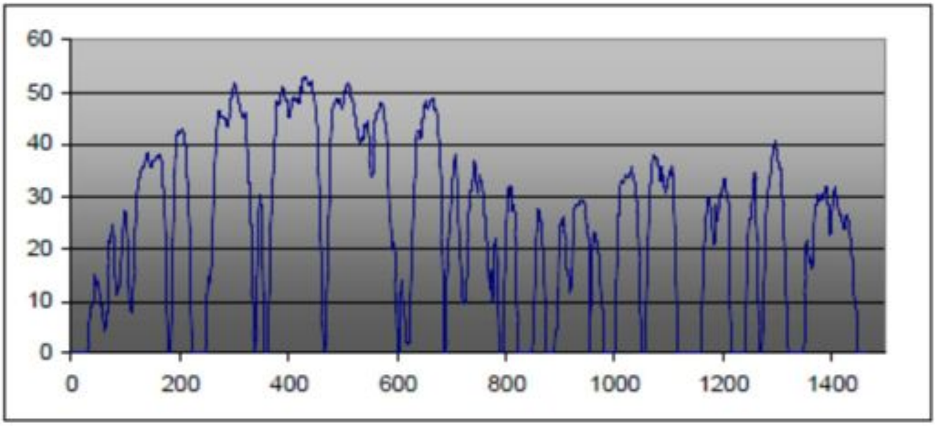

Figure 8.10. Line 550 profile, speed vs. time.

Instrumentation of the second campaign

For the second campaign, the test equipment was borrowed from JRC VELA. The equipment comprised of PEMS analyser for gaseous emissions components (SEMTECH-DS) and a prototype particulate matter analyser (Figure 8.11).

Test program of the second campaign

Three diesel buses were tested for the second campaign (not the same vehicle individuals as in the chassis dynamometer measurements):

- EEV EGR
- EEV SCR
- EEV SCRT.

Now the on-road measurements were carried out at Varkaus airport, not within normal city traffic. Two cycles were driven, the Braunschweig bus cycle and the SORT 2 cycle. UITP – the International Association of Public Transport has developed test cycles for on-road fuel consumption measurements. SORT stands for "**S**tandardised **O**n-**R**oad **T**est Cycles". The SORT cycles are made up of "trapezes". The SORT 2 cycle (Table 8.8) depicts mixed or easy urban driving and regarding fuel consumption delivers similar results as the Braunschweig cycle.

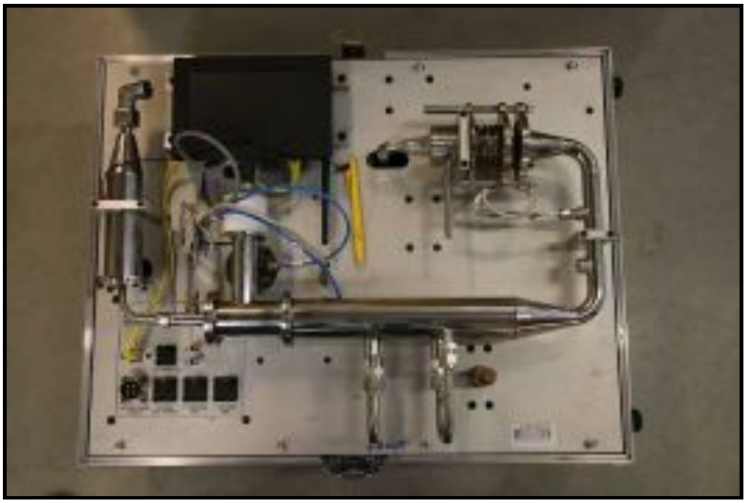

Figure 8.11. PEMS PM measurement instrument prototype by JRC VELA.

Table 8.8. Characteristics of the SORT cycles. (SORT 2004)

Comparison of the 3 SORT-Cycles (14,3 t)

	SORT 1	SORT 2	SORT 3
Rated average speed	12.6	18.6	26.3
Stops/km	5.8	3.3	2.1
Stop time (%)	39.7	33.4	20.1
Trapeze 1 v-const. (km/h) /length (m)	20 / 100	20 / 100	30 / 200
Acceleration (m/s²)	1.03	1.03	0.77
Trapeze 2 v-const. (km/h) /length (m)	30 / 200	40 / 220	50 / 600
Acceleration (m/s²)	0.77	0.62	0.57
Trapeze 3 v-const. (km/h) /length	40 / 220	50 / 600	60 / 650
Acceleration (m/s²)	0.62	0.57	0.46
Length of stops (s)	20 / 20 / 20	20 / 20 / 20	20 / 10 / 10
Total length (m)	520	920	1 450
Deceleration (m/s²)	0.8	0.8	0.8
Fuel consumption (l/100 km)	ca. 50	ca. 42	ca. 39

The testing was divided into two parts, warm-up phase and stabilized phase. Before testing the vehicles were allowed to cool down to ambient temperature. Test temperatures were in the range of 0 to -5 ^{o}C. Before commencing measurements, the vehicles were allowed to idle 5 minutes to raise air pressure. The testing was done by repeating the test cycles until stabilization in engine temperature was reached.

For reference, the vehicles were also tested on the chassis dynamometer using the Braunschweig cycle.

8.4 Cost assessment methods

8.4.1 General

Within the IEA Bus Project both indirect (external) and direct costs were estimated. It has to be pointed out that the calculations for both cases are based on a number of assumptions, and all values should therefore be considered indicative.

8.4.2 External costs of emissions

The estimation of external costs is based on the principles European Directive on the promotion of clean and energy efficient vehicles, 2009/33/EC. This Directive presents a methodology of calculating lifetime energy and emission costs. However, the costs for pollutants are taken from the 2008 Handbook on estimation of external costs in the transport sector, as this document provides a more comprehensive set of cost factors than the Directive (Handbook 2008).

Figure 8.12 shows the schematic of calculating external costs.

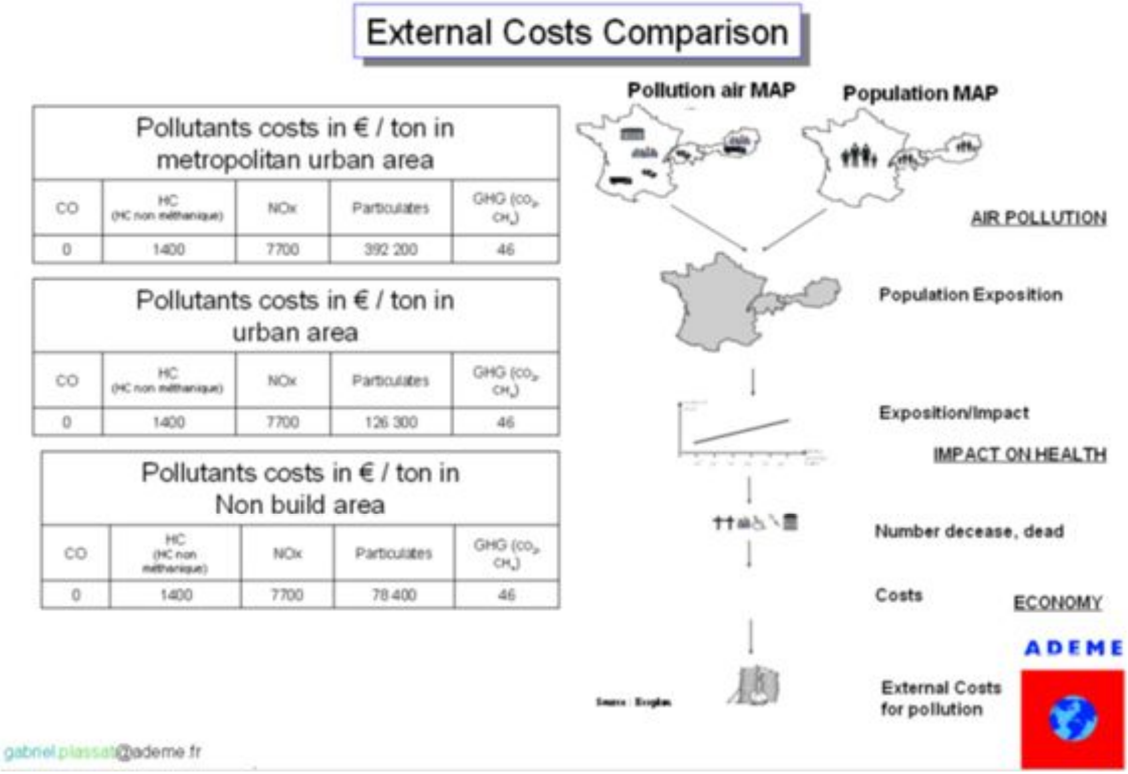

Figure 8.12. The principle in calculating external costs. Figure by Gabriel Plassat, ADEME.

8.4.3 Direct costs

In the calculation of direct costs the investment cost of the vehicle itself, the cost of fuel and urea and the maintenance costs are taken into account. The calculations were made for European vehicles.

The estimates of investment costs for various types of buses were provided by Mr. Sami Ojamo, technical director of Veolia Transport Finland. Veolia Transdev is a global player in the field of public transport, with some 60,000 buses and operations in 28 different countries. The maintenance costs are estimates by VTT, gathered over time from discussions with several vehicle operators.

The estimates of fuel costs are based on fuel prices without taxes. The diesel price is current (December 2011) diesel spot price in the U.S. The natural gas price is also based on U.S. spot prices in December 2011. The energy price of natural is converted into CNG by using a multiplication factor of 1.5.

Prices for biofuels are based on the 2011 IEA publication "Technology Roadmap: Biofuels for Transport" (Biofuels for Transport 2011).

The calculations of direct costs were based on the following assumptions:

- all figures without taxes (no VAT or energy taxes)
- lifetime 15 years, residual value zero
- interest rate 5%
- annual mileage 80,000 km
- fuel consumption based on actual Braunschweig data (estimated for imaginary Euro VI vehicle)
- urea consumption estimated at 4% of fuel consumption for SCR equipped values (6% for the imaginary Euro VI diesel vehicle).

More details are given in Paragraph 14.3.

9. Limitations

9.1 Limitations of WTT analyses

9.1.1 General

In this report the WTT analysis was performed by applying a set of models and methodologies described in Chapter 8.2 (GREET, GHGenius, RED), all based on LCA approach. The LCA results are often vulnerable to uncertainties and sensitivities. Uncertainty can occur due to the choices made for the system boundary setting and the allocation method used or due to the considerations of the displacement credits for co-products. Uncertainty occurs also due to uncertain calculation parameters used or due to lack of data (Huijbregts 2002). However, no uncertainty assessment of the WTT results has been done in this report. The results also present rather average cases than specific biofuel chains, as average data is often used. It is important to keep in mind that the WTT results presented in this report are only valid with the calculation assumptions and choices made here, and might change if different calculation assumptions were used.

The three methodologies used here have their own limitations. For example the emissions due to manufacturing the farming equipment are not considered according to the RED methodology, but can be considered in GREET and GHGenius calculations. Also some common limitations for all methodologies occur in this study. For example, the possible emissions from indirect land use changes due to biofuel raw material production have been excluded from the WTT assessment, but are presented in Chapter 9.1.2. Also other indirect impacts might take place due to market effects of biofuel production. For example the production of biofuels might have an impact on the use of fossil fuels (Rajagopal et al. 2011). These effects should be studied with wider economic models and are not included in this study.

Sometimes the limitations of WTT assessment can occur due to badly known emission impacts, such as the soil carbon stock change due to biomass harvesting. When biomass is not harvested, a part of the carbon content of the biomass is absorbed into soil. Therefore, the carbon content of the soil is decreased when biomass is harvested, and this might significantly affect the GHG balance of a biofuel product (Soimakallio et al. 2009). However, this parameter is very uncertain and there is not much information available related to the soil carbon stock changes of various biomasses, so it is often excluded from the assessment. Uncertainties and lack of knowledge are often related also to various other emission impacts, such as the impacts of biomass harvesting on nutrient balances, the feedback mechanism from soil to biomass productivity, nitrous oxide emissions from fertilization and cultivation, and process emissions from technologies under development (Soimakallio et al. 2009).

9.1.2 Indirect land use change

Several recent studies have expressed a concern that indirect land use impacts might occur due to increased biofuel production and ambitious targets for biofuel use. Indirect land use change might take place when biofuel production will compete for land under cultivation or for raw materials use. This might occur due to population growth, changed eating habits, and increased need for renewable energy sources.

The raw materials and the associated land used for biofuel production might initially be used for some other purposes including food, animal feed, materials, or energy production. If the land area is then taken for the biofuel production, the displaced production will be relocated elsewhere or grown by some other method (Figure 9.1). Such indirect impacts due to competition for raw materials or land area may generate important impacts related to biofuel chains but may also be very difficult to quantify in a traditional LCA approach

In the past three years, economic models were adapted to model potential global LUCs as a result of U.S. corn ethanol production (Fargione et al. 2008, de Santi et al. 2008). In particular, the Food and Agricultural Policy Research Institute (FAPRI) model at Iowa State University was used by Searchinger et al. (2008) and by the U.S. EPA (2010b) (in conjunction with the FASOM model at the Texas A&M University) for its RFS development, and the GTAP model was used by the CARB for its LCFS development (California Air Resources Board 2009; Hertel et al. 2010).

The early versions of these models did not adequately address some of the critical issues, such as crop yield growth in response to increased commodity price, future trends of both supply and demand of grains, close examination of available land types and amount in key countries, detailed simulation of substitution between DGS and conventional animal feeds inside economic models, energy sector demand and supply elasticities in the modern era, and productivity of marginal lands brought into biofuels production, among other issues. Since January 2008, Purdue University, with the support of the U.S. Department of Energy and Argonne National Laboratory, has made significant modifications to the GTAP model to remedy these problems (Tyner et al. 2010). Compared with previous studies, an upgraded GTAP model from this effort shows a lower amount of LUCs for the United States to reach 56.8 billion liters of corn ethanol production in 2015. Estimates by EPA, CARB, and Hertel et al. reduce LUCs by 60% from that of Searchinger et al.

Although advances in economic models have been made in the past two years to address LUC effects, LUC simulations continue to be subject to great uncertainty. Four of the remaining issues that need further research are as follows.

- First, more sensitivity tests on prospective growth in crop demand and supply are needed by region and agricultural ecological zone (AEZ). The future growth in the demand and supply of agricultural commodities – particularly coarse grains – is a critical determinant of the impacts of biofuel programs. If global income and population growth, and dietary transition lead to greater growth in demand for coarse grains than in supply, the impacts of biofuels mandates would be greater. On the other hand, if new technologies and broader adoption of these technologies lead to greater growth in supply, the impacts of biofuels mandates would be reduced.
- Second, improved data and information on land use and land cover change could be helpful to improve model parameters and structure. This is particularly important for other regions of the world because less is known about land use and land conversion.
- Third, as we add cellulosic feedstocks to GTAP for land use analysis, we will need to effectively capture the interactions among the different feedstocks, and between these feedstocks and standard commodity markets.
- Fourth, the modeling and analysis will need to be dynamic so that we can better capture the dynamics of cellulosic and other second-generation feedstocks.
- Fifth, carbon stock in above- and below-ground biomass and soil carbon contents among different land types in different global regions are subject to great uncertainties. Efforts are needed to cumulate data in these areas to reduce the uncertainties.

Because of these and other remaining uncertainties, indirect land use change is not included as a component of the present analysis.

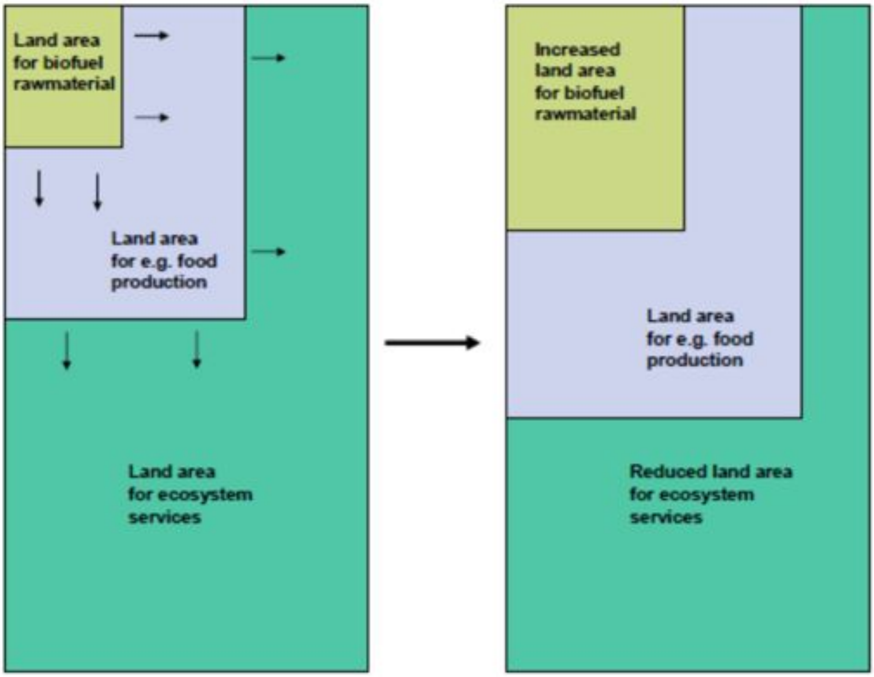

Figure 9.1. When biomass is produced for biofuel raw material the production of biomass for other purposes may shift to another location and cause indirect land use change. (Figure from Soimakallio et al. 2009)

9.2 Limitations of TTW analyses

Engine and chassis dynamometer measurements deliver data calculated from a number of individually determined traceable parameters. The methodology for measuring fuel consumption as well as exhaust emissions is documented in various standards and regulations.

Fuel consumption can be gravimetrically measured very accurately, with only some ±1% of inaccuracy. When the heating value of the fuel is known with adequate accuracy, the same applies to vehicle energy consumption. However, the accuracy for emission measurements is not as good, due to the fact that several pieces of equipment and instruments are needed to form the results: chassis dynamometer to produce simulation of the driving situation, CVS for determining exhaust flow, analyzers to determine concentrations, calibration gases etc., and their individual inaccuracies are all summed up in the final result. Therefore, for measurements of regulated emissions, VTT has estimated inaccuracy to be at the level of ±15% (Nylund et al. 2011).

The measurements for regulated emissions and CO_2 are basically designed to evaluate whether an engine or a vehicle meets certain limit values for emissions when running on a standardized test fuel according to a certain test cycle. For the bulk of the bus chassis dynamometer testing only regulated emission components were measured. Even so, these measurements are sufficient to make comparisons between different drivetrain alternatives in terms of their GHG emissions. This is the case as the greater part of the greenhouse gases in end-use can be accounted for by measuring CO_2 and CH_4. Vehicle tailpipe N_2O emissions are normally low, below 0.1 g/km, compared to the typical CO_2 emission levels of 1200–2000 g/km, so the contribution of N_2O is negligible, even if its equivalence multiplier is around 300.

However, measuring regulated emissions only is not always sufficient to depict the health effects and the toxicity of exhaust. Measurements of unregulated emissions are often arduous and expensive, but some of these measurements are essential in fuel research. Therefore, the work within the IEA Bus project also encompassed some analysis of unregulated components. Unfortunately drawing unambiguous conclusions from measurements of unregulated components is often difficult, as a fuel switch typically affects some parameters in a positive and some parameters in a negative way. The scientific community has not been able to agree on a universal and unequivocal harmfulness index for vehicle exhaust.

It is often debated whether standardized test cycles are representative of real-life operating conditions. Therefore, in the IEA Bus project, several bus specific transient type driving cycles were used to provide a truthful picture of the various technology alternatives.

Cross calibration between EC and VTT was not in the scope of the project. It should be kept in mind that differences in procedures can generate variations: coastdown procedures, using different tires and in the case of measuring fuel consumption gravimetric measurement vs. carbon balance calculation.

In addition, there are some differences in equipment, e.g., regarding the chassis dynamometers. Therefore, comparison between European and North-American vehicles should be considered indicative, at the most. First and foremost the project is intended to demonstrate the fuel effects in diesel engines and also the effect of hybridization on fuel efficiency and emissions. In addition, VTT tested several dedicated alternative fuel vehicles using CNG, ethanol and DME.

9.3 Limitations of the cost assessment

Estimation of external costs is not an exact science, and the outcome totally depends on the cost factors used. In this case it is important to realize that the nuisance or harmfulness of emissions depends on location and people density.

In the case of passenger cars the vehicle vendors provide price tables for vehicles. This is not the case for heavy-duty vehicles and buses, as the pricing is normally settled in bilateral negotiations. Therefore the bus prices used in the calculations are rough estimates. The same goes for fuel prices, as fuel prices may vary significantly depending on the geographical area. When calculating direct costs, the parameter with the best accuracy is the vehicle fuel consumption.

It was not possible to make an in-depth assessment of maintenance costs within this project. In general, the vehicles are becoming increasingly complicated with ever tightening emission regulations. Some vehicle types and fuels are just on the verge of real market penetration, and we lack solid experience of these vehicles. In the case of CNG, the experience at least in Finland is that CNG vehicles require somewhat more maintenance than diesel vehicles.

As for hybrid vehicles, the maintenance costs for brakes will be lower compared to conventional vehicles. On the other hand, the energy storage of a hybrid has a certain operating life, typically some 5–8 years, and the renewal of the energy storage could constitute a significant addition to the maintenance costs.

10. Test program (engine and vehicle tests)

10.1 General

The main variables in the experimental part of the project were:

- vehicle platforms (diesel, diesel hybrids, CNG, ethanol, DME)
- diesel-type fuels
  - conventional
  - diesel fuels from unconventional fossil sources (natural gas, oil sands derived fuels)
  - biodiesel fuels (methyl esters as well as hydrotreated vegetable oils)
- vehicle test cycles (megacity, mid-sized city, suburban etc.).

The vehicle test cycles are presented in Paragraph 8.3.2.

The total number of combinations evaluated was high, in the order of 170.

10.2 Vehicle platforms

10.2.1 General

The vehicle type chosen for vehicle testing was a standard two-axle city bus, with a length of some 12 meter or 40 feet. One exception was the DME vehicle. No DME bus was available, so VTT tested a heavy-duty DME truck instead.

Emphasis was on current vehicles, even though the vehicle matrix also comprised prototype vehicles as well as older diesel vehicles. As buses are typically in service for more than 20 years (10–15 years at the first operator), it was deemed interesting to evaluate to which degree the performance of old vehicles can be improved by just switching fuels.

When setting up the project it was agreed that the brands of the vehicles will not be disclosed. Therefore the vehicles are identified by technology and emission certification class only.

The correspondence between different emission certification classes is presented in Chapter 7.

10.2.2 EC chassis dynamometer

EC tested seven diesel vehicles, two of them with a hybrid powertrain. Data for the vehicles is given in Table 10.1.

Table 10.1. Data for the vehicles tested at EC.

Vehicle Code	Engine Disp. (L)	Emission Control	Driveline	Emission Certification	Test Inertia (kg)
EPA 1998 8.3L	8.3	DOC	Conventional	Pre-EPA 2004	13835
EPA 2007 8.9L	8.9	EGR, DPF	Conventional	EPA 2007	13960
EPA 2007 8.9L Hybrid	8.9	EGR, DPF	Hybrid	EPA 2007	15309
EPA 2007 6.7L Hybrid	6.7	EGR, DPF	Hybrid	EPA 2007	14866
EPA 2010 8.9L (1)	8.9	DPF, SCR	Conventional	EPA 2010	13835
EPA 2010 8.9L (2)	8.9	DPF, SCR	Conventional	EPA 2010	13835
EPA 2010 8.9L (3)	8.9	DPF, SCR	Conventional	EPA 2010	13523

DOC:Diesel Oxidation Catalyst
DPF: Diesel Particulate Filter (wall flow) – active/semi-active catalyzed
SCR: Selective Catalytic Reduction

The buses in the dataset had accumulated different totals of kilometers prior to testing and the maintenance schedule or history of the buses was not made available to EC. The vehicle transmissions were typical of North American transit buses however they may vary from bus to bus.

10.2.3 VTT chassis dynamometer

All in all, VTT tested 14 different vehicles:

- six diesel buses with conventional powertrains, including one light-weight bus
- four diesel hybrid buses
- two CNG vehicles
- one ethanol vehicle
- one DME vehicle (truck).

12 vehicles were tested specifically for the IEA Bus Project, and the results of two other buses (one on EN590 only and one on EN590 and 100% HVO) tested at VTT for other projects could be incorporated.

Data for the vehicles is given in Table 10.2. The DME vehicle was a 26 ton three-axle prototype truck with high output, 440 hp. The testing of this vehicle differed from the testing of the buses in the following ways: The high-output truck was tested on a relative load level corresponding to the buses. However, by doing so, the amount of work accumulated over the test cycle was significantly higher than for the buses (some 18 kWh for the DME vehicle and some 11 kWh for regular buses in the Braunschweig cycle, corresponding to the maximum output ratio of 440 hp. vs. some 270 hp.). To get comparable results, the fuel consumption and emission values were then scaled to correspond to the amount of work accumulated by the buses. For this vehicle, the results must be considered indicative only; partly because the vehicle was a prototype which had not been fully optimized and partly because the test procedure differed from the other vehicles.

The group of hybrid buses included three parallel hybrids and one series hybrid. The latter one was a prototype vehicle. One of the parallel hybrids had a special configuration. The vehicle had no gearbox. When accelerating from standstill the diesel engine is disengaged, and only the electric motor delivers traction power. At a given speed, the diesel engine is connected directly to the rear axle with the help of a mechanical clutch. In addition to the special driveline configuration, this vehicle had supercapacitors for energy storage, whereas the other hybrids had batteries as well as more conventional driveline configurations.

The mileage of the vehicles varied from 2,000 to 835,000 km, and all vehicles were in good condition (no faulty vehicles).

Table 10.2. Data for the vehicles tested at VTT.

Vehicle Code	Engine	Fuel	Emission Control	Driveline	Emission Certif.	Test Inertia (kg)	Energy Storage (Type)
Euro II	9.6	Diesel	n/a	Conventional	Euro II	14,975	n.a.
Euro III	9.0	Diesel	n/a	Conventional	Euro III	15,050	n.a.
EEV/EGR	9.0	Diesel	EGR, FTF	Conventional	EEV	15.250	n.a.
EEV/SCR	7.2	Diesel	SCR	Conventional	EEV	15.100	n.a.
EEV/SCRT*)	7.8	Diesel	SCR, CRT	Conventional	EEV	14.965	n.a.
EEV/SCRT LW*)	6.7	Diesel	SCR, CRT	Conventional	EEV	11.640	n.a.
Hybr. 1	6.7	Diesel	SCR	Parallel hybrid	EEV	14.750	Battery
Hybr. 2	4.8	Diesel	SCR	Parallel hybrid	EEV	15.080	Battery
Hybr. 3	6.7	Diesel	SCR	Parallel hybrid No gearbox	EEV	15.643	Supercaps
Hybr. 4	5.9	Diesel	SCR	Series hybrid	EEV	15.195	Battery
CNG SM	11.9	Methane	λ=1 TWC	Conventional	EEV	15.350	n.a.

CNG LB	9.0	Methane	Lean-burn OC	Conventional	Euro V	15.125	n.a.
Ethanol	9.0	Additive treated ethanol	OC	Conventional	EEV	15.105	n.a.
DME	12.8	DME	OC	Conventional	n.a.	24.250[*] *)	n.a.

*) Vehicles tested for other VTT projects
**) Actual test inertia, results scaled to 15,000 kg
DOC: Diesel Oxidation Catalyst
EGR: Exhaust Gas Recirculation
FTF: Flow-Through Filter
LW: Light-Weight
SCR: Selective Catalytic Reduction
TWC: Three-Way Catalyst
OC: Oxidation Catalyst

10.2.4 vTI engine dynamometer

The data for the Mercedes-Benz OM 906 LA engine is presented in Paragraph 8.3.3.

10.2.5 On-road measurements (AVL & VTT)

Table 10.3 presents data for the vehicles of the 2009 on-road measurements.

Table 10.3. Test vehicle data for the 2009 Helsinki on-road campaign.

	Diesel Euro III	Diesel EEV	CNG EEV
Model year	2003	2009	2009
Mileage (km)	720856	26227	93856
Test weight (kg)	14040	14440	14640
Emission control system	DOC	EGR+FTF	TWC

10.3 Test fuels

10.3.1 General

The groups of fuels and fuels tested in the project were:

- conventional diesel fuel (various commercial grades and certification fuels)
- diesel fuel from unconventional fossil sources

  - natural gas based GTL
  - and oil sands derived fuels OS
- biodiesel fuels
  - canola/rapeseed methyl ester CME, RME
  - soy methyl ester SME
  - Jatropha methyl ester JME
  - tallow/waste fry oil methyl ester TME
  - hydrotreated vegetable oil HVO
- alternative fuels for dedicated vehicles
  - compressed natural gas/methane CNG
  - additive treated ethanol ETOH
  - di-methyl ether DME.

Some fuel or components were tested both as such (neat/straight) and as a blending component (e.g. FAME and HVO), some only as such (e.g. JME) or a blending component (e.g. TME).

Detailed information on the test fuels are given in Appendices 3–4.

It should be noted that all fuels, including the baseline diesel fuels, were practically sulfur-free, meaning that sulfur content was below 15 or 10 ppm. If the reference point had been low-quality diesel fuel with, e.g., 1000 ppm sulfur, the emission benefits of fuel switching would have been larger than those accounted for in this study. Fuel sulfur has a direct link to particulate emissions.

10.3.2 EC chassis dynamometer

The fuels tested at EC were:

- ULSD COM: Commercial seasonal or No. 2 Ultra Low Sulfur Diesel (ULSD, S <15 ppm) commercially available from the National Capital Region of Canada
- ULSD CERT: U.S. EPA 2007 Tier 2 ULSD certification fuel
- ULSD OS: commercially available oilsands derived commercial ULSD from Western Canada
- CME: canola methyl ester
- SME: soy methyl ester
- TME: tallow/waste fry oil methyl ester
- HVO: hydrotreated vegetable oil (paraffinic).

Of these fuels, ULSD and HVO were tested as such, CME, SME and TME only as blends:

B5 fuels containing 5% (vol.) biocomponent:

- 5% CME in CERT
- 5% CME in OS
- 5% SME in CERT

- 5% TME in CERT.

B20 fuels containing 20% (vol.) biocomponent:

- 20% CME in COM
- 20% CME in OS
- 20% HVO in COM
- 20% SME in CERT
- 20% TME in CERT.

10.3.3 VTT chassis dynamometer

The diesel replacement fuels tested as such at VTT were:

- EN590: European low-sulfur (S <10 ppm) diesel fuel without biocomponents
- GTL: synthetic diesel fuel from natural gas (paraffinic)
- HVO: hydrotreated vegetable oil (paraffinic)
- JME: Jatropha methyl ester
- RME: rapeseed methyl ester.

Several blends were prepared:

- 93% EN590 + 7% RME
- 70% EN590 + 30% RME
- 70% EN590 + 23% HVO + 7% RME
- 70% EN590 + 30% HVO
- 50% EN590 + 50% HVO
- 70% HVO + 30% RME.

In addition, VTT tested three fuels requiring dedicated engines:

- CNG: compressed natural gas
- DME: di-methyl-ether
- additive treated ethanol.

10.3.4 vTI engine dynamometer

vTI tested four fuels:

- DF: European CEC certification diesel fuel
- JME: Jatropha methyl ester
- RME: rapeseed methyl ester
- HVO (NExBTL): hydrotreated vegetable oil (paraffinic).

vTI tested the fuels as such.

10.3.5 On-road testing

AVL’s and VTT’s on-road testing was carried out using commercial fuels, meaning EN590 diesel fuel and CNG.

10.4 Overall test matrix (chassis dynamometer)

Table 10.4 presents the overall test matrix at EC, and Table 10.5 the overall test matrix at VTT.

Table. 10.4. Test matrix at EC.

Test Bus	Test Fuel	UDDS	MAN	CBD	OCTA	BRA	ADEME	JE05
EPA 1998 8.3L	ULSD COM	X	X			X	X	
	ULSD OS	X						
	HVO	X						
	B20 CME-COM	X						
	B20 HVO-COM	X						
EPA 2007 8.9L	ULSDCOM	X	X	X		X	X	
	ULSD CERT	X	X			X	X	X
	ULSD OS	X	X		X	X	X	
	B5 CME-CERT	X						
	B5 SME-CERT	X						
	B5 TME-CERT	X					X	
	B5 CME-OS	X						
	B20 SME-CERT	X				X	X	
	B20 TME-CERT	X						
EPA 2007 8.9L Hybrid	USLD OS		X					
	B5 CME-OS		X					
	B20 CME-OS		X					
EPA 2007 6.7L Hybrid	ULSD COM	X	X		X		X	
	ULSD OS	X	X					
	B5 CME-OS	X	X					
	B20 CME-OS	X	X					
EPA 2010 8.9L (1)	ULSD COM	X	X		X	X		
	ULSD OS	X	X			X		
	HVO	X						
	B20 CME-COM	X						
	B20 HVO-COM	X	X			X		
	B20 CME-OS	X						
EPA 2010 8.9L (2)	ULSD CERT	X	X	X	X			
EPA 2010 8.9L (3)	ULSD CERT	X	X	X	X			
	HVO	X	X					

Table 10.5. Test matrix at VTT.

Test Bus	Test Fuel	ADEME	BRA	UDDS	JE05	NYBUS	WTVC
Euro II	EN590	X	X	X			
	HVO	X	X				
	JME	X	X				
Euro III	EN590	X	X	X			
	GTL		X				
	HVO	X	X				
	JME	X	X				
	RME		X				
	93EN590/7RME		X				
	70EN590/30RME		X				
	70EN590/23HVO/7RME		X				
	70EN590/30HVO		X				
	50EN590/50HVO		X				
	70HVO/30RME		X				
EEV/EGR	EN590	X	X	X	X	X	X
	GTL	X	X				
	HVO	X	X				
	RME	X	X				
	93EN590/7RME	X	X				
	70EN590/30RME	X	X				
	70EN590/23HVO/7RME	X	X				
	70EN590/30HVO	X	X				
	50EN590/50HVO	X	X				
	70HVO/30RME	X	X				
EEV/SCR	EN590	X	X	X	X	X	X
	GTL	X	X				
	HVO	X	X				
	RME	X	X				
	93EN590/7RME	X	X				
	70EN590/30RME	X	X				
	70EN590/23HVO/7RME	X	X				
	70EN590/30HVO	X	X				
	50EN590/50HVO	X	X				
	70HVO/30RME	X	X				
EEV SCRT	EN590		X				
	HVO		X				
EEV SCR LW	EN590		X				
Hybr. 1	EN590	X	X	X	X	X	X
Hybr. 2	EN590	X	X	X	X	X	X

Hybr. 3	EN590	X	X	X	X	X	X
Hybr. 4	EN590	X	X	X	X	X	X
CNG SM	CNG	X	X	X			
CNG LB	CNG		X				
ETOH	Ethanol	X	X	X	X	X	X
DME	DME	X	X			X	

Results

11. Results and discussion – WTT

11.1 General

In the WTT comparison different fuel chains from different feedstocks were evaluated by the GREET model (USA), GHGenius model (Canada) and RED methodology (EU). The biofuels studied are presented in Table 11.1. The fuel chains were chosen based on preferences at different regions. The number of fuels in the WTT assessment is higher compared to the number of fuels actually tested in vehicles. However, the WTT assessment is done for neat fuels only, whereas the vehicle testing also covered fuel blends.

Table 11.1. The fuel chains assessed by GREET, GHGenius and RED methodology.

	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
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[illegible]

Please note when interpreting the results:

The GREET model takes into account the carbon absorption during the biomass growth. The WTT emission might be negative, if more CO_2 is absorbed during the biomass growth than released in the biofuel production. Consequently, the GREET model also takes into account the actual CO_2, CH_4, and N_2O emissions of biofuel combustion. The negative WTW emissions might occur because GREET considers the displacement credits for co-products (in some cases).

The RED method does not take into account the carbon absorption during the biomass growth and consequently considers the CO_2 emissions of biofuel combustion zero. The RED method does not consider the CH_4 and N_2O emissions of biofuel combustion as they are assumed to be similar for biofuels and for fossil fuels. The RED results should be compared with the sum of WTT and TTW results of the GREET-model.

The GHGenius model considers the CO_2 emissions due to biofuel combustion as zero (as the RED), but calculates the CH_4 and N_2O emissions for combustion.

(See also Chapter 8.2.5)

11.2 GREET (US)

Table 11.2 (for GHG emissions) and the charts below summaries the GREET outputs for each of the transit bus AF pathways included in the USA set (ethanol is included because of interest in e-diesel, or use of that fuel in spark-engine powered buses). The tables for energy consumption and criteria pollutants are presented in Appendix 5. Fuel combustion values shown in the charts represent the nominal end-use consumption of the fuel based on a standardized fuel consumption of about 11 l/100 km, so they are low for 40+-passenger urban transit buses. However, ratios are valid.

For gas-to-liquids fuels, GREET uses a hybrid input set based on energy and emissions data from the SASOL and Shell GTL processes, as these are the only two currently prominent candidates for commercial-scale production. Note in Figure 11.1 the high WTT component of total energy use (megajoules of energy in vs. megajoules of fuel out) on the fuel pathway as compared to conventional (low-sulfur) diesel, the result of the energy intensiveness of the current GTL production processes. Because considerable quantities of natural gas are used in current production plants, this disparity is also reflected in Figure 11.2 (fossil fuels) and, to a lesser extent, in Figure 11.4 (CO_2-equivalent GHG emissions). On the other hand, petroleum consumption is lower (Figure 11.3) and predominantly end use criteria pollutants (Figures 11.5–11.8) are comparable, as are the implicit shares attributable to fuel transport. The higher input energy requirements and "sweetening" of feedstock gas in GTL production combined with maritime transport powered by bunker fuel result in higher $PM_{2.5}$ (Figure 11.9) and SO_x (Figure 11.10).

Upstream inputs for compressed natural gas are, as expected, equal to or less than for diesel fuels in all categories (gas is transported in pipeline, with NO_x emissions occurring at compressor stations), although the higher GWP of methane produces similar overall WTT GHGs. The need for sulfur removal and disposal from conventional natural gas raises its SO_x contribution. (The lower energy density of this fuel will be reflected in higher PTW values for some variables, and the end use CH_4 emissions of methane power may be high but uncertain.)

Sugarcane-based ethanol currently requires long-distance transport to the USA for use as a fuel, and process emissions as well as WTT energy use are high for most pollutants (the model here is for Brazilian-based plants). Because it is a renewable fuel, it features net GHG savings for the WTT component, though not as dramatic as for soy-based biodiesel, even when land use change is incorporated. According to GREET, ethanol from corn stover, switchgrass and farmed wood delivers negative full fuel cycle GHG emissions. This is because the displacement credit for co-produced electricity is taken into account.

Diesel from, respectively, soy esterification and refinery processing of soy feedstock (hydrogenated vegetable oil, so-called "renewable diesel") are similar in profile. Renewable diesel requires more energy input at the refinery, with higher use of process heat from (non-petroleum) fossil fuel. Again, since both originate from renewable feedstocks, net GWP-based GHGs are negative. However, both BD and RD generate high VOCs from the reformulation processes, and stacks at refineries are responsible for higher NO_x and particulate matter than those at esterification plants. Interestingly, whilst renewable diesel still accounts for upstream SO_x emissions comparable to those for GTL, soy biodiesel does not involve sulfur combustion at any stage of the process (no sulfur in soybeans or most esterification fuels), so when the displacement method is applied relative to the soy meal and glycerin co-products displaced in current processes, overall less sulfur dioxide than the status quo is generated. Urban NO_x is noteworthy for almost every pathway owing to the end-use NO_x generated by diesel vehicles fueled by all alternatives.

Table 11.2. GHG emissions for several fuels according to the GREET model.

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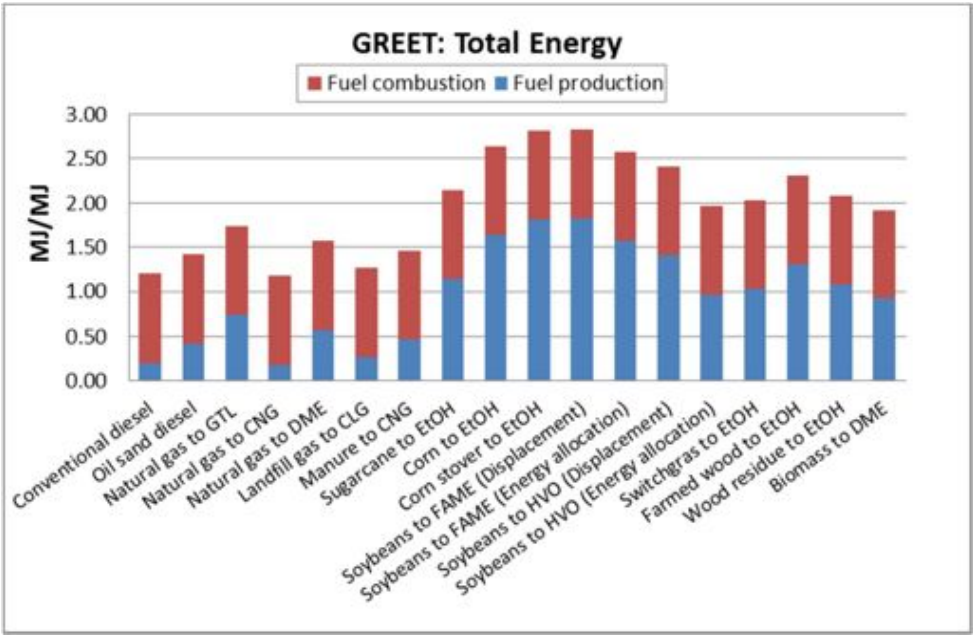

Figure 11.1. Total energy consumption per MJ fuel.

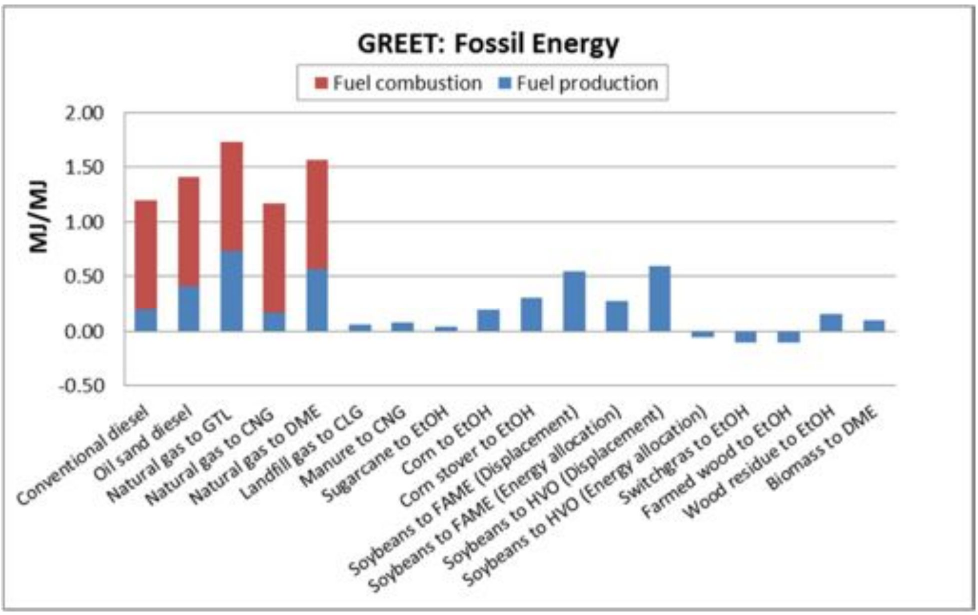

Figure 11.2. Fossil fuel consumption per MJ fuel.

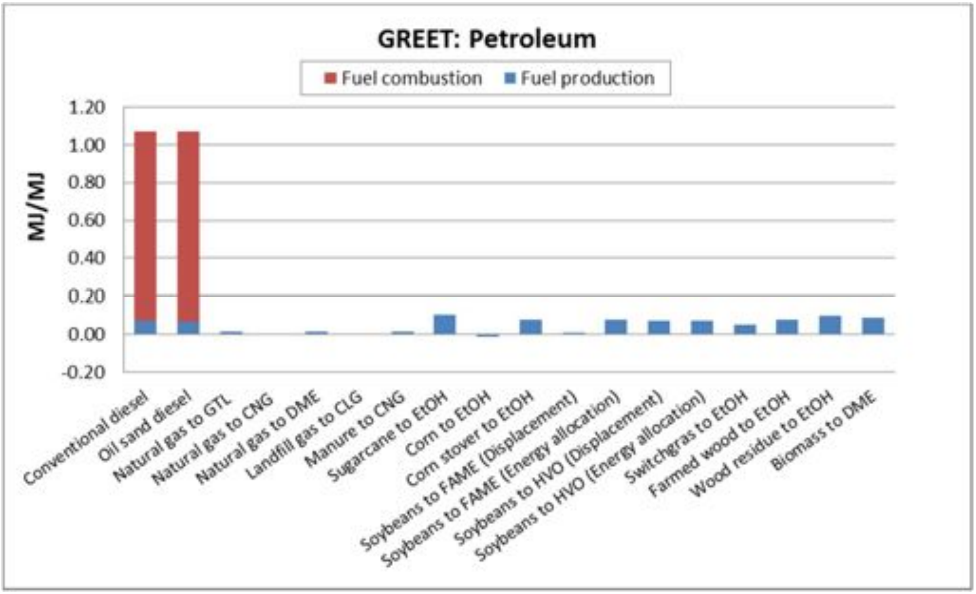

Figure 11.3. Petroleum consumption per MJ fuel.

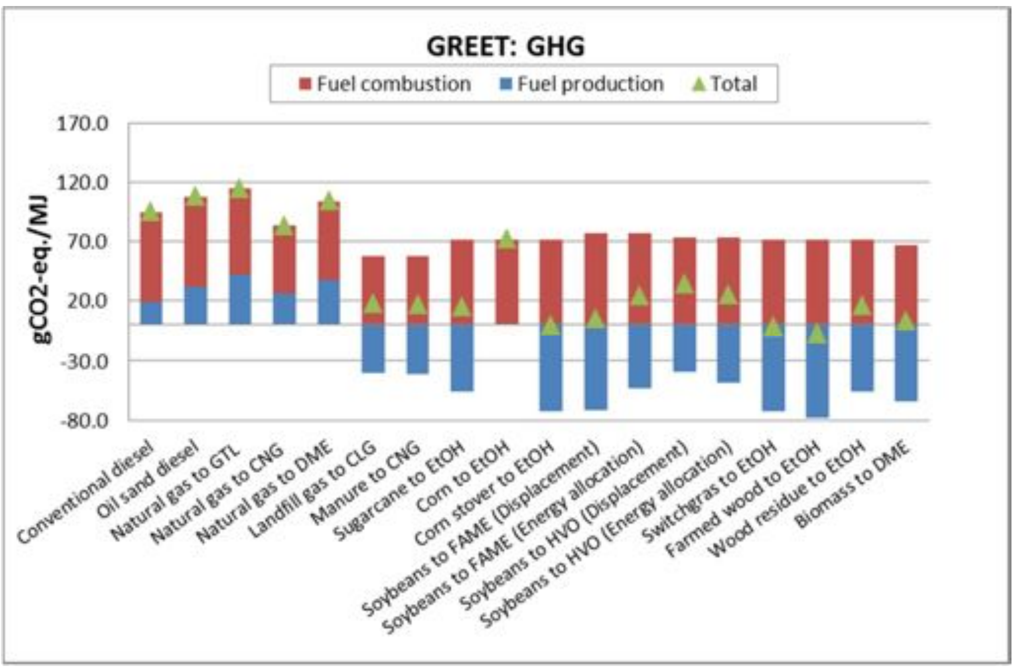

Figure 11.4. The GHG emissions per MJ fuel.

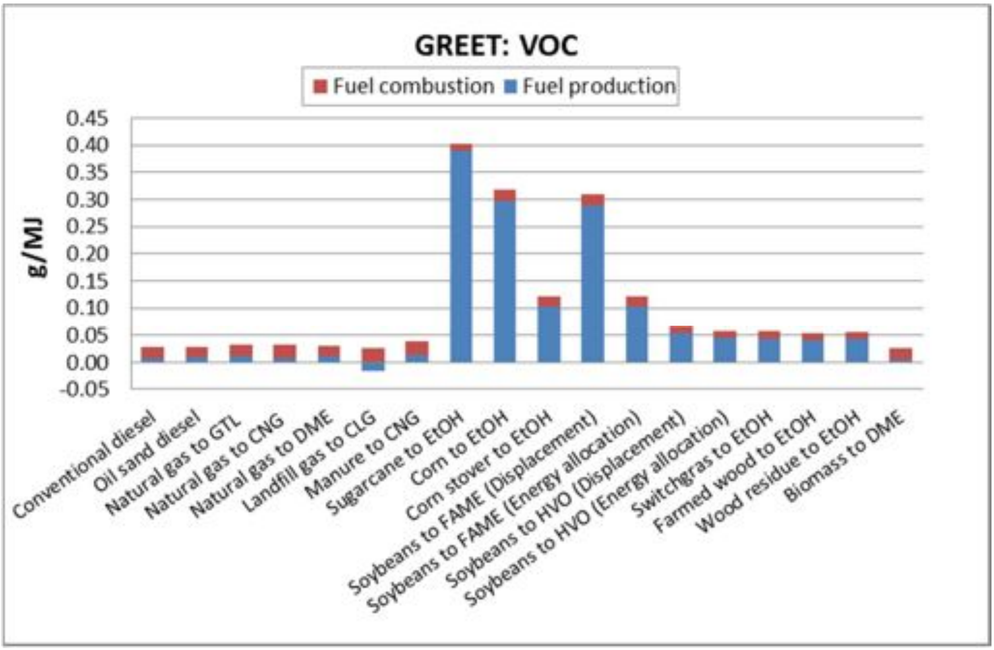

Figure 11.5. The VOC emissions per MJ fuel.

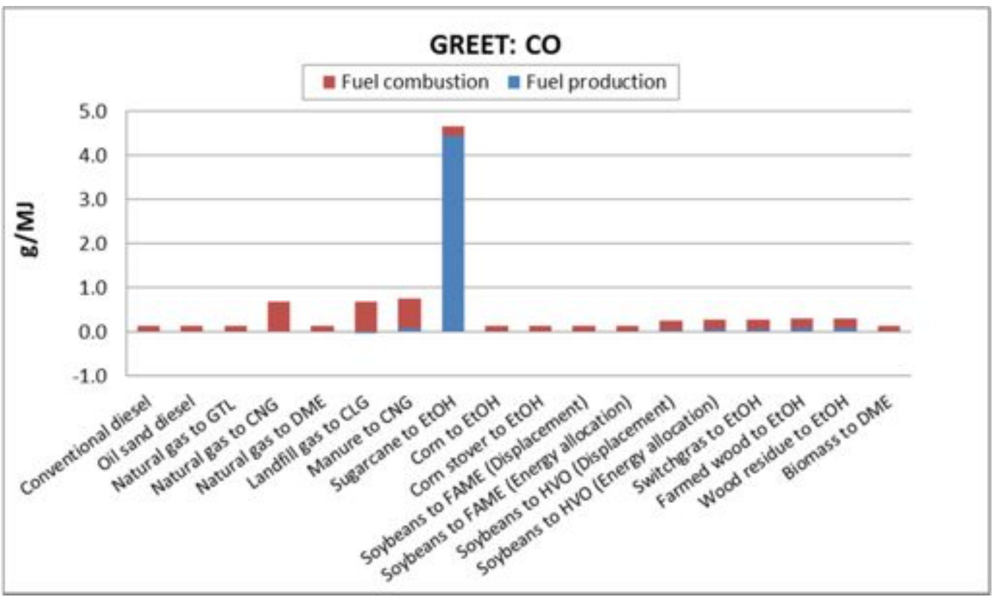

Figure 11.6. The CO emissions per MJ fuel.

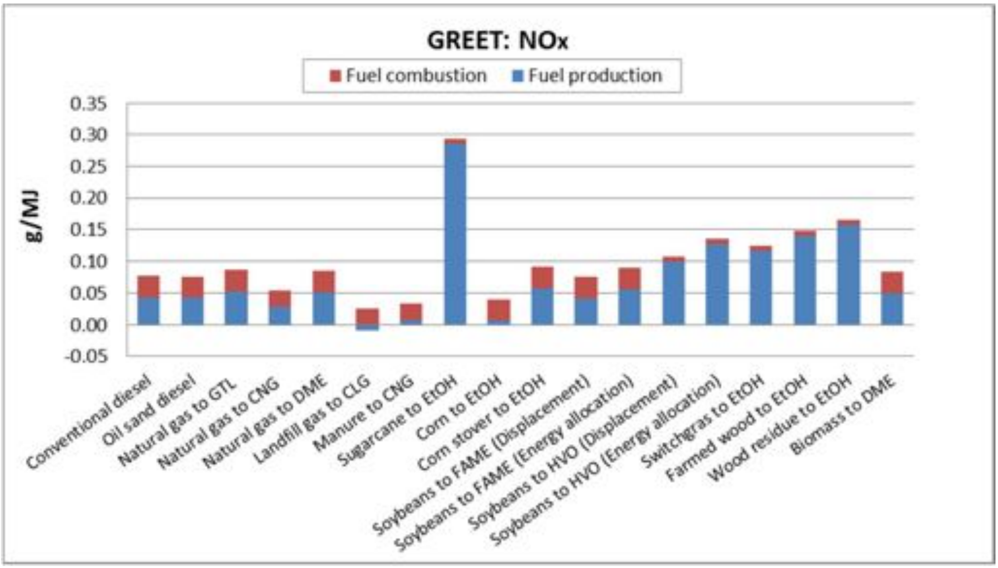

Figure 11.7. The NO_x emissions per MJ fuel.

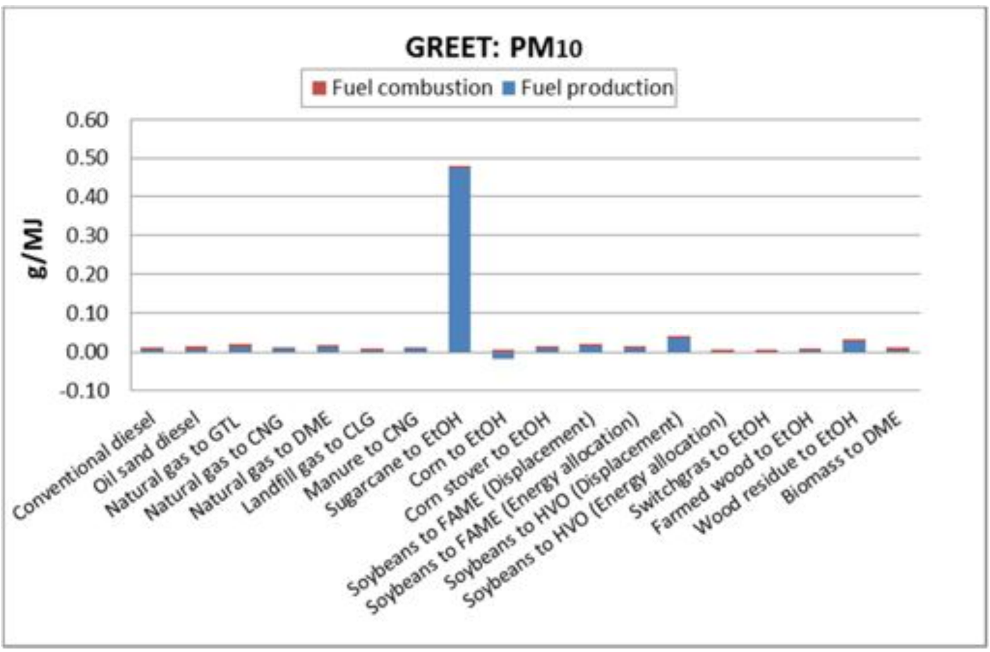

Figure 11.8. The PM_{10} emissions per MJ fuel.

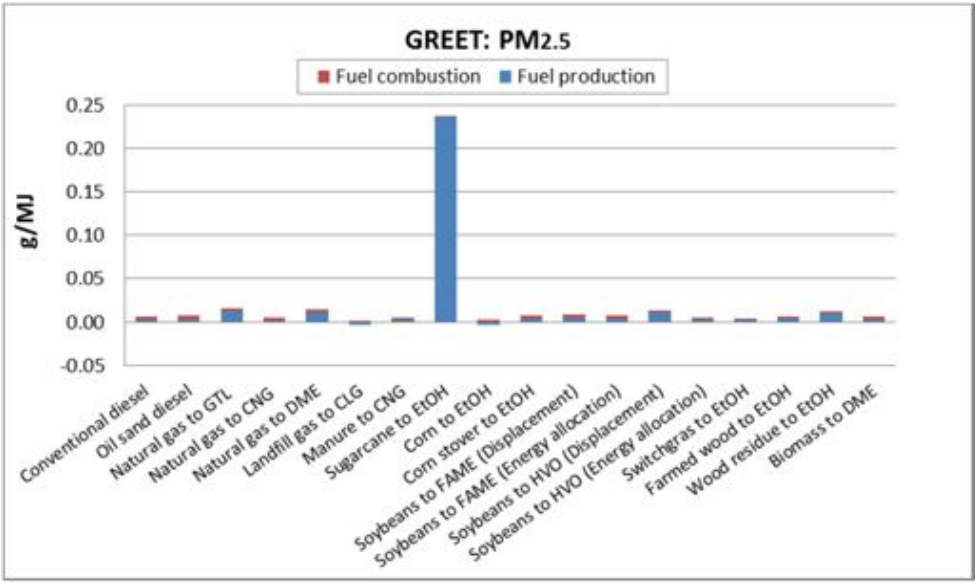

Figure 11.9. The PM2.5 emissions per MJ fuel.

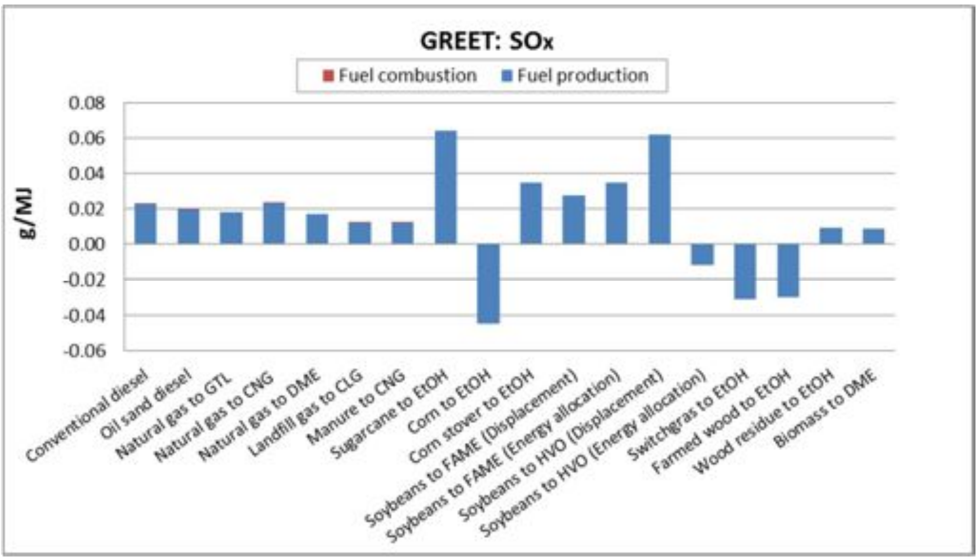

Figure 11.10. The SO_x emissions per MJ fuel.

11.2.1 GHGenius (Canada)

Tables 11.3 (lifecycle GHG) and 11.4 (fuel properties) summarize the GHGenius outputs for each of the transit bus fuel pathways that were studied in the Canadian set. Fuel combustion values shown in the charts were calculated using a nominal end-use diesel fuel consumption of approximately 50 l/100 km. Other fuels were analyzed on a relative energy requirement per distance travelled basis as compared to a diesel base case. Since the values are presented on an emissions per energy basis, the actual fuel consumption is not critical.

Table 11.3. Summary of Lifecycle GHG Results for GHGenius.

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Table 11.4. Fuel Properties Used for GHGenius.

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LNG is assumed to use a modern high-pressure direct injection, compression ignition LNG engine, producing similar power and efficiency as a diesel engine, while CNG is assumed to use a less efficient lean-burn, spark ignition engine.

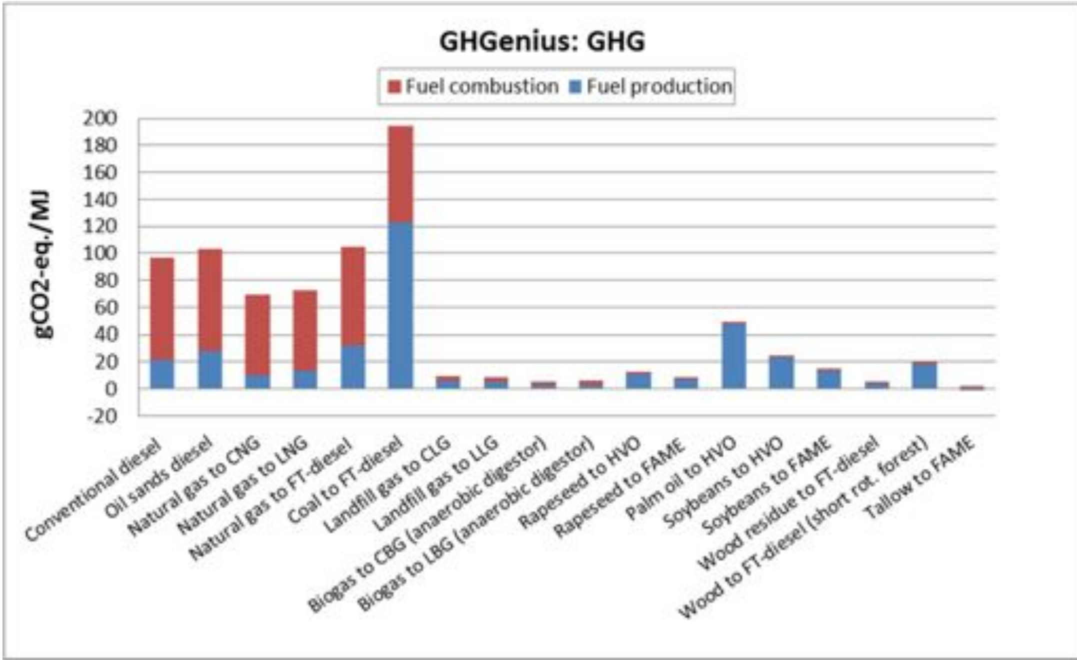

Figure 11.11. Lifecycle GHG Emission Results from GHGenius.

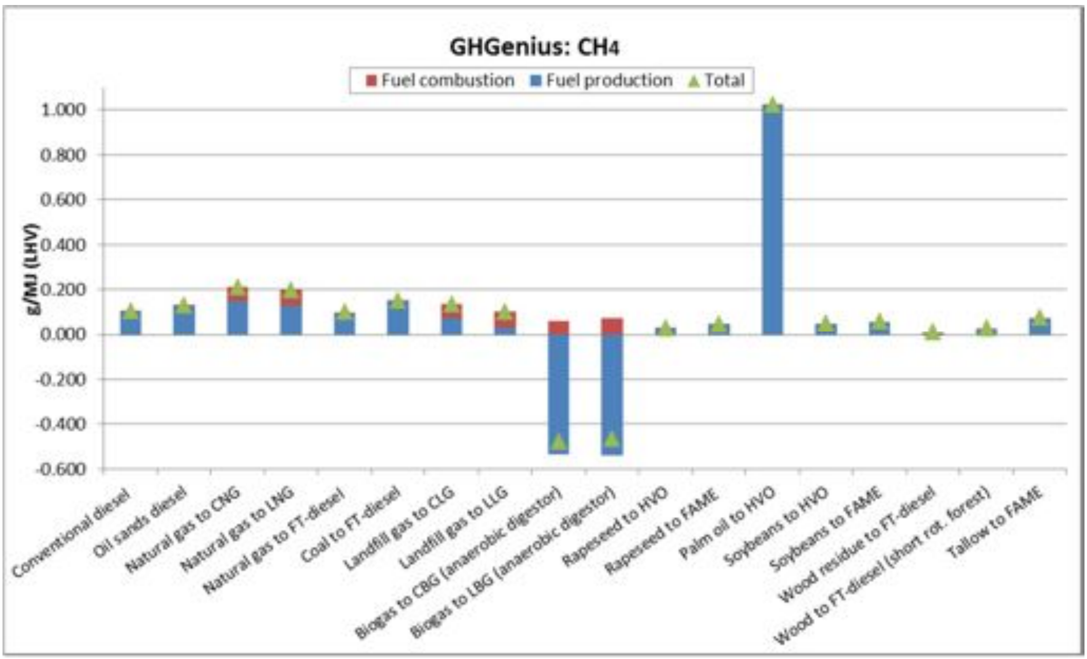

Figure 11.12. Lifecycle CH_4 Emissions from GHGenius.

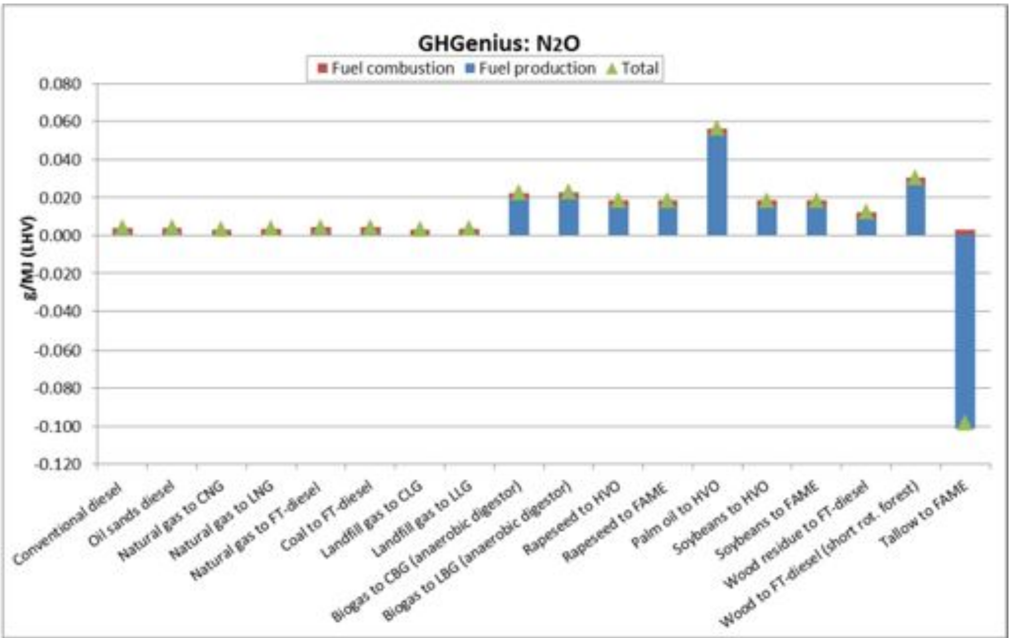

Figure 11.13. Lifecycle N_2O Emissions from GHGenius.

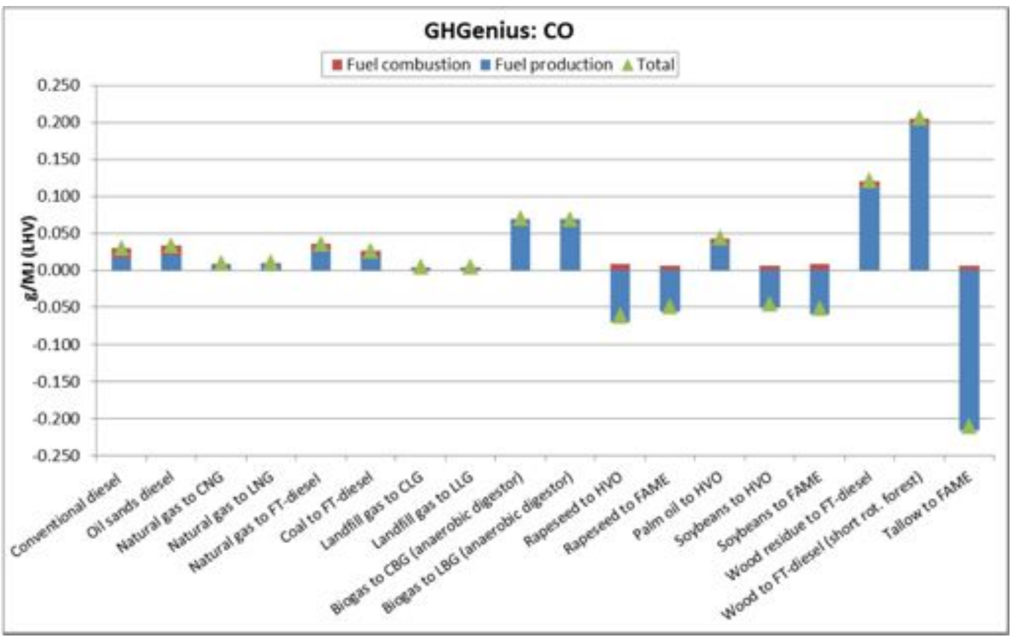

Figure 11.14. Lifecycle CO Emissions from GHGenius.

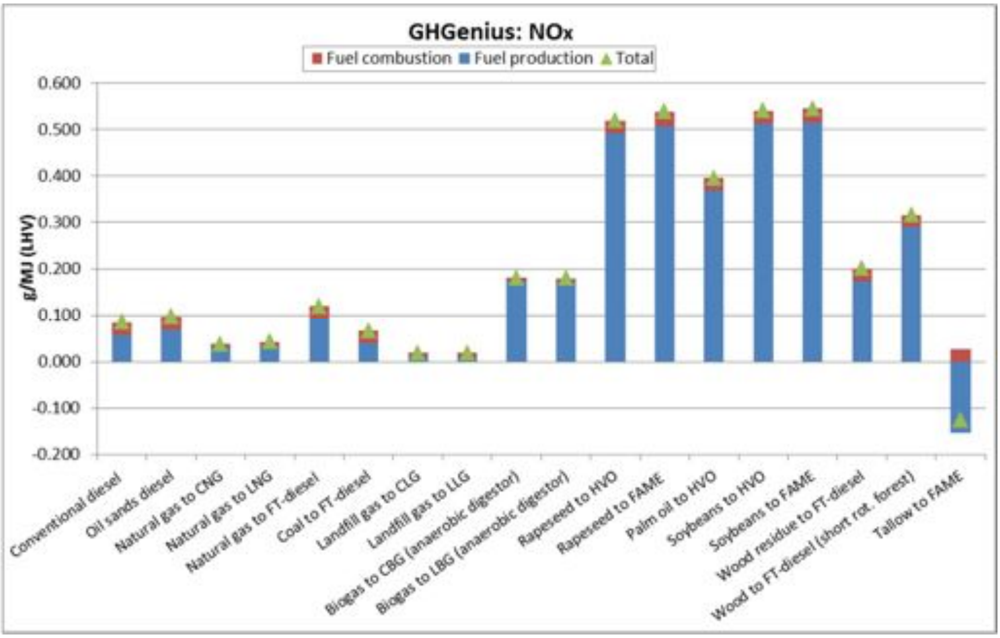

Figure 11.15. Lifecycle NO_x Emissions from GHGenius.

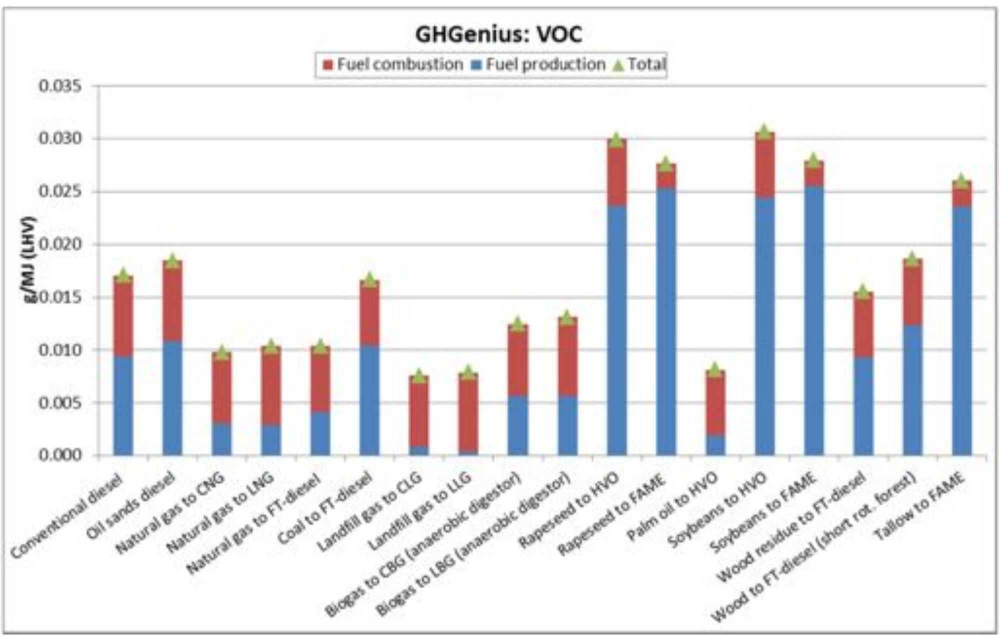

Figure 11.16. Lifecycle VOC Emissions from GHGenius.

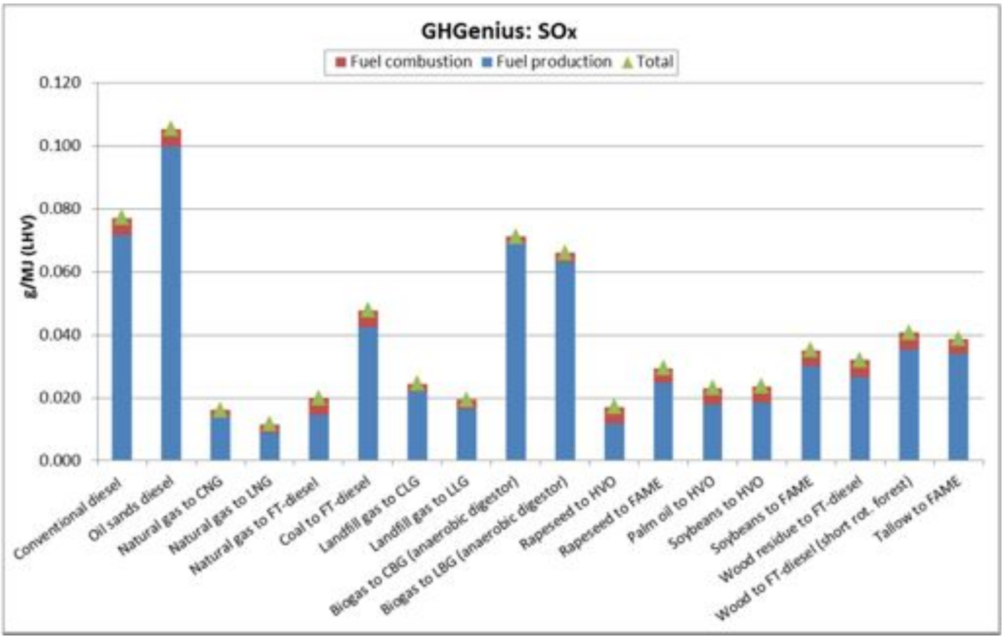

Figure 11.17. Lifecycle SOx Emissions from GHGenius.

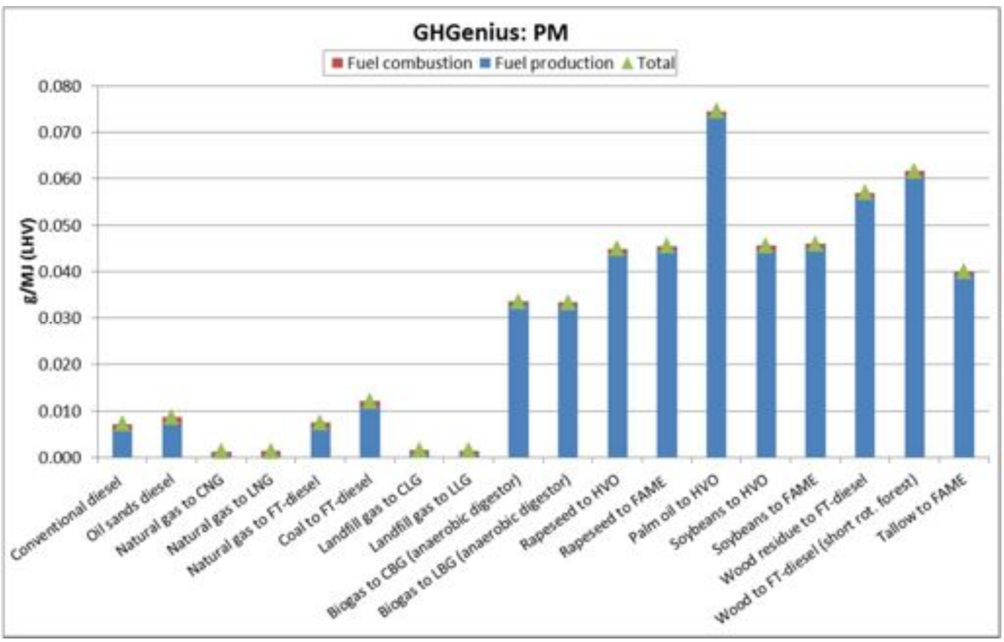

Figure 11.18. Lifecycle PM Emissions from GHGenius.

It is interesting to note that while most of the alternatives to petroleum diesel offer lifecycle GHG savings, many of the alternative fuels actually have higher lifecycle emissions of other pollutants. There can be numerous reasons for this, including more complex production pathways with more inputs.

Despite this, it is important to recognize the differences in the suitability of the approach between lifecycle emissions of GHGs and lifecycle emissions of other criteria air contaminants. GHGs tend to have long residence times in the atmosphere, typically measured in decades or even centuries (the primary species, like methane, may degrade sooner, with a more long-lived GHG species, like CO_2, remaining), leading to long-term, cumulative impacts. The impact, climate change, is also global in nature. On the other hand, many criteria air contaminants have relatively short residence times in the atmosphere, which may be as short as several days or several weeks. Consequently, impacts often tend to be more localized and shorter term in nature.

For example, SO_x will be washed out of the atmosphere during rainfall producing acid rain, which may affect a local watershed. If the source of these SOx emissions is located far from another source in the production cycle, then the impacts may be separate and non-cumulative. Furthermore, if point sources of emissions are sufficiently spread out or far from heavily populated areas, then the impacts may also be minimized relative to if the emissions were concentrated in one region. This means that two fuels could have the same lifecycle emissions of a given pollutant yet have vastly different impacts associated with the pollutant. For these reasons, one must use caution when comparing fuels using a lifecycle approach for non-GHG air pollutants.

11.2.2 RED (EU)

The GHG emissions of the fuel chains studied are presented in Table 11.6. When possible, the default values given in the RED are used as WTT emission factors. For the fuels which do not have a default value in the RED (natural gas and Jatropha FAME) the GHG emissions are evaluated from other sources but respecting the methodology of the RED. The results are also presented in Figure 11.19. Other pollutants than GHG emissions are not evaluated as the RED methodology concerns only GHG emissions.

Table 11.5. The emission factors of the fuels studied according to the RED methodology and the references used for each fuel.

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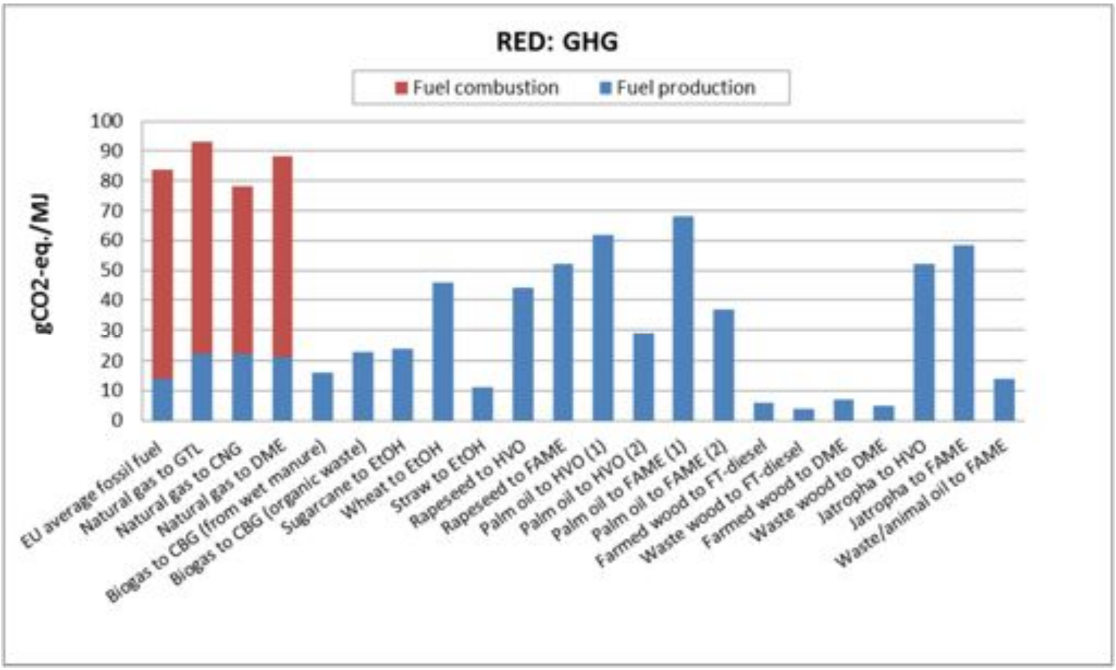


Figure 11.19. GHG emissions according to the RED and JEC-study.

12. Results and discussion – TTW

12.1 General

As mentioned in 10.1, the total number of combinations (vehicle, fuel, driving cycle) in the chassis dynamometer measurements is in the order 180. Full sets of data are presented in Appendices 6 (EC) and 7 (VTT). Due to the extensive data it is not possible to present all results in the form of graphs.

At EC, the Manhattan cycle was used for all test vehicles. VTT, on the other hand, used the Braunschweig bus cycle as a measuring rod for its bus measurements. For some vehicles, ADEME, Braunschweig, UDDS and JE05 were driven by both laboratories.

Figure 12.1 shows a schematic of VTT's chassis dynamometer test program and presentation of results. The Tier 1 level encompasses vehicle technology, including hybridisation and alternative fuel vehicles. On this level the variations in performance from vehicle to vehicle is larger (at maximum 1:10) than on Tier 2 level, encompassing driving cycles and diesel substitute fuels and showing variations up to 1:5 (1:2 for diesel substitute fuels). As EC didn't run alternative fuel platforms, the schedule was somewhat more constricted, but it basically follows the same layout.

All chassis dynamometer results are presented relative to driven distance, e.g. g/km, liter/km or MJ/km.

Some vehicles utilize SCR systems for NO_x reduction. The SCR systems use urea (32.5% solution, by weight) as a reducing agent, and the consumption of the solution is some 5% of the fuel consumption. Urea affects vehicle energy consumption only indirectly, as it is a reactant and not a fuel. When urea is decomposed, CO_2 and ammonia (NH_3) are formed. The amount of CO_2 for the 32.5% urea solution is 0.24 kg CO_2/kg solution. As the urea solution consumption is typically 2–2.5 kg/100 km, this means that the CO_2 contribution from urea decomposition is in the order of 5–6 g/km, i.e. negligible (less than 1%) of the tailpipe CO_2 emission (typical level 1000–1500 g/km).

From the operator's point of view, urea solution with a price of some 50% of diesel fuel, adds some 2% on top of the cost of the fuel itself. Urea is also commented upon in Chapter 13 (WTW assessment).

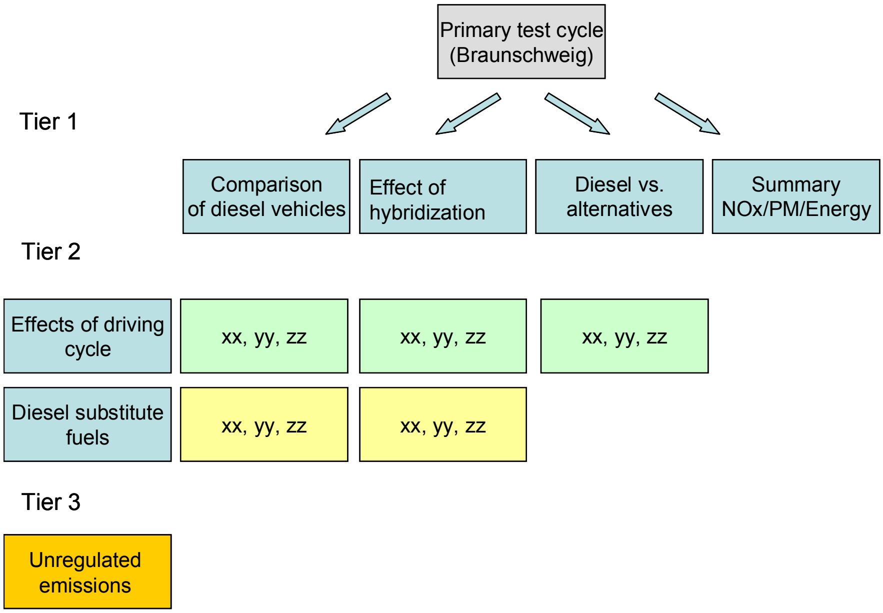


Figure 12.1. Schematic of VTT's test program and presentation of results.

12.2 EC's chassis dynamometer results

12.2.1 General

As shown in Table 10.3, the work at EC encompassed 7 vehicle platforms, 7 test cycles and 13 different fuel alternatives, producing a total of 68 different combinations.

The results are presented as follows:

- Comparison of vehicle platforms: Manhattan cycle, regulated emissions, CO_2 and fuel consumption
- Influence of driving cycle: 1998, 2007, 2010 (1), 2010 (2) and 2010 (3) platforms with conventional power train and 2007 hybrid with 6.7 l engine, NO_x, PM and fuel consumption
- Fuel effects
  - 1998, 2007 and 2010 (1) platforms with conventional power train, UDDS driving cycle, regulated emissions, all fuels
  - For the 1998, 2010 (1) and 2010 (3) platforms 100% replacement fuels, data also for fuel consumption and tailpipe CO_2 emissions.

For most of the buses, EC measured CH_4 and N_2O. However, these components in most cases added only some 1–3% to the equivalent CO_2 emission, and therefore only CO_2 is accounted for in the Figures.

The results presented in 12.2.2 and 12.2.3 are for ULSD diesel, in most cases commercial ULSD. Some data sets were generated using oil sands derived ULSD and certification ULSD. The possible fuel effects, however, are much smaller than the effects of vehicle platform or driving cycle.

In general the 47mm Emfab™ filters that were used for particulate mass determinations had very low net mass changes for those vehicles equipped with diesel particulate filter systems. This gravimetric method for the determination of the PM mass emission rate produced high standard deviations in the sample set. Comparison of these results is limited.

Many of the buses were installed with active/semi active DPFs. Certain operating conditions coupled with the associated increase in exhaust temperature resulted in the DPFs going into a regeneration condition. This was observed to affect exhaust emission rates and fuel consumption repeatability within the dataset. Repeats tests were required in order to avoid emissions analysis during a regeneration event.

12.2.2 Comparison of vehicle platforms

Figures 12.2 and 12.3 (vehicles with conventional powertrains) and 12.4 and 12.5 (MY 2007 vehicle platforms including hybrids) show a comparison of vehicle platforms when tested using the Manhattan bus cycle. The Manhattan cycle was the one cycle driven with all vehicle platforms.

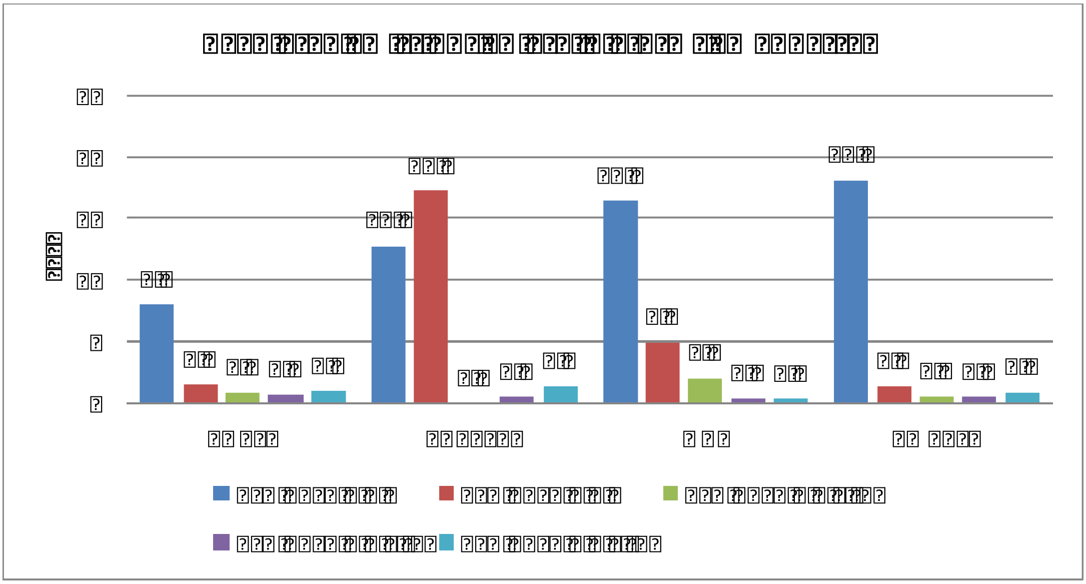


Figure 12.2. Regulated emissions for diesel vehicles with conventional power-trains. North-American vehicles, Manhattan cycle.

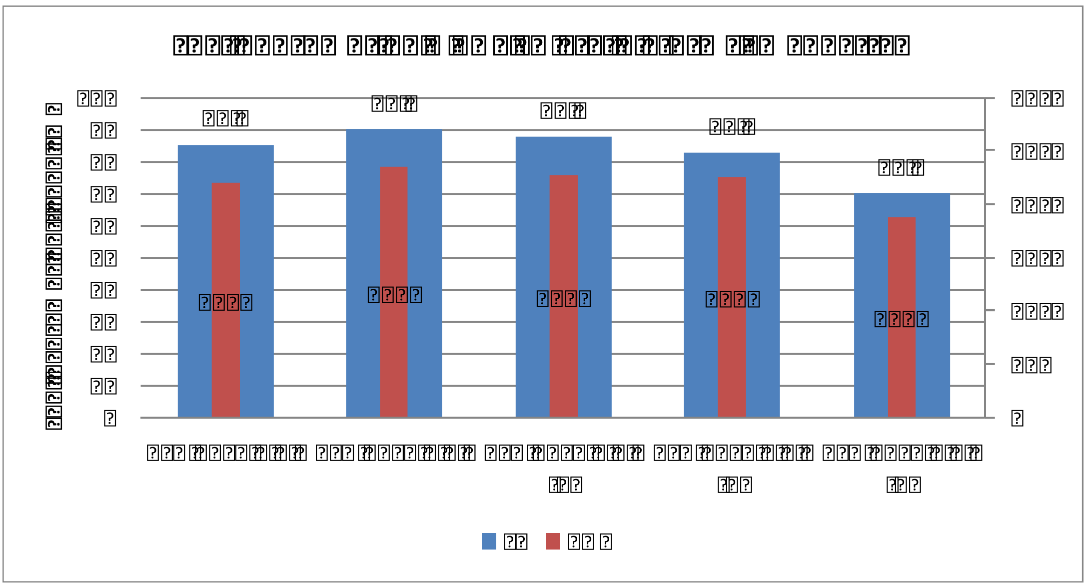


Figure 12.3. Fuel consumption and CO_2 emissions for diesel vehicles with conventional powertrains. North-American vehicles, Manhattan cycle.

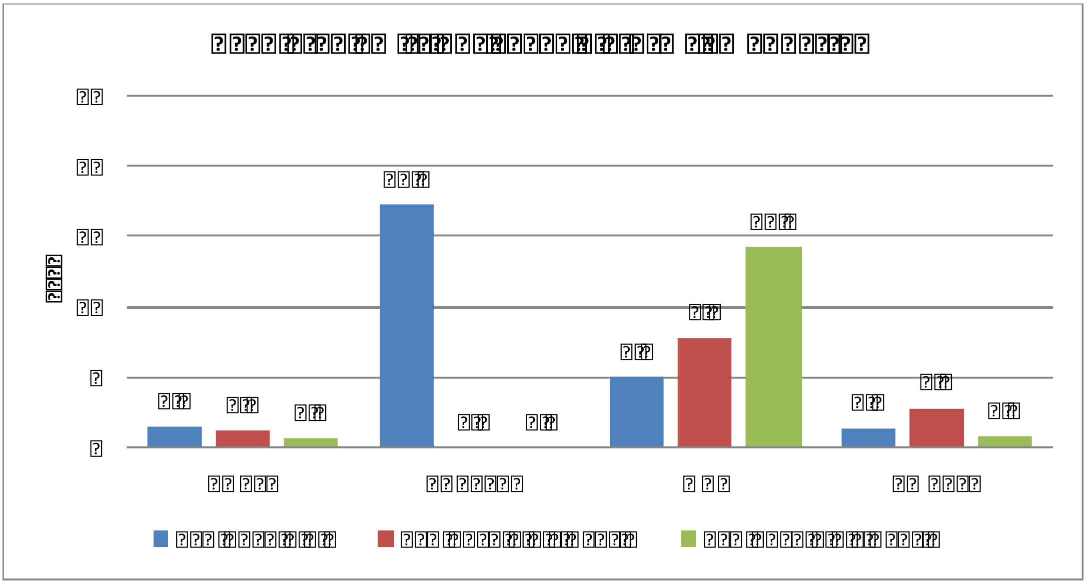


Figure 12.4. Regulated emissions for 2007 vehicles with conventional and hybrid powertrains. North-American vehicles, Manhattan cycle.

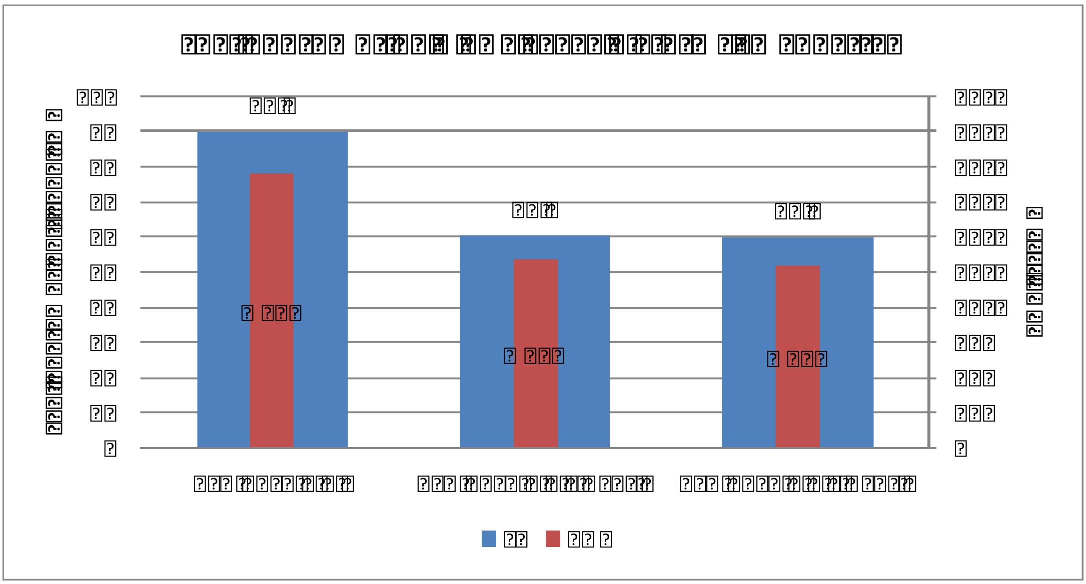


Figure 12.5. Fuel consumption and CO_2 emissions for 2007 vehicles with conventional and hybrid powertrains. North-American vehicles, Manhattan cycle.

Figure 12.2 clearly demonstrates the tremendous reductions in regulated emissions with tightening emission regulations; at maximum a reduction of some 97% for NO_x as well as PM comparing the 1998 vehicle with 2010 vehicles. Already the EPA 2007 platforms deliver significantly reduced PM emissions, thanks to DPFs. NO_x emissions are brought to from EPA 2007 going to EPA 2010 by implementing SCR technology.

All of the buses, with the exception of the oldest bus EPA 1998, produced very low CO and THC emissions; in many cases at the instrumentation and method detection limits.

For fuel consumption, the changes are small, as the 1998 vehicle has a fuel consumption equivalent to the average of the 2010 vehicles. The 2010 (3) bus had an optimized transmission which resulted in lower fuel consumption compared to the other 2010 buses. Hybridization, on the other hand, reduced fuel consumption some 30–35% for the Manhattan cycle. Data for other cycles is presented in 12.2.3.

Interestingly, on the 2007 vehicles hybridization seems to increase NO_x emissions. This is likely the result of changes to the exhaust temperature profile that may arise when a diesel engine is coupled with a hybrid drive system, which can be different than the way a standard diesel engine operates during engine certification testing.

As for particulates, no unambiguous trend of the effect of hybridization can be seen (all 2007 vehicles were equipped with DPFs).

12.2.3 Effects of driving cycle

EC used at maximum seven driving cycles in its bus evaluation. Six vehicles were tested with several cycles:

- EPA 1998 8.3 L, 4 cycles
- EPA 2007 8.9 L, 7 cycles
- EPA 2007 6.7 L hybrid, 4 cycles
- EPA 2010 8.9 L (1), 4 cycles
- EPA 2010 8.9 L (2), 4 cycles
- EPA 2010 8.9 L (3), 4 cycles.

The effects of driving cycle on NO_x, PM (the two most important components for urban air quality) and fuel consumption are presented in Figures 12.6–12.11.

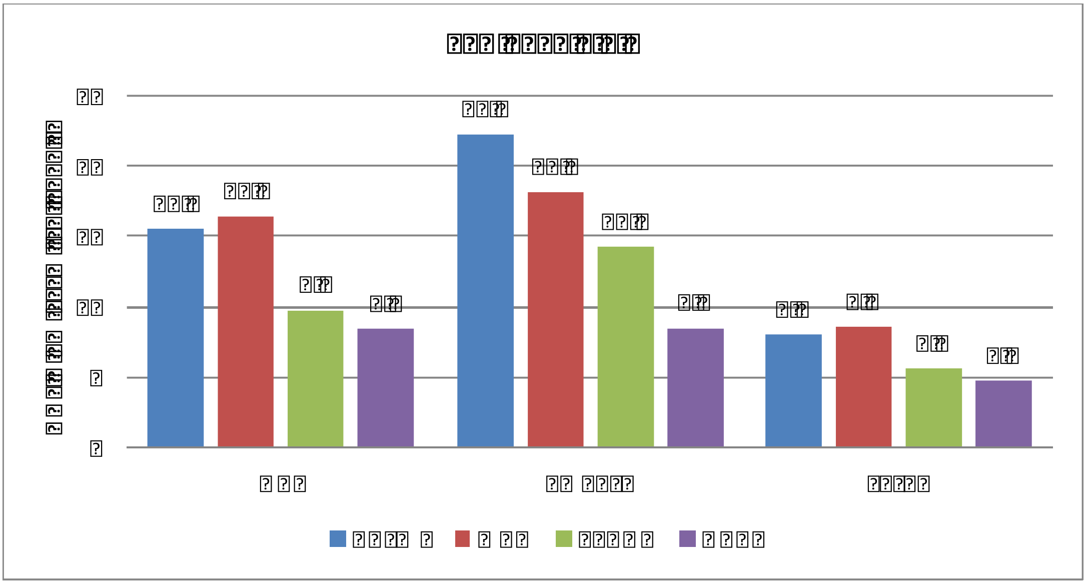


Figure 12.6. The effect of driving cycle on NO_x, PM and fuel consumption. EPA 1998 8.3 L.

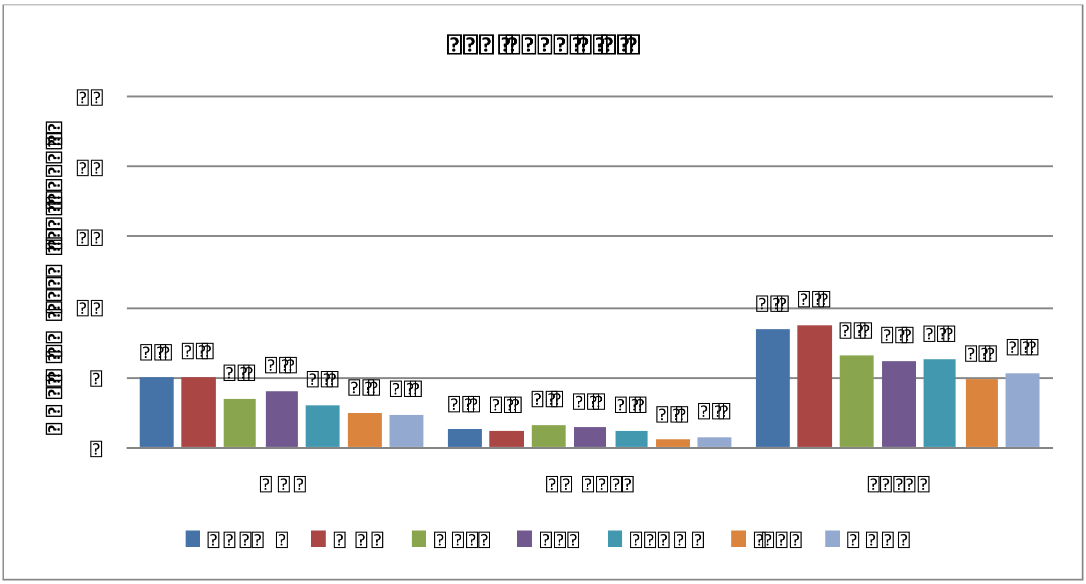


Figure 12.7. The effect of driving cycle on NO_x, PM and fuel consumption. EPA 2007 8.9 L.

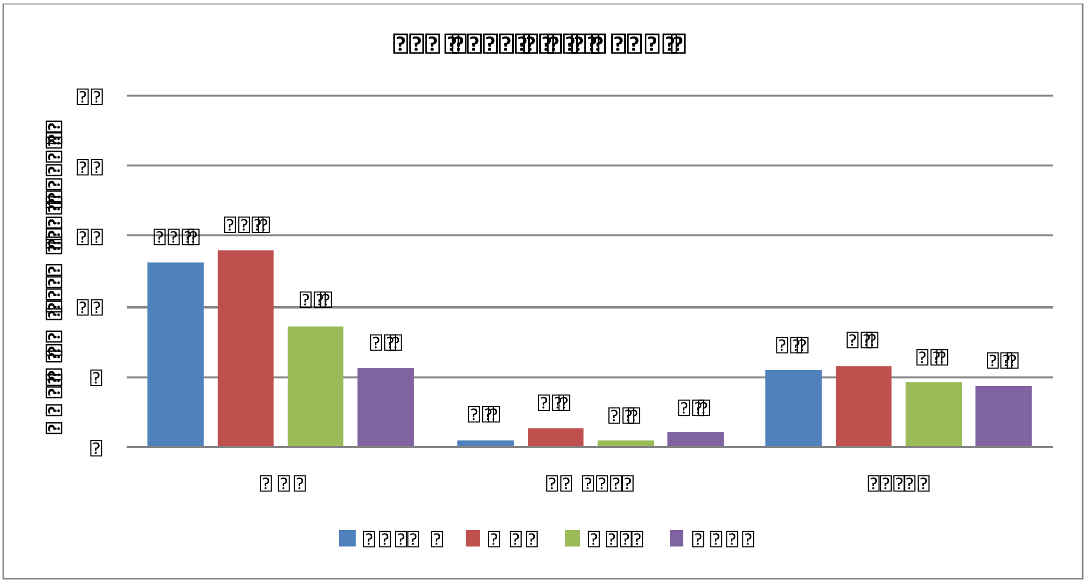


Figure 12.8. The effect of driving cycle on NO_x, PM and fuel consumption. EPA 2007 6.7 L hybrid.

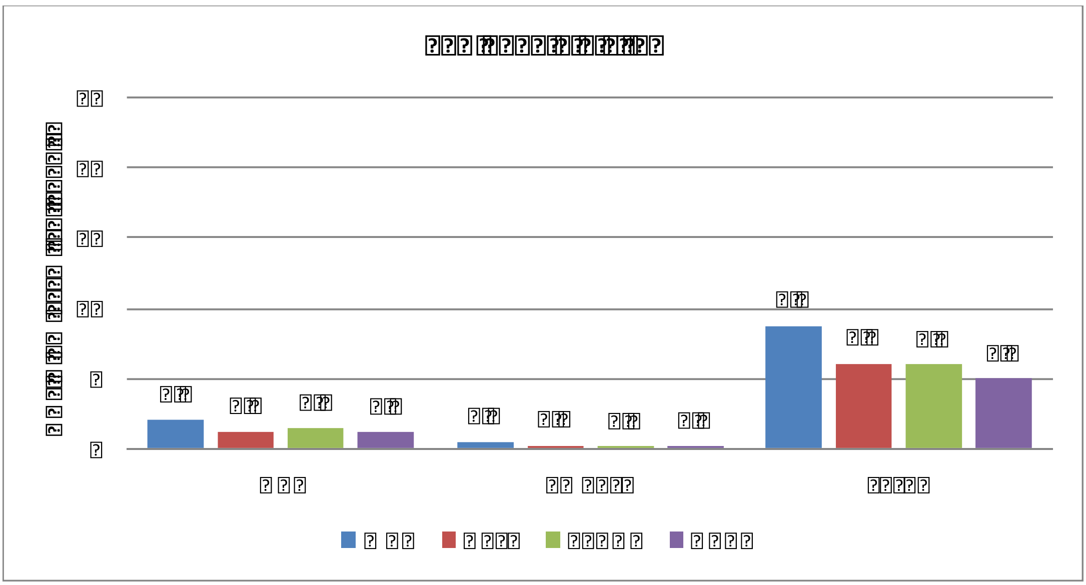


Figure 12.9. The effect of driving cycle on NO_x, PM and fuel consumption. EPA 2010 8.9 L (1).

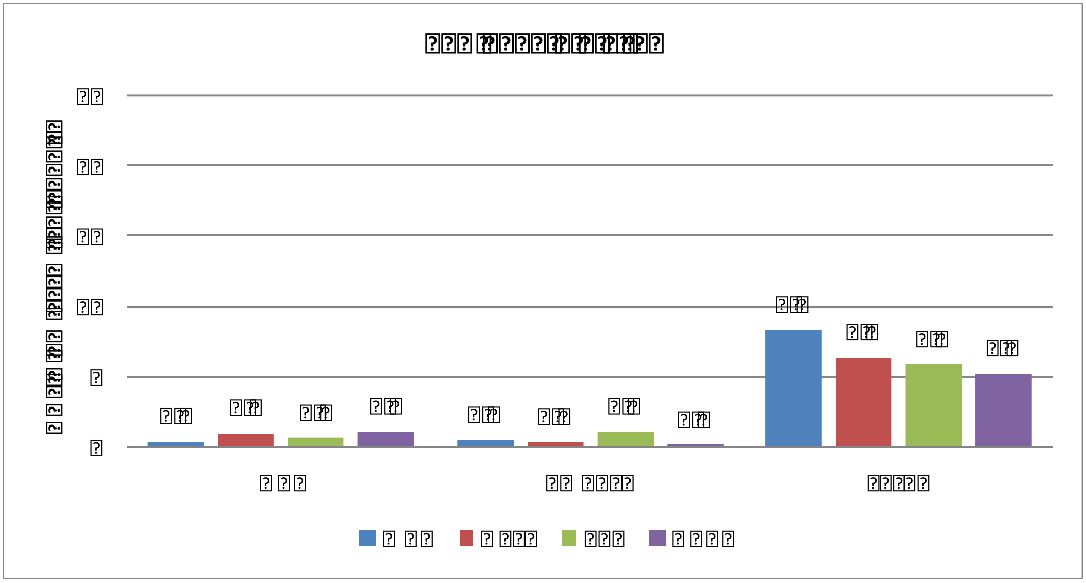


Figure 12.10. The effect of driving cycle on NO_x, PM and fuel consumption. EPA 2010 8.9 L (2).

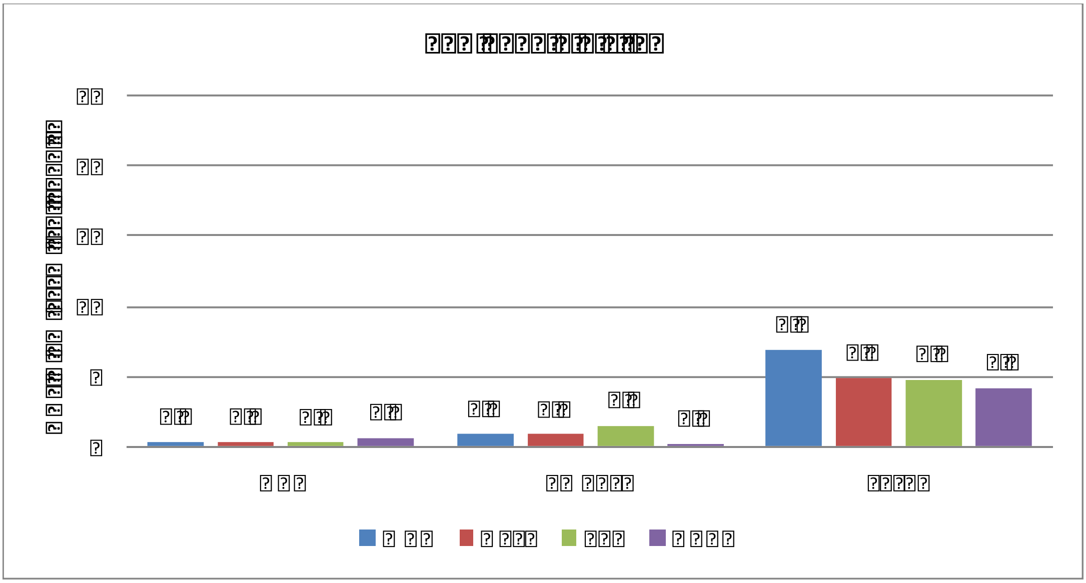


Figure 12.11. The effect of driving cycle on NO_x, PM and fuel consumption. EPA 2010 8.9 L (3).

Of the cycles used at EC, Manhattan is one of the most severe one for fuel consumption, PM and in most cases also for NO_x. The “extreme ends” tested with five vehicles were Manhattan and UDDS. Going from UDDS to Manhattan, the increase in fuel consumption is some 60–80% for the vehicle with conventional power train and some 30% for the hybrid. Correspondingly, the increase in NO_x is on an average 110% for four of the vehicles (75–150%). For one vehicle (EPA 2010 8.9 L (3)), NO_x is reduced by some 60%. In all cases PM emissions are increased, but range is quite wide, from +30% to +400%.

Figure 12.12 presents the effect of hybridization on fuel consumption. For ADEME, Manhattan and OCTA, hybridization saves 30–35% fuel. In the UDDS cycle the benefit is smaller, some 20%.

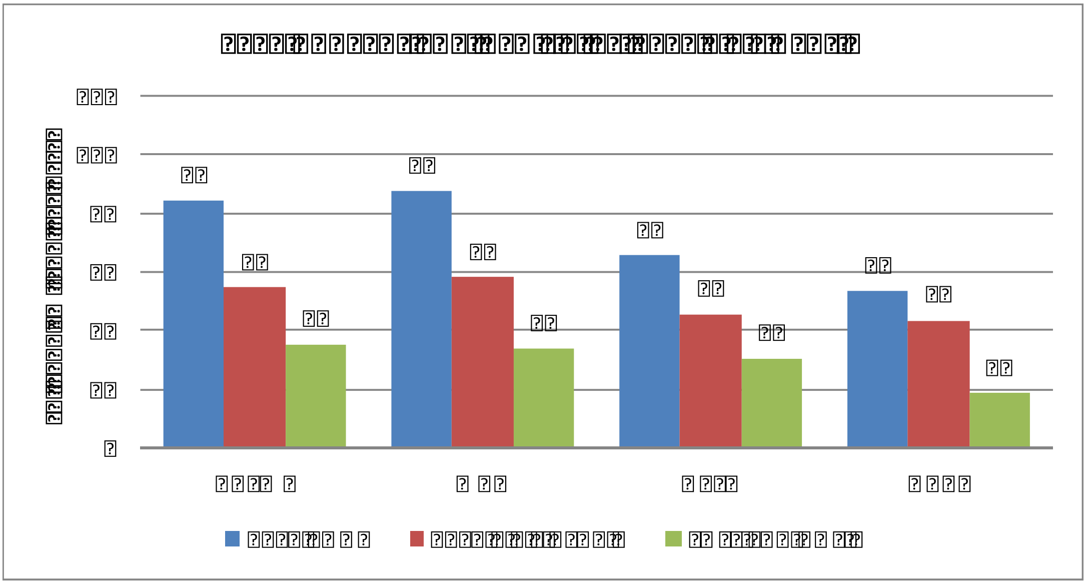


Figure 12.12. The effect of hybridization on fuel consumption.

12.2.4 Fuel effects

The UDDS cycle was chosen to illustrate the fuel effects on regulated emissions. Results are shown for three vehicle platforms:

- EPA 1998 8.3 L
- EPA 2007 8.9 L
- EPA 2010 8.9 L (1).

The results are presented in Figures12.13–12.15 (all tested fuels).

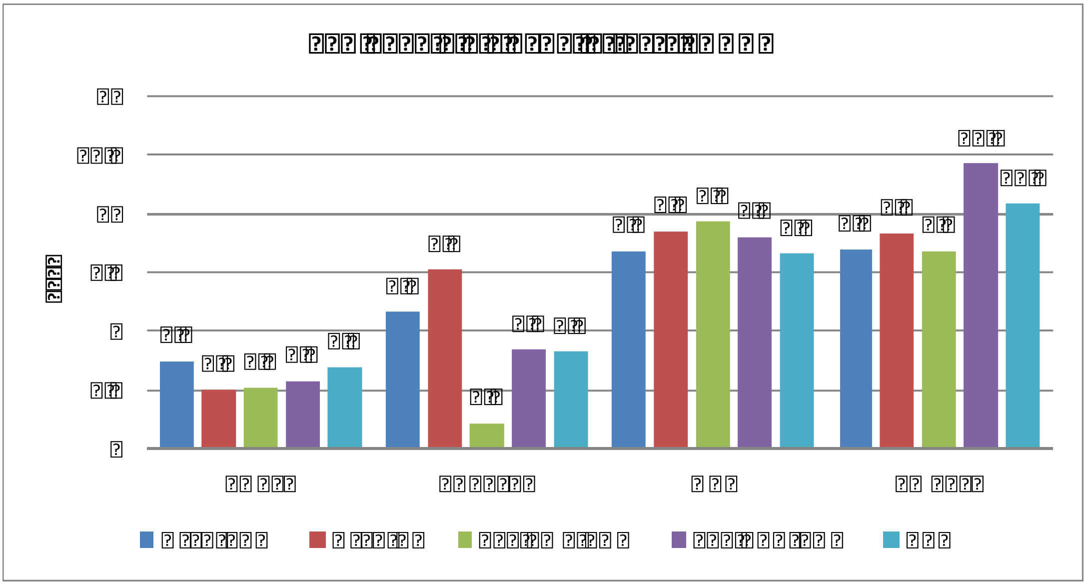


Figure 12.13. Fuel effects on regulated emissions. EPA 1998 8.3 L.

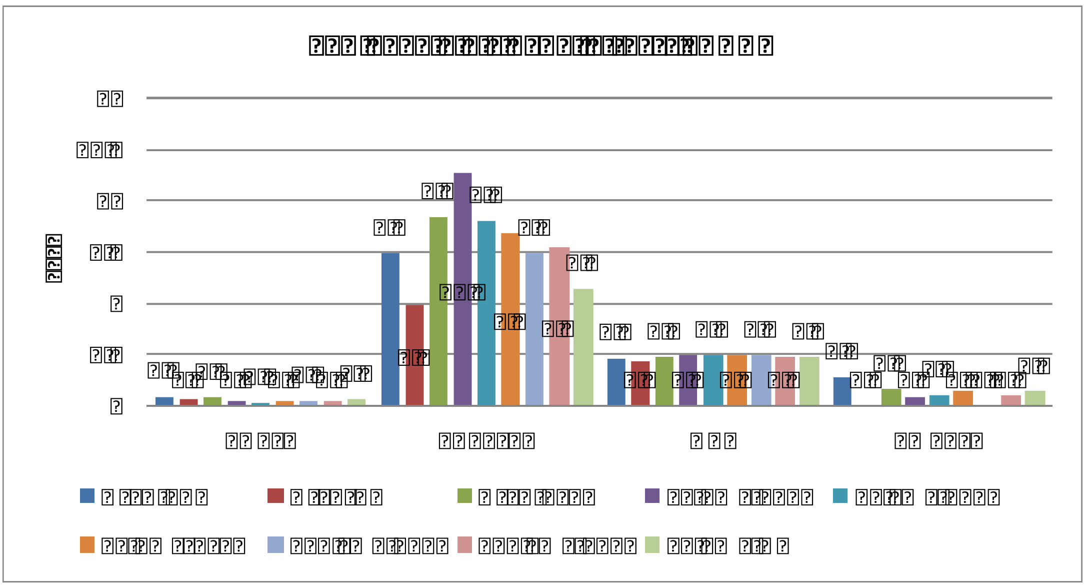


Figure 12.14. Fuel effects on regulated emissions. EPA 2007 8.9 L.

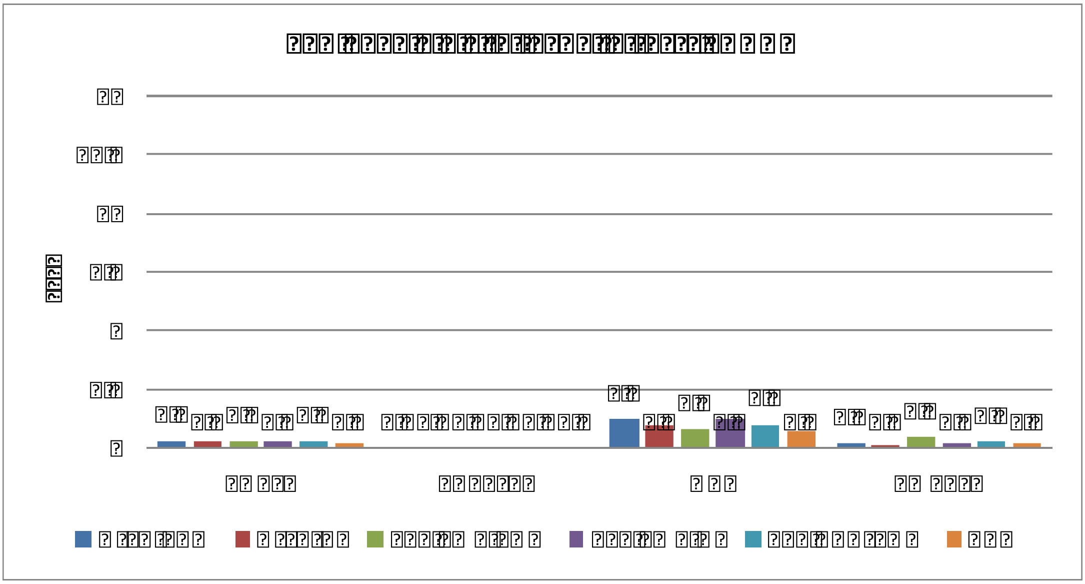


Figure 12.15. Fuel effects on regulated emissions. EPA 2010 8.9 L (1).

The use of the emission control technologies overshadowed or masked the effects of the varying fuel properties on the measured emissions.

In an attempt to accentuate fuel effects, results for 100% replacement fuels are presented separately. At EC, these fuels (neat fuels) were ULSD from oil sands (OS) and HVO.

100% HVO was tested in three vehicles, EPA 1998 8.3 L, EPA 2010 8.9 (1) and EPA 2010 8.9 (3). ULSD OS was tested in two vehicles, EPA 1998 8.3 L and EPA 2010 8.9 (1). All vehicles were tested using the UDDS cycle, the EPA 2010 (3) in addition with the Manhattan cycle. The HVO and ULSD OS results in comparison to conventional ULSD (either ULSD COM or ULSD CERT) fuel are shown in Figures 12.16, 12.18 and 12.20 (regulated emissions) and 12.17, 12.19 and 12.21 (volumetric and gravimetric fuel consumption, energy consumption and tailpipe CO_2).

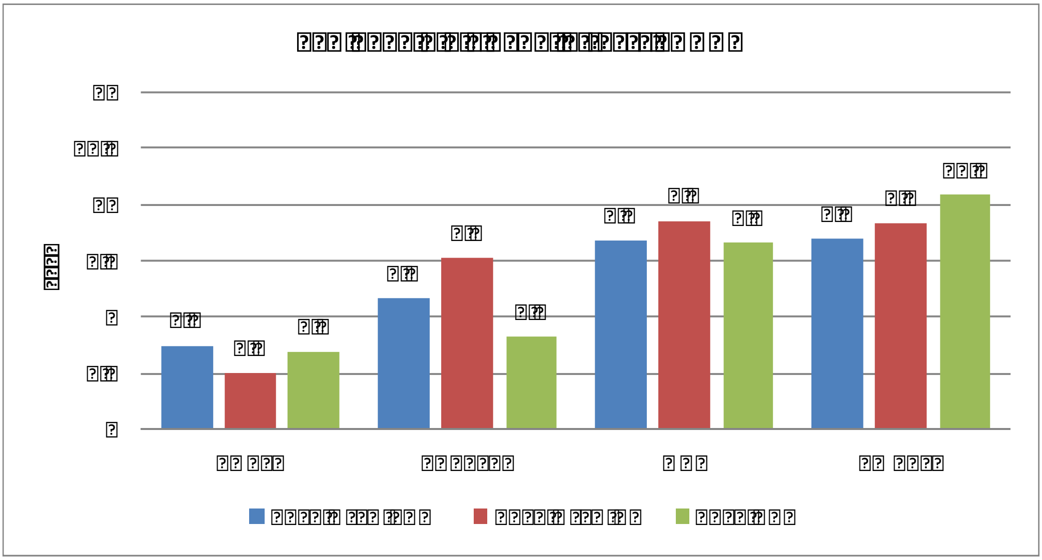


Figure 12.16. A comparison of regulated emissions for ULSD COM vs. 100% oil sands derived ULSD OS and 100% HVO in the EPA 1998 8.3 L vehicle using the UDDS cycle.

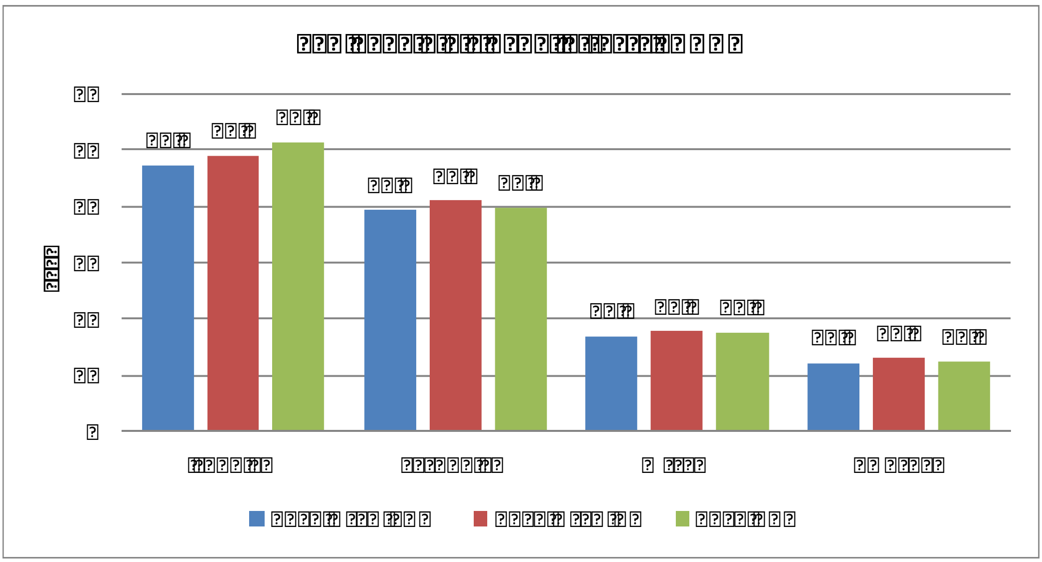


Figure 12.17. A comparison of fuel consumption (volumetric and gravimetric), energy consumption and tailpipe CO_2 for ULSD COM vs. 100% oil sands derived ULSD OS and 100% HVO in the EPA 1998 8.3 L vehicle using the UDDS cycle. Indicative as fuel consumption is based on carbon balance of the exhaust gases.

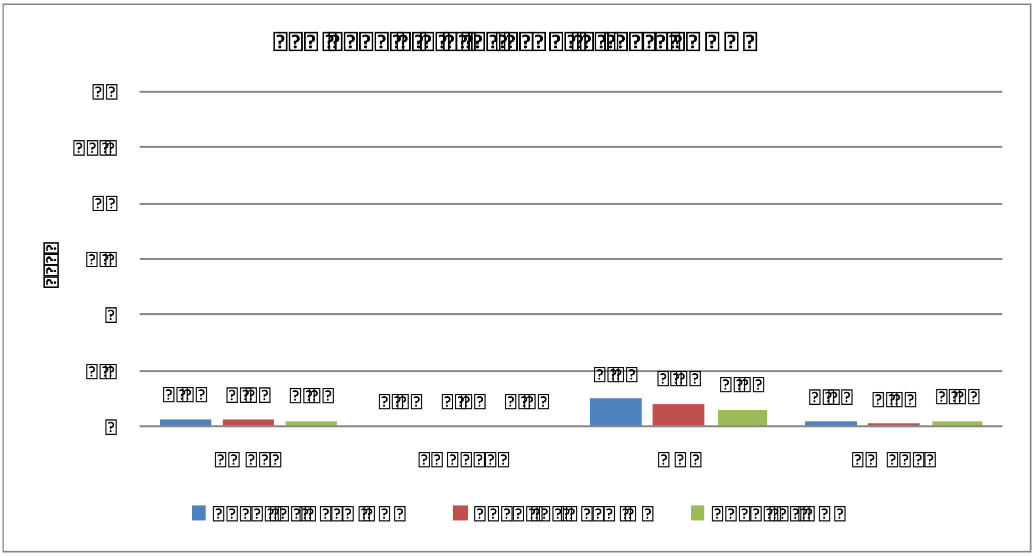


Figure 12.18. A comparison of regulated emissions for ULSD COM vs. 100% oil sands derived ULSD OS and 100% HVO in the EPA 2010 8.9 L (1) vehicle using the UDDS cycle.

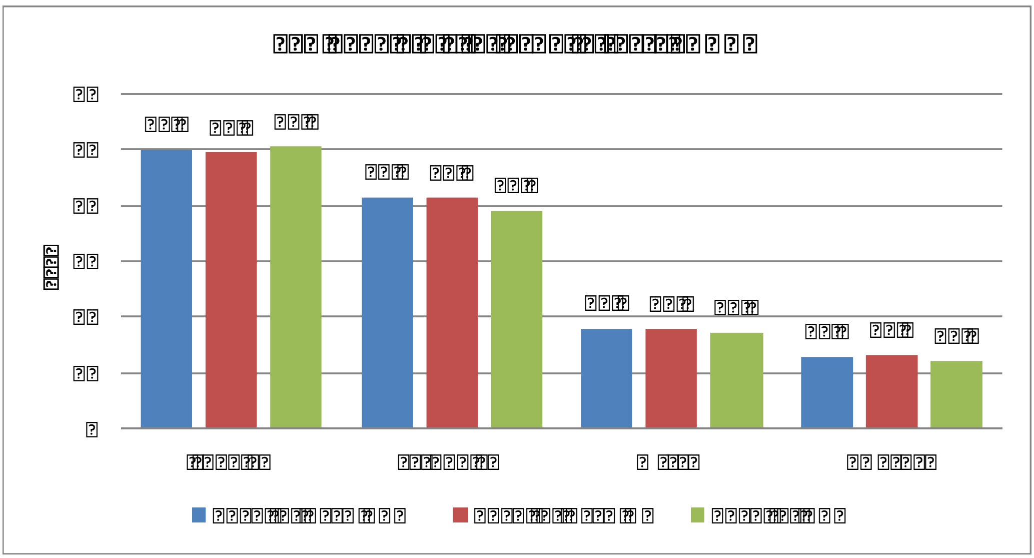


Figure 12.19. A comparison of fuel consumption (volumetric and gravimetric), energy consumption and tailpipe CO_2 for ULSD COM vs. 100% oil sands derived ULSD OS and 100% HVO in the EPA 2010 8.9 L (1) vehicle using the UDDS cycle. Indicative as fuel consumption is based on carbon balance of the exhaust gases.

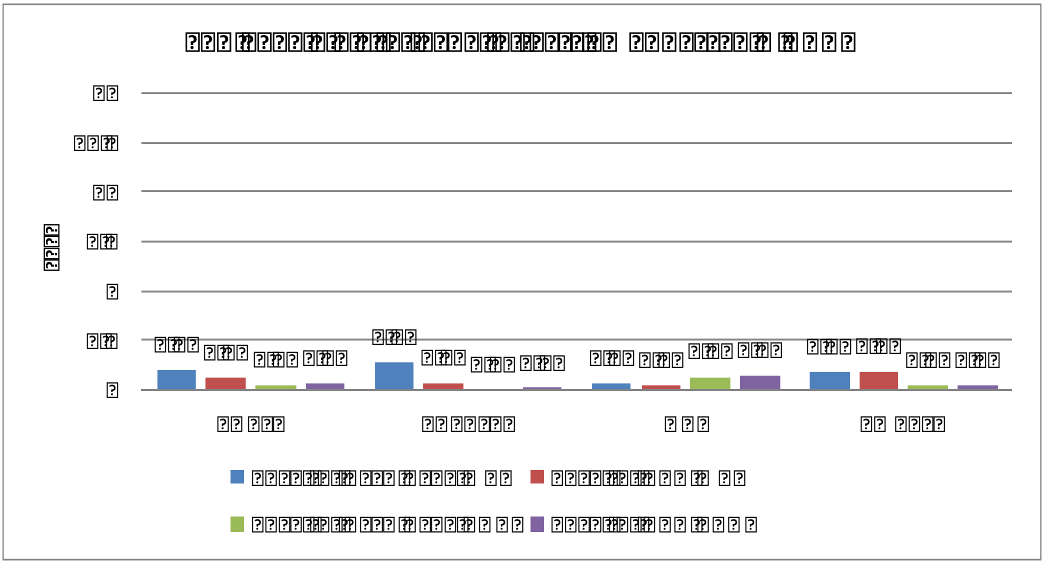


Figure 12.20. A comparison of regulated emissions for ULSD CERT vs. 100% HVO in the EPA 2010 8.9 L (3) vehicle using the Manhattan and UDDS cycles.

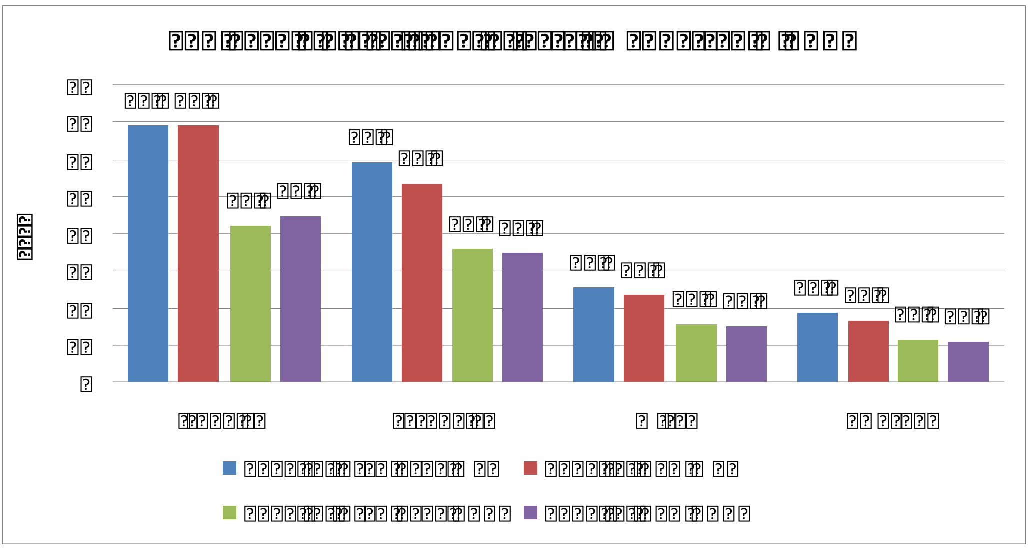


Figure 12.21. A comparison of fuel consumption (volumetric and gravimetric), energy consumption and tailpipe CO_2 for ULSD CERT vs. 100% HVO in the EPA 2010 8.9 L (3) vehicle using the Manhattan and UDDS cycles.

This commercial oil sands derived ULSD had roughly the same density (835 kg/m^3) as the seasonal commercial ULSD (830 kg/m^3), whereas HVO is lighter (775 kg/m^3). The certification fuel is rather dense, 855 kg/m^3. The light paraffinic HVO fuel can be expected to reduce NO_x emissions to some extent, but more specifically PM emissions.

The fuel effects depend on the test cycle. For UDDS and the 1998 platform, ULSD OS increased NO_x emissions (some 10%), whereas the effect of HVO was negligible. In the 2010 (1) platform using UDDS both ULSD OS and HVO reduced NO_x emissions, 16% and 38%, respectively.

Still looking at UDDS, in the 1998 platform both ULSD OS and HVO increased PM emissions, HVO some 20% in comparison with ULSD COM. For HVO this is an exceptional result because normally HVO clearly reduces PM emissions (see VTT's results for Euro II and III vehicles in Paragraph 12.3). In the 2010 (1) platform, ULSD OS cut PM emissions in half, whereas HVO increased PM emissions marginally. Considering the very low absolute PM levels, these variations are most probably to be attributed to variations in the functioning of the 2010 (1) vehicle and the exhaust after-treatment system rather than to the fuel.

In the 2010 (3) platform HVO decreased CO and THC emissions in the Manhattan cycle, but increased these emissions in the UDDS cycle. For both cycles, 100% HVO increased particulates some 5–10%. As for NO_x, 100% HVO delivered a 35% reduction in the Manhattan cycle but a small increase (some 10%) in the UDDS cycle. Please observe that the absolute NO_x and PM levels are extremely low.

At EC, the fuel consumption was calculated from exhaust flow and exhaust composition, not measured directly. Therefore the results in Figures 12.17, 12.19 and 12.21 are indicative. Based on density and estimating that both fuels have the same net heating value (43.3 MJ/kg, measured value for ULSD COM), ULSD COM and ULSD OS should give roughly the same mass and volume based fuel consumption (within 1%), and also equivalent energy consumption. HVO is lighter, which results in slightly higher volumetric fuel consumption. On the other hand, heating value is slightly higher (44 MJ/kg), which should result in marginally lower gravimetric fuel consumption.

In the 1998 platform, both ULSD OS and HVO seem to increase gravimetric fuel consumption and energy consumption over ULSD COM. In the 2010 (1) platform, on the other hand, ULSD COM and ULSD OS give equivalent gravimetric fuel consumption and energy consumption, whereas HVO gives some 5% lower values. In the 2010 (3) platform HVO reduced energy consumption 1–7% in comparison to ULSD CERT, depending on the cycle.

However, the methodology used to determine fuel consumption is not accurate enough to directly compare fuels regarding energy consumption.

12.2.5 Results for unregulated emissions

EC measured several unregulated components, including carbonyl compounds, N_2O and particulate numbers.

Figures 12.22 through 12.24 display the effects on drive cycle, fuels, and technologies on emissions of formaldehyde and acetaldehyde.

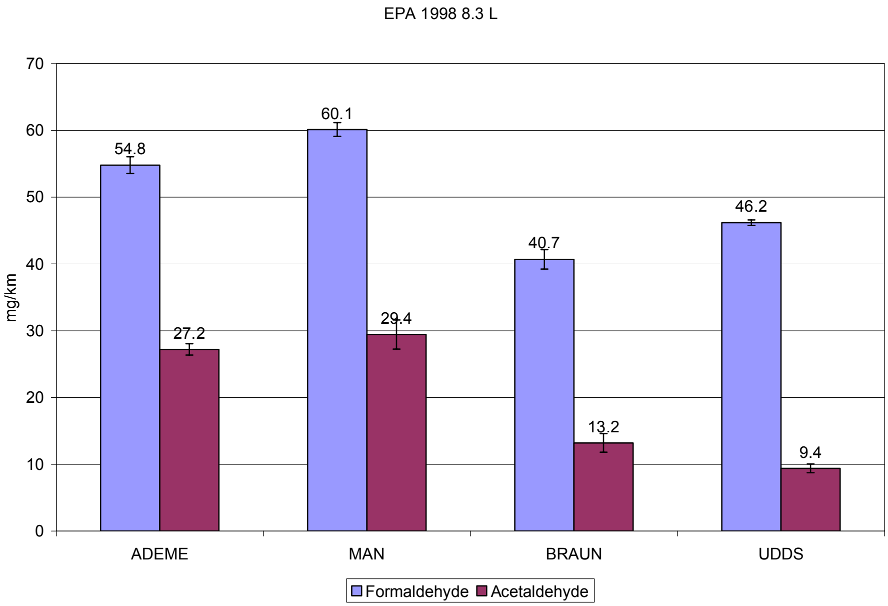


Figure 12.22. Effects of driving cycle on carbonyls.

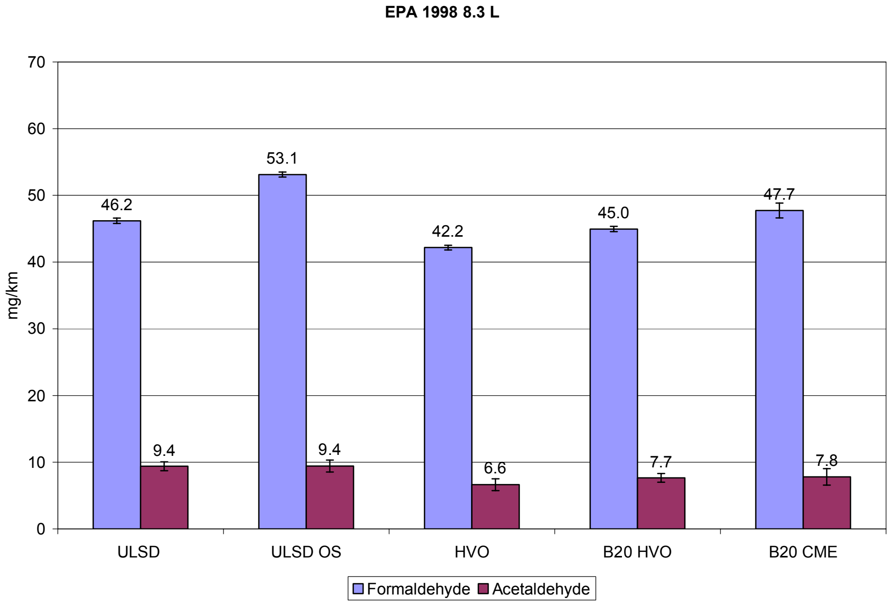


Figure 12.23. Fuel effects on carbonyls.

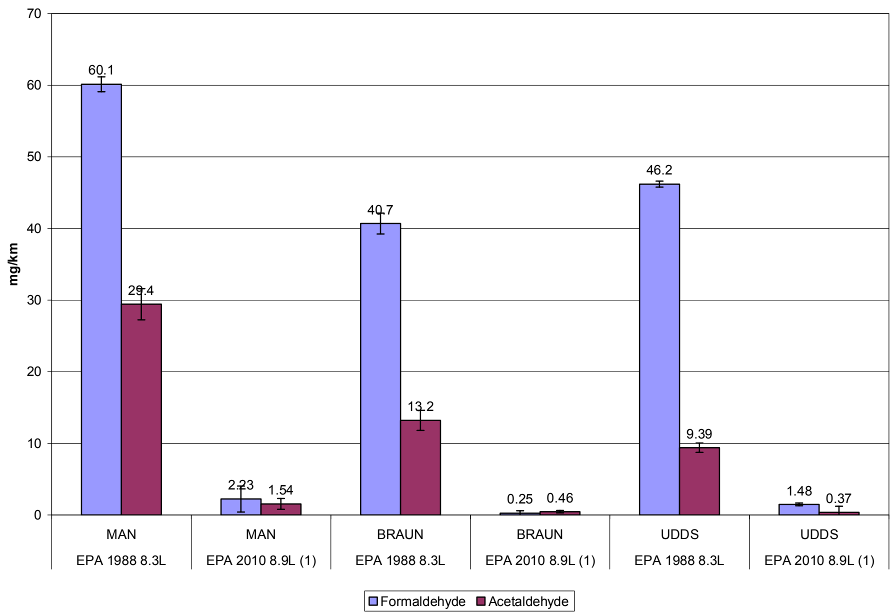


Figure 12.24. Effects of technologies on carbonyls.

Emissions of carbonyls from the oldest technology bus compared to all the other buses, especially the 2010 technologies, were significantly higher. With the EPA 1998 bus, the higher averaged speed UDDS and Braunschweig cycle produced lower carbonyl emissions compared to the lower averaged speed ADEME and Manhattan. With the EPA 1998 bus, HVO and B20 HVO blend produced less carbonyls compared to other test fuels.

Figures 12.25 through 12.27 display N_2O and CO_2 GHG equivalent emissions for the Manhattan, Braunschweig and UDDS cycles respectively. As mentioned above the N_2O and CH_4 emissions from these buses as a very small impact on overall GHG emissions. However, it can be noted that in some cases, likely dependent on the catalyst coating used for the SCR catalysts, the N_2O emissions were increased with the 2010 buses compared to the other bus technologies.

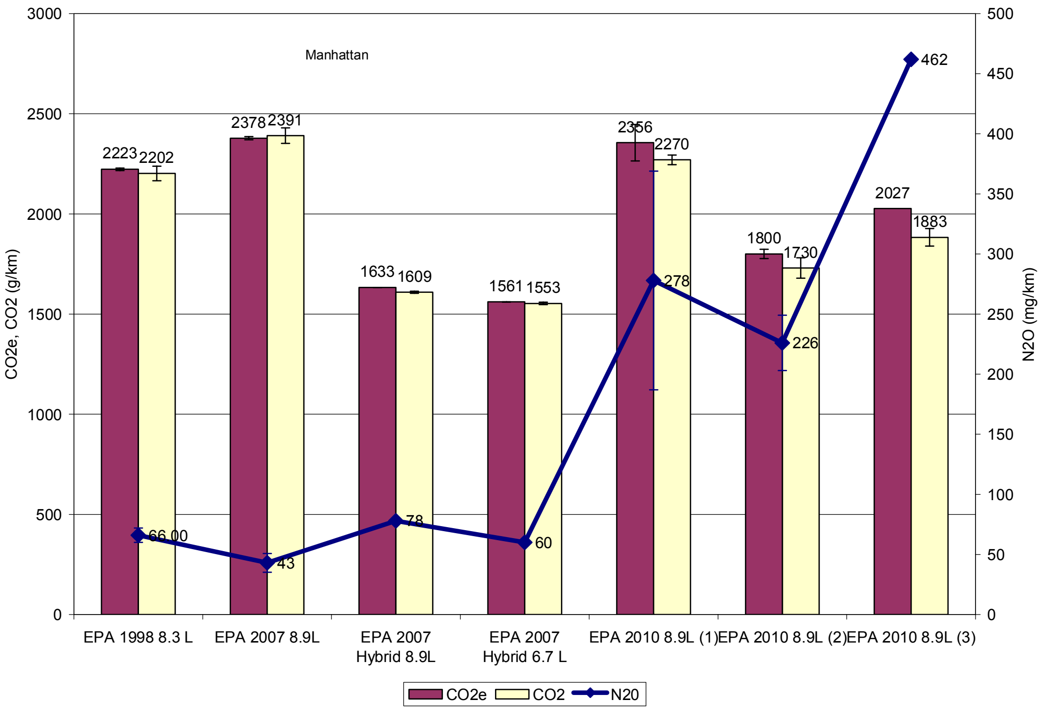


Figure 12.25. GHG emissions from the Manhattan cycle.

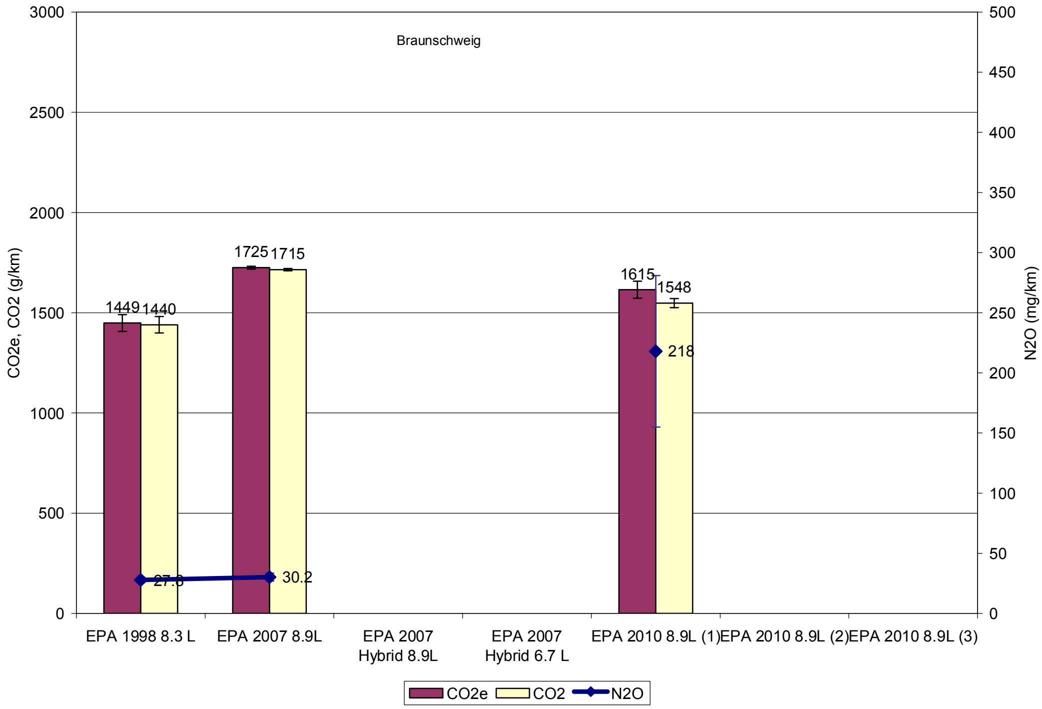


Figure 12.26. GHG emissions from the Braunschweig cycle.

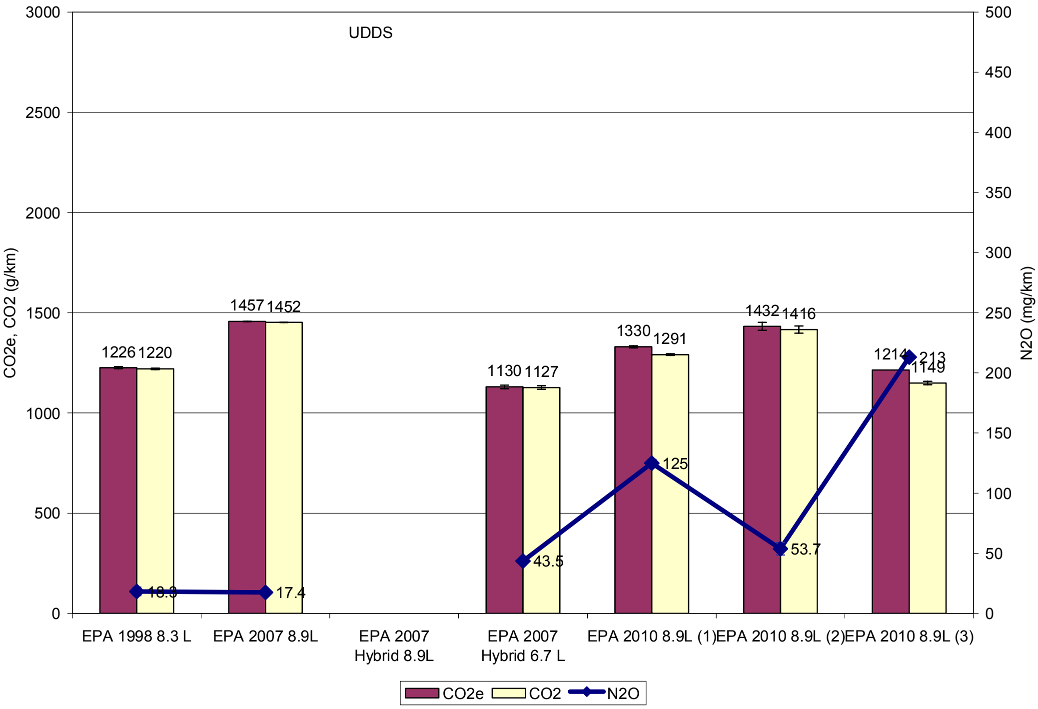


Figure 12.27. GHG emissions from the UDDS cycle.

At EC, for all buses, with the exception of the older EPA 1998 bus, aerosol particles were sampled directly from the CVS without the use of secondary dilution. The exhaust was then directed to engine exhaust particle sizer (EEPS) for particle number concentration and size distribution measurements. A Dekati mini diluter was used as secondary dilution for the EPA 1998 bus.

Figure 12.28 shows the average particulate number size distributions obtained from different driving cycles from the EPA 1998 8.3 L bus with ULSD fuels. Uncertainties displayed in the figure represent the standard deviation derived from multiple repeats. In general, all average number size distributions generally showed bimodal distributions. The number concentration of the nucleation mode particles emitted during the UDDS was much higher compared to the other cycles.

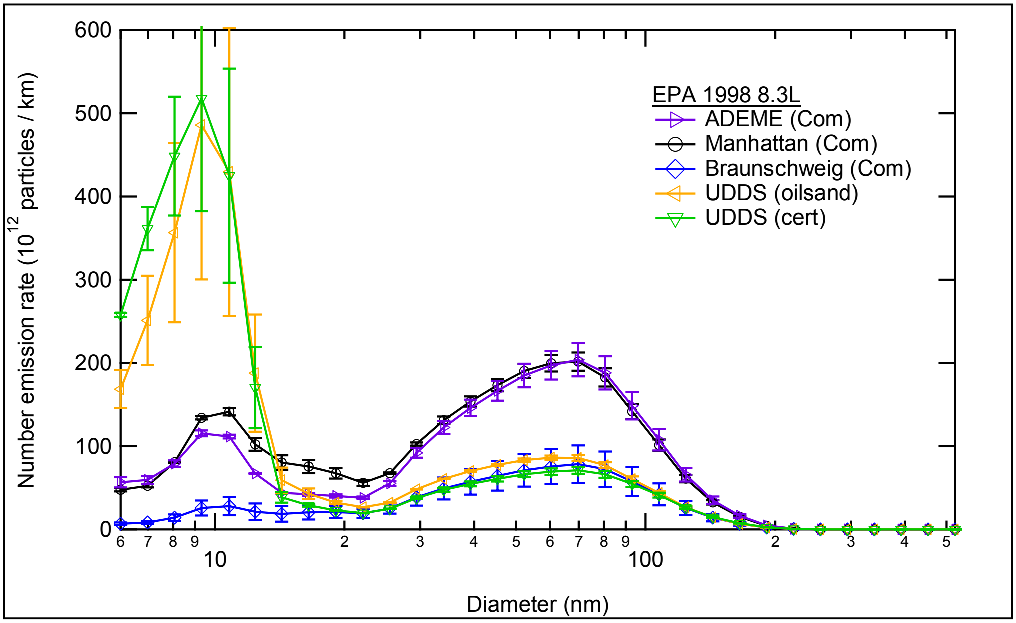


Figure 12.28. Average particle number size distributions for EPA 1998 for various drive cycles.

Differences in particle number distributions are noted between the lower averaged speed ADEME and Manhattan cycles compared to the higher speed Braunschweig and UDDS. A similar trend is noted with the size distribution from the EPA 2007 8.9 L bus graphed in Figure 12.29 with the higher speed Japanese JE05 cycle and UDDS showing a lower number of particles. Of note is the decrease in the number emission rate from the 2007 bus with DPF, with the number emission rate scale being one tenth of that of the older 1998 bus.

Further differences were noted between older and new technology buses as illustrated in Figure 12.30. The green line represents the EPA 1998 bus without DPF. The other lines represent the particle size distribution from the 2010 bus with varying drive cycles. The insert shows that there were particles with the 2010 bus however note the scale maximum of 5 * 10^{12} for the 2010 bus compared to 600 * 10^{15} particles per km for the 1998 bus.

Particle number emission rates from the buses with DPF are orders of magnitude lower compared to bus without DPF. Comparing the EPA 1998 bus to the EPA 2010, mass emission rates have been reduced by more than 99%.

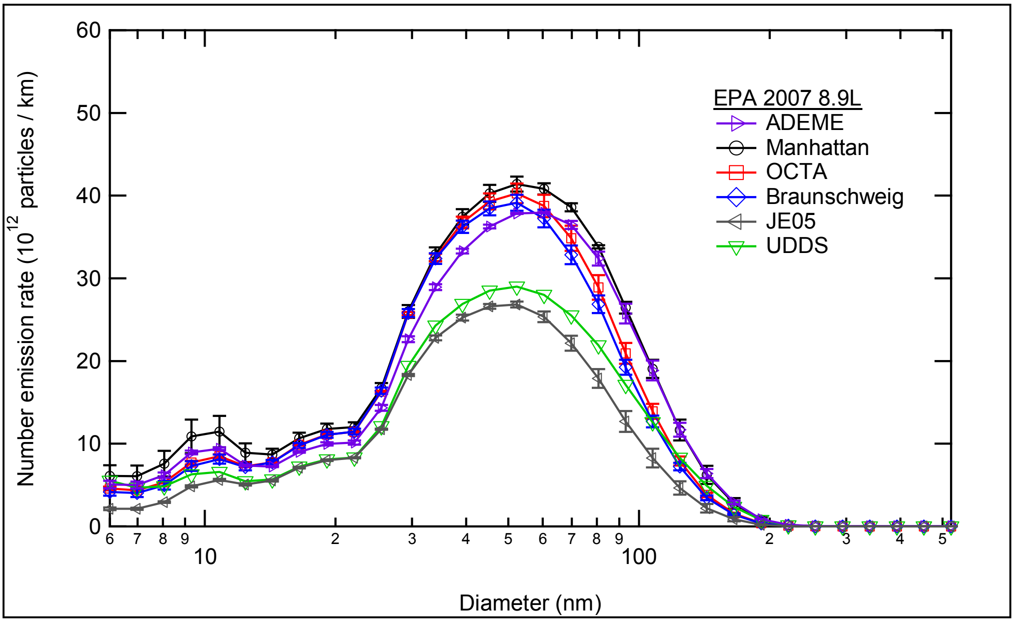


Figure 12.29. Average particle number size distributions for EPA 2007 for various drive cycles.

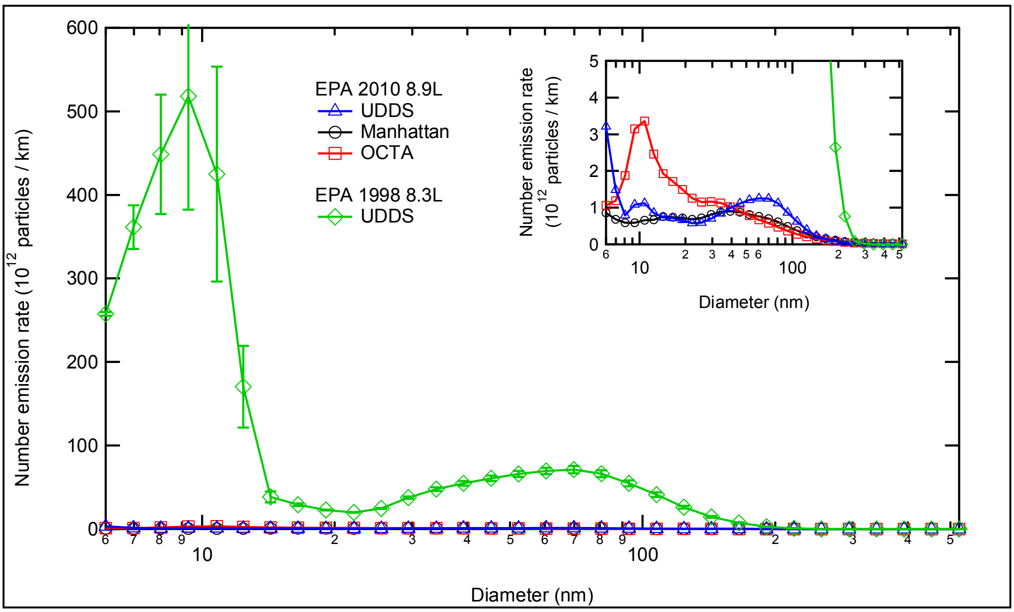
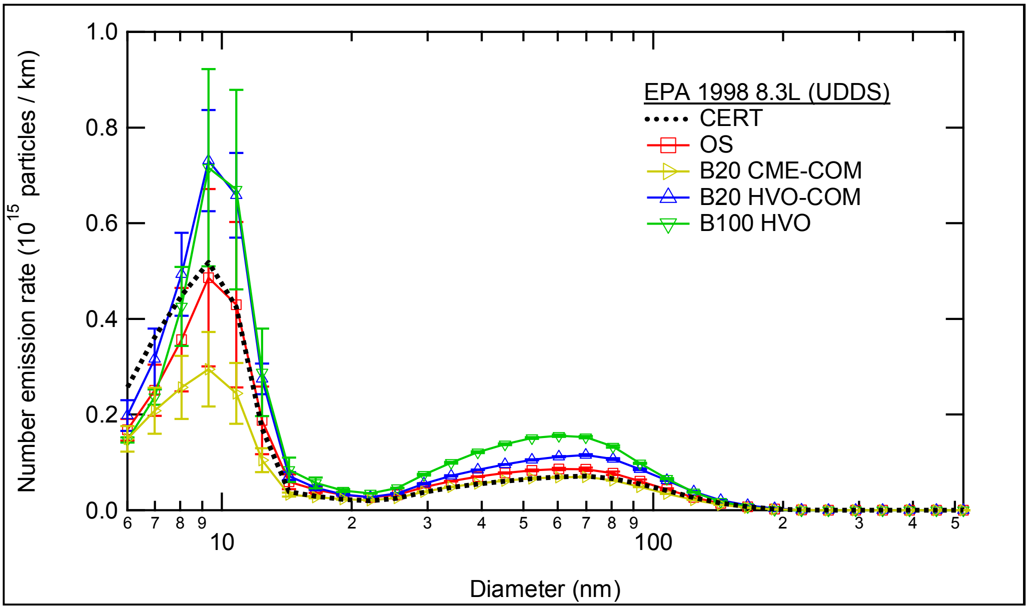
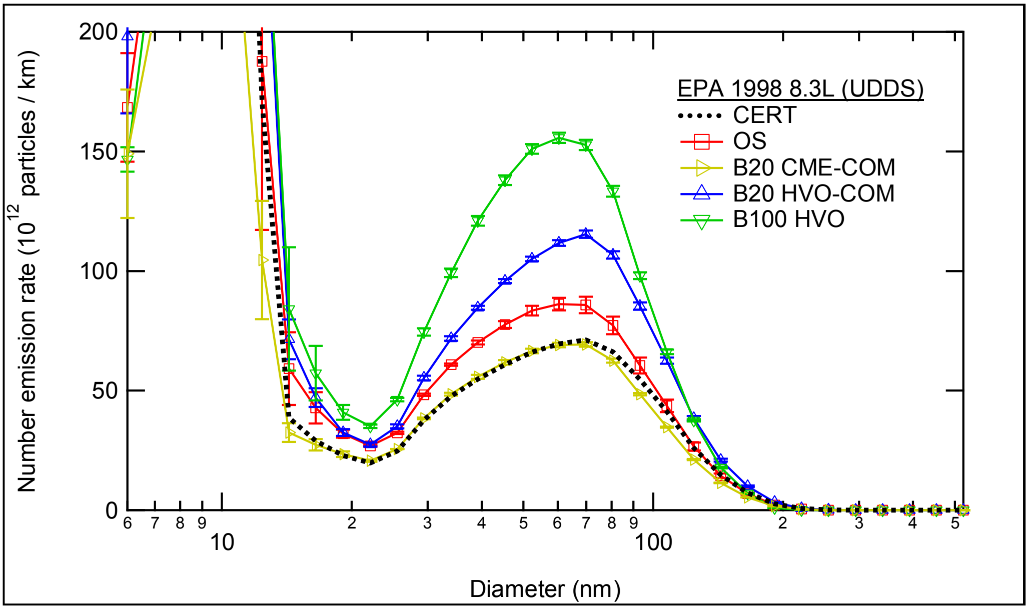


Figure 12.30. Comparison of average particle number size distributions for EPA 1998 and EPA 2010.

Both particle number and mass emission rates for the 2010 bus were so low that no conclusive relationship regarding the particulate matter reduction and biodiesel fuel content can be derived for that bus.

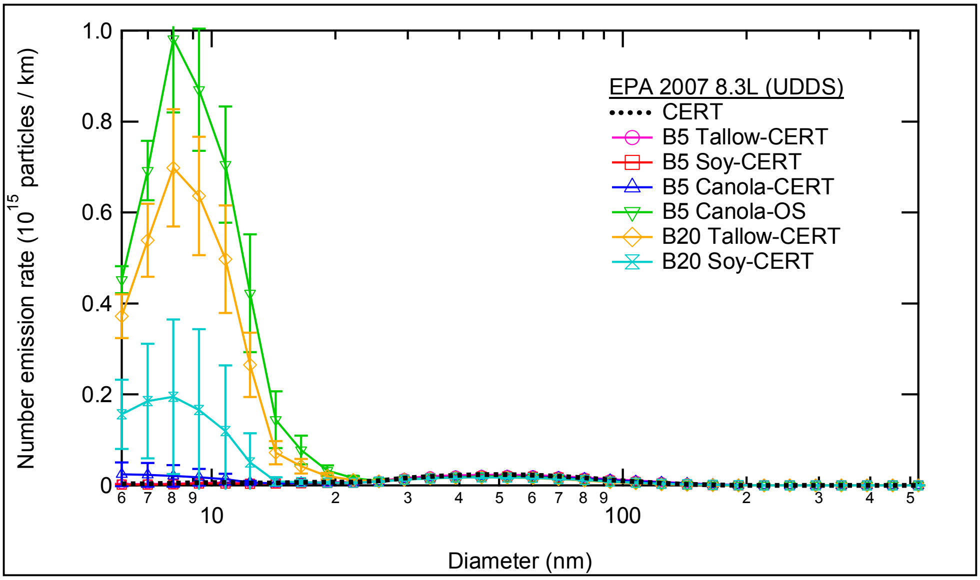
However, Figures 12.31 (A) and 12.31 (B) display the results from the EPA 1998 8.3 L bus operated with the UDDS cycle with different fuels. Figures A and B are the same charts with different scales. Among all fuels, particle emissions were generally similar. For this bus, 100% HVO and B20 made from HVO gave slightly higher nucleation mode particles. The lowest particle number emission rates were observed with the B20 made from Canola.

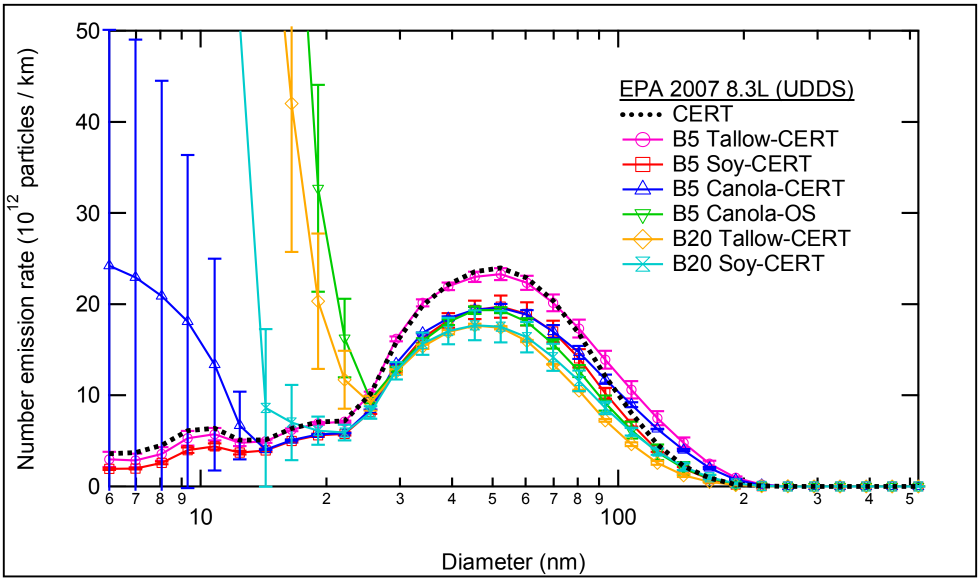




Figures 12.31 (A) & (B). Fuel effects on average particle number size distributions for EPA 1998.

Figures 12.32 (A) and 12.32 (B) display the results from the conventional EPA 2007 bus. These graphs illustrate particle size distributions for various biodiesel blends operating on the UDDS cycle. For the fine soot particle mode (30–200 nm), biodiesel (regardless if was blended with oilsands derived diesel, ULSD diesel or CERT) generally yielded lower particle emissions with the largest reductions observed for the B20 blends.





Figures 12.32 (A) & (B). Fuel effects on average particle number size distributions for EPA 2007.

12.2.6 General observations

As mentioned previously, the work conducted at EC encompassed 7 vehicle platforms, 7 test cycles and 13 different fuel alternatives, producing a total of 68 different test combinations.

The Manhattan cycle was the one cycle driven with all the above-mentioned platforms and results of North American buses tested over this cycle clearly demonstrated the emissions reductions achieved with tightening emission regulations in the last decade or so. After completion of this test program, it was found that the main parameter affecting emissions and fuel consumption was vehicle technologies.

Reductions of up to 97% were observed for NO_x and PM, the two key components for urban air quality, when comparing the EPA 1998 vehicle with the EPA 2010 vehicles. Significant decreases in PM emissions were observed starting with the EPA 2007 platforms, due to their DPFs, while NO_x emissions were drastically reduced with the EPA 2010 platforms by implementation of SCR technology.

All of the buses, with the exception of the EPA 1998, produced very low CO and THC emissions; in many cases at the instrumentation and method detection limits.

For fuel consumption, the changes were small, as the 1998 vehicle had a fuel consumption equivalent to the average of two of the 2010 vehicles. Bus 2010 (3), with its optimized transmission, produced an approximate 17% reduction in fuel consumption. Hybridization, however, reduced fuel consumption by some 30–35% when looking at the lower average speed cycles.

Overall, the effects of varying fuels on measured emissions were overshadowed or masked by the use of emission control technologies. However, certain trends were noted during this program. In the 1998 platform, ULSD OS increased NO_x emissions (some 10%), whereas the effect of HVO was negligible. In the 2010 platform both ULSD OS and HVO reduced NO_x emissions, 15% and 38%, respectively. In the 1998 platform, both ULSD OS and HVO increased PM emissions. For HVO this is an exceptional result because normally HVO clearly reduces PM as discussed in Section 12.3. With the 2010 platform, it should be noted that PM and NO_x levels were very low, and as differences were varied, they could potentially be attributed to variations in the functioning of the exhaust after-treatment system rather than to the fuel.

As for the impact of fuel consumption with varying fuels, in the 1998 platform, both ULSD OS and HVO seemed to increase gravimetric fuel consumption and energy consumption over ULSD COM. In the 2010 (1) platform, on the other hand, ULSD COM and ULSD OS gave equivalent gravimetric fuel consumption and energy consumption, whereas HVO gave some 5% lower values. However, the methodology used to determine fuel consumption is not accurate enough to directly compare fuels regarding energy consumption.

EC measured several unregulated components, including carbonyl compounds, methane, N_2O and particulate numbers. The N_2O and CH_4 emissions from these buses had a very small impact on overall GHG emissions (CO_2e increased 1–3% over CO_2). However, it can be noted that in some cases, likely dependent on the catalyst coating used for the SCR catalysts, the N_2O emissions were increased with the 2010 buses compared to the other bus technologies. Generally, emissions of carbonyls from the oldest technology bus were significantly higher than those of the other buses, especially with the EPA 2010 platforms. With the EPA 1998 bus, HVO and the B20 HVO blend produced less carbonyls compared to other test fuels.

Over this program, all average particle number size distributions generally showed bimodal distributions. The number concentration of the nucleation mode particles emitted during the UDDS was much higher compared to the other cycles. Differences in particle number distributions were noted between the lower averaged speed cycles compared to the higher averaged speed cycles. Further differences were also noted between older and newer technology buses. Particle number emission rates from buses with DPF were several orders of magnitude lower compared to bus without DPF. Comparing the EPA 1998 bus to the EPA 2010 buses, mass emission rates were reduced by more than 99%.

Both particle number and mass emission rates for the 2010 buses were so low that no conclusive relationship regarding the particulate matter reduction and biodiesel fuel content can be derived for these buses. For the 2007 conventional platform, biodiesel (regardless of the blending agent) generally yielded lower particle emissions for the fine soot particle mode (30–200 nm), with the largest reductions observed for the B20 blends. Finally, for the EPA 1998 platform, varying fuels didn't have much effect on particle emissions. However, HVO and B20 HVO gave slightly higher nucleation mode particles while the lowest particle number emission rates were observed with the B20 Canola.

12.3 VTT's chassis dynamometer results

12.3.1 General

Work at VTT encompassed 14 vehicle platforms, 6 test cycles and 14 different fuel alternatives, producing a total of 110 different combinations (Table 10.4). In addition to diesel and diesel replacement fuels, VTT also tested natural gas (CNG), additive treated ethanol and di-methyl-ether (DME). As stated in paragraph 10.2.3, the DME vehicle was a prototype heavy-duty truck, simulated as a bus. Therefore the results for DME must be considered indicative, at the most.

The results are presented as follows:

- Comparison of diesel vehicles, effects of hybridization and comparison of diesel vs. alternative fuel vehicles: Braunschweig cycle, regulated emissions, CO_2 and fuel consumption
- Influence of driving cycle: diesel vehicles 3–6 cycles, hybrid vehicle 6 cycles, alternative fuel vehicles 3–6 cycles, NO_x, PM and fuel consumption

- Fuel effects: diesel vehicles with conventional power train, Braunschweig driving cycle, regulated emissions and fuel consumption.

Please observe that the Figures have different scales compared to the Figures for North American vehicles.

VTT didn't analyse N_2O systematically, and CH_4 was only measured for the CNG, ethanol and DME vehicles. For these vehicles CH_4 is taken into account with a factor of 23 when calculating equivalent CO_2 emissions. The equivalence ratio for N_2O is 298 (values from RED, corresponding to IPCC 2001).

In VTT's measurement, the urea consumption of the SCR vehicles was typically 2–5% of the fuel consumption (on a weight basis). In the NYBUS cycle urea consumption was close to zero, as exhaust temperature is too low for urea injection.

In some cases when comparing vehicles, there is a small discrepancy between fuel consumption and CO_2 values. With the exception of the DME vehicle, fuel and energy consumption values are based on gravimetric measurement of fuel consumption. The CO_2 emission is measured from the exhaust, and this measurement is less accurate than the gravimetric measurement of fuel consumption.

12.3.2 Comparison of vehicle platforms

Diesel powered vehicles (conventional powertrain and hybrids)

Figures 12.33 and 12.34 (diesel vehicles with conventional powertrains) and 12.35 and 12.36 (current diesels and hybrids) show a comparison of diesel vehicle platforms when tested using the Braunschweig bus cycle. At VTT, this cycle was the one cycle driven with all vehicle platforms.

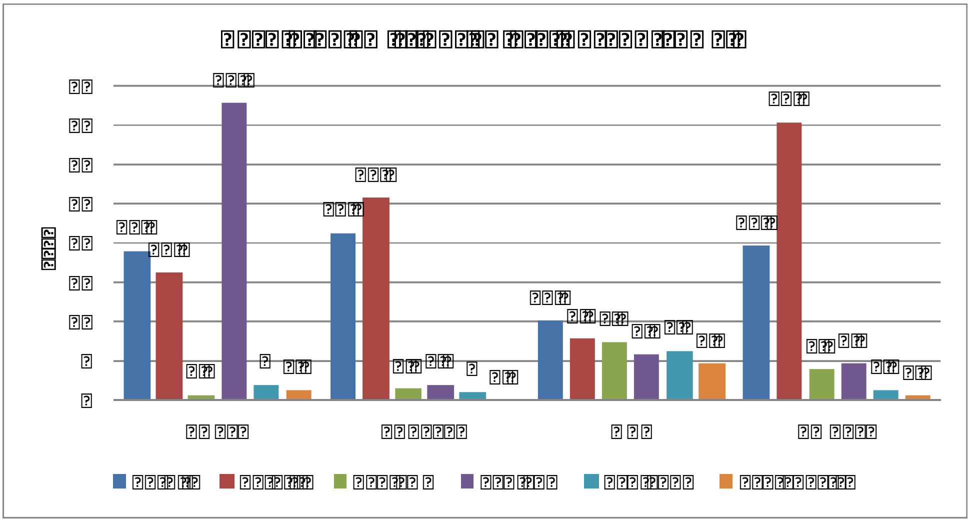


Figure 12.33. Regulated emissions for diesel vehicles with conventional powertrains. European vehicles, Braunschweig cycle. N.B.: The PM emission of the tested Euro III vehicle was rather high, average value of corresponding vehicles (same model) tested at VTT is some 0.20 g/km.

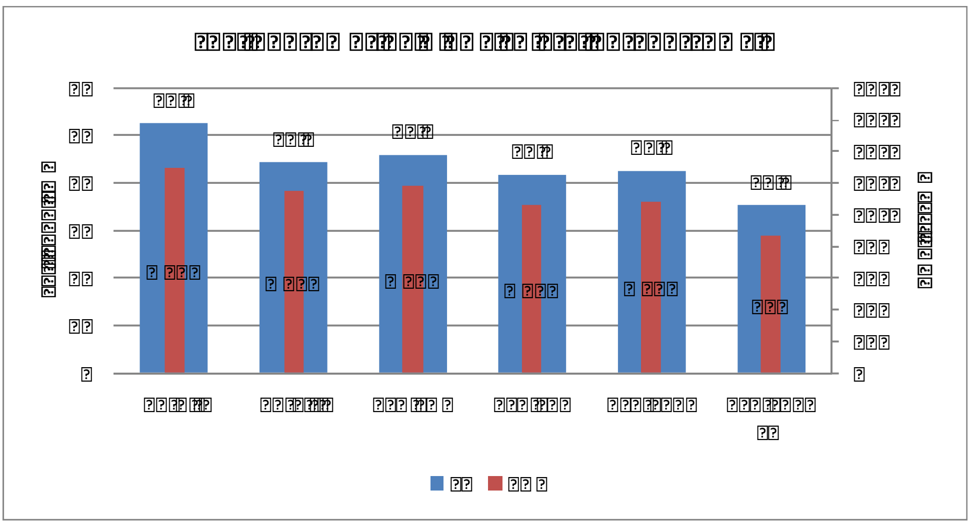


Figure 12.34. Fuel consumption (l/100 km) and CO_2 emissions for diesel vehicles with conventional powertrains. European vehicles, Braunschweig cycle.

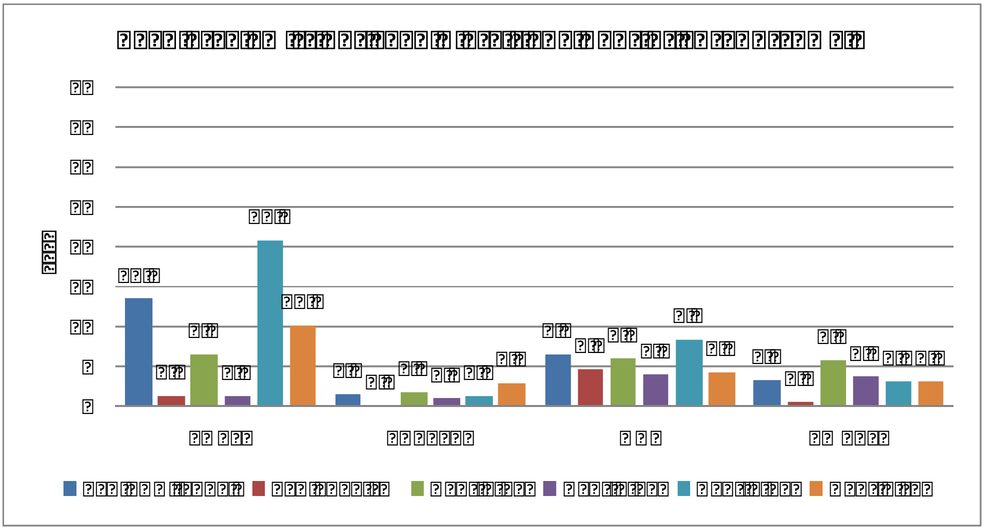


Figure 12.35. Regulated emissions for diesel vehicles with conventional and hybrid powertrains. Current European vehicles, Braunschweig cycle.

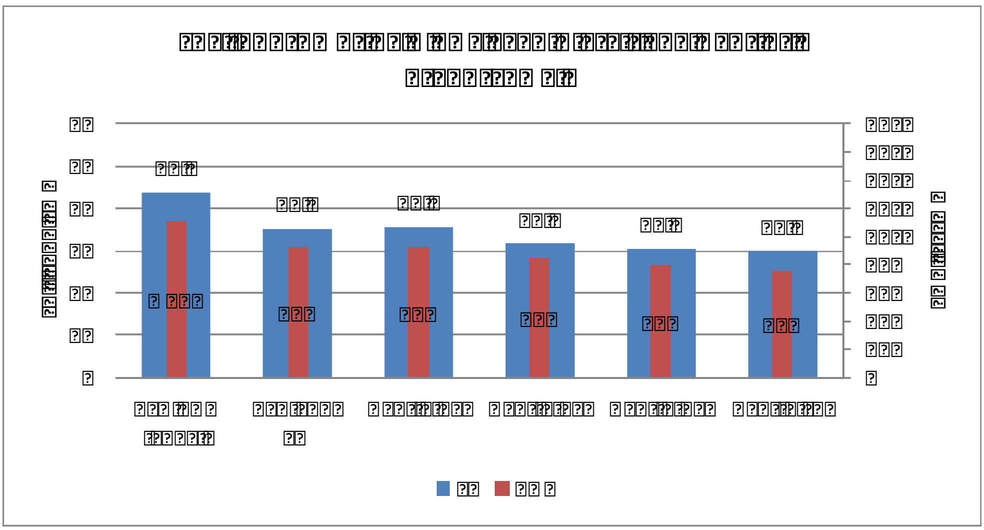


Figure 12.36. Fuel consumption (l/100 km) and CO_2 emissions diesel vehicles with conventional and hybrid powertrains. Current European vehicles, Braunschweig cycle.

For European vehicles, the progress in regulated emissions has not been as remarkable as for North American vehicles. In round figures NO_x emissions have been cut some 40% and PM emissions some 80% going from Euro II (late 90's) to

EEV (current regulation). As shown by EC's measurements, for North America both NO_x and PM have been reduced more than 95% going from EPA 1998 to EPA 2010.

For Braunschweig, the conventional European EEV certified vehicles on an average emitted some 6.5 g NO_x/km, EGR giving slightly higher NO_x than SCR. Without actual particulate filter (EGR and SCR), the PM emission of the EEV diesels was some 0.04 g/km. For the wall-flow filter equipped SCRT vehicle PM emission was some 0.015 g/km. The EEV SCRT vehicle thus delivers roughly equivalent emission performance as the EPA 2007 8.9 L vehicle. The EPA 2010 8.9 L (1) vehicle only emitted some 1.5 g NO_x/km and some 0.002 g PM/km in the Braunschweig cycle.

The light-weight SCRT vehicle performed very well as it delivered lowest regulated emissions (CO second lowest value) as well as lowest fuel consumption in the group of vehicles with conventional power train.

In the case of European vehicles, the oldest vehicle (Euro II) gives the highest fuel consumption. Within the EEV class, the EGR vehicle has some 10% higher fuel consumption compared to vehicles with SCR technology. Here it should be noted that the SCR vehicles require urea reagent, on an average some 5% of the fuel volume. In the Braunschweig, the fuel consumption of the EEV certified buses is some 45 l/100 km, whereas the North American vehicles consume some 60 l/100 km. Low regulated emissions come at the cost of increased fuel consumption.

These values stated above are for vehicles with conventional design and conventional power train. For fuel consumption, the light-weight bus came close to the fuel consumption values of the hybrids (see Figure 12.36).

In the case of European vehicles and the Braunschweig cycle, hybridization reduced fuel consumption (and CO_2) on an average 27% (19 32%) compared to EEV average without hybridization. No clear benefits of hybridization on regulated emissions could be seen. One of the hybrids had high NO_x emissions, while another vehicle delivered high PM values. None of the hybrids had actual wall-flow particulate filters. Compared to the average of EEV EGR and EEV SCR (SCRT vehicle excluded), hybridization on an average reduced NO_x emission 15% and PM emissions 8%. The presupposition was that hybridization would reduce PM emissions at least in proportion to fuel consumption. The performance of the hybrids will be discussed further in paragraph 12.3.3.

Alternative fuel vehicles

The alternative fuel vehicles evaluated were two CNG vehicles, one ethanol vehicle and one DME vehicle. Average values for EEV diesels are used as reference (light-weight SCRT vehicle excluded). The alternative fuel vehicles corresponded either to EEV (stoichiometric CNG and ethanol) or Euro V (lean-burn CNG actual Euro V certification, DME manufacturer's statement). Again it should be noted that the DME was a prototype HD truck simulated as a bus, and therefore the results for DME should be considered indicative only.

Figure 12.37 shows regulated emissions and Figure 12.38 shows fuel and energy consumption.

In Figures 12.34 and 12.36 above fuel consumption is shown as l/100 km, in the case of alternative fuel vehicles the fuel consumption is shown as kg/100 km and as energy consumption (MJ/km, Figure 12.38).

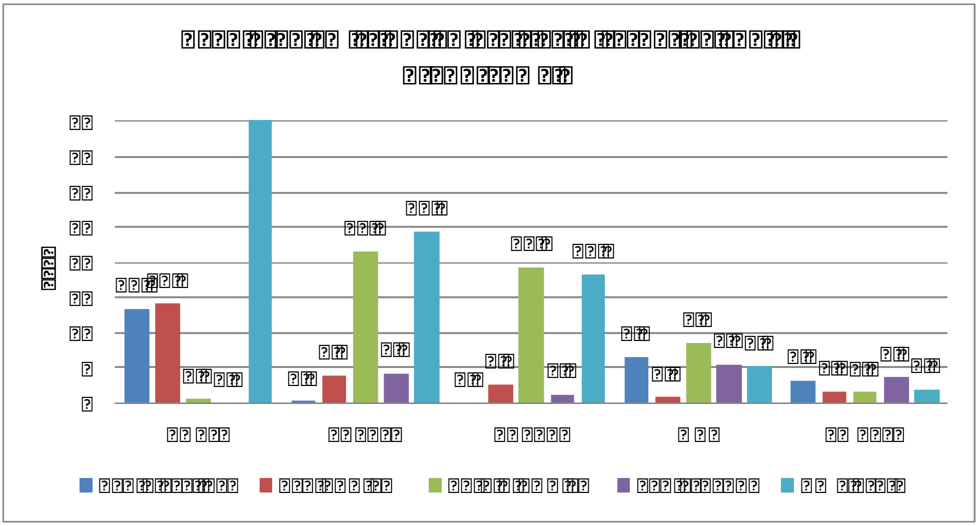


Figure 12.37. Regulated emissions for current diesel vehicles and alternative fuel vehicles. European vehicles, Braunschweig cycle.

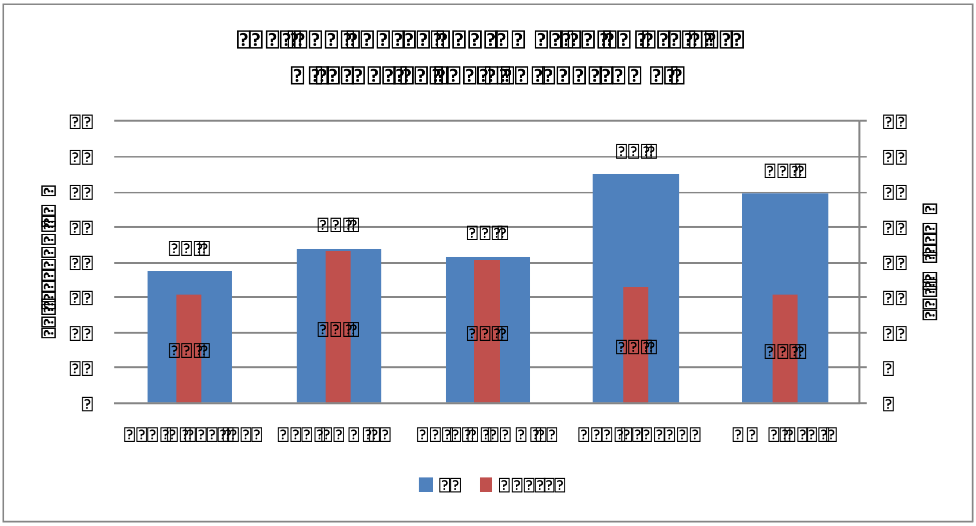


Figure 12.38. Fuel (kg/100 km) and energy consumption (MJ/km) for current diesel vehicles and alternative fuel vehicles. European vehicles, Braunschweig cycle.

The variation in regulated component emission is quite significant. CNG delivers lowest (stoichiometric) as well as highest (lean-burn) NO_x emissions, with a ratio of some 1:10. Both ethanol and DME delivers slightly lower NO_x compared to diesel average.

In the case of PM, in the Braunschweig cycle ethanol delivers performance equivalent to average diesel. However, the average PM reduction for all six cycles evaluated was 50% in comparison with the EEV EGR diesel (see 12.3.3). CNG gives lowest PM emissions, some 0.015 g/km, i.e. half of diesel average and equivalent to wall-flow filter equipped diesel (SCRT). DME comes quite close to CNG. Stoichiometric CNG delivers lowest aggregate NO_x + PM emissions.

In comparison with the other technologies, the lean-burn CNG vehicle and the DME vehicle have quite high hydrocarbon emissions, in these cases the greater part of THC being CH_4. Diesel delivers lowest THC emissions.

The DME vehicle has very high CO emissions, some 25 g/km. This together with the high THC value is an indication that transient control was not yet fully optimized in the prototype vehicle. The vehicle might momentarily have been running on rich mixture (λ <1) in transients, and the manufacturer already has updated the control software several times since the time of testing at VTT.

The diesel vehicle using SCR technology and the stoichiometric CNG vehicle have a CO emission of some 1.5–4 g/km, whereas lean-burn CNG and ethanol have close to zero CO emission.

A fair comparison of fuel consumption is done on energy basis, not on volumetric or gravimetric basis. Here the differences are much smaller than for the regulated emissions, but still quite substantial. Diesel is the most fuel efficient option. The CNG vehicles consume 32–39% more energy compared to EEV diesel average of 15.5 MJ/km. The lean-burn CNG vehicle gives roughly equivalent tailpipe CO_{2eqv} emissions as EEV diesel average, stoichiometric CNG somewhat higher (~4%).

The energy consumption of the ethanol vehicle is some 6% higher compared to EEV diesel average, but in comparison with the EEV EGR diesel, the ethanol vehicle delivers roughly the same energy efficiency (16.4 MJ/km for diesel, 16.5 MJ/km for ethanol).

The energy consumption of the DME vehicle was equivalent to EEV diesel average. However, again it must be pointed out that the results for the DME vehicle are indicative, as the driveline design (mechanical gearbox instead of automatic gearbox), engine power and scaling of the results differs from the other vehicles. However, the indication is that the prototype DME vehicle, in comparison to EEV diesel average, delivers corresponding energy efficiency, somewhat lower NO_x emissions and PM emissions lower than diesel average and ethanol, approaching CNG level for PM.

<u>Summary of performance</u>

Figures 12.39 (NO_x), 12.40 (PM), 12.41 (tailpipe equivalent CO_2) and 12.42 (energy consumption) present overviews of performance for all types of vehicles.

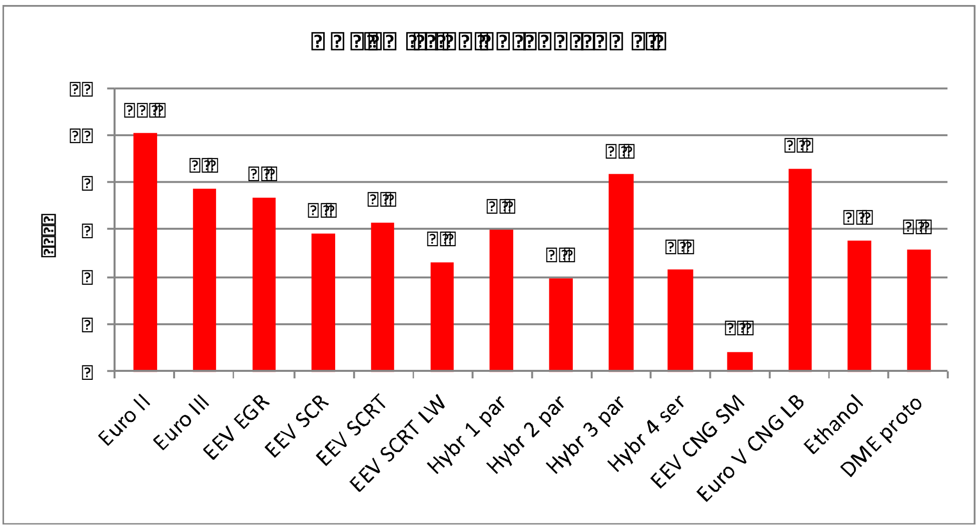


Figure 12.39. NO_x emissions of all tested European vehicles. Braunschweig cycle.

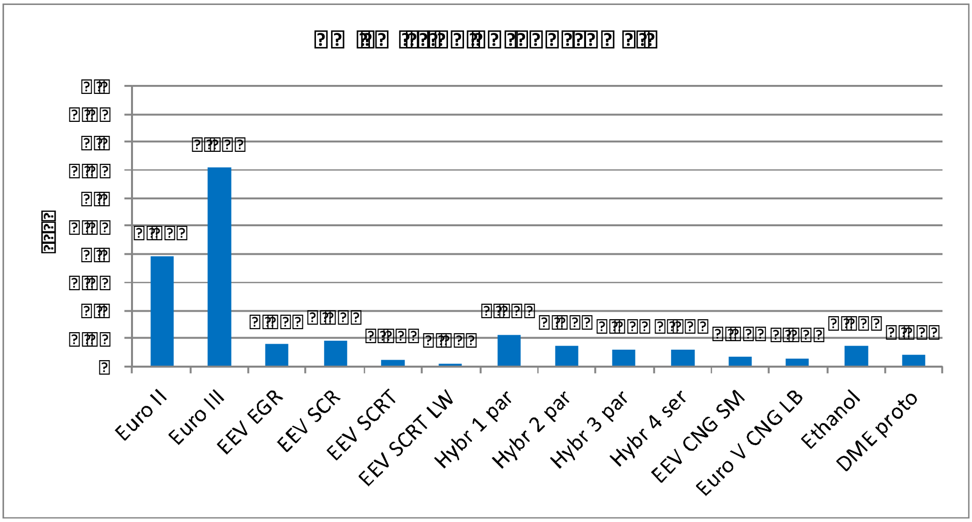


Figure 12.40. PM emissions of all tested European vehicles. Braunschweig cycle.

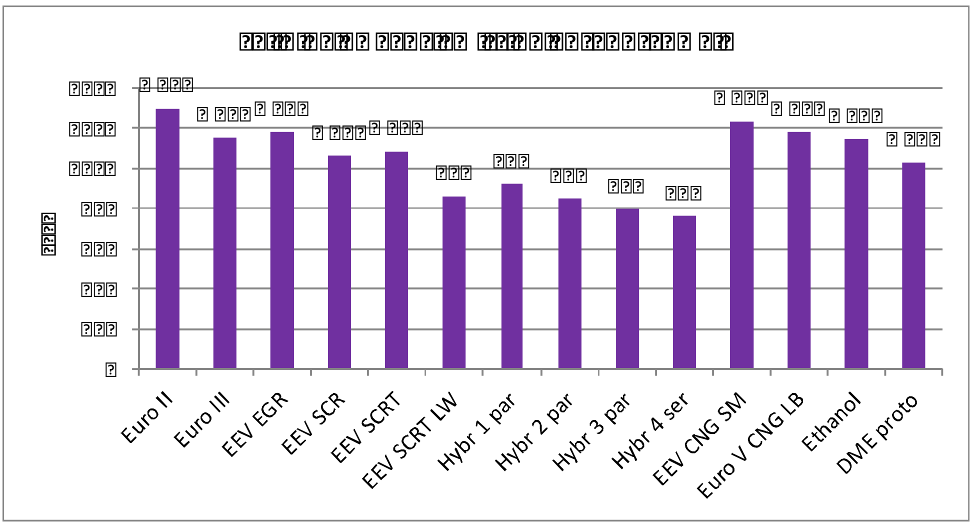


Figure 12.41. Tailpipe CO_{2eqv} emissions of all tested European vehicles. Braunschweig cycle. CH_4 taken into account with a factor of 21 for CNG, ethanol and DME.

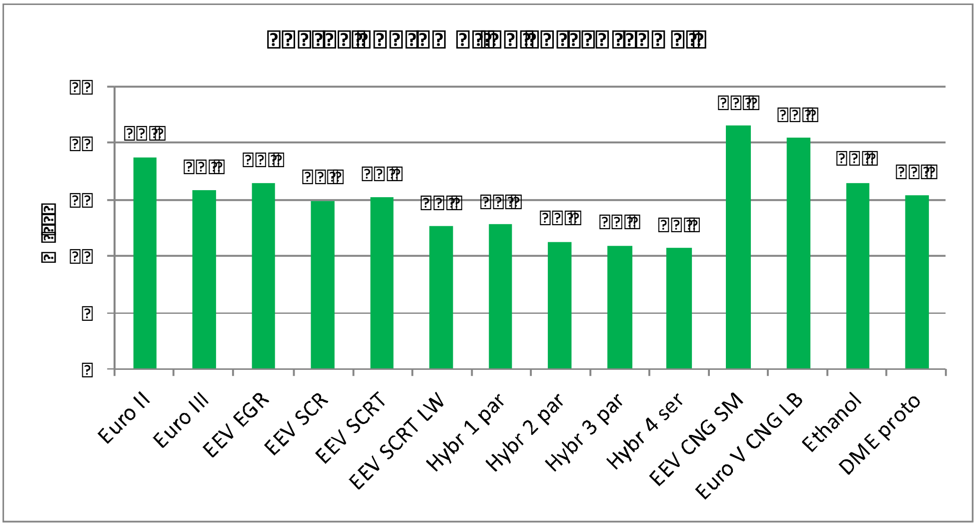


Figure 12.42. Energy consumption of all tested European vehicles. Braunschweig cycle.
The highest and lowest numbers from Figures 12.39 to 12.42 are summarized in Table 12.1. In round figures, energy consumption varies by a factor of 2, NO_x emissions by a factor of 10 and PM emissions by a factor of 70.

Table 12.1. Highest and lowest numbers for NO_x, PM, CO_{2eqv} and energy consumption. Braunschweig cycle.

Parameter	Highest		Lowest		Ratio
	Techn.	Value	Techn.	Value	
NO_x (g/km)	Euro II	10.1	CNG SM	0.84	12
PM (g/km)	Euro III	0.35	SCRT LW	0.005	70
CO_2eqv (g/km)	Euro II	1300	Hybr. 4 s.	761	2
Energy consumption (MJ/km)	CNG SM	21.5	Hybr. 4 s.	10.4	2

In the Braunschweig cycle, the amount on work on the crankshaft of the engine of a typical two-axle bus is some 1.8 kWh/km. This makes it possible to convert emissions certification class limit values in g/kWh into approximate distance based (g/km) emission values. This conversion is indicative only, as the load pattern of the Braunschweig bus cycle differs from the European Transient Cycle (ETC) used for certification.

Table 12.2 presents a rough equivalency of engine values in g/kWh versus distance based values in g/km for the different emission certification classes. The numbers in the Table include a factor of 1.25, in accordance with the U.S. "not-to-exceed" (NTE) thinking. The NTE requirement means that an engine's emissions under no circumstances (different driving situations or different load) may exceed the emission limits by more than a factor of 1.25 (DieselNet).

The following calculation example is for Euro III NO_x:

- Limit for engine 5.0 g/kWh
- Multiplication factor for distance conversion 1.8 kWh/km
- NTE factor 1.25
- Distance based reference value 5*1.8*1.25= 11.3 g/km.

Table 12.2. Equivalency (approximation) of engine certification values in g/kWh versus distance based values in g/km for the Braunschweig bus cycle. Two-axle city bus at half load.

	NO_x (g/kWh)	NO_x incl. NTE (g/km)	PM (g/kWh)	PM incl. NTE (g/km)
Euro III	5.0	11.3	0.16	0.36
Euro IV	3.5	7.9	0.03	0.068
Euro V	2	4.5	0.03	0.068
EEV	2	4.5	0.02	0.045
Euro VI*)	0.4	0.9	0.01	0.023

*) as of 2013 for new type approvals

Figure 12.43 presents a NO_x vs. PM diagram for EEV diesels, hybrids and alternative fuel vehicles. The distance based limit values generated in the way described above are incorporated in Figure 12.40 as dotted boxes. The Figure also contains the data point for the EPA 2010 8.9 L (1) vehicle.

Figure 12.43 shows that tested over the Braunschweig cycle, only the stoichiometric CNG vehicle delivers true EEV performance as it would actually qualify for Euro VI. The EPA 2010 vehicle comes close to Euro VI (NO_x slightly above the limit). Hybrids 2 and 4 are just within EEV limits. The light-weight is just outside the Euro V/EEV box for NO_x, but its PM emission would qualify for Euro VI level.

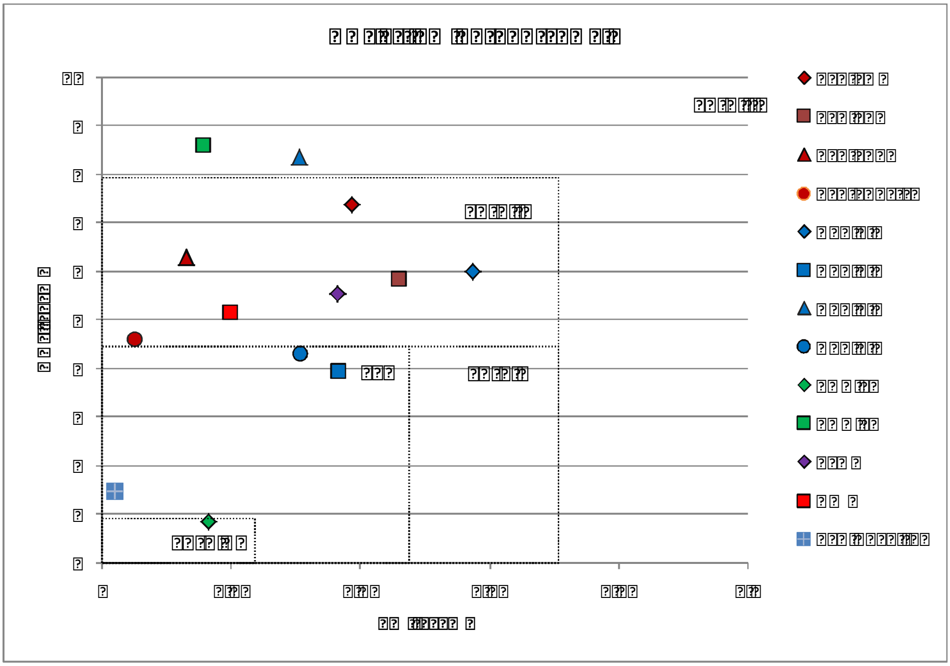


Figure 12.43. NO_x vs. PM for EEV diesels, hybrids and alternative fuel vehicles. Included is also the data point for the North-American EPA 2010 8.9 L (1) vehicle.

Table 12.3 summarizes the performance of the various vehicle platforms (indicative assessment). For NO_x, Hybrid 3 and lean-burn CNG (the latter with Euro V certification) only deliver Euro III level performance. For PM, 10 out of 11 European vehicles deliver EEV or close to EEV performance, and only Hybrid 1 clearly fails to reach EEV PM level. In fact, four vehicles would quality for the Euro VI PM limit. This indicates that it is easier to attain EEV PM levels than EEV NO_x levels.

Table 12.3. Indicative rating of the true emission performance EEV diesels, hybrids and alternative fuel vehicles.

Vehicle	NO_x	PM	Overall rating
Diesel EEV EGR	Euro IV	EEV	Euro IV
Diesel EEV SCR	Euro IV	Euro IV/V	Euro IV
Diesel EEV SCRT	Euro IV	Euro VI	Euro IV
Diesel EEV SCRT LW	Euro IV	Euro VI	Euro IV
Hybrid 1 parallel	Euro IV	Euro IV/V	Euro IV
Hybrid 2 parallel	EEV	EEV	EEV
Hybrid 3 parallel	Euro III	EEV	Euro III
Hybrid 4 series	EEV	EEV	EEV
CNG stoichiometric	Euro VI	Euro VI	Euro VI
CNG lean-burn	Euro III	Euro VI	Euro III
Ethanol	Euro IV	EEV	Euro IV
DME	Euro IV	Euro VI	Euro IV
EPA 2010 8.9 L (1)	EEV	Euro VI	EEV

All in all, this example points out that drawing conclusions on emission performance based on emission certification class only may produce overoptimistic views.

12.3.3 Effects of driving cycle

VTT used at maximum six driving cycles in its bus evaluation. When only three cycles were used they were ADEME, Braunschweig and UDDS, with the exception of the DME, for which the cycles were New York Bus, ADEME and Braunschweig. Ten vehicle platforms were chosen to demonstrate the effects of driving cycle on NO_x, PM (the two most important components for urban air quality) and fuel consumption:

- Euro II diesel, 3 cycles (Figure 12.44)
- Euro III diesel, 3 cycles (Figure 12.45)
- EEV EGR diesel, 6 cycles (Figure 12.46)
- EEV SRC diesel, 6 cycles (Figures 12.47 and 12.48)
- Four hybrids, average and 6 cycles (Figures 12.49 to 12.57)
- EEV CNG stoichiometric, 3 cycles (Figure 12.58)
- Ethanol, 6 cycles (Figure 12.59)
- DME, 3 cycles (Figure 12.60).

It should be noted that only NYBUS, ADEME and Braunschweig are typical city bus cycles, whereas JE05, UDDS and WHVC are more representative for truck operations.

Figure 12.48 shows NO_x emission, urea consumption and ratio of urea to fuel consumption for the SCR vehicle. In the case of hybrids, average performance values for the cycles are presented in Figure 12.49. Figure 12.50 shows the effect of hybridization on fuel consumption as a function of driving cycle. Figures 12.51–12.56 show results for each cycle one at the time, showing the differences from vehicle to vehicle for a specific cycle. Figure 12.57 presents average NO_x, PM and fuel consumption values for the hybrids.

Diesel vehicles with conventional powertrain

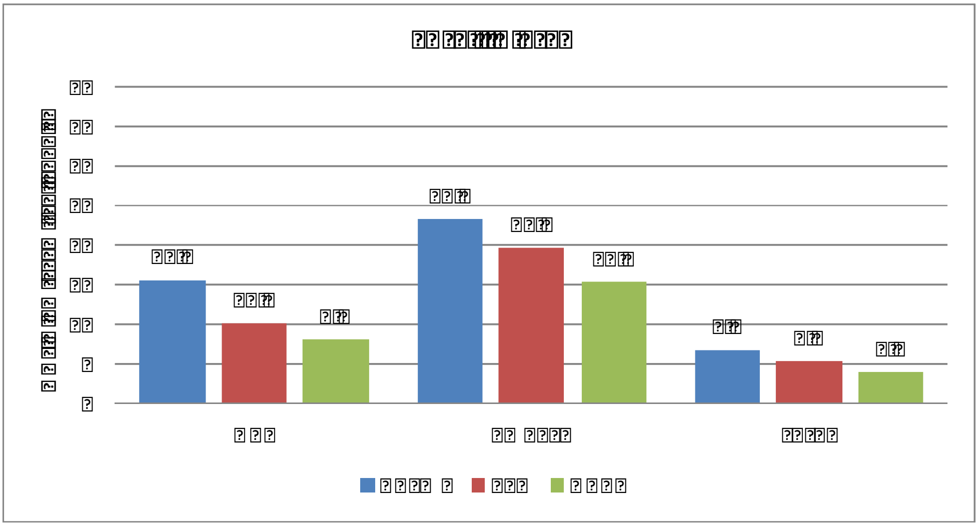


Figure 12.44. The effect of driving cycle on NO_x, PM and fuel consumption. Euro II diesel.

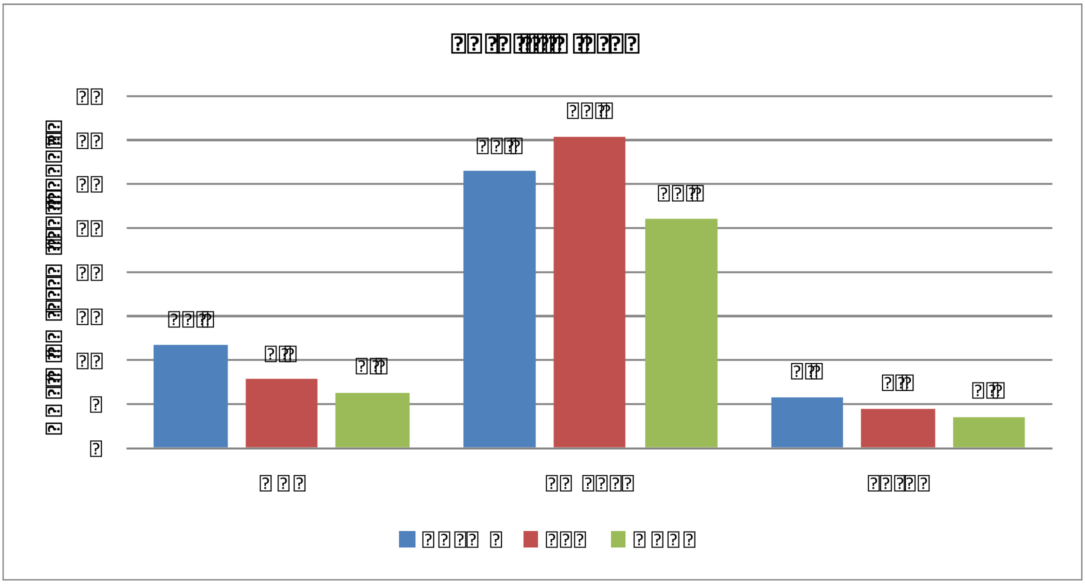


Figure 12.45. The effect of driving cycle on NO_x, PM and fuel consumption. Euro III diesel. N.B.: This specimen had rather high PM emissions.

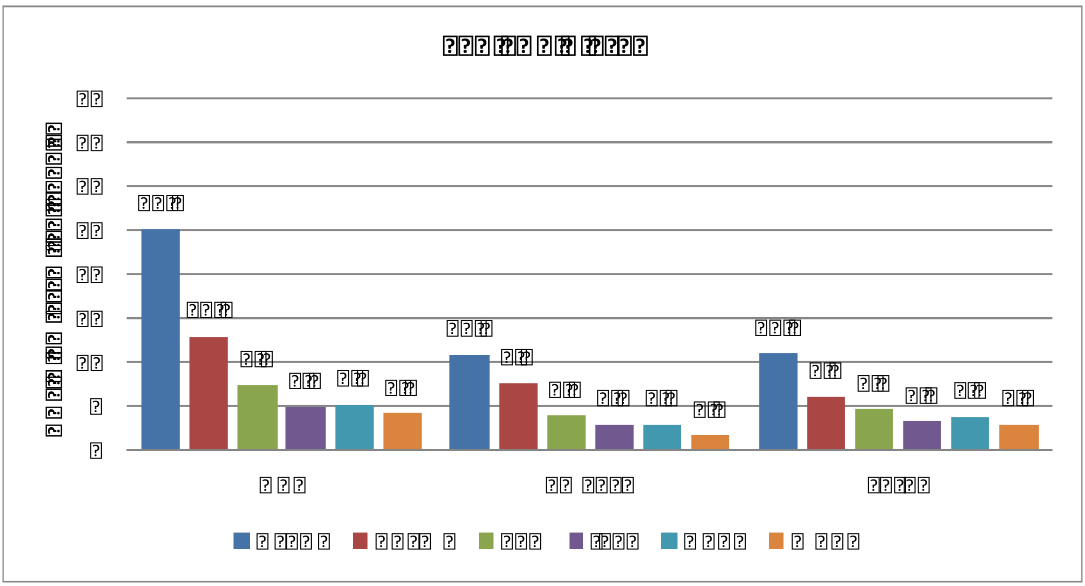


Figure 12.46. The effect of driving cycle on NO_x, PM and fuel consumption. EEV EGR diesel.

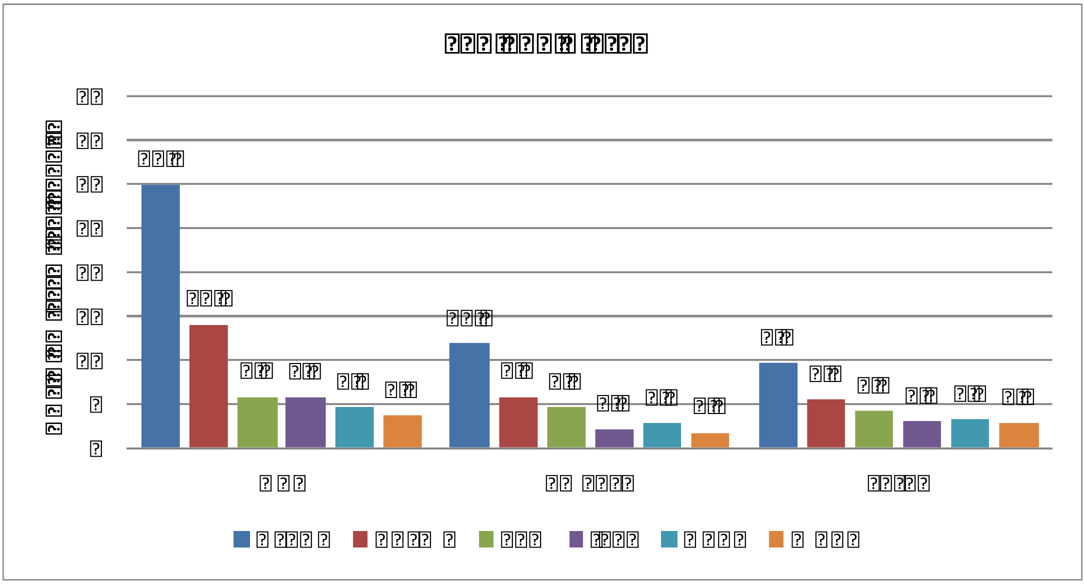


Figure 12.47. The effect of driving cycle on NO_x, PM and fuel consumption. EEV SCR diesel.

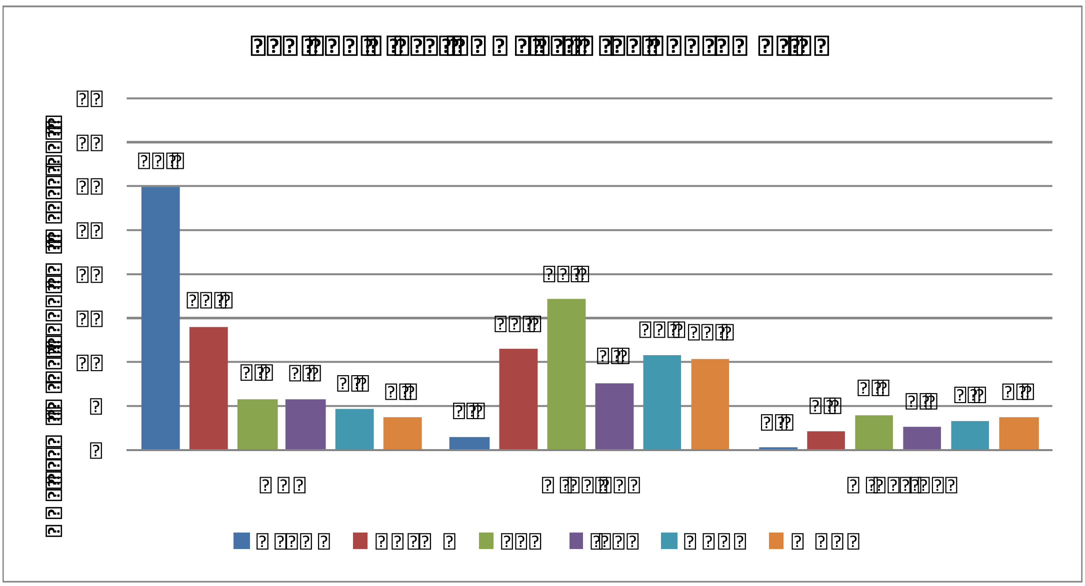


Figure 12.48. NO_x emission, urea consumption (l/100 km) and ratio of urea to fuel consumption (volumetric) for the SCR vehicle.

For Euro II, Euro III and EEV diesels, the ADEME cycle gives some 60–70% higher fuel consumption than the UDDS cycle. Correspondingly, the increase in NO_x is 80–200% and the increase in PM 20–160%, in round figures. The EEV EGR vehicle shows the highest increase in PM (162%), whereas the SCR vehicle shows the highest increase in NO_x (204%).

The EEV EGR and EEV SCR vehicles were tested on six cycles. The cycles are presented in an order from lowest (NYBUS) to highest (WHVC) average speed. With the exception of one cycle, JE05, NO_x, PM and fuel consumption all fall with increasing cycle average speed. The JE05 has marginally lower average speed than UDDS, but is less severe than UDDS. Going from WHVC to NYBUS, fuel consumption increases some 250%, and NO_x as well as PM emissions increase some 500–700%. The profiles in Figures 12.46 and 12.47 are actually surprisingly uniform, meaning that there are no really significant differences in performance between the EGR and the SCR vehicle.

Figure 12.48 shows NO_x emission, urea consumption and urea to fuel ratio for the SCR vehicle. The vehicle seems to be designed to use some 4% of urea compared to the volume of fuel. However, when exhaust temperature is low, urea cannot be injected. Already for the ADEME cycle the relative urea consumption is down to some 2%, and in the NYBUS the vehicle hardly uses any urea, which means that for the NYBUS cycle, the SCR catalyst is more or less inactive, and that for NO_x, the actual tailpipe emission is roughly equivalent to engine out emission.

Hybrid vehicles

For hybrid vehicles, on an average, fuel consumption increases some 140%, NO_x emissions some 450% and PM emissions increase some 180% going from WHVC to NYBUS (Figure 12.49). Thus the variations are smaller than for the vehicles with conventional powertrain. Figure 12.50 shows average fuel consumption for the two vehicle categories. In the NYBUS cycle hybridization saves close to 40% fuel, whereas the benefit of hybridization is marginal for UDDS and WHVC, below 10%. Naturally hybrid systems for city buses are optimized for stop-and-go operation.

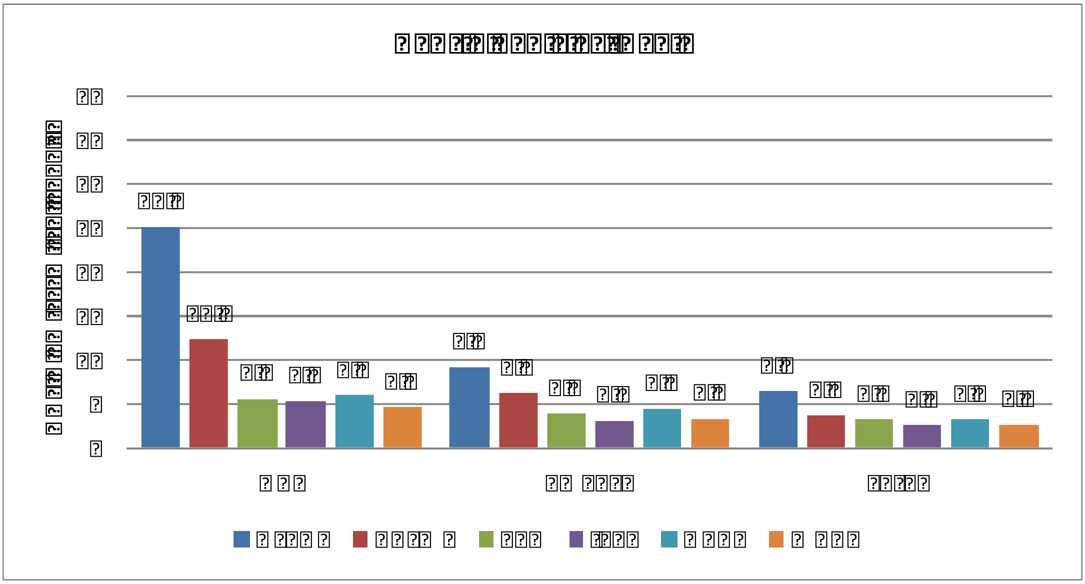


Figure 12.49. The effect of driving cycle on NO_x, PM and fuel consumption. Average values for hybrid vehicles.

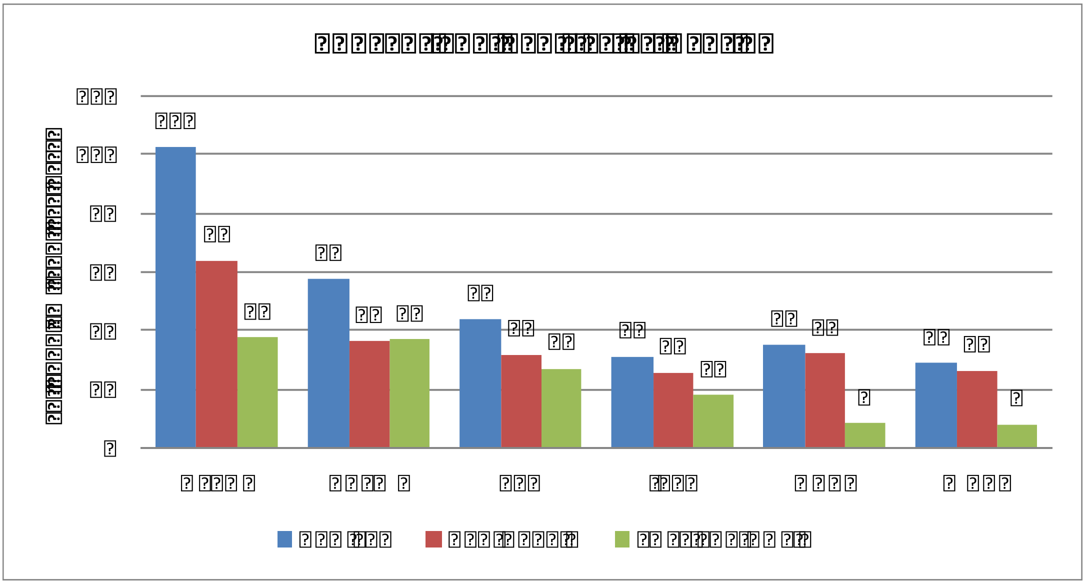


Figure 12.50. The effect of hybridization on fuel consumption.

There are significant variations in performance within the group of hybrids, especially regarding emissions. The demanding cycles, NYBUS, ADEME and Braunschweig, accentuate the differences, whereas with cycles with higher average speed, vehicle to vehicle differences are reduced.

Here it should be noted that JE05, UDDS and WHVC in fact are not very representative for bus operation. In addition, vehicles Hybrid 3 (parallel) and Hybrid 4 (series) have a top speed limitation of 70 km/h. Therefore the results for JE05, UDDS and WHVC should be considered indicative only for these vehicles as the maximum speeds in these cycles cannot be reached, and a high correction factor for accumulated work was needed (some 1.1 for JE05, 1.3 for UDDS and 1.2 for WHVC).

For Hybrid 2 (parallel), the fuel consumption value for NYBUS is also indicative, as the correction factor for accumulated work was unusually high, not due to the vehicle itself, but rather due to a temporary malfunction of the dynamometer.

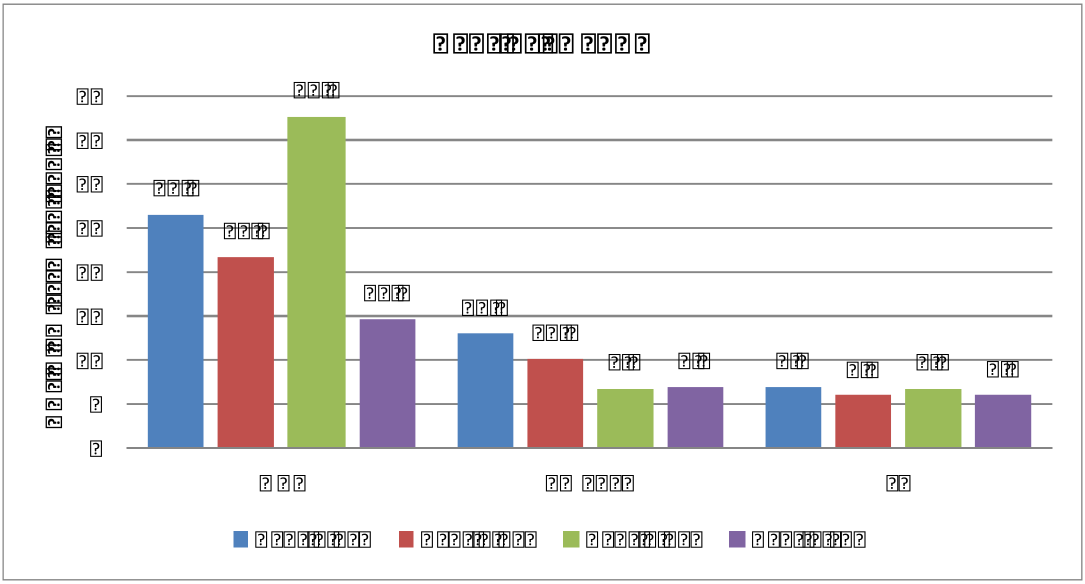


Figure 12.51. NO_x, PM and fuel consumption for the hybrid buses. New York Bus cycle. N.B.: Fuel consumption result for Hybrid 2 (parallel) indicative only due to significant correction of accumulated work.

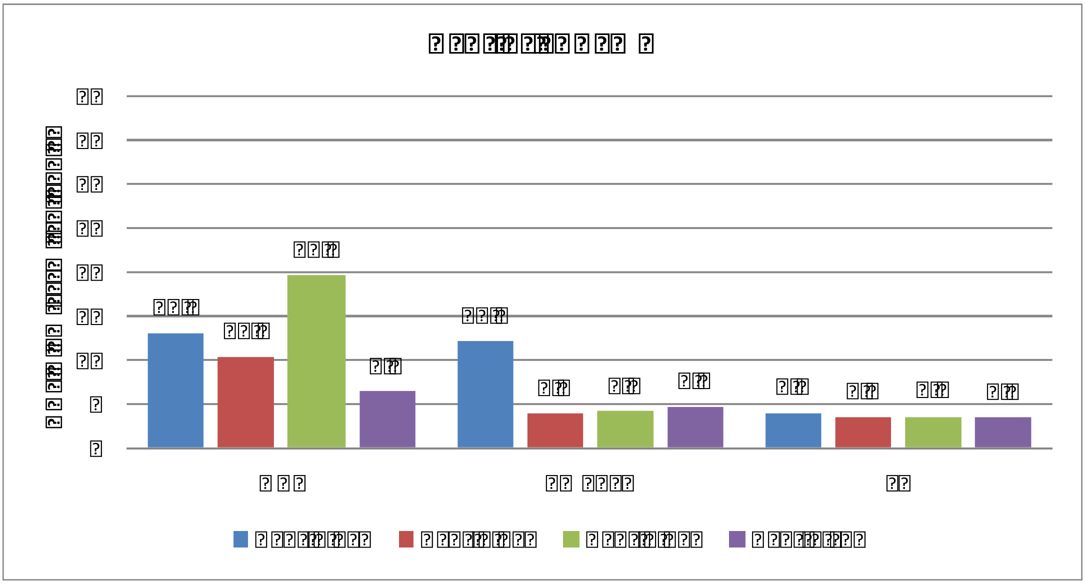


Figure 12.52. NO_x, PM and fuel consumption for the hybrid buses. ADEME cycle.

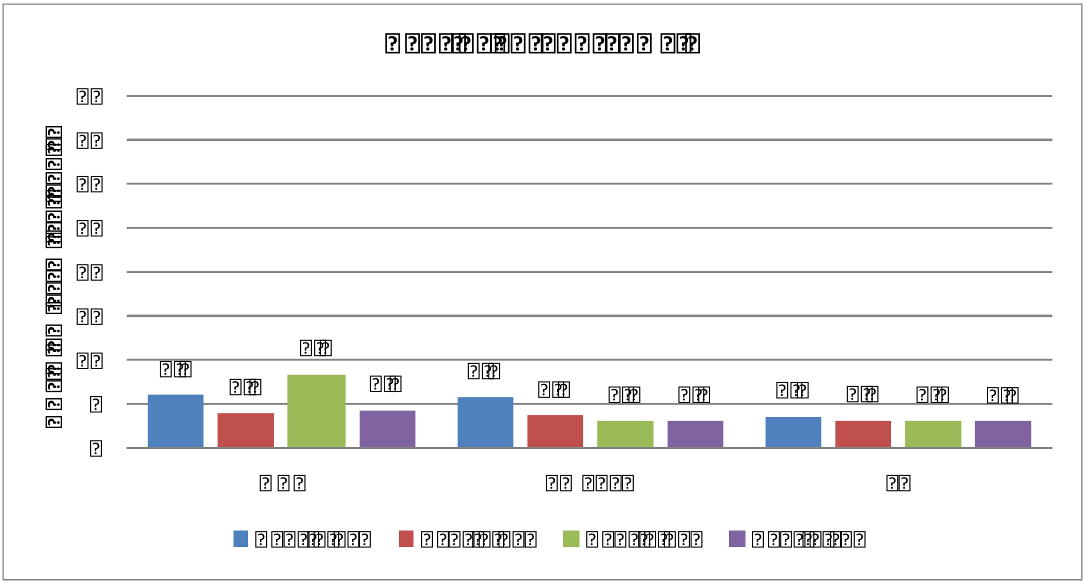


Figure 12.53. NO_x, PM and fuel consumption for the hybrid buses. Braunschweig cycle.

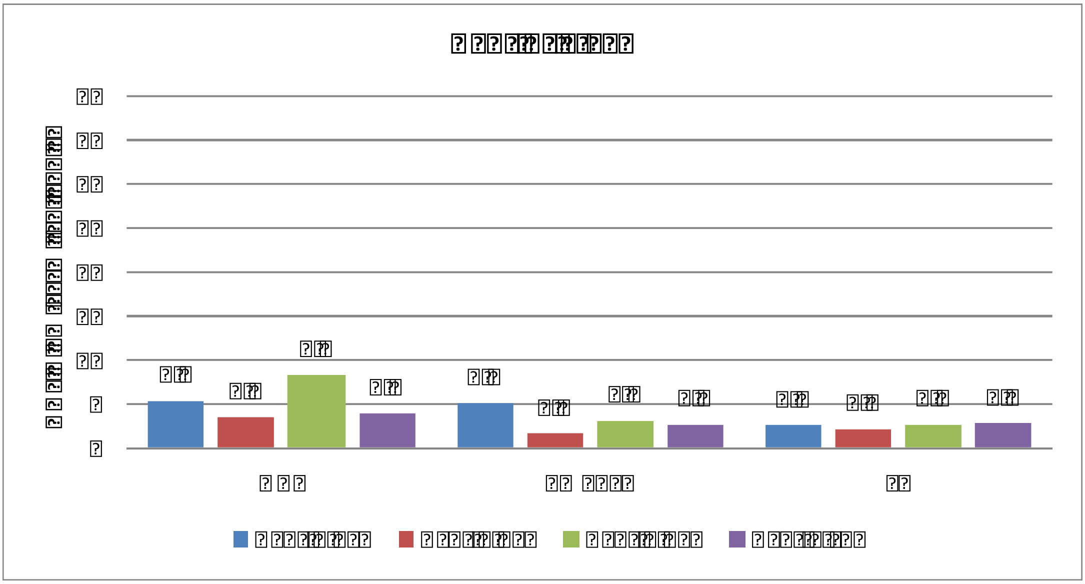


Figure 12.54. NO_x, PM and fuel consumption for the hybrid buses. JE05 cycle.

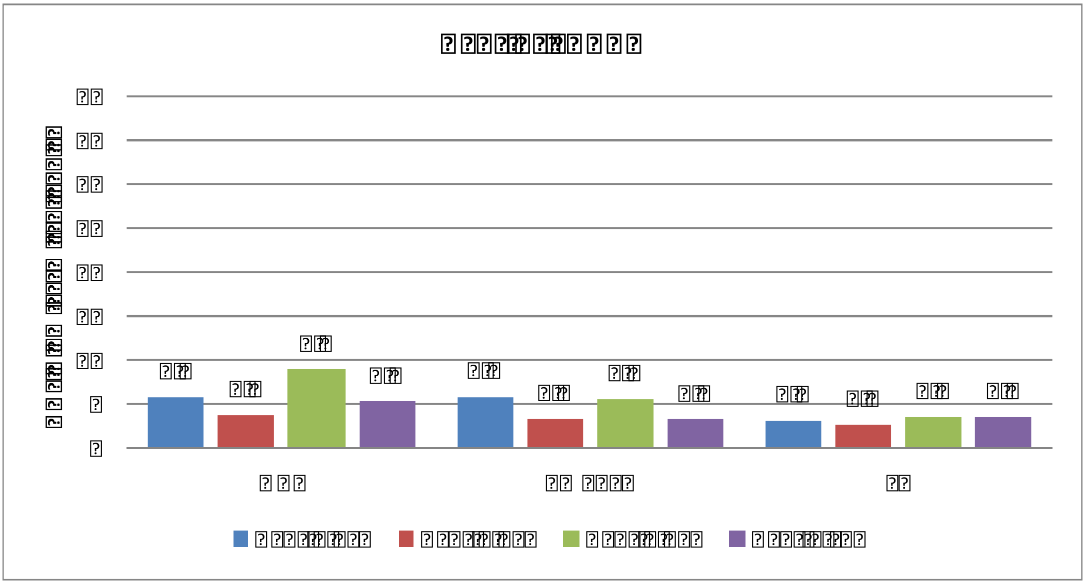


Figure 12.55. NO_x, PM and fuel consumption for the hybrid buses. UDDS cycle.

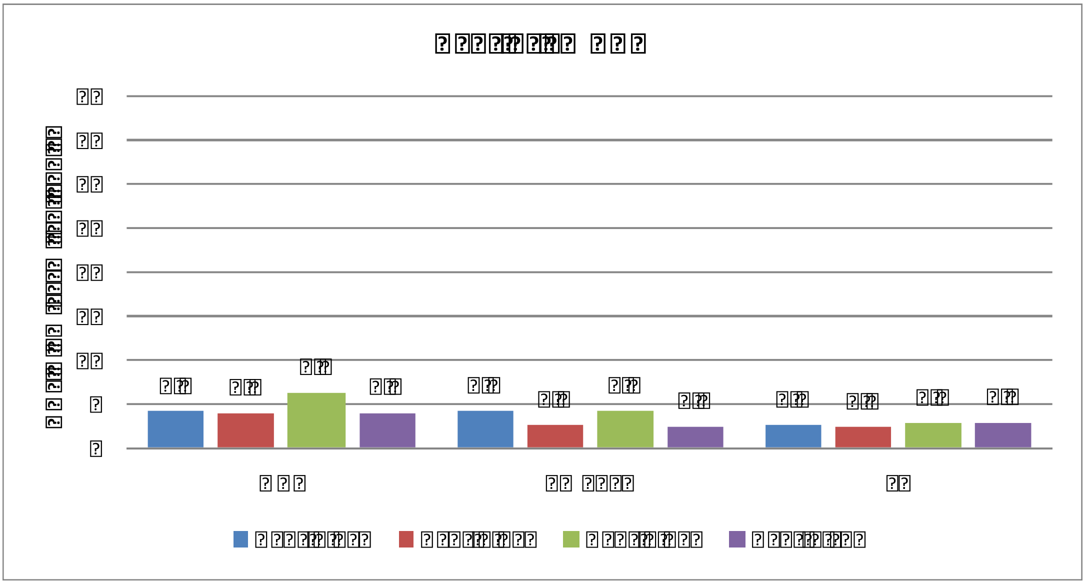


Figure 12.56. NO_x, PM and fuel consumption for the hybrid buses. WHVC cycle.

Figure 12.57 shows average values for the six cycles. Maximum differences between vehicles are (worst compared to best):

- fuel consumption +15% (Hybrid 1 parallel. worst, Hybrid 2 parallel best)
- NO_x emission +100% (Hybrid 3 parallel worst, Hybrid 4 series best)
- PM emission +130% (Hybrid 1 parallel worst, Hybrid 4 series best).

Hybrid 1 (parallel) suffers from a small energy storage and a small electric motor, not enabling full recuperation of kinetic energy. In addition Hybrid 1 (parallel) suffers from high PM emissions. Hybrid 3 (parallel), on the other hand, suffers from high NO_x emissions.

Hybrid 4 (series) delivers lowest overall NO_x and PM emissions, and lowest average fuel consumption for the most demanding cycles, the "real" bus cycles NYBUS, ADEME and Braunschweig. Taking into account all cycles, Hybrid 2 (parallel) delivers best fuel average economy, and in fact, equivalent fuel consumption compared to Hybrid 4 (series) in the NYBUS and ADEME cycles (value for NYBUS with reservation).

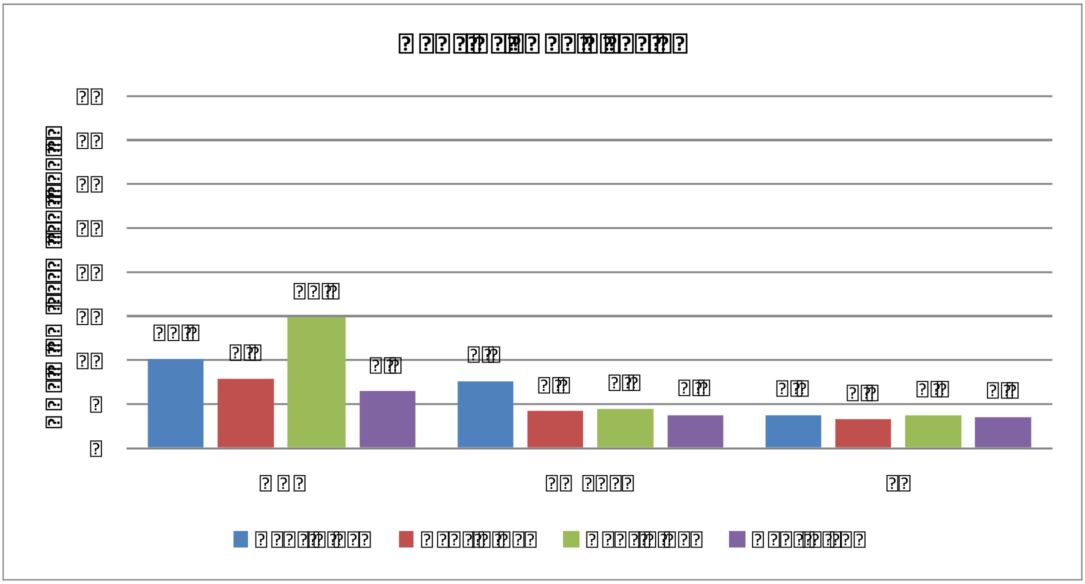


Figure 12.57. Average NO_x, PM and fuel consumption values for the hybrid buses. Average values for six cycles.

<u>Alternative fuel vehicles</u>

The stoichiometric CNG vehicle consistently shows low emissions and little variation in emissions from cycle to cycle. The increase in NO_x from UDDS to ADEME was in the same order of magnitude as for Euro II and Euro III diesel, a factor of two. For the ADEME cycle, NO_x was 12–14 g/km for the EEV diesels and the hybrids, but only 1.5 g/km for the stoichiometric CNG vehicle. PM emissions were more or less constant regardless of the cycle.

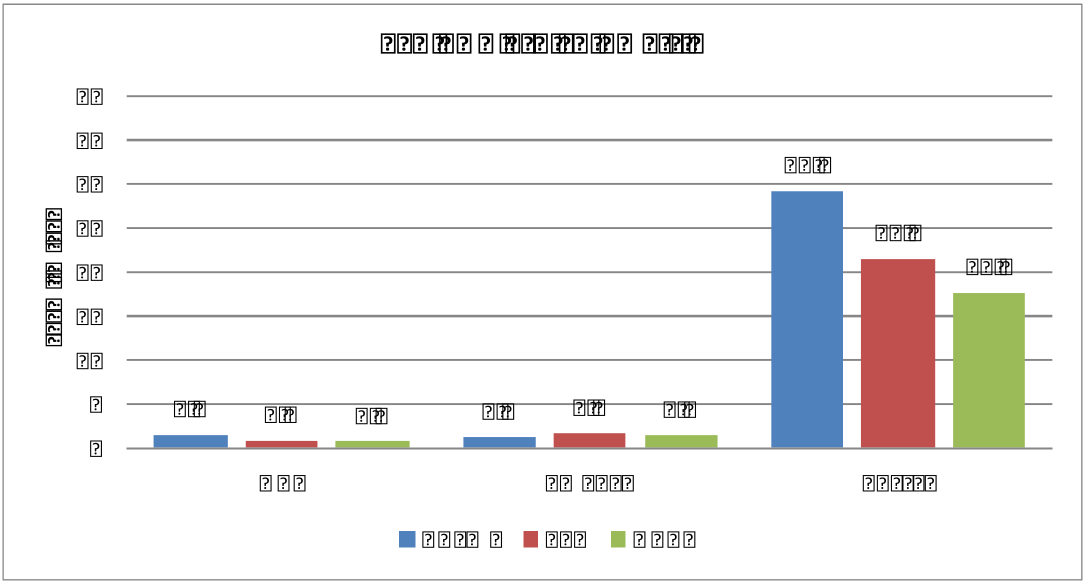


Figure 12.58. The effect of driving cycle on NO_x, PM and fuel consumption. EEV CNG stoichiometric.

The performance profile of the ethanol vehicle resembles the one of the EEV EGR diesel. However, the ethanol vehicle delivers lower PM emissions for all cycles, average -50%. The only cycle in which the PM reduction is marginal is the Braunschweig cycle (see 12.3.2). In addition, the ethanol vehicle also produces lower energy consumption and lower NO_x emission in the challenging NYBUS cycle.

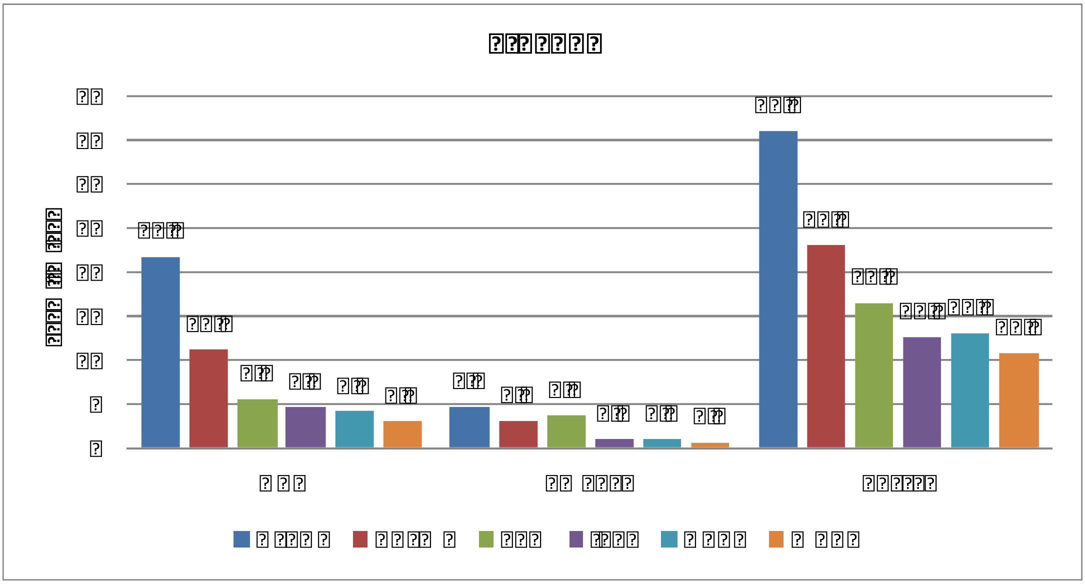


Figure 12.59. The effect of driving cycle on NO_x, PM and fuel consumption. Ethanol vehicle.

The DME vehicle was tested using a different testing scheme compared to the other vehicles: NYBUS, ADEME and Braunschweig. The performance in the Brauschweig cycle was already commented upon in 12.3.2. In the NYBUS cycle and the ADEME cycle the DME delivers equivalent PM emissions compared to the ethanol vehicle, but some 50% lower NO_x emissions. As for energy consumption, the indication is that the DME vehicle delivers slightly better efficiency than the ethanol vehicle in NYBUS, ADEME as well as Braunschweig. Both ethanol and DME clearly beat stoichiometric CNG in energy consumption for all cycles.

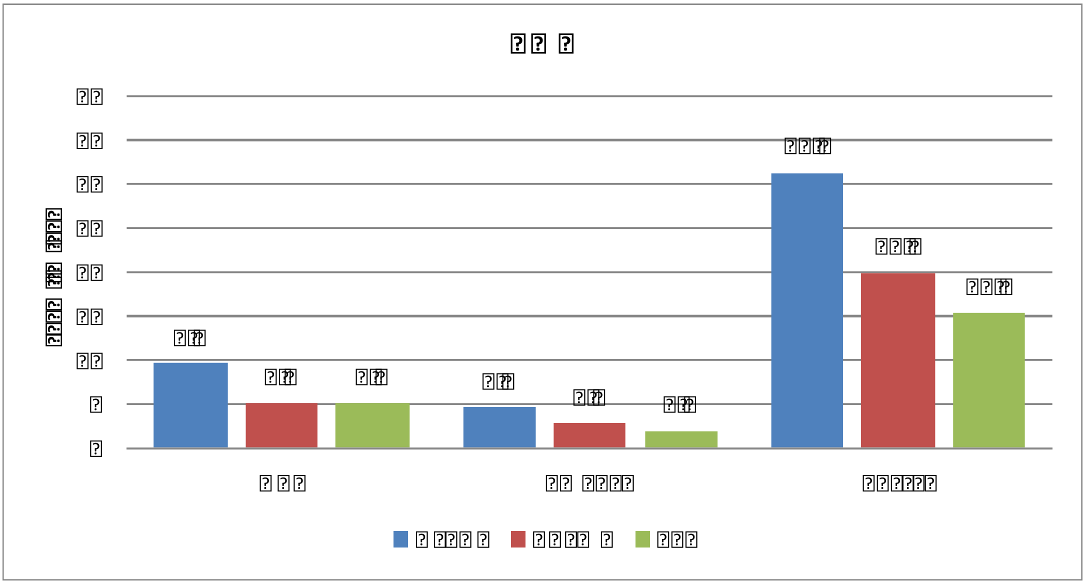


Figure 12.60. The effect of driving cycle on NO_x, PM and fuel consumption. DME vehicle.

12.3.4 Fuel effects

The Braunschweig cycle was chosen to illustrate the fuel effects on regulated emissions. Results are shown for four vehicle platforms:

- Euro II diesel (regular diesel + two 100% replacement fuels)
- Euro III diesel (regular diesel + four 100% replacement fuels and blended fuels)
- EEV EGR diesel (regular diesel + three 100% replacement fuels and blended fuels)
- EEV SCR diesel (regular diesel + three 100% replacement fuels and blended fuels).

The four 100% replacement fuels (neat fuels) tested by VTT were:

- GTL
- HVO
- JME
- RME.

All these fuel were tested in the Euro III vehicle. JME was not tested in the EEV certified vehicles, and GTL and RME were not tested in the Euro II vehicle.

Regulated emissions, fuel consumption (volumetric and gravimetric), energy consumption and tailpipe CO_2 emission for the 100% replacement fuels in comparison with commercial diesel fuel are presented in Figures 12.61–12.68. Figures 12.69–12.72 show the effect of 100% HVO fuel on NO_x, PM and CO_2 emissions and energy consumption of EEV diesel vehicles.

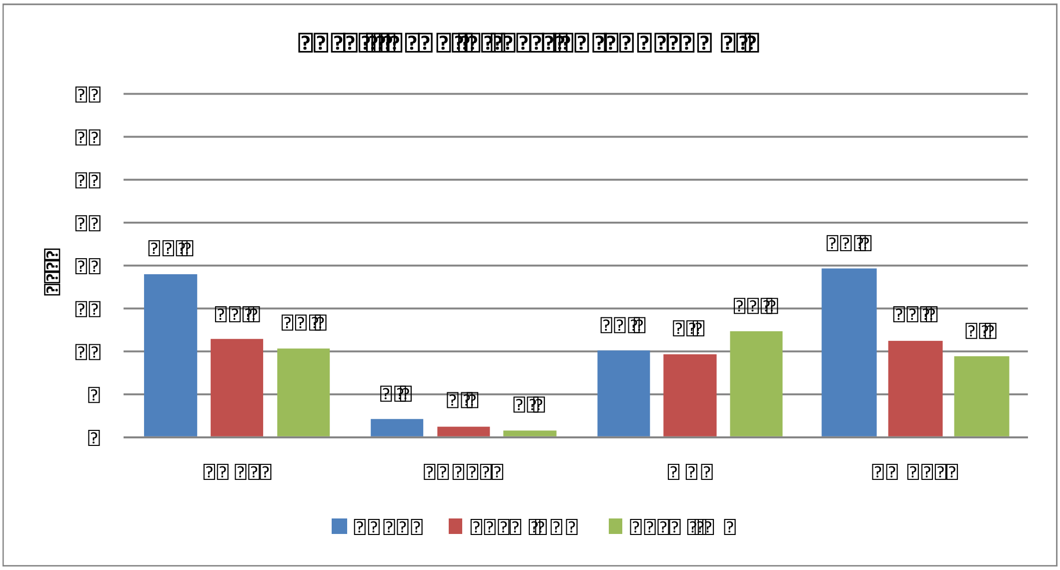


Figure 12.61. Fuel effects on CO, THC, NO_x and PM emissions. Euro II diesel.

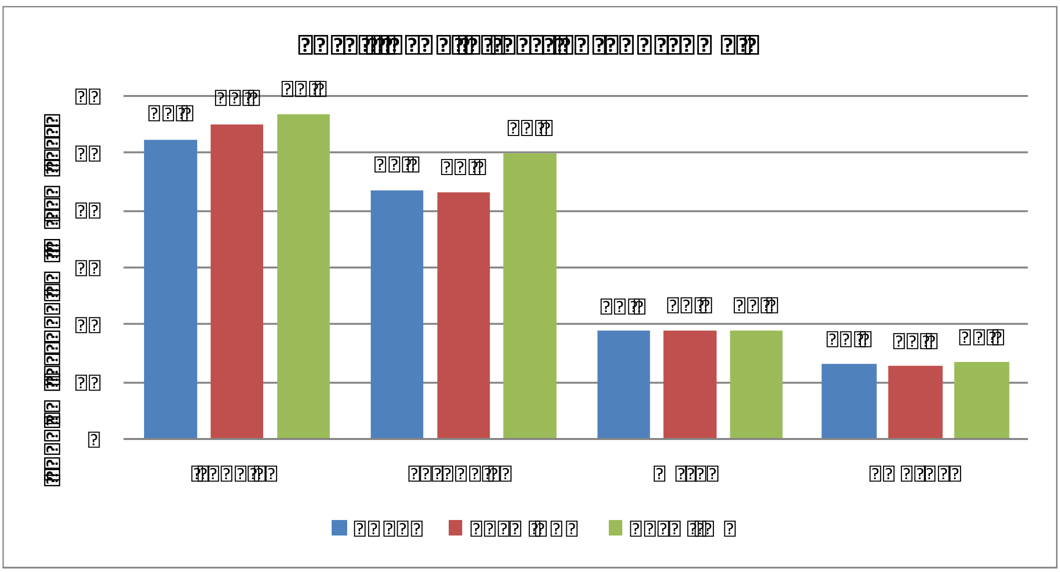


Figure 12.62. Fuel effects on volumetric and gravimetric fuel consumption, energy consumption and tailpipe CO_2 emissions. Euro II diesel.

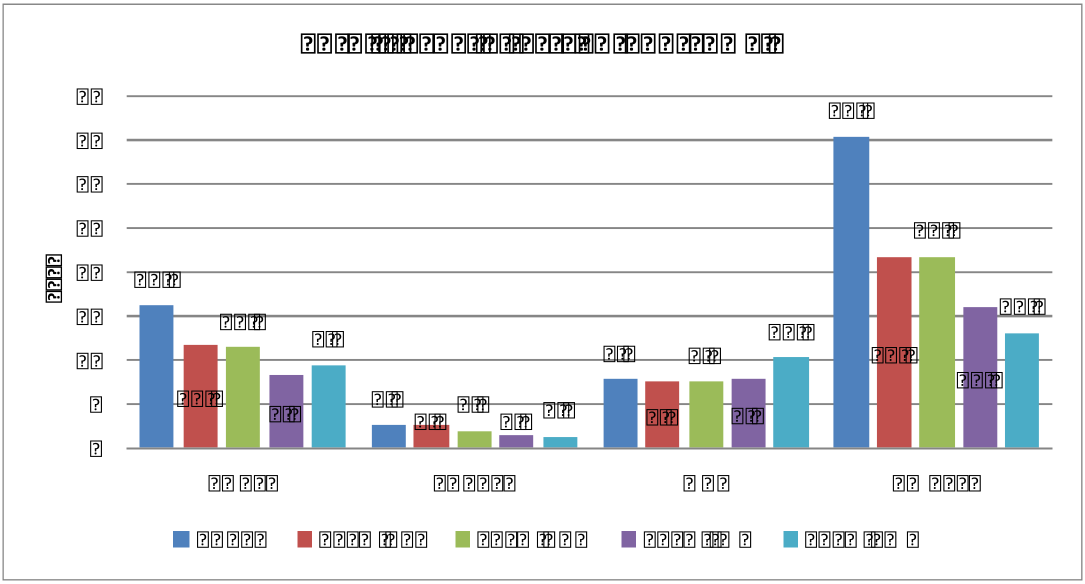


Figure 12.63. Fuel effects on CO, THC, NO_x and PM emissions. Euro III diesel.

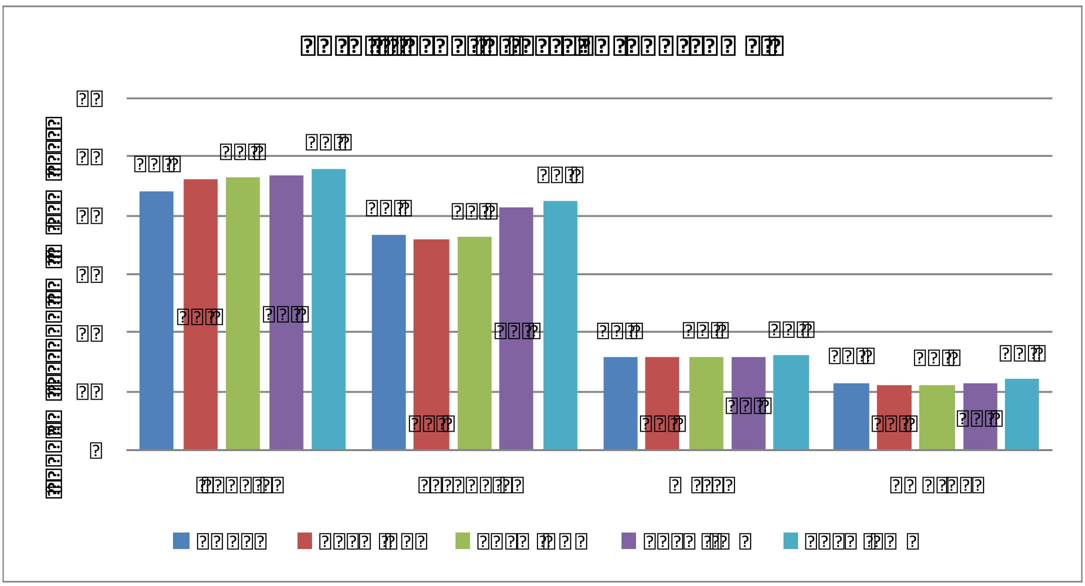


Figure 12.64. Fuel effects on volumetric and gravimetric fuel consumption, energy consumption and tailpipe CO_2 emissions. Euro III diesel.

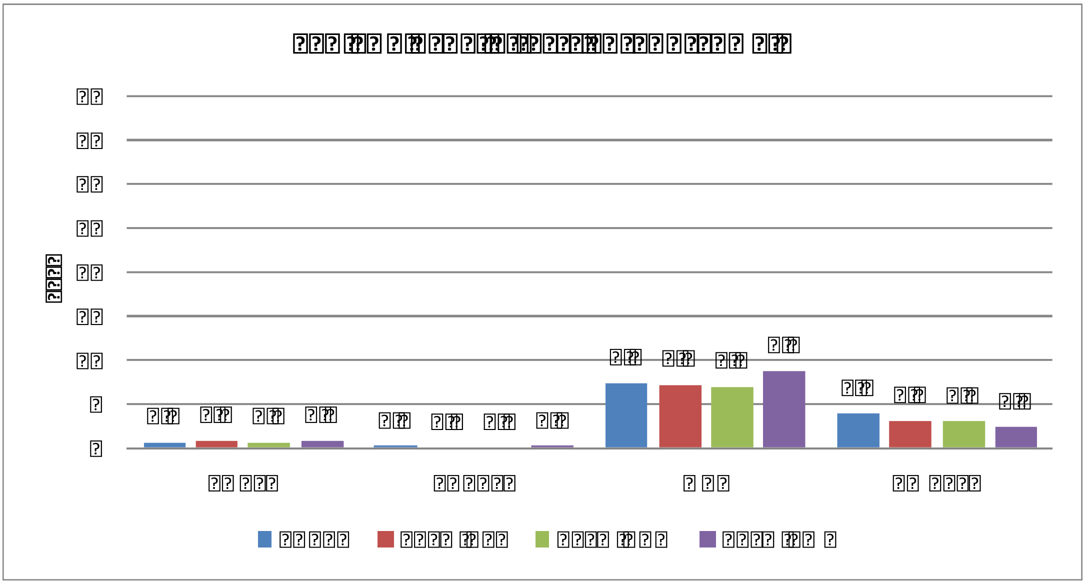


Figure 12.65. Fuel effects on CO, THC, NO_x and PM emissions. EEV EGR diesel.

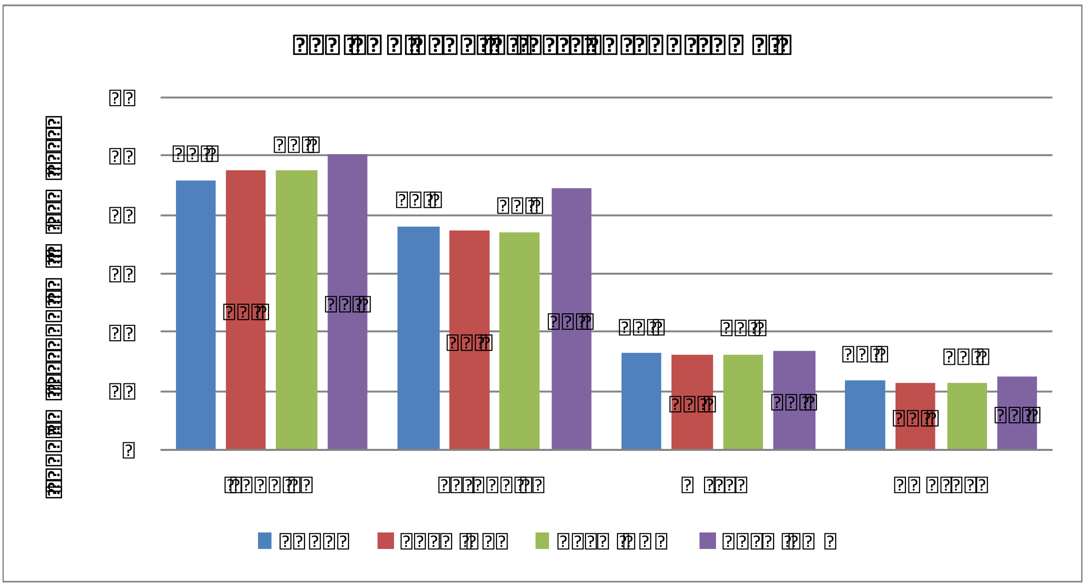


Figure 12.66. Fuel effects on volumetric and gravimetric fuel consumption, energy consumption and tailpipe CO_2 emissions. EEV EGR diesel.

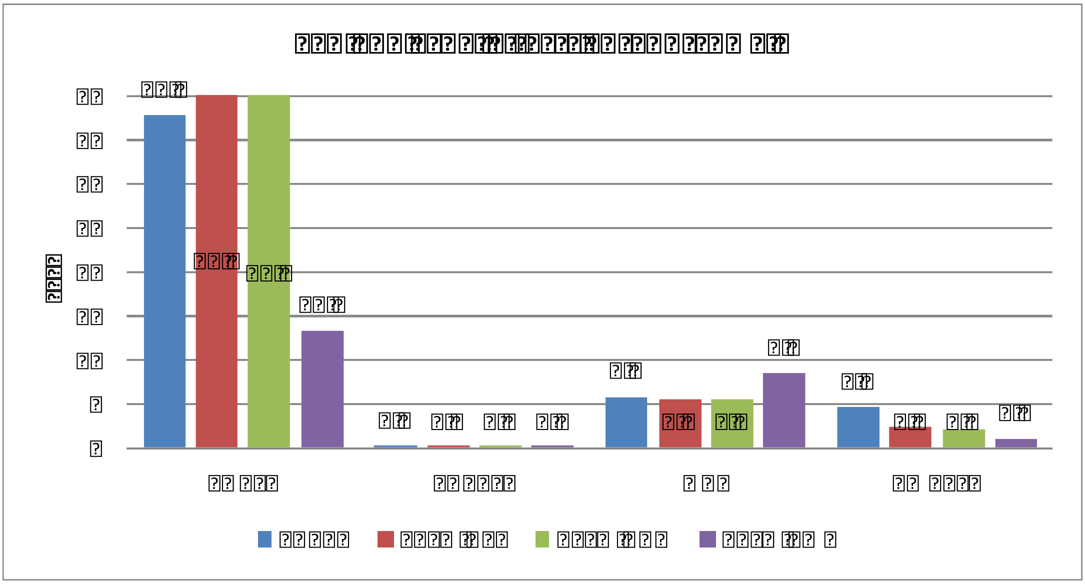


Figure 12.67. Fuel effects on CO, THC, NO_x and PM emissions. EEV SCR diesel.

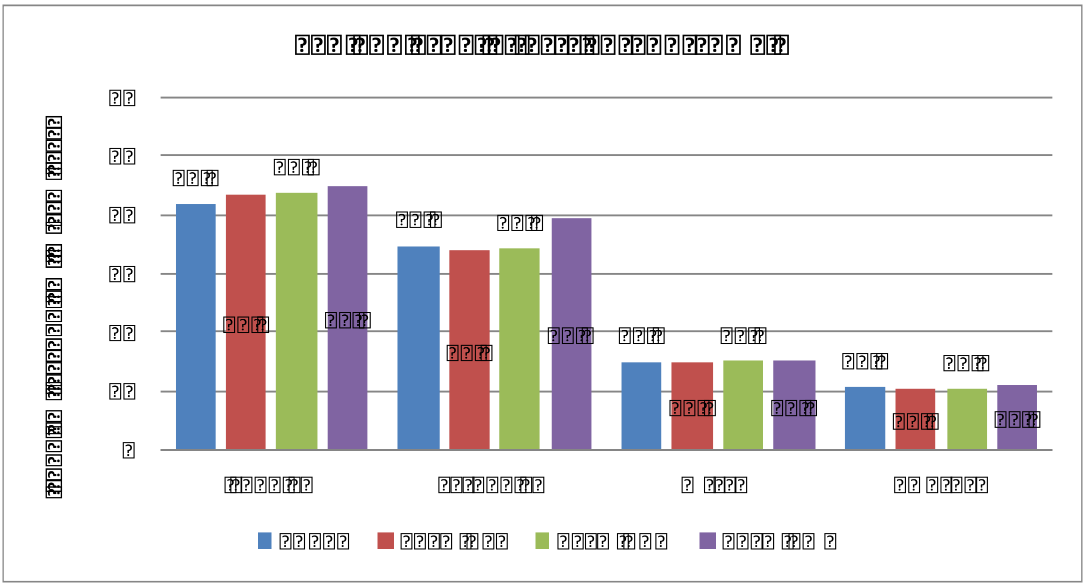


Figure 12.68. Fuel effects on volumetric and gravimetric fuel consumption, energy consumption and tailpipe CO_2 emissions. EEV SCR diesel.

Fatty acid methyl esters (in this case JME and RME) are known to be effective in reducing PM emissions, but the drawback is increased NO_x emissions (EPA 2002, Krahl et al. 2007). PM emission reductions are some 40–75% compared to EN590 diesel. The increase in NO_x is some 20–45%. The EEV SCR vehicle shows the strongest response for NO_x as well as PM. JME in comparison with RME (tested in the Euro II vehicle) shows smaller increase in NO_x as well as smaller reduction in PM.

HVO and GTL were tested in parallel in Euro III, EEV EGR and EEV SCR. Both these fuels are paraffinic diesel fuels fulfilling CWA 15940, and as could be expected, both fuels delivered almost identical NO_x and PM emissions. For all vehicle platforms, paraffinic diesel (GTL, HVO) reduced NO_x 3–4%. PM was reduced 20–50%, the EEV EGR vehicle showing the lowest and the EEV SCR vehicle showing the highest response for PM.

In the case on fuel effects on emissions, one should look at absolute effects as well as relative effects. In the case of the Euro II vehicle, a 52% reduction in PM emissions (JME) means 0.1 g PM/km. For the EEV EGR vehicle, a 76% reduction in PM emissions (RME) only means 0.04 g/km in absolute terms. The reduction in NO_x when using 100% GTL or HVO is only some 0.2–0.4 g/km in absolute terms, regardless of vehicle at an average NO_x emission level of some 8 g/km.

Fuel consumption in l or kg/100 km will vary with density and energy content. In the case of GTL and HVO, volume based fuel consumption will increase some 4–5% over regular diesel mainly due to lower density, whereas mass based fuel consumption will be marginally (~2%) reduced. However, the effect of fuel on energy consumption is in practice negligible. A test with 17 different vehicles showed an average reduction of 0.2% in energy consumption for 100% HVO over regular diesel fuel (Erkkilä et al. 2011). As for tailpipe CO_2 emissions, GTL and HVO on average give a small advantage (-3%) over regular diesel whereas FAME fuels have a disadvantage (+3%) over regular diesel.

In the Euro II and the Euro III vehicle paraffinic fuels and FAME fuels reduce CO and THC emissions. In the case of the EEV EGR vehicle fuel has limited effects on CO and THC emissions, whereas in the case of the EEV SCR vehicles paraffinic fuels tend to increase and FAME tend to decrease CO emissions in comparison with regular diesel fuel. It should be noted that in the case of SCR vehicles decomposition of urea in the SCR catalyst contribute to CO emissions, so variations in CO emissions can be also attributed to factors other than the fuel.

Figures 12.69–12.72 show NO_x, PM, CO_2 and energy consumption with 100% HVO in comparison with EN590 diesel fuel in the EEV certified diesel vehicles (EGR, SCR, SCRT). Average reductions are 14% for NO_x, 41% for PM and 4% for tailpipe CO_2. The SCRT responds very positively to 100% HVO both for NO_x (-32%) and PM (-54%), and this explains the high average values. The fuel effect on energy consumption is negligible. Similar effects could be expected with GTL or other paraffinic fuels.

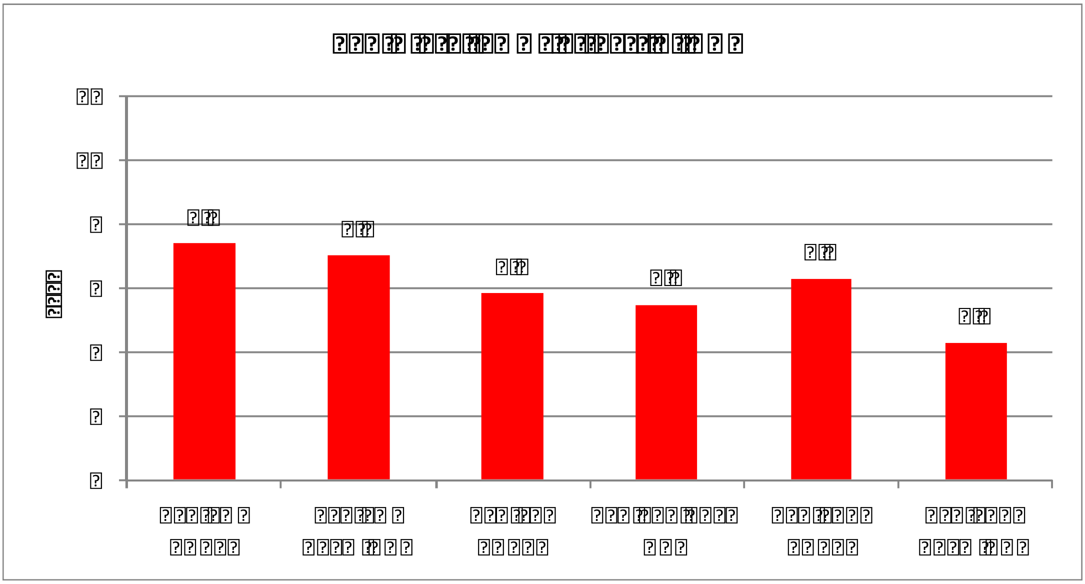


Figure 12.69. The effect of HVO on NO_x emissions in EEV certified diesel vehicles.

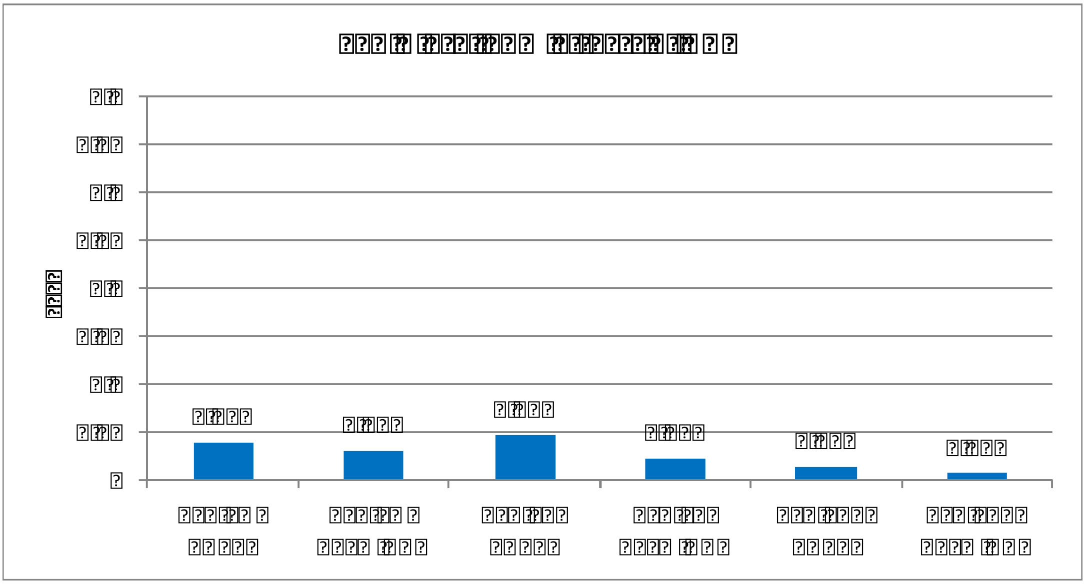


Figure 12.70. The effect of HVO on PM emissions in EEV certified diesel vehicles.

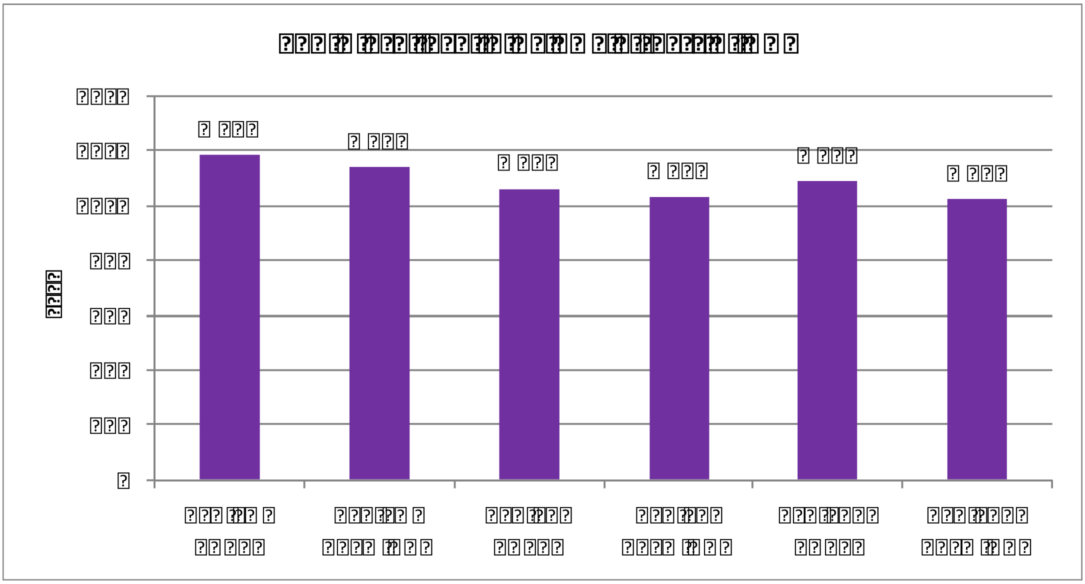


Figure 12.71. The effect of HVO on tailpipe CO_2 emissions in EEV certified diesel vehicles.

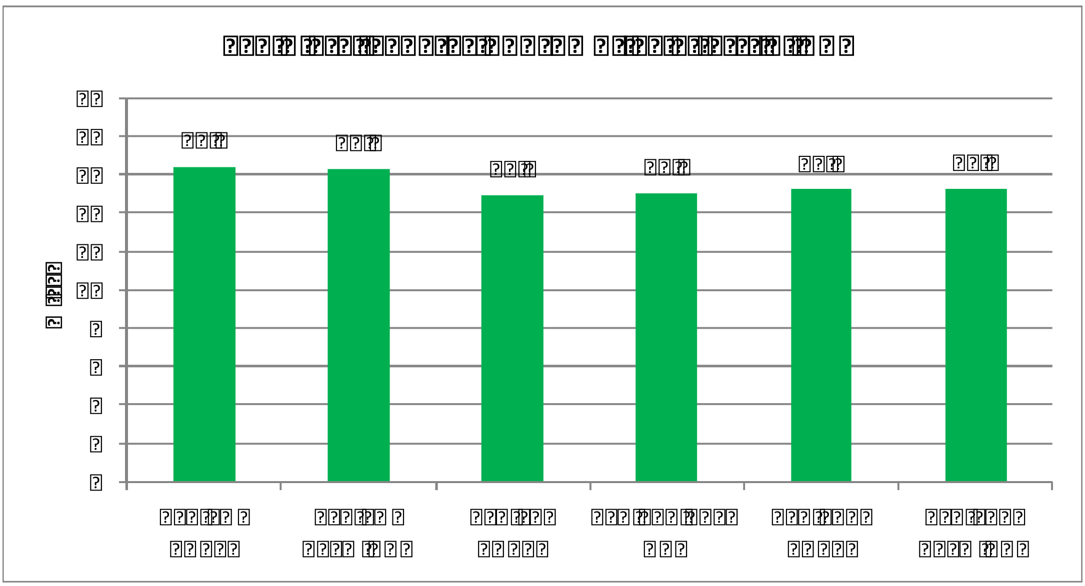


Figure 12.72. The effect of HVO on energy consumption in EEV certified diesel vehicles.

Figures 12.73–12.78 show the effect of all tested fuels, neat and blended fuels, on NO_x and PM emissions of Euro III, EEV EGR and EEV SCR diesel vehicles.

The blended fuels basically perform as can be expected on basis of the performance of the neat fuels. For some reason, the blend of 70% EN590 and 30% HVO gives higher NO_x emissions than straight EN590 in the Euro III vehicle and in the EEV EGR vehicle.

RME, even in blends, increases NO_x and reduces PM. In the Euro II vehicle, a blend of 70% HVO and 30% RME gives a slight increase in NO_x, but a substantial reduction in PM, demonstrating that some hybrid blends could be of interest. The Euro III vehicle and the EEV SCR vehicle react more strongly to the fuel than the EEV EGR vehicle, especially regarding PM.

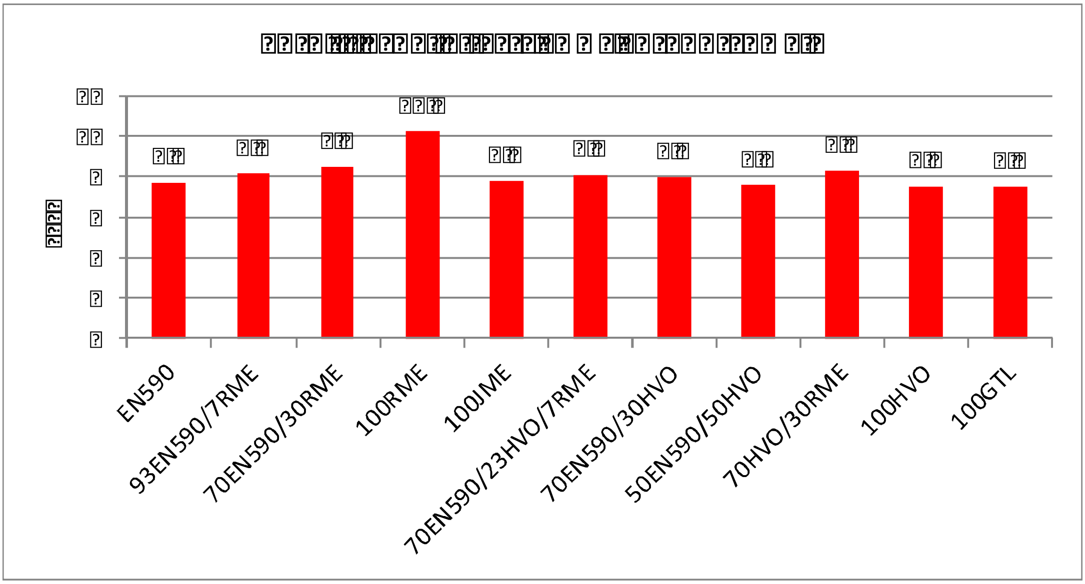


Figure 12.73. Fuel effects on NO_x emission. Euro III diesel.

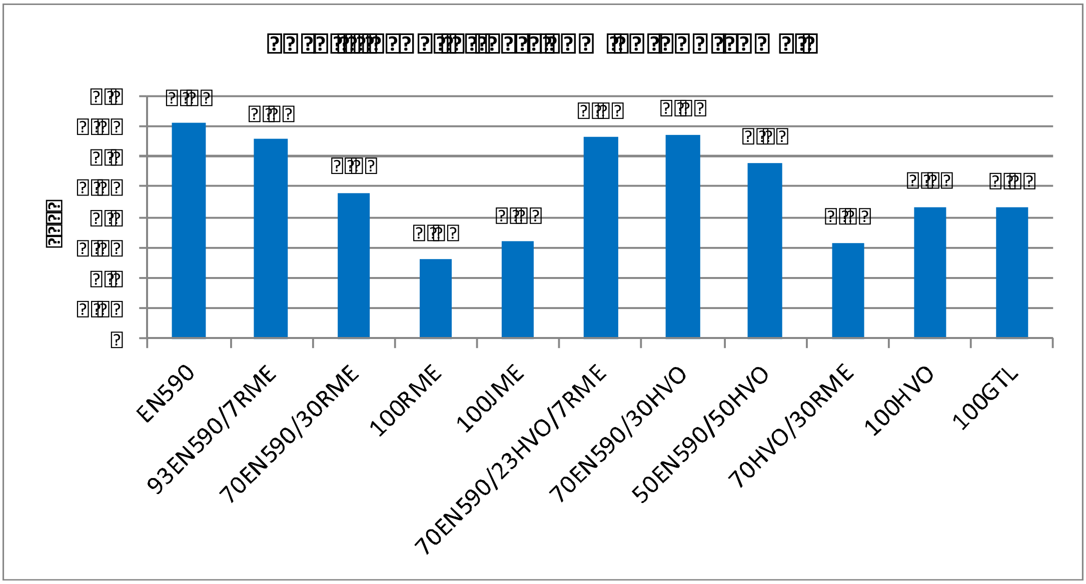


Figure 12.74. Fuel effects on PM emission. Euro III diesel.

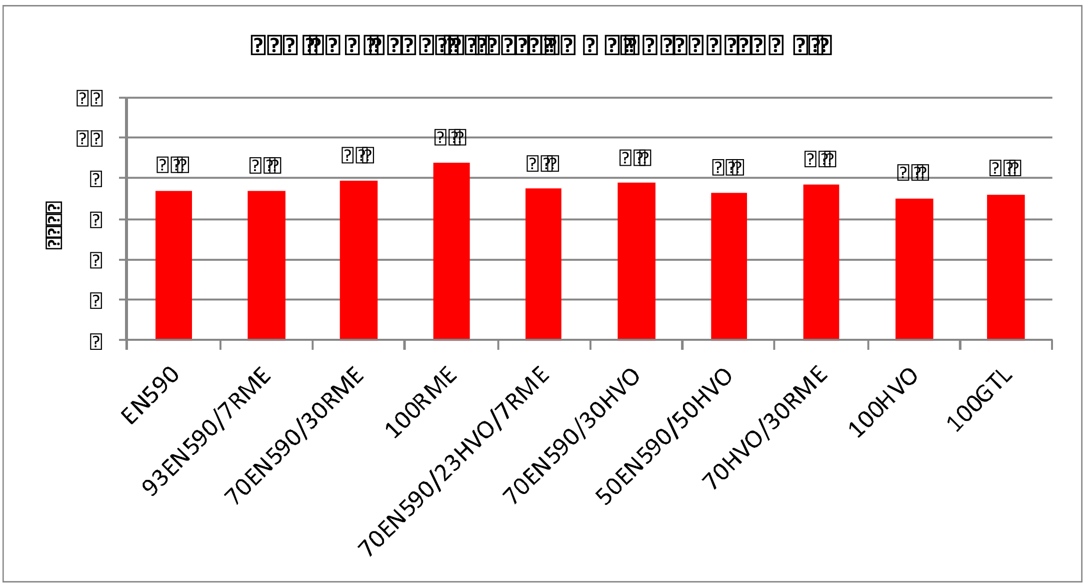


Figure 12.75. Fuel effects on NO_x emission. EEV EGR diesel.

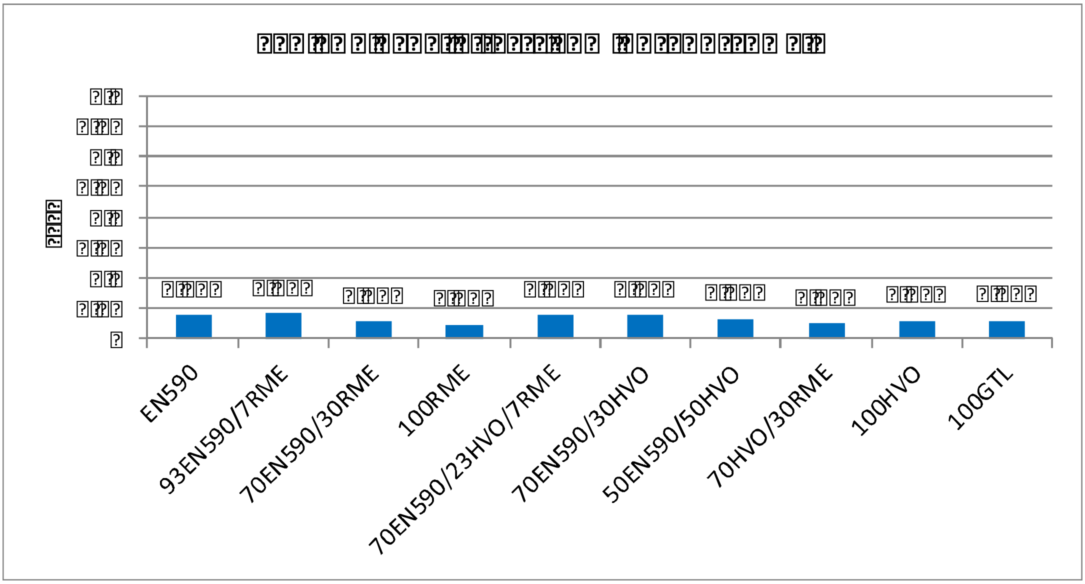


Figure 12.76. Fuel effects on PM emission. EEV EGR diesel.

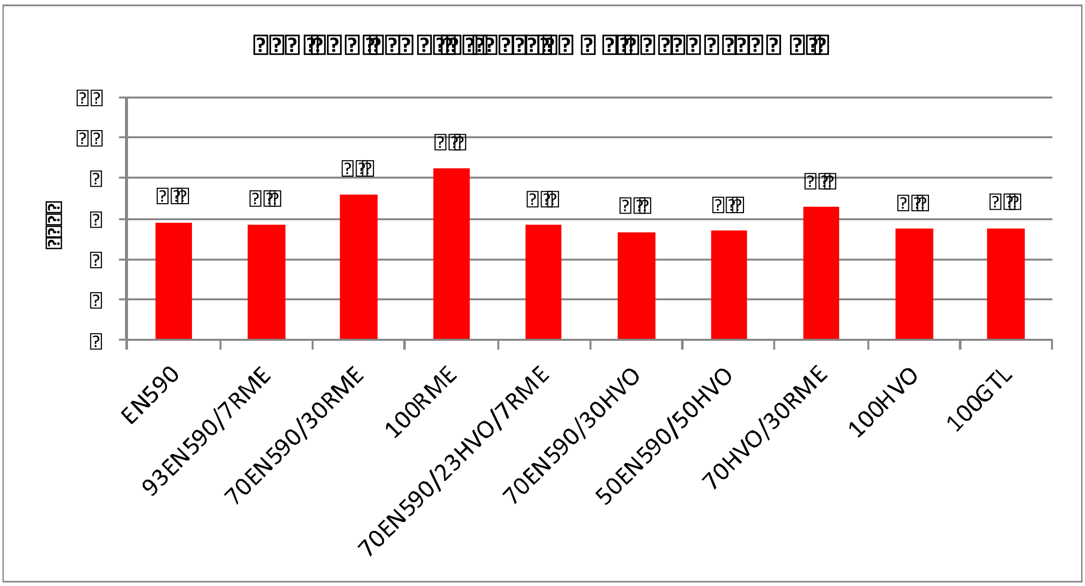


Figure 12.77. Fuel effects on NO_x emission. EEV SCR diesel.

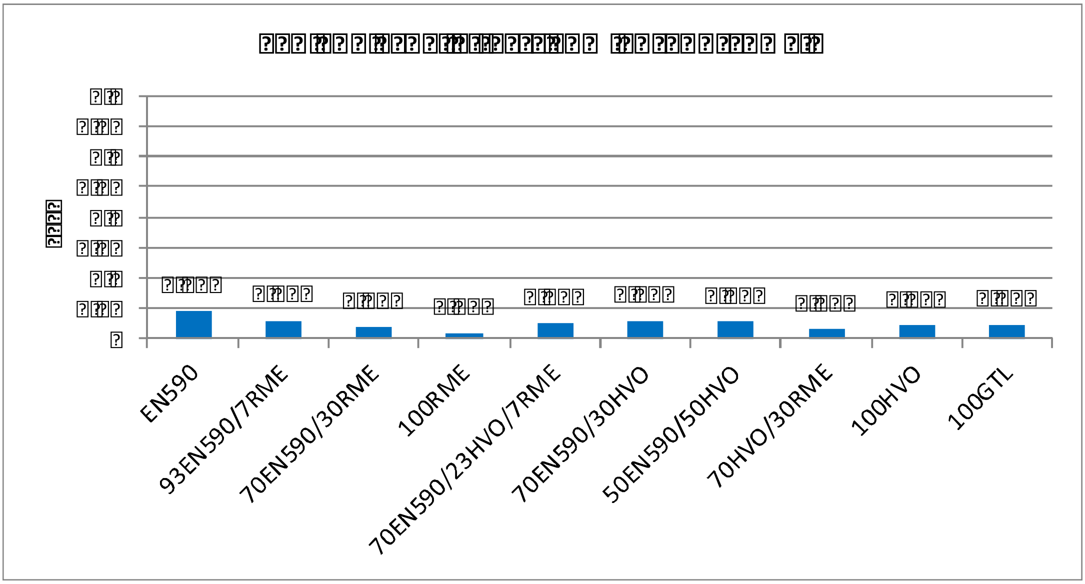


Figure 12.78. Fuel effects on PM emission. EEV SCR diesel.

12.3.5 Results for unregulated emissions

The focus in VTT's chassis dynamometer activity was in regulated emissions, CO_2 and fuel consumption. However, also some measurements of unregulated components were carried out.

<u>Particulate numbers</u>

Figure 12.79 presents particulate number size distribution for a number of technology alternatives (indicative). Three groups are formed: highest particulate numbers for diesel Euro III, EEV EGR, EEV SCR and ethanol, lowest numbers for CNG and DME in between.

In the smallest size class measured (20 nm) CNG delivers almost two orders of magnitude lower numbers than the other technologies. The assumption is that the diesels with wall-flow filters would produce particulate numbers comparable to CNG.

The general perception is that small particulates are more harmful than big particles, as the small ones penetrate deeper into the human body than the big ones.

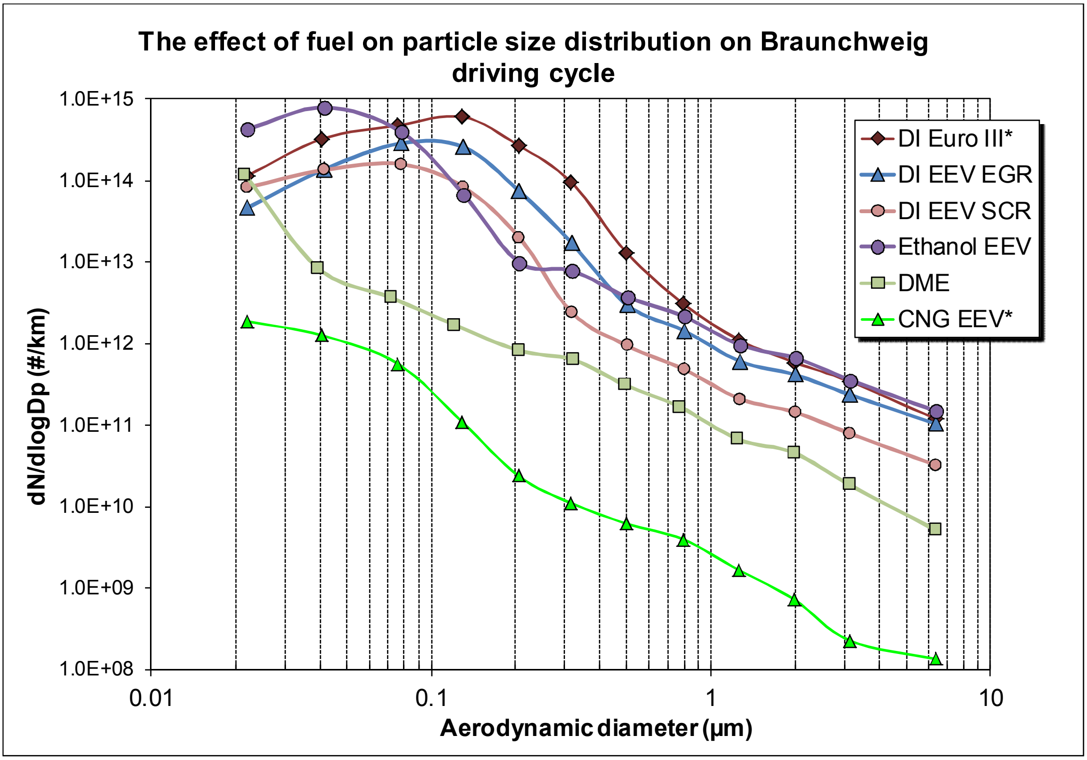


Figure 12.79. Particulate number size distribution for a number of technology alternatives (indicative).

In a parallel project, VTT measured the effect of 100% HVO on particulate number size distribution (Nylund et al. 2011). The reference fuel was EN590, and the general methodology for the measurements was in congruence with the IEA Bus Project. The test cycle was Braunschweig, and two of three vehicles were of the same type as in the IEA Bus Project, Euro III and EEV SCR. The third vehicle was a vehicle with EGR, of the same brand as the EGR vehicle in the IEA Bus Project, but slightly older and with Euro IV emission certification instead of EEV certification.

Figures 12.80 to 12.82 show particle number size distribution for the individual vehicles (linear scale for particle sizes). Markings for scatter of the results have been included to depict repeatability.

In the case of the Euro III vehicle, fuel had negligible effects on particle size distribution and particle numbers in the different particle size categories, despite the fact that particle mass, expressed as g/km, was reduced 7% when going from regular diesel fuel to 100% HVO. These findings are actually in congruence with vTI's findings for another Euro III certified engine (see Paragraph 12.4). In EC's measurements, 100% HVO increased both particle mass and particle numbers in the EPA 1998 bus (see Paragraph 12.2).

For the Euro IV vehicle and the EEV vehicle fuel had a clear effect on particle numbers. Compared to regular diesel, 100% HVO reduced particle numbers in all size classes by 17–40%.

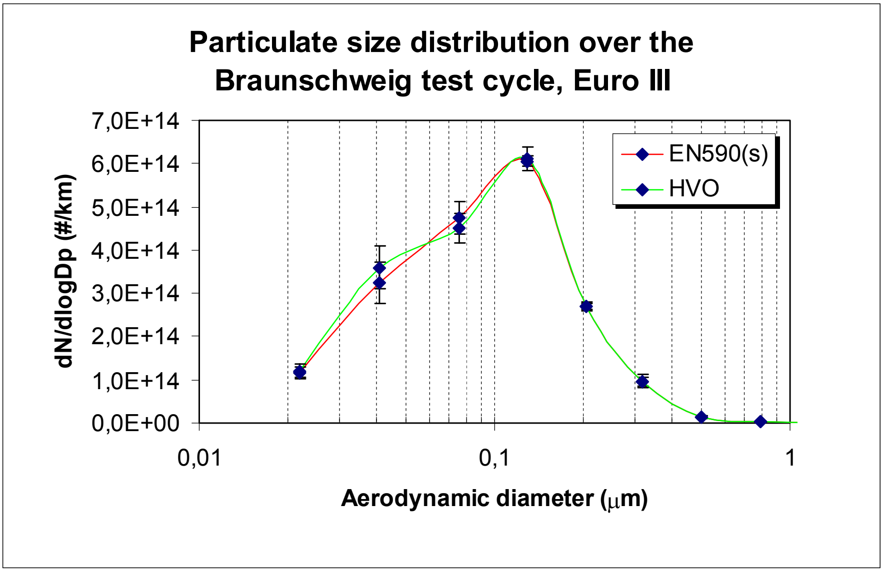


Figure 12.80. Particulate number size distribution for the Euro III vehicle.

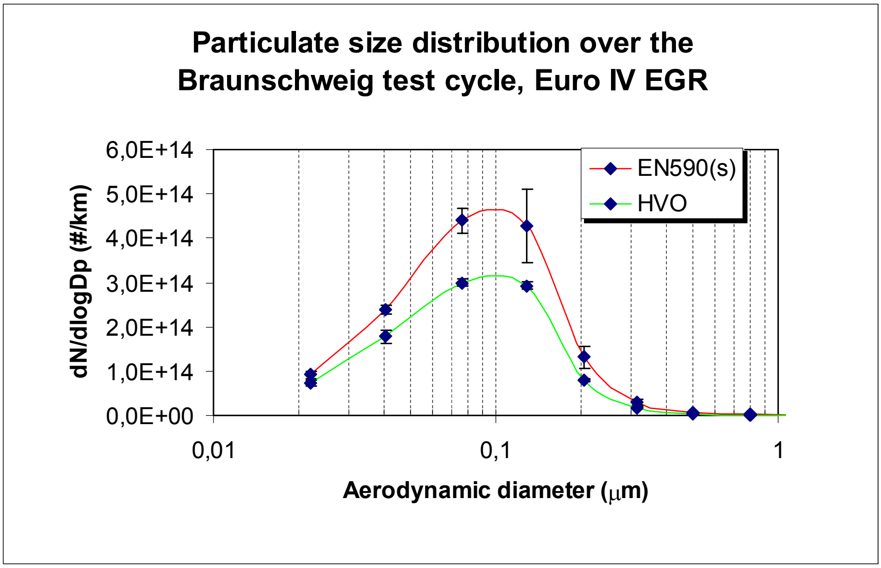


Figure 12.81. Particulate number size distribution for the Euro IV EGR vehicle.

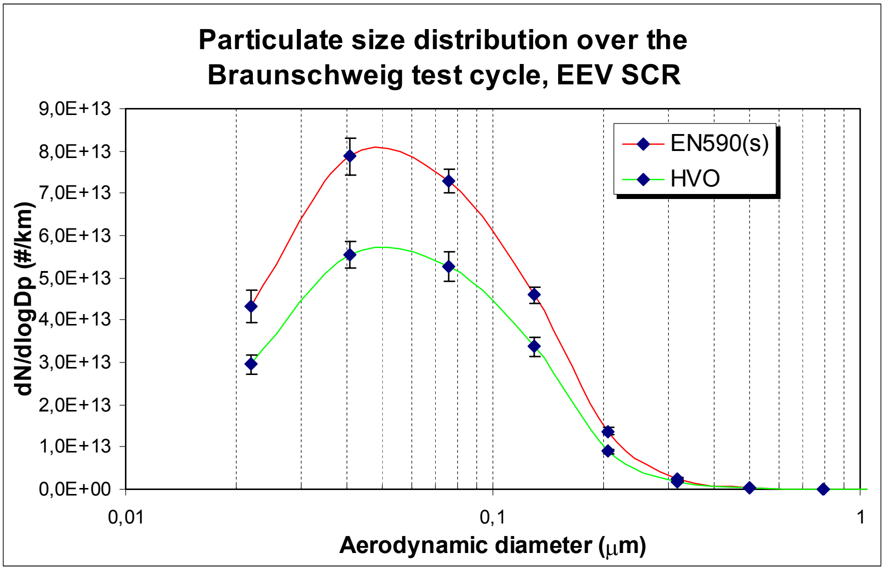


Figure 12.82. Particulate number size distribution for the EEV SCR vehicle.

Switching from regular diesel to 100% HVO did not significantly change the profile of the particulate number size distribution curves. This is true for all three vehicles tested. This means that HVO does not affect the distribution between small and large particle in an adverse way (the numbers of small particles remain constant or decreases). This is important, since small particles are considered more harmful than larger particles.

Figure 12.83 shows a comparison of the particle number emissions for the three vehicles. In this case the scale for particle size is logarithmic to make it possible to show the results of all three vehicles in the same figure. The Euro III and the Euro IV vehicle show almost identical results, whereas particle numbers are reduced approximately with one order of magnitude for the EEV vehicle. However, in comparison with the two other vehicles, the EEV vehicle shows a slightly different size distribution profile with, in relative terms, higher numbers of small and lower numbers of large particles.

Although HVO reduces particulate mass and in most case also particle numbers, the results on particle number size distribution demonstrate that particle numbers first and foremost depend on vehicle technology, not fuel.

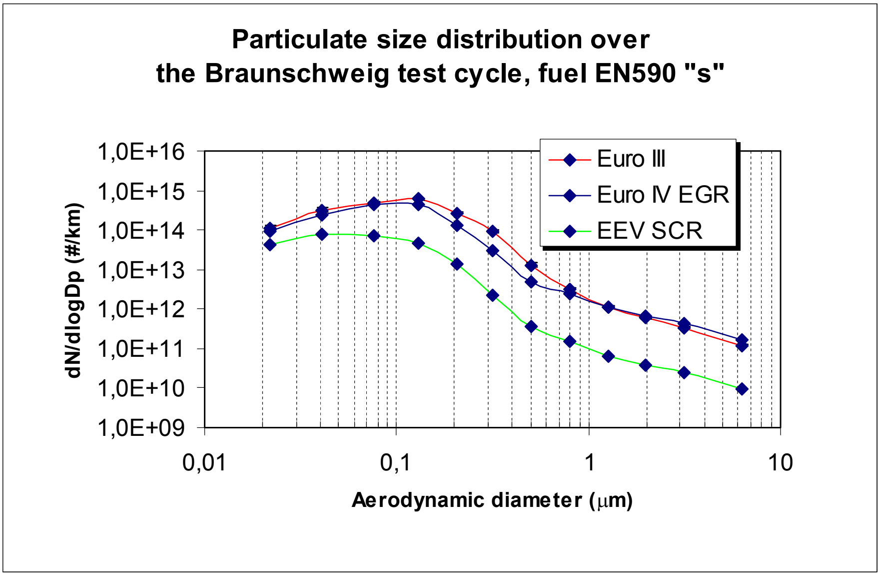


Figure 12.83. Comparison of particle numbers of the three vehicle individuals (Euro III, Euro IV and EEV) using regular diesel fuel. All vehicles without wall-flow particulate filters.

Direct NO_2 emissions

In emission legislation, the sum of NO (nitric oxide) and NO_2 (nitrogen dioxide), i.e. NO_x, is regulated. The chemistry in the balance between NO and NO_2 is quite complex. However, in most cases the equilibrium goes from NO towards NO_2. The latter is a more aggressive component, e.g., irritating respiratory organs, and therefore air quality limits are set specifically for NO_2. In conventional diesel engines without exhaust after-treatment, NO is totally dominating over NO_2 when measured at the tailpipe. However, catalytically active PM reducing after-treatment systems such as diesel oxidation catalysts and coated filters tend to increase the relative share of NO_2.

In Europe, the combination of an increasing share of diesel passenger cars and the introduction of exhaust after-treatment in general on diesel vehicles has led to a situation in which total NO_x emissions have been reduced, but the NO_2 levels in urban environments have not been reduced. This means that the direct emission of NO_2 has become a problem (Gjerstad 2011).

Figure 12.84 shows NO_2 and NO portions for various vehicle technologies.

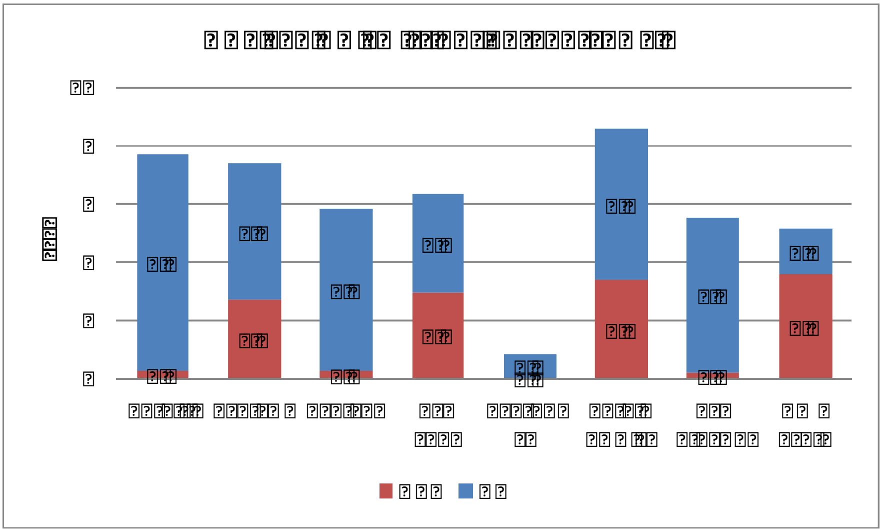


Figure 12.84. NO_2 and NO emissions for various bus technologies.

Regarding direct NO_2 emissions, the vehicles clearly fall into two distinct groups, high emitters (diesel EEV EGR, diesel EEV SCRT, CNG lean-burn, DME) and low emitters (diesel Euro III, diesel EEV SCR, CNG stoichiometric and ethanol). In the first group, the share of NO_2 in NO_x is 35–70%, and in the latter below 5%. In absolute numbers the values are 2.7–3.6 g/km for the first group and 0.0–0.3 g/km for the latter group.

A similar trend, regarding direct NO_2 emissions, was noted with the buses tested at Environment Canada. Over the UDDS cycle, buses equipped with catalyzed DPFs had an NO_2 in NO_x percentage range of 34 to 55% with the bus equipped with DOC only having a percentage NO_2 in NO_x under 5%. This translates to absolute values from 0.18 to 2.3 g/km and 0.04 g/km.

12.3.6 General observations

VTT's measurements confirm the observations from Environment Canada; the main parameter affecting the regulated emissions is the vehicle itself. Switching old vehicles to new ones, whether fuelled by diesel or alternative fuels, will deliver huge reductions in local emissions.

Figures 12.85 and 12.86 present a comparison between two generations of vehicles, EPA 1998 and Euro II representing old vehicles and EPA 2010 and EEV representing current vehicles. The results are for the Brauschweig cycle.

It is interesting to see that Euro II and EPA 1998 deliver almost equivalent NO_x, PM and fuel consumption. CO and THC are lower for the EPA 1998 platform, thanks to a properly working oxidation catalyst. The EPA 2010 (1) platform is significantly cleaner than the EEV SCRT vehicle with 75% lower NO_x and 85%

lower PM, the latter resulting from a more efficient and denser particulate filter. However, the very low emissions have a high price, as the EPA 2010 (1) vehicle consumes some 40% more fuel than the EEV SCRT vehicle. The EPA 2010 (3) was not tested over the Braunschweig cycle, but as mentioned in 12.2.2, this vehicle had some 20% lower fuel consumption compared to the two other EPA 2010 vehicles, approaching the fuel efficiency of European vehicles.

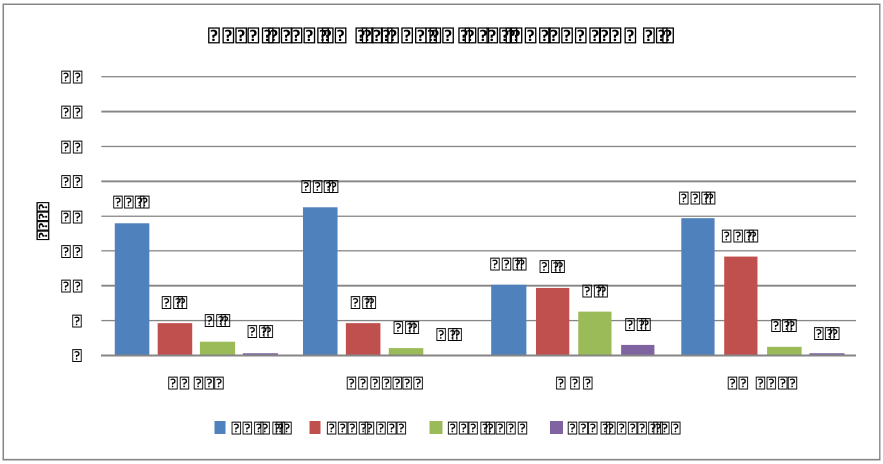


Figure 12.85. Regulated emissions for diesel vehicles with conventional powertrains. North-American and European vehicles, Braunschweig cycle.

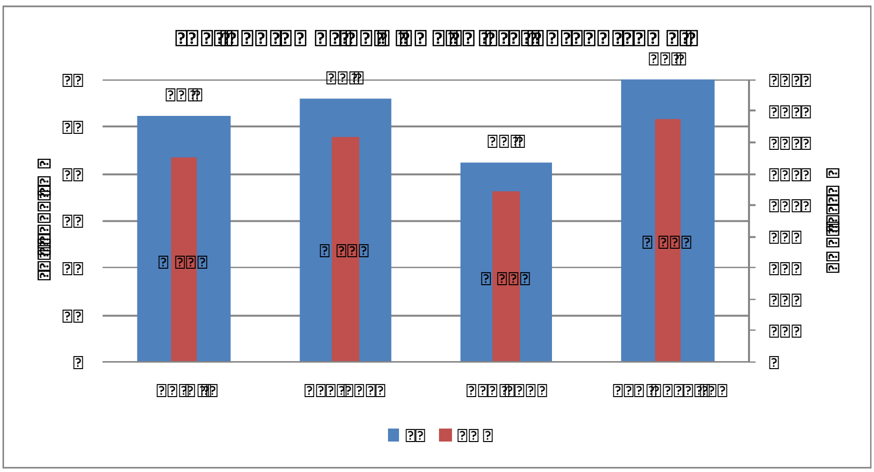


Figure 12.86. Fuel consumption (l/100 km) and CO_2 emissions for diesel vehicles with conventional powertrains. North-American and European vehicles, Braunschweig cycle.

Looking at fuel effects, switching from conventional diesel fuel to alternative diesel fuels such as paraffinic diesel or FAME can reduce particulates up to 50%. Paraffinic fuels tend to reduce NO_x emissions somewhat, whereas FAME type biodiesels slightly increase NO_x emissions.

Alternative fuels (CNG, DME, ethanol) reduce PM emissions compared to diesel average. However, this benefit vanishes if the comparison is with a particulate filter equipped diesel.

It is clear that the current European vehicles have some difficulties in meeting real-life EEV performance. The critical emission component is NO_x. As for PM, the oncoming Euro VI level seems to be quite easily attainable with particulate filter equipped vehicles or alternatively CNG. In fact, the stoichiometric CNG vehicle already fulfils Euro VI requirements for NO_x and PM.

Fuel efficiency has improved with improving vehicle technology, but only marginally for vehicles with conventional power train. Hybridization and light-weighting typically cuts fuel consumption by some 20–30%. Alternative fuels vehicles utilizing diesel combustion (DME, additive treated ethanol) provide diesel-like efficiency, whereas the current CNG vehicles using the Otto cycle with spark-ignition consume significantly more energy.

The findings can be summarized as follows:

- Old vs. new vehicles
  - 10:1 and even more for regulated emissions
  - 100:1 for particulate numbers
  - close to neutral for fuel efficiency (improvement from Euro II to EEV, but Euro VI is expected to increase fuel consumption over EEV)
- Hybridization and light-weighting
  - 20–30% reduction in fuel consumption
  - not automatically beneficial for regulated emissions
- Effect of driving cycle
  - 5:1 for fuel consumption and regulated emissions
- Fuel effects (when replacing regular diesel)
  - 2.5:1 at maximum (particulates)
- Alternative fuels (in dedicated vehicles)
  - low PM emissions but not automatically low NO_x emissions
  - fuel efficiency depends on combustion system (compression or spark-ignition).

12.4 vTI's engine dynamometer work

12.4.1 General

von Thünen Institute carried out detailed evaluations of both regulated and unregulated exhaust emissions using a Euro III level heavy-duty diesel engine installed in an engine dynamometer. The engine didn't have any exhaust after-treatment devices, and therefore accentuates the fuel effects on emissions. The testing was done with straight fuels only. The fuels were (the abbreviations used in the Figures within brackets):

- commercial diesel fuel corresponding to EN590 (DF)
- rapeseed based FAME (RME)
- Jatropha based FAME (JME)
- hydrotreated vegetable oil HVO (NExBTL).

For all evaluations at least six measurements were included (unless otherwise stated), whereby the average was created from all individual results.

The results for regulated components are compared to the Euro III limit values:

- CO: 2.1 g/kWh
- THC: 0.66 g/kWh
- NO_x: 5.0 g/kWh
- PM: 0.1 g/kWh.

12.4.2 Fuel effects on engine maximum output and fuel consumption

The maximum torque at the different speeds for the ESC test were determined with diesel fuel. For the other fuels the maximum torque couldn't be reached, due to their lower volumetric energy content. Therefore, the average power during the ESC test was reduced some 2–3% (Figure 12.87). For all other modes, except those with maximum torque, the same torque was used with all fuels.

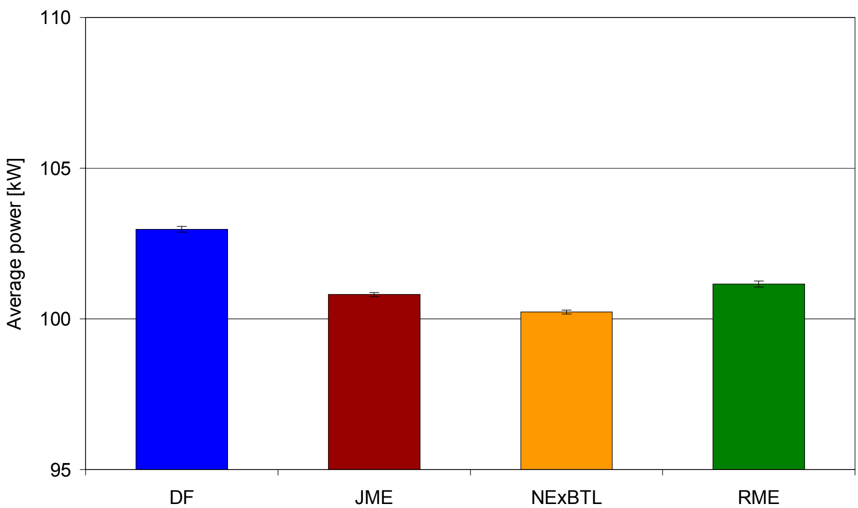


Figure 12.87. Average power in the ESC test for different fuels with the OM 906 engine.

The specific consumption for DF and NExBTL was almost the same. The methyl esters have a lower specific energy content due to their oxygen content. Therefore, the specific consumption (in g/kWh) was about 15% higher (Figure 12.88).

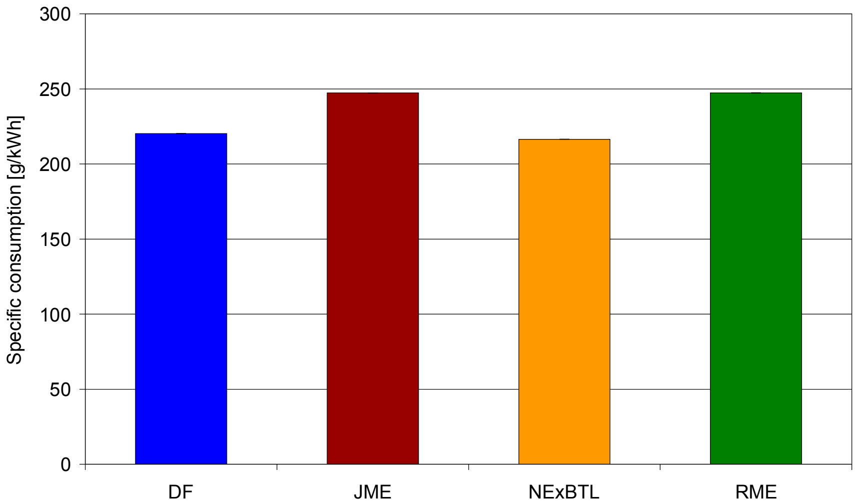


Figure 12.88. Specific fuel consumption in g/kWh (ESC test, OM 906).

12.4.3 Results for regulated exhaust gas components

The CO emissions for all fuels are by far under the limit of 2.1 g/kWh for Euro III engines. RME and JME show clear advantages. DF and NExBTL produce twice the amount of CO compared to RME (Figure 12.89).

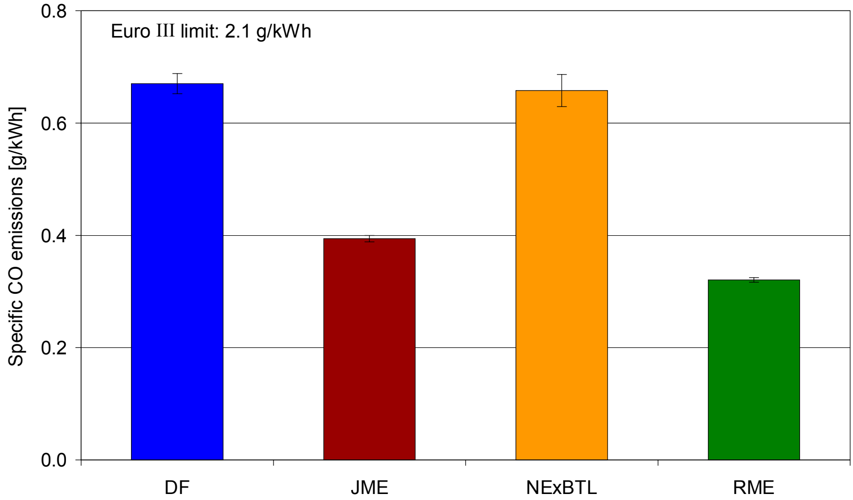


Figure 12.89. Specific CO emissions in g/kWh (ESC test, OM 906).

The limit for total hydrocarbon emissions according to Euro III is 0.66 g/kWh. The measured values were significantly lower for all types of fuels (Figure 12.90). Again DF and NExBTL deliver equivalent emissions. The oxygenated fuels reduce THC emissions somewhat, RME more than JME.

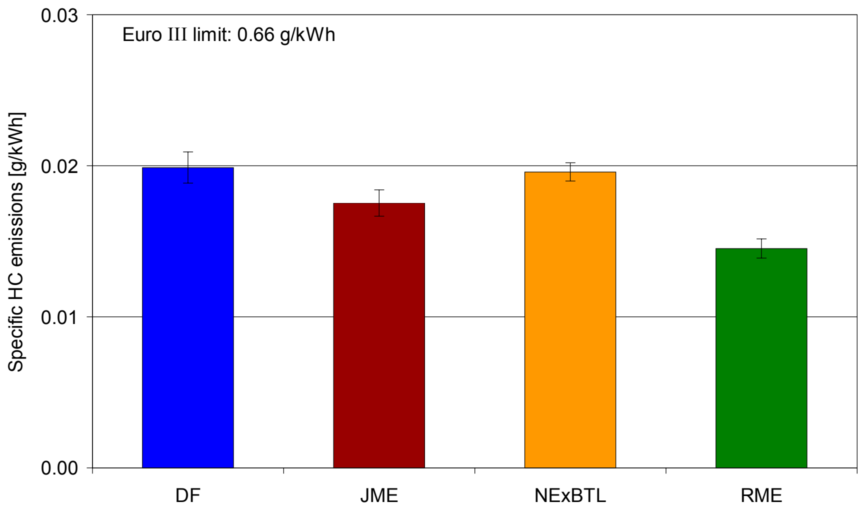


Figure 12.90. Specific HC emissions in g/kWh (ESC test, OM 906).

The oxygenated fuels increased NO_x emissions. Consequently the Euro III limit of 5.0 g/kWh was exceeded by RME and JME, if only by 5% in the case of JME. DF was just below the Euro III limit, and NExBTL reduced NO_x 15% relative to DF (Figure 12.91).

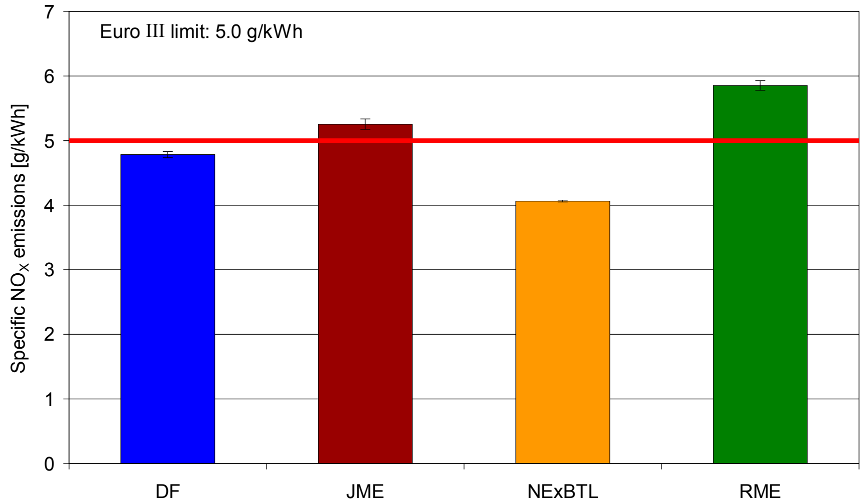


Figure 12.91. Specific NO_x emissions in g/kWh (ESC test, OM 906).

Figure 12.92 shows NO and NO_x traces over the ESC test. As the engine has no exhaust after-treatment, the nitrogen oxides are primarily emitted as NO; NO_2 levels are low.

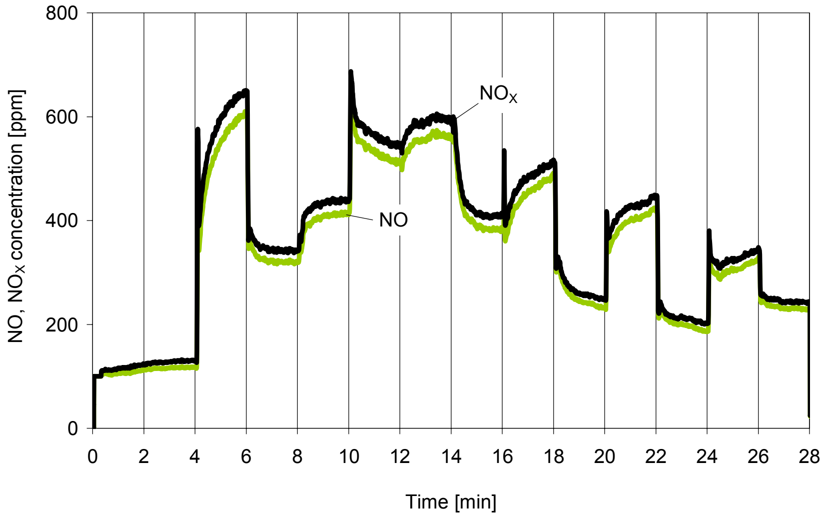


Figure 12.92. NO and NO_x concentrations traces (ESC test, OM 906, Run OM676, NExBTL).

The oxygenated fuels (JME, RME) deliver a 35% reduction in PM emissions compared to DF. The reduction in PM for NExBTL was smaller, some 8%. The emission limits of 0.1 g/kWh was met by all fuels (Figure 12.93).

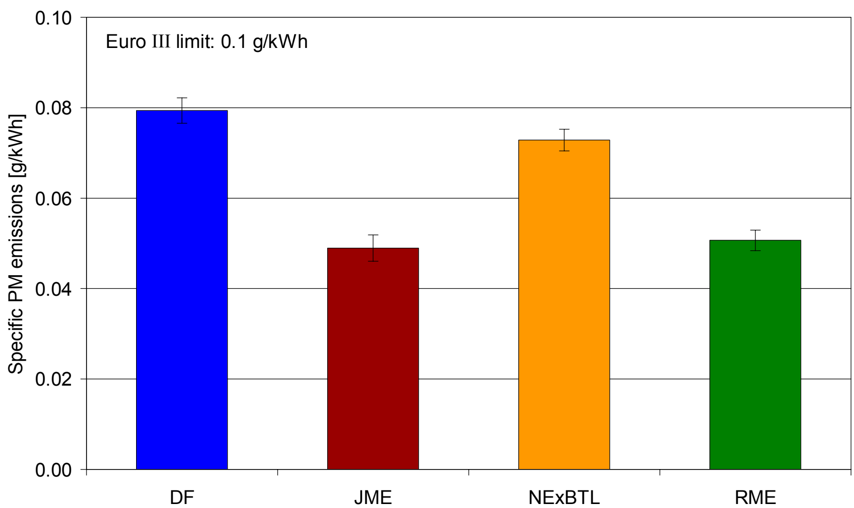


Figure 12.93. Specific PM emissions in g/kWh (ESC test, OM 906).

12.4.4 Results of the unregulated exhaust gas components

Particulate number and particulate size distribution

vTI measured particulate numbers with two instruments, SMPS and ELPI.

Figure 12.94 shows the particulate number distribution measured by SMPS. The averages of at least five individual measurements are shown here. The SMPS results show that the DF and NExBTL differ only slightly, and NExBTL show somewhat higher particulate numbers. RME, on the other hand, delivers lower particulate numbers. JME falls in between DF and RME. In the range of ultra-fine particles JME is comparable to DF, but with increasing particulate diameter the numbers approach those of RME.

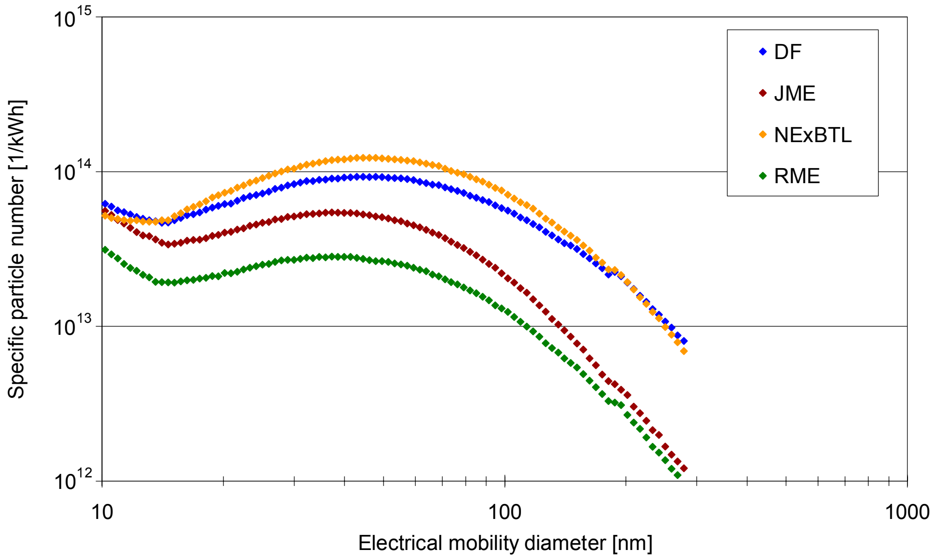


Figure 12.94. Specific particulate number distribution in crude exhaust gas (SMPS, ESC test, OM 906).

The ELPI results (Figure 12.95) showed good congruence with the SMPS results. DF and NExBTL delivered similar numbers, and RME gave lowest numbers. For the first three stages up to 156 nm JME produced somewhat higher numbers than RME, for the remaining stages equivalent numbers.

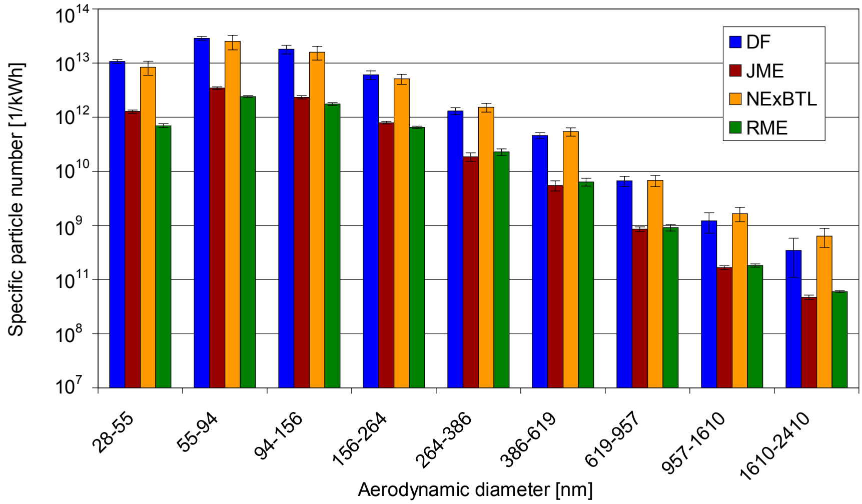


Figure 12.95. Specific particle number distribution in raw exhaust gas (ELPI, ESC test, OM 906).

Carbonyl emissions

The main constituents in carbonyl emissions are formaldehyde, acetaldehyde and acrolein. Acetone couldn't be determined due to high background levels. NExBTL produced highest form- and acetaldehyde emissions. However, the differences between the fuels are not significant (Figure 12.96). EC, on the other hand, noted a reduction in carbonyl emissions with 100% HVO.

2-butanone and n-butyraldehyde were determined together because of equal retention times. For m-tolualdehyde only small amounts could be detected.

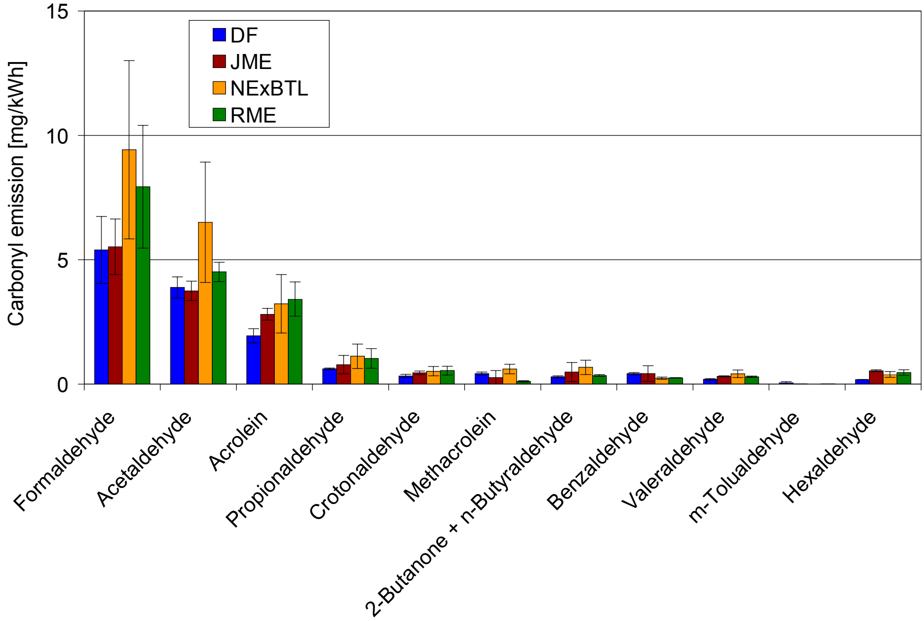


Figure 12.96. Specific carbonyl emissions (ESC test, OM 906).

PAH emissions

PAHs were sampled both from particulate extracts from filters and from condensate. Figures 12.97 (particulate extract) and 12.98 (condensate) show PAH results. The lightweight PAHs were mainly found in the condensate, and the higher PAHs were found in the filter fraction.

DF had the highest emission of PAHs with four or less rings (exclusive BaA). In the particulate extracts DF, JME and RME showed similar amounts of PAHs with five or more rings (inclusive BaA). However, as these compounds are also found in the condensate with JME and RME, JME and RME display highest aggregate numbers for PAHs with five or more rings. Compared to the other fuels, NExBTL showed lower PAH concentrations both in the particulate extracts and the condensates.

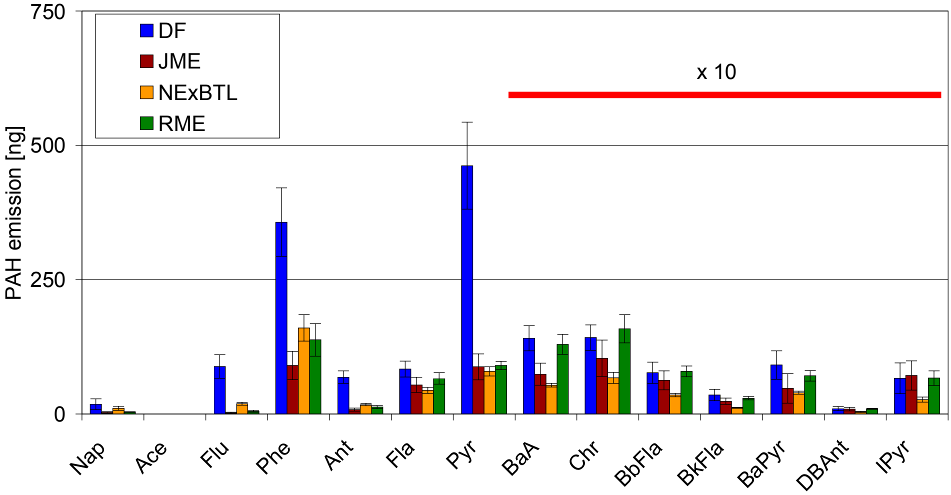


Figure 12.97. PAHs in particulate sampled during the ESC test (OM 906) [for the abbreviations of the compounds, cf. Table 8.6].

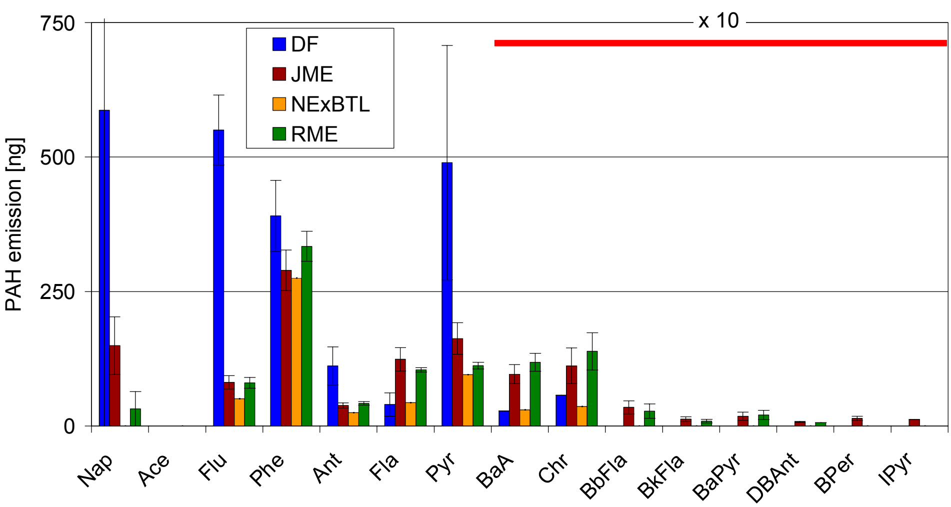


Figure 12.98. PAHs in condensate sampled during the ESC test (OM 906) [for the abbreviations of the compounds, cf. Table 8.6].

<u>Mutagenicity of the organically soluble particulate fraction</u>

The extraction of the particulate sampling filters, which was performed at the University of Bochum, resulted in similar total particulate mass profile as the gravimetric determination in the Institute of Agricultural Technology and Biosystems Engineering of the vTI in Braunschweig (Figure 12.99). The lowest PM emissions were measured for RME and JME, the highest for DF. The percentage of organically soluble particle mass (SOF) varied strongly from fuel to fuels. The methyl esters had a lower percentage of insoluble particle mass in comparison with DF and NExBTL, but a higher soluble particle mass, which is most probably caused by the emission of unburned fuel (Ruschel 2010).

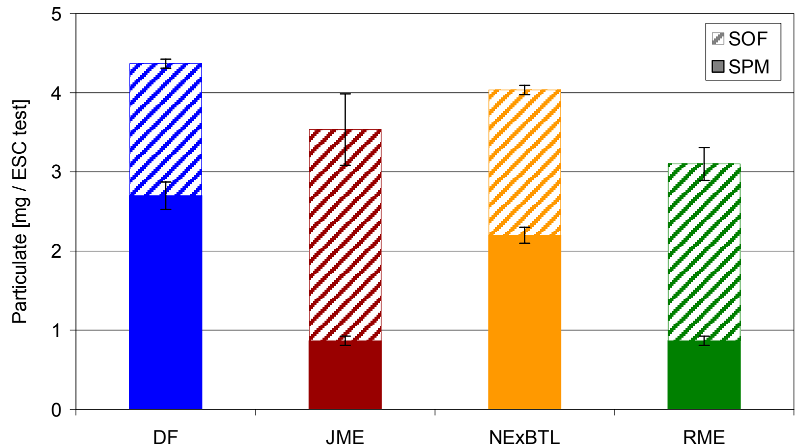


Figure 12.99. Soluble (SOF) and insoluble (SPM) particulate matter fractions in raw exhaust gas (ESC test, OM 906).

Using the bacteria test strain TA98, the mutagenicity of NExBTL was significantly lower compared to the three other fuels (Figure 12.100). RME showed unexpectedly high mutagenicity, significantly higher than for DF. In previous studies with the same test engine DF has produced higher mutagenicity than RME. Now the two methyl esters were quite comparable, with slightly lower mutagenicity for JME.

For all fuels the direct (-S9) mutagenicity is higher than the indirect (+S9) mutagenicity after metabolic activation of extracts by rat liver enzymes. This speaks for the theory that the largest part of the mutagenicity was caused by substituted PAHs (for example, nitro-PAH). These are mostly direct mutagens while the native PAHs require a metabolic activation through the formation of epoxides.

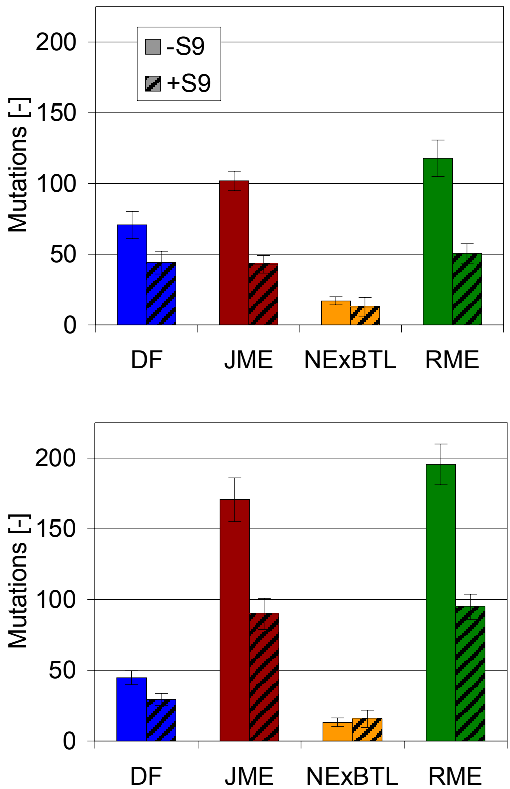


Figure 12.100. Mutagenicity of PM extracts (left) and condensates (right) in strain TA98 (ESC test, OM 906).

NExBTL also produced lowest mutagenicity when using the somewhat less sensitive tester strain TA100 (Figure 12.101). In comparison to DF, the methyl esters didn't increase mutagenicity as much with TA100 as with TA98, but the higher mutagenicity is still accentuated in the condensates.

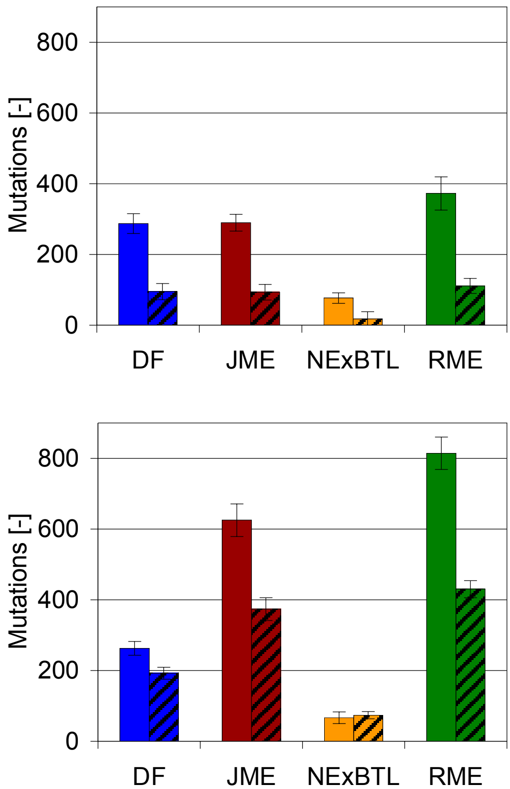


Figure 12.101. Mutagenicity of PM extracts (left) and condensates (right) in strain TA100 (ESC test, OM 906).

12.4.5 Discussion

In case of the two FAME-type fuels, JME and RME, JME delivered better results with respect to NO_x, carbonyl emissions and mutagenicity. On the other hand, JME had higher CO and THC emissions, and in addition, higher numbers of particulates smaller than 300 nm. These emission trends are comparable to those of palm oil derived methyl ester and, and can be explained by less double bonds in the fatty acids of the methyl ester and the shorter chain length (Munack et al. 2006). However, due to the fatty acid characteristics, the cold filter plugging point (CFPP) for JME is only 0 °C, and therefore this fuel can only be used in warm climate.

In comparison with DF, NExBTL showed similar or better emission results except for carbonyl emissions. In particular, NExBTL exhibited very low mutagenicity of the exhaust, and had the lowest PAH emissions compared to the three other fuels. This trend of lower emissions had also been found for GTL fuel, which has comparable properties (Munack et al. 2005).

12.5 On-road measurements

12.5.1 First campaign

AVL reported on CO, THC, NO_x, soot (depicting PM emissions) and CO_2 for three bus routes in Helsinki. The buses were (same individuals as for the chassis dynamometer measurements):

- Euro III diesel
- EEV EGR diesel
- Stoichiometric CNG.

As CO and THC are of less importance, only NO_x, soot and tailpipe CO_2 will be discussed here.

<u>NO_x</u>

For NO_x (Figures 12.102–12.104) CNG by far delivers the lowest emissions, a factor of five compared to the Euro III bus. The lowest emission levels from all vehicles were measured on Route 3 (550) and the highest from Route 1 (194). No significant differences were detected when comparing the results from load vs. no load. The results indicate that NO_x emissions of the EEV bus were higher for every test on Route 1 compared to the Euro III bus.

<u>Soot</u>

The soot emissions (Figures 12.105–12.107) clearly reveal the differences from the tested vehicles. The soot emissions from the Euro III bus are in the magnitude of ten times higher compared to the EEV vehicle however, 10 mg of soot from the EEV bus must be considered to be low. For the CNG vehicle soot emissions were below detection limit.

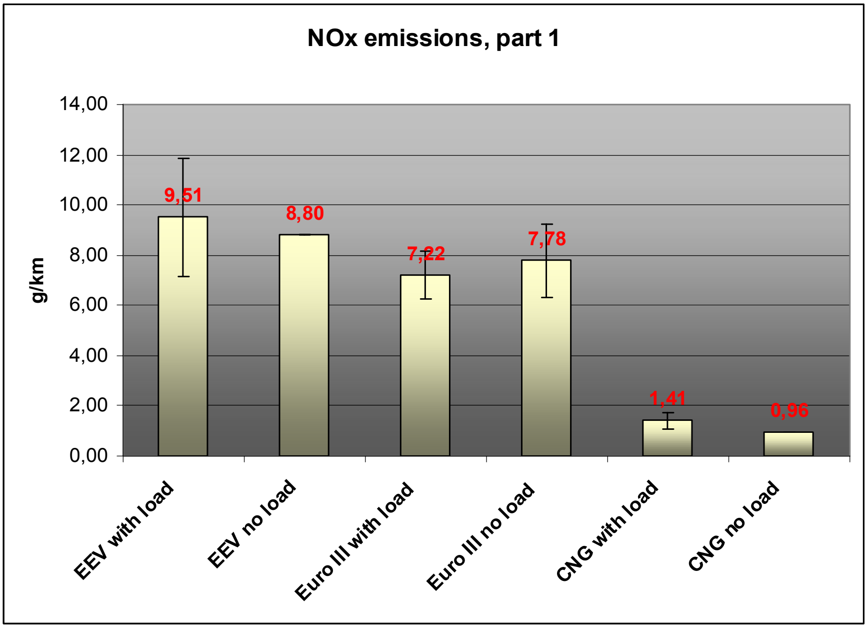


Figure 12.102. NO_x emissions for Route 1 (194).

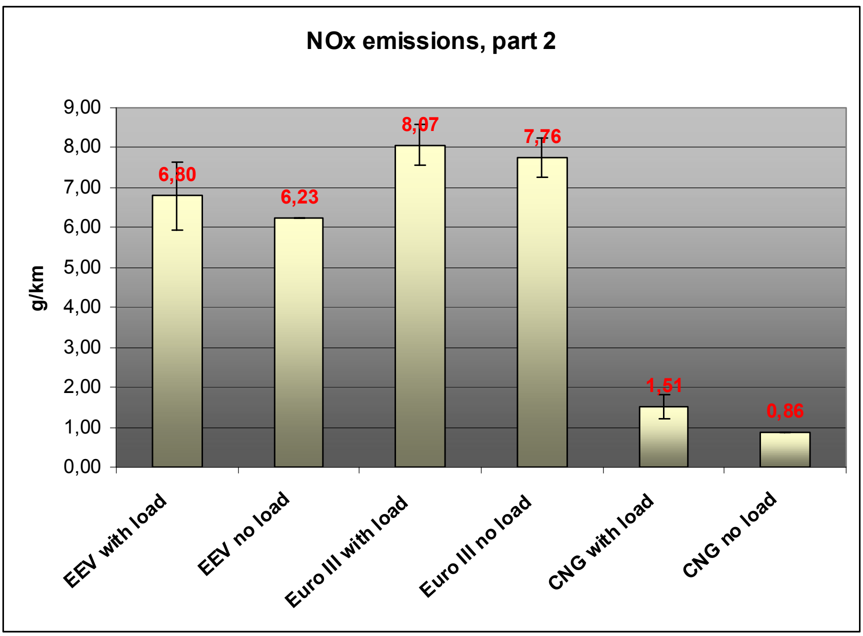


Figure 12.103. NO_x emissions for Route 2 (63).

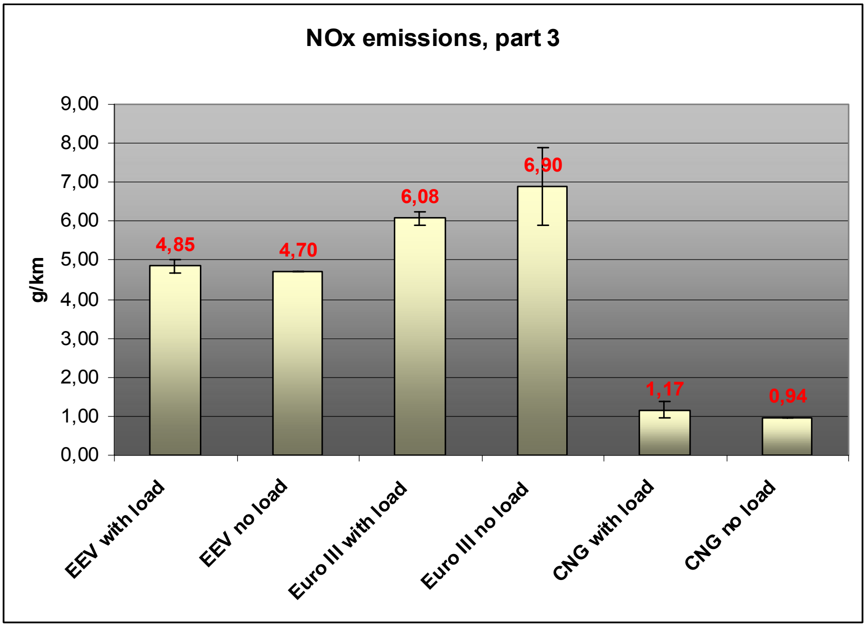


Figure 12.104. NO_x emissions for Route 3 (550).

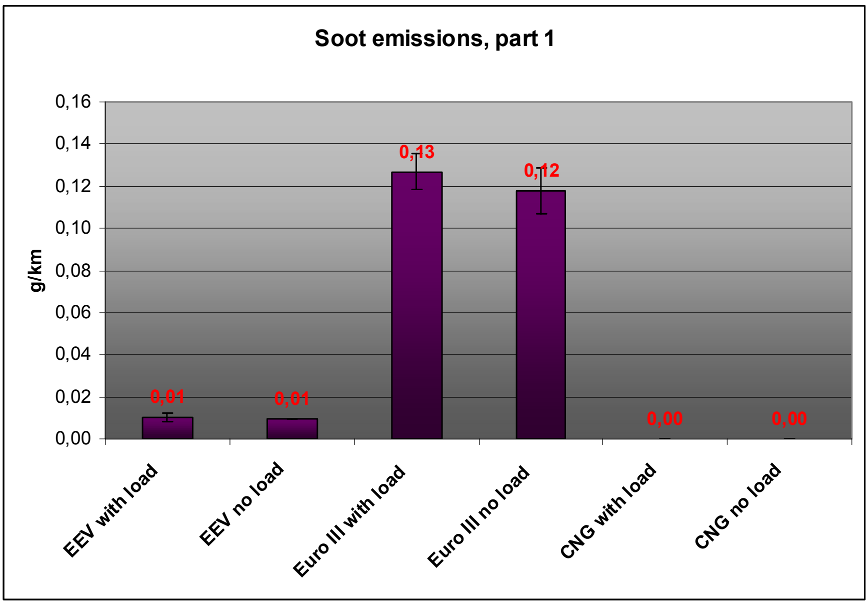


Figure 12.105. Soot emissions for Route 1 (194).

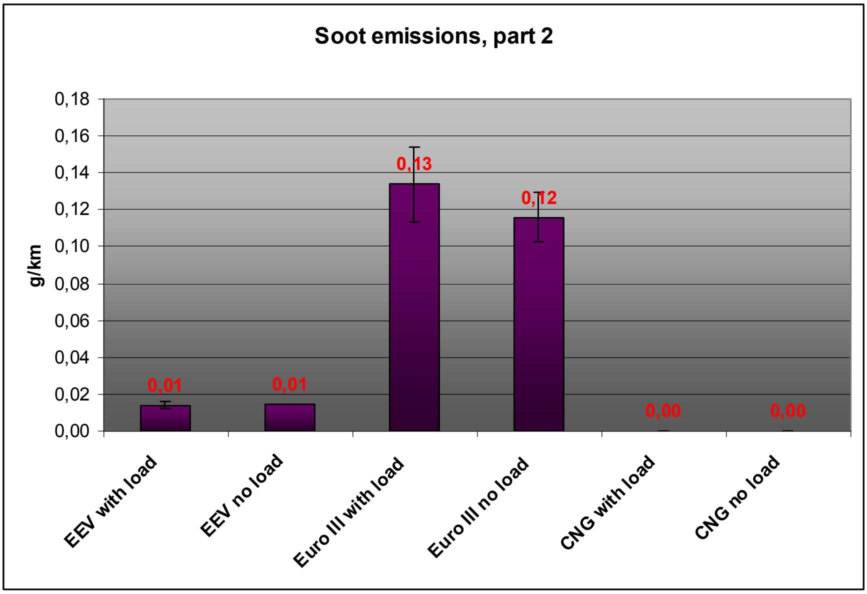


Figure 12.106. Soot emissions for Route 2 (63).

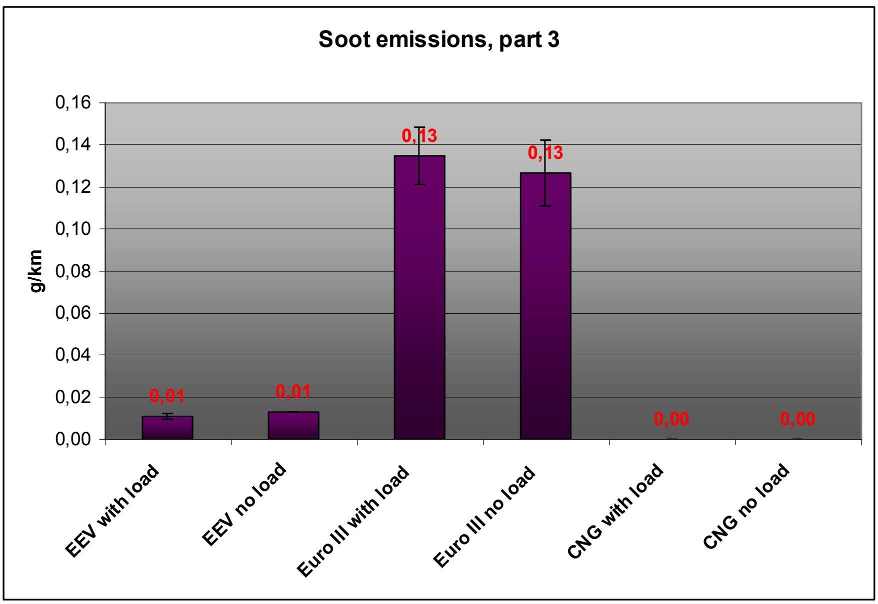


Figure 12.107. Soot emissions for Route 3 (550).

CO_2

When comparing the tailpipe emissions of CO_2, Figures 12.108–12.110, it can be seen that the Euro III and EEV diesel buses deliver lower tailpipe emissions than the CNG vehicle. The lowest emission levels from all vehicles were measured on Route 3 and the highest from Route 2 with more start and stop. A slight reduction of CO_2 i.e. fuel consumption were detected when driving with no extra load.

The EEV diesel vehicle is more fuel efficient than the Euro III diesel vehicle (the EEV diesel delivers lower CO_2 emissions).

Discussion

Table 12.4 and Figure 12.111 present summaries of AVL's on-road measurement results. The presented values are average values for unloaded and loaded vehicle. The chassis dynamometer results for the Braunschweig cycle are included as a reference. The vehicles were the same individuals for the on-road and chassis dynamometer measurements.

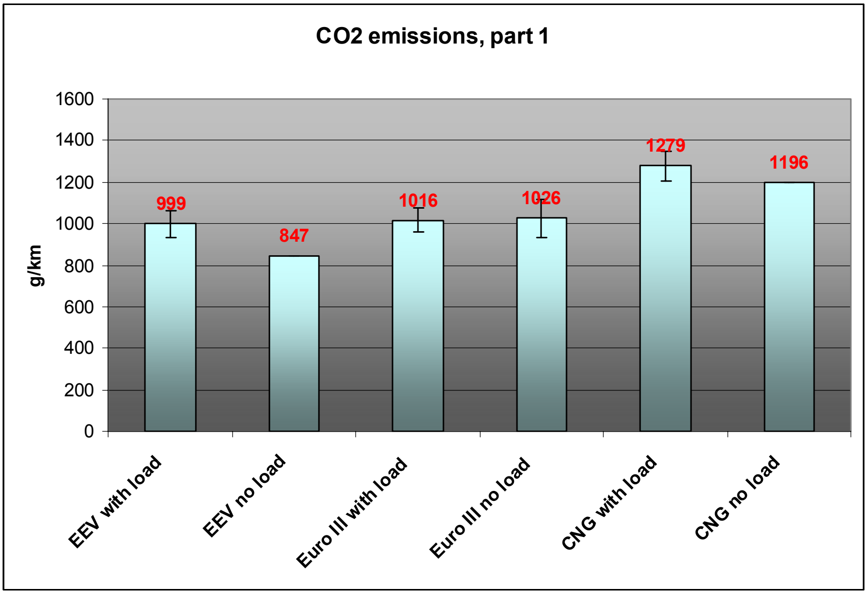


Figure 12.108. CO_2 emissions for Route 1 (194).

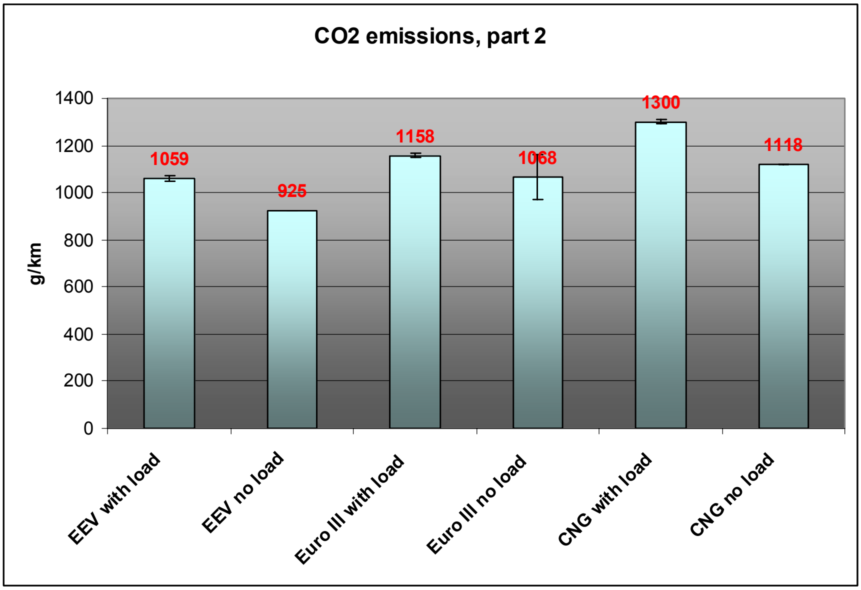


Figure 12.109. CO_2 emissions for Route 2 (63).

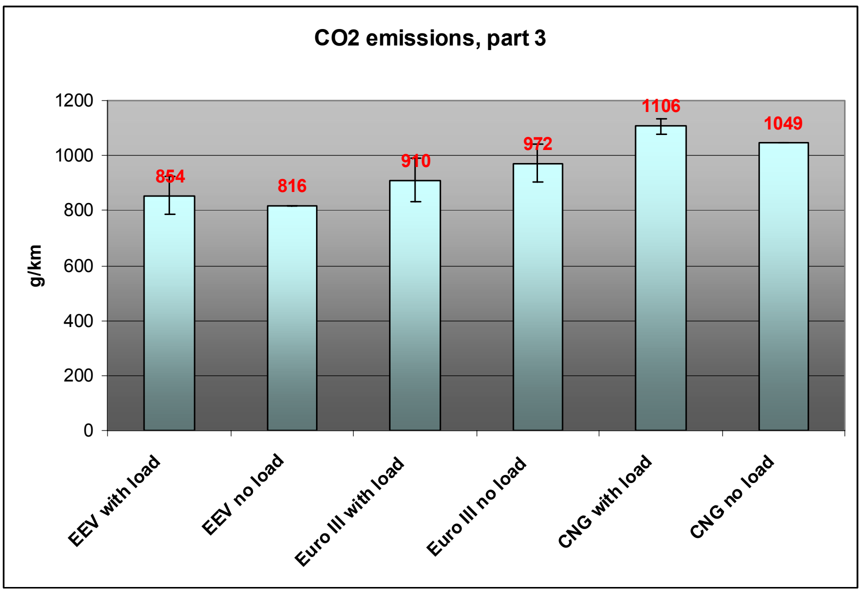


Figure 12.110. CO_2 emissions for Route 3 (550).

In general, the results of the first on-road measurement campaign were well in line with the results of the chassis dynamometer measurements for NO_x and CO_2. Route 2 (Helsinki bus line 63) delivers results which are rather close to the Braunschweig cycle. On the road, the EEV diesel was more fuel efficient than the Euro III diesel (some 10% less fuel), whereas the results on the chassis dynamometer for the Braunschweig cycle were the other way around (EEV EGR some 4% more fuel compared to Euro III).

On the road, the CNG vehicle consumed significantly more energy than the diesels, on average 50–65%. On the chassis dynamometer, the corresponding figure was some 30%. Here it should be noted that the energy consumption for the on-road measurements was derived from the CO_2 emission, whereas the results for the chassis dynamometer are based on the more accurate method of measuring fuel consumption gravimetrically.

AVL's soot measurement system was sufficient to separate out the vehicle types, but not accurate enough to bring out the effects of driving cycle. The soot levels for the on-road measurements were roughly 1/3 of the particulate mass values measured on the chassis dynamometer.

The on-road measurements confirmed the general findings of the chassis dynamometer measurements for these specific vehicles (Euro III diesel, EEV EGR diesel, stoichiometric CNG):

- no NO_x benefit going from Euro III to EEV EGR diesel
- low NO_x emissions with CNG independent of driving cycle
- high soot emissions with Euro III diesel, significant reduction going to EEV EGR diesel, very low PM emissions with CNG
- higher tailpipe CO_2 emissions with CNG compared to diesel
- significantly higher energy consumption with CNG compared to diesel.

Table 12.4. Summary of AVL's on-road measurement results.

Av. values	Euro III diesel	EEV diesel	EEV CNG
Route 1 (194)			
NO_x (g/km)	7.50	9.16	1.19
Soot (g/km)	0.13	0.01	0.00
CO_2 (g/km)	1021	923	1238
Energy cons. (MJ/km)	13.9	12.6	22.0
Route 2 (63)			
NO_x (g/km)	7.92	6.52	1.19
Soot (g/km)	0.13	0.01	0.00
CO_2 (g/km)	1113	992	1209
Energy cons. (MJ/km)	15.2	13.5	21.5
Route 3 (550)			
NO_x (g/km)	6.49	4.78	1.06
Soot (g/km)	0.13	0.01	0.00
CO_2 (g/km)	941	835	1078
Energy cons. (MJ/km)	12.9	11.4	19.2

Braunschweig (chassis dynamometer)			
NO_x (g/km)	7.7	7.4	0.84
PM (g/km)	0.35	0.04	0.02
CO_2 (g/km)	1154	1183	1223
Energy cons. (MJ/km)	15.8	16.4	21.1

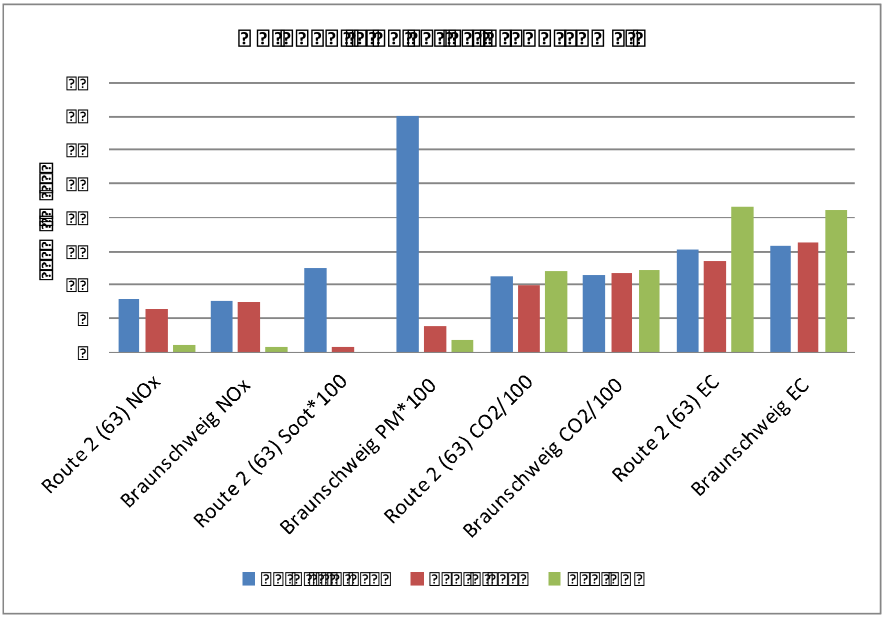


Figure 12.111. Comparison of on-road (Route 2, Helsinki 63) and chassis dynamometer (Braunschweig results).

12.5.2 Second campaign

As stated in 8.3.4, the second campaign was aimed at studying the start-up performance of the emission control systems. The vehicles evaluated were (corresponding vehicles but not the same individuals as for the chassis dynamometer measurements):

- EEV EGR diesel
- EEV SCR diesel
- EEV SCRT diesel.

Before each cold start measurement, the vehicles were allowed to idle 5 minutes to raise air pressure.

The prototype particulate sampling system didn't perform in a satisfactory manner, so reporting is limited to NO_x emissions only. Figures 12.112–12.114 show NO_x emissions as a function of test repetition number for the various technologies. The Figures are for Braunschweig with a duration of some 30 minutes. Each Figure includes three curves:

- cold start (on-the-road)
- warm start (on-the-road)
- warm start (chassis dynamometer, reference).

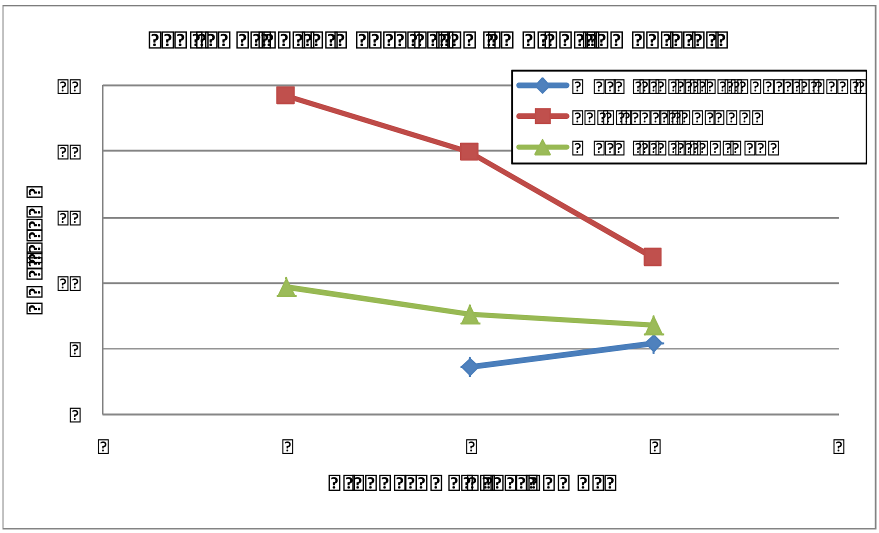


Figure 12.112. Development of NO_x emissions as a function of number of repetitive tests. Braunschweig cycle, EEV EGR diesel vehicle.

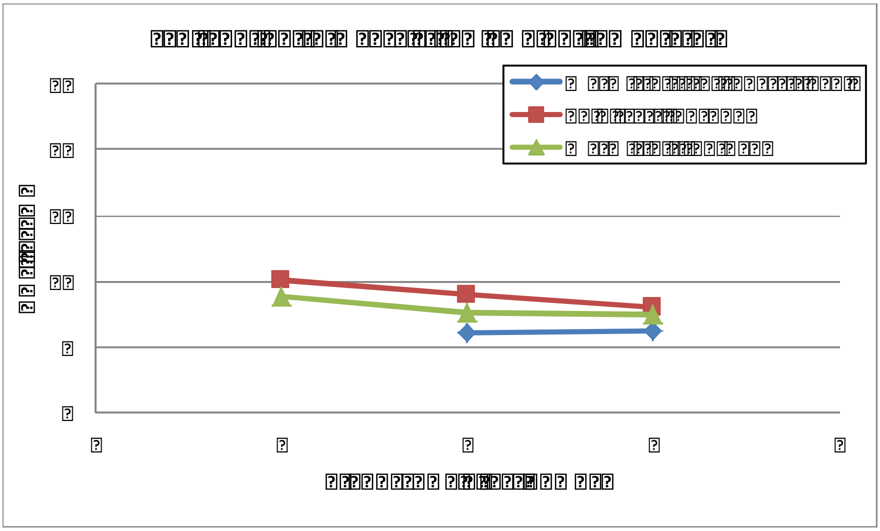


Figure 12.113. Development of NO_x emissions as a function of number of repetitive tests. Braunschweig cycle, EEV SCR diesel vehicle.

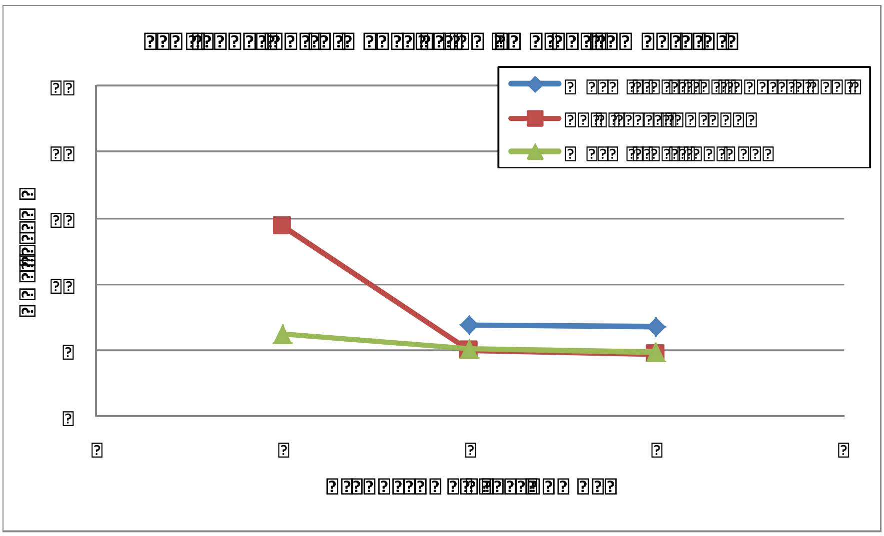


Figure 12.114. Development of NO_x emissions as a function of number of repetitive tests. Braunschweig cycle, EEV SCRT diesel vehicle.

After a cold start, the NO_x emission stabilizes after two to four repetitive cycles. Temperature has little effect on the NO_x emissions of the SCR vehicle, with all results in the range of 6–10 g/km. In the case of the SCRT vehicle, cold start increases NO_x with a factor of 3 (absolute value 15 g/km), for the EGR vehicle with a factor of some 4 (absolute value 25 g/km).

The presumption was that the SCR equipped vehicles would display greater temperature dependence than the EGR vehicle in the cold start phase. However, this was not the case. The results indicate that in the EEV EGR vehicle, the EGR rate is temperature controlled, delivering full EGR rate only when the engine is fully warmed up.

For all vehicles, the stabilized NO_x level, whether on the road or on the chassis dynamometer, is 5–7 g/km. This is an indication of two things. Firstly, the on-road measurements and the chassis dynamometer measurements correlate rather well. Secondly, when warmed up, all three vehicles deliver roughly equivalent NO_x performance.

Figures 12.115 and 12.116 show development of exhaust and coolant temperatures for the EEV EGR diesel vehicle. The exhaust temperature is already stabilized at the end of the first cycle, whereas the coolant temperature has only just stabilized at the end of the third cycle.

Figures 12.117–12.119 show coolant temperatures and NO_x emissions in parallel. These graphs are generated by running repetitive SORT 2 cycles (duration some 3 minutes) after cold start and the 5 minute idling period. Figure 12.111 shows that it takes some 40 minutes to stabilize the NO_x emission on the EEV EGR vehicle, and half of that, some 20 minutes, for the SCR vehicles. Both SCR vehicles show a "local" NO_x peak at some 30 minutes after start. There are substantial differences in the time needed to reach stabilized coolant temperature, 25 minutes for the SCR vehicle, 45 minutes for the EGR vehicle and some 60 minutes for the SCRT vehicle.

The conclusion is that cold start has an effect on emissions, in this case NO_x emissions. However, taking into account that a city bus is normally operated up to 18 hours a day, the contribution from one real cold start per day to emissions is negligible. Ambient temperature as such has little effects on the emissions of a warmed-up vehicle.

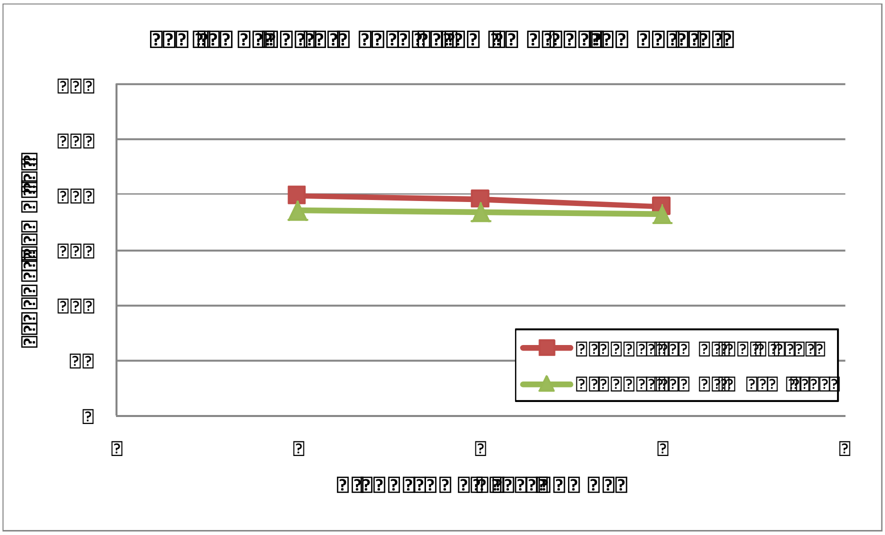


Figure 12.115. Development of exhaust temperature. Braunschweig cycle. EEV EGR diesel.

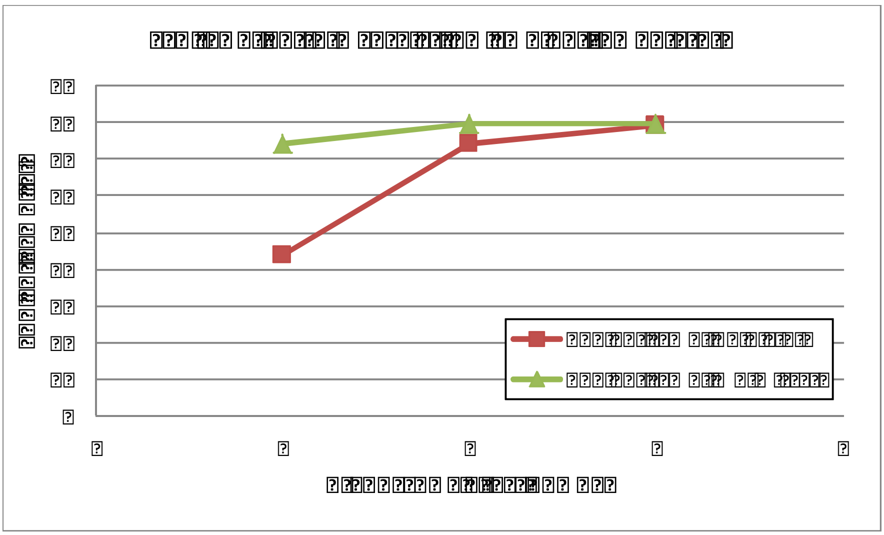


Figure 12.116. Development of exhaust temperature. Braunschweig cycle. EEV EGR diesel.

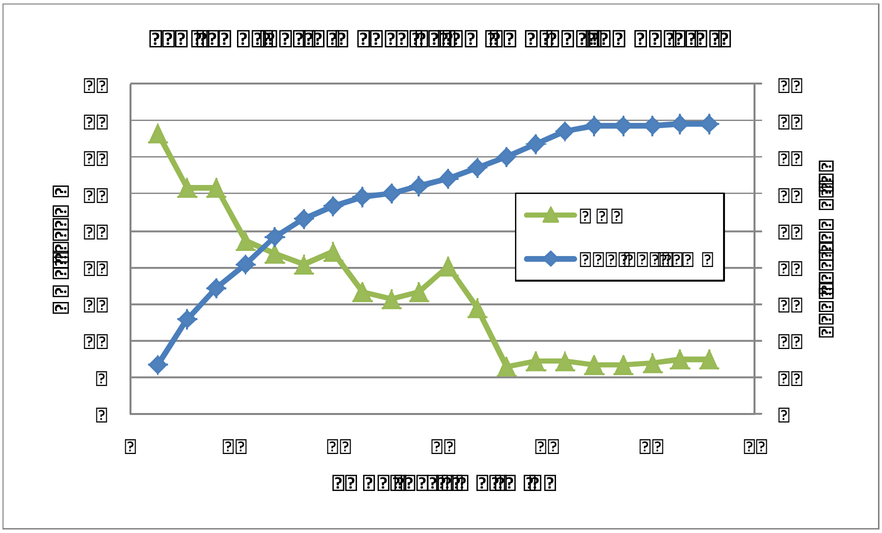


Figure 12.117. Development of coolant temperature and NO_x emission. SORT 2 cycle, EEV EGR diesel.

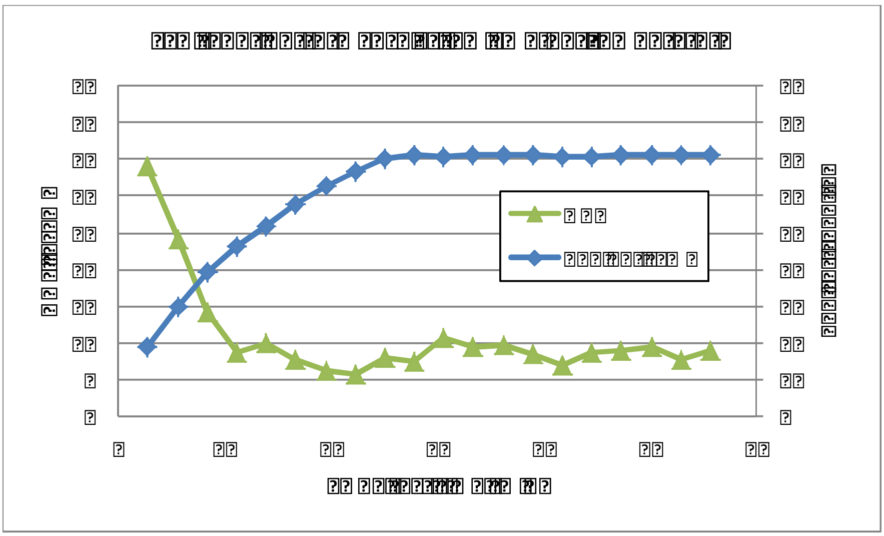


Figure 12.118. Develepment of coolant temperature and NO_x emission. SORT 2 cycle, EEV SCR diesel.

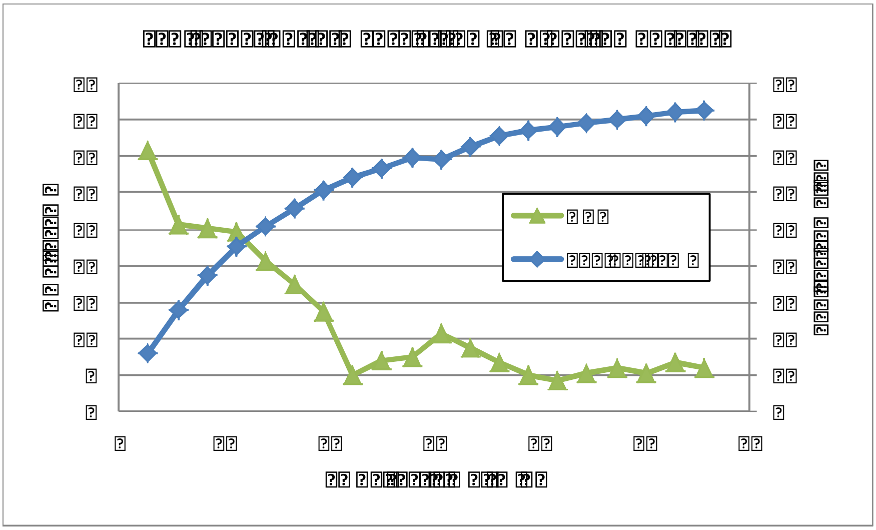


Figure 12.119. Development of coolant temperature and NO_x emission. SORT 2 cycle, EEV SCRT diesel.

13. WTW results

13.1 General

In Chapter 11, a WTT (well-to-tank) comparison of fuels from different feedstocks was presented. Three different models were used for the assessment: GREET model (USA), GHGenius model (Canada) and RED methodology (EU).

Most assessments focus on greenhouse gases, and the WTT results are typically presented in the form of g CO_{2eqv}/MJ_{fuel}. To calculate WTW (well-to-wheels) values, one needs to know the fuel or the energy consumption per driven unit of distance.

In Chapter 12, tank-to-wheel data (end-use) was presented. Included in the data is energy consumption as well as CO_2, CH_4 and for some vehicles also N_2O emission.

The specific CO_2 emission of diesel fuel combustion is typically some 75 g CO_{2eqv}/MJ, and the WTT emission some 20 g CO_{2eqv}/MJ. With an energy consumption of 16 MJ/km (typical European vehicle, Braunschweig cycle), the WTW GHG emission is some 1500 g CO_{2eqv}/km (16 * 95= ~1500).

In the case of RED, the combustion of a biofuel is considered CO_2 neutral. CH_4 and N_2O can be added to the combustion emissions.

GHGenius also considers combustion of biofuels carbon neutral. However, for the combustion part of biofuels GHGenius presents CO_{2eqv} consisting of CH_4 and N_2O.

GREET has another approach, as it presents CO_2, CH_4 and N_2O for the combustion of all fuels. Biofuels are taken into account with a negative value for WTT CO_{2eqv} (the carbon absorption of the growing biomass is counted as a negative emission).

In addition to greenhouse gas emissions, GREET and GHGenius also present estimates for energy use and criteria emissions (CO, VOC, NO_x, $PM_{2.5}$, PM_{10} and $SO_{x)}$. Values are given for fuel production as well as fuel combustion. The RED methodology only considers greenhouse gas emissions.

Eight vehicles were chosen to demonstrate WTW results:

- Older diesel vehicles
  - EPA 1998
  - Euro II
- Current diesel vehicles
  - EPA 2010 (1)
  - EEV SCRT
  - Hybrid 4 (series)
- Alternative fuel vehicles
  - CNG (stoichiometric)
  - Ethanol
  - DME (prototype vehicle).

The CO_{2eqv} values were calculated as follows:

RED

- Fuel production values according to Table 11.5
- Fuel combustion values
  - Diesel 73.3 g CO_{2eqv}/MJ[7] (not 70.0 as in Table 11.5)
  - Synthetic diesel 70.8 g CO_{2eqv}/MJ[3]
  - CNG (methane) 56.2 g CO_{2eqv}/MJ[3]
  - Combustion of biofuels CO_2 neutral
  - CH_4 added to combustion emissions for CNG, ethanol and DME (CO_2 equivalence 23[8])
  - The N_2O emissions from combustion is not accounted for.

GHGenius

- Full lifecycle CO_{2eqv} emissions according to Table 11.3
- Combustion of biofuels considered CO_2 neutral, CH_4 and N_2O from combustion taken into account.

GREET

- Fuel production and fuel combustion CO_{2eqv} emissions according to Table 11.2.

In each case, the emissions from fuel combustion were calculated from energy consumption of the buses and the tabulated specific CO_2eqv emissions. Only in the case of RED, measured CH_4 emissions were added.

There are some reasons for using tabulated values for combustion and vehicle energy consumption to determine end-use emissions instead of using measured tailpipe CO_2, CH_4 and N_2O emissions. At VTT, vehicle energy consumption was, with the exception of one vehicle, determined from gravimetric fuel consumption, a method that provides better accuracy than calculation from exhaust gas flow and exhaust composition. Secondly, VTT didn't measure tailpipe N_2O emissions. Thus it was decided to use tabulated values (GHGenius, GREET) catering for CO_2, CH_4 and N_2O.

[7] JEC WTW 2011, Edwards et al.
[8] RED (based on IPCC 2001).

The fuel used in heavy-duty ethanol engines is not neat ethanol, but hydrous ethanol treated with additives. This assessment, however, is done as if this fuel was neat ethanol.

The abbreviations used for the fuel chains in the following Figures and Tables are presented in Chapter 11.

13.2 CO_{2eqv} comparison of vehicle and fuel combinations

Figures 13.1–13.3 (five diesel vehicles) and 13.4–13.6 (SCRT diesel vehicles and alternative fuel vehicles) present summaries of WTW values for different vehicle and fuel combinations. The values are compiled using RED, GHGenius and GREET, respectively. The abbreviations used for fuels are explained in Tables 11.2 (GREET), 11.4 (GHGenius) and 11.6 (RED). The driving cycle is Braunschweig.

In Figures 13.1–13.3, all diesel fuel alternatives covered in the WTT assessments are included. Figures 13.4–13.6 (SCRT diesel, CNG, ethanol and DME) include the fossil alternatives for diesel and CNG and in addition, the biofuel alternatives delivering the highest and the lowest overall CO_{2eqv} for all vehicle categories. All Figures have the same scale (0–4000 g CO_{2eqv}/km). According to GREET, ethanol from corn stover, switchgrass and farmed wood shows a negative GHG balance. The calculated WTW value for farmed wood ethanol is -118 g CO_{2eqv}/km, shown in Figure 13.6 as zero.

It is clear that for WTW greenhouse gas emissions fuel is more decisive than vehicle. Within diesel vehicles and diesel hybrids, the ratio between highest (EPA 2010 (1)) and lowest (Hybrid 4 series) WTW value is 2:1, proportional to fuel consumption. As for fuels, the ratio between highest and lowest WTW value is 120:1 (CTL from coal versus tallow FAME, values from GHGenius).

Table 13.1 presents a summary of CO_{2eqv} values. The values are for the vehicles covered in Figures 13.4–13.6. Included are four fossil pathways (GTL, conventional diesel, CNG, natural gas based DME) and the renewable pathways delivering highest and lowest WTW CO_{2eqv}values. Please note that this assessment only covers the fuels listed in Chapter 11. This assessment probably covers the best of biofuels, but not the worst ones.

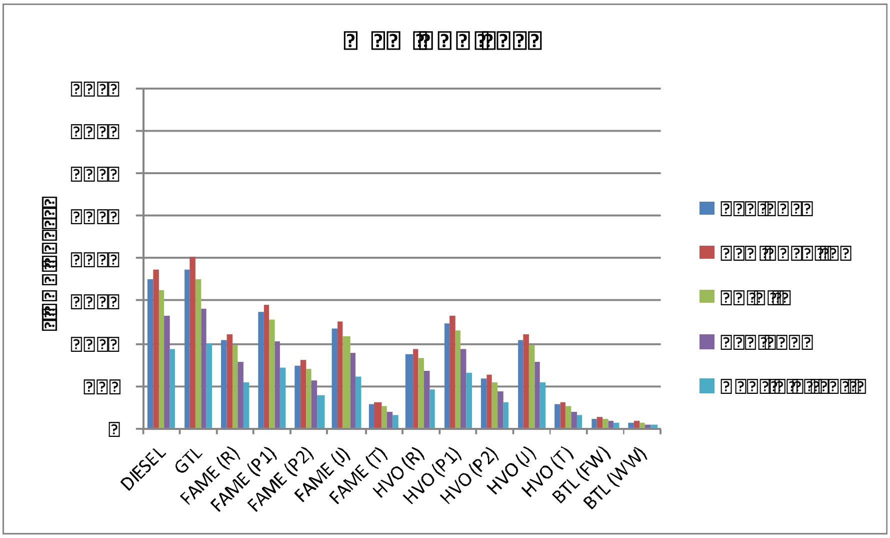


Figure 13.1. WTW GHG emissions for diesel vehicles. RED methodology. Braunschweig cycle. FAME (J), HVO (J) and HVO (T) estimations.

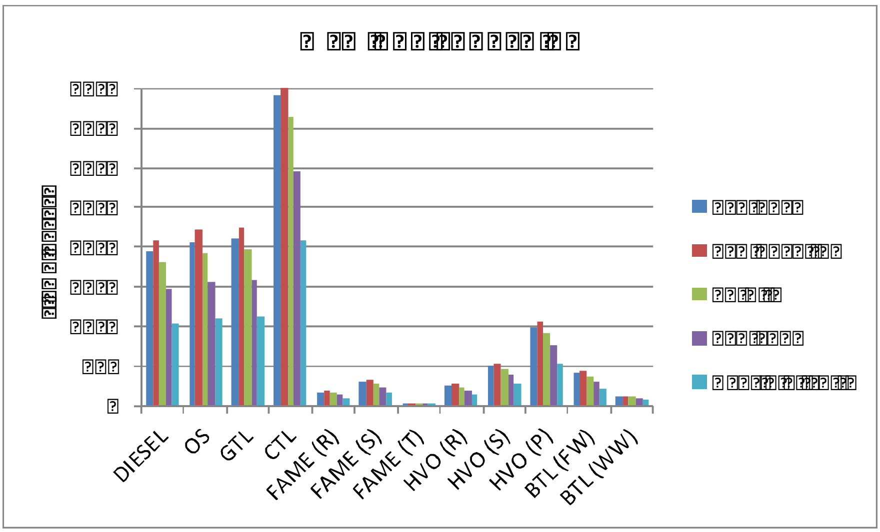


Figure 13.2. WTW GHG emissions for diesel vehicles. GHGenius methodology. Braunschweig cycle.

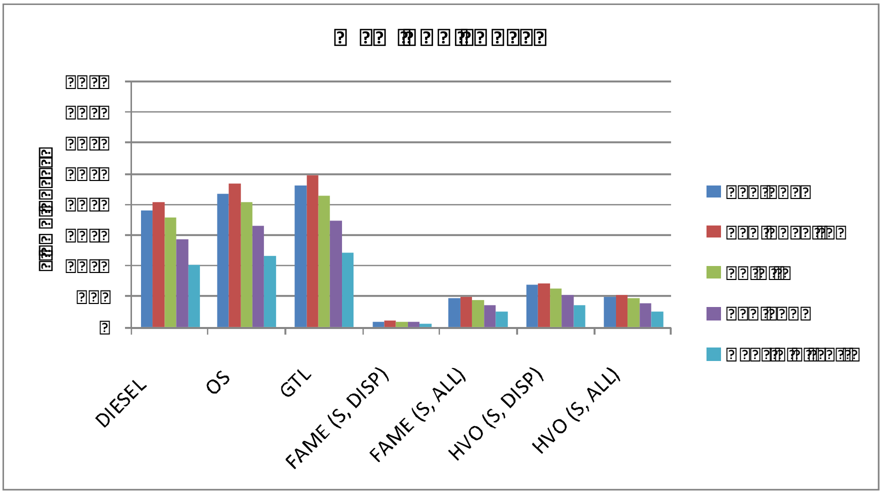


Figure 13.3. WTW GHG emissions for diesel vehicles. GREET methodology. Braunschweig cycle.

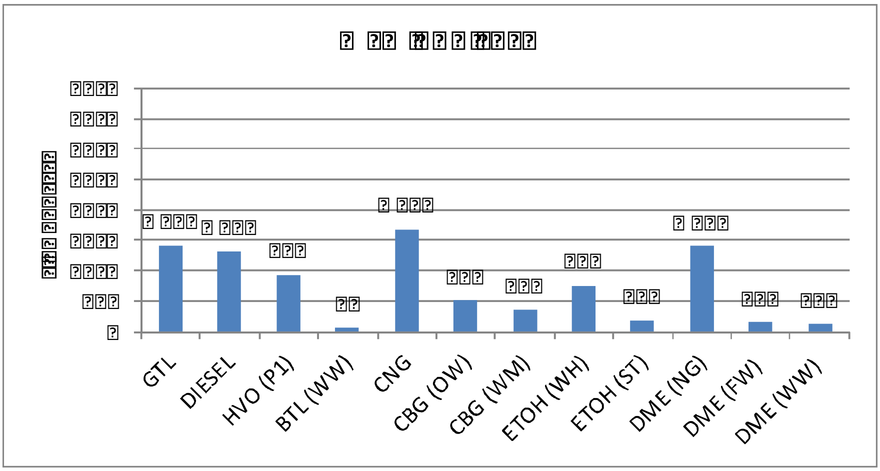


Figure 13.4. WTW GHG emissions for SCRT diesel and alternative fuel vehicles. RED methodology. Braunschweig cycle.

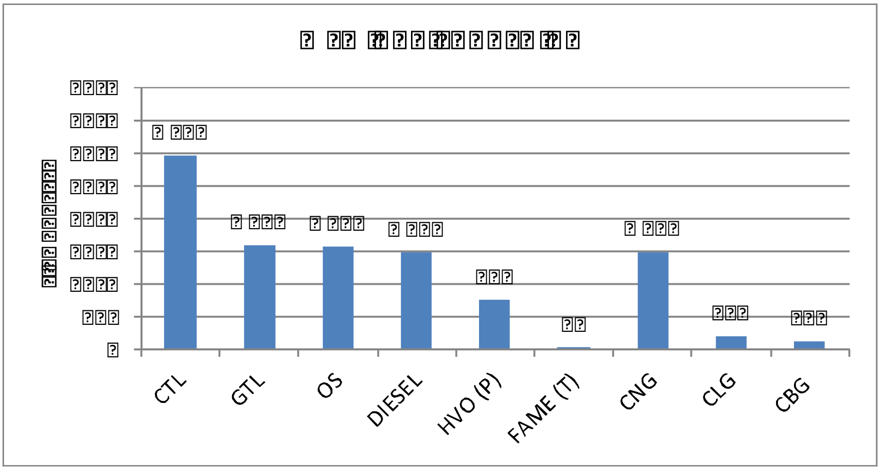


Figure 13.5. WTW GHG emissions for SCRT diesel and alternative fuel vehicles. GHGenius methodology. Braunschweig cycle.

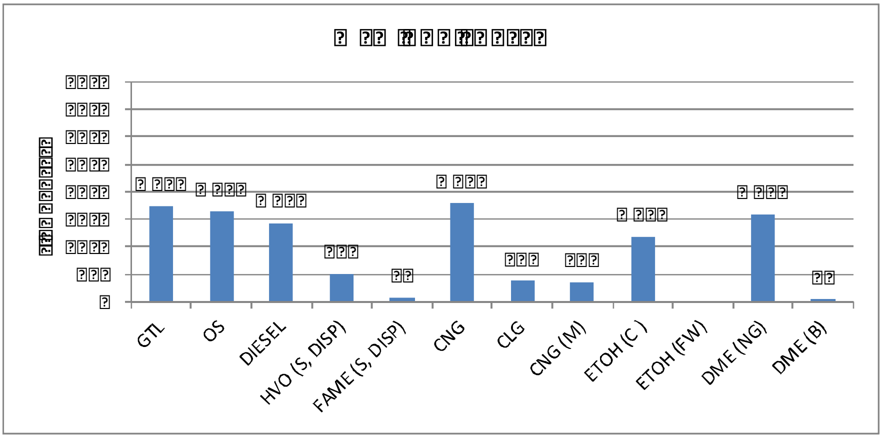


Figure 13.6. WTW GHG emissions for SCRT diesel and alternative fuel vehicles. GREET methodology. Braunschweig cycle.

Table 13.1. Summary of CO_{2eqv} values. Highest and lowest value for each category highlighted.

	Diesel fossil		Diesel renewable		GNG	CBG ren.		Ethanol		DME fossil	DME renewable	
	GTL	conv.	max	min		max	min	trad.	lign.		max	min
RED			HVO(P1)	BTL(WW)		OW	WM	WH	ST		FW	WW
	1417	1324	943	61	1693	500	350	764	185	1399	151	120
GHGEN			HVO(P)	FAME(T)		LF	OW					
	1590	1473	751	24	1489	195	124					
GREET			HVO(D)	FAME(D)		CLG	CNG(M)	C	FW			B
	1745	1441	513	75	1794	372	360	1189	-119	1596		41
AVG	1584	1413			1659					1498		
Relative to regular diesel (%)												
	+12	100			+17					+6		

For diesel, both conventional and GTL, RED (in combination with JEC combustion values) gives lower WTW CO_{2eqv} values than GHGenius or GREET. For CNG, the situation is reversed.

The values for diesel fuel and CNG combustion are in rather good congruence, for obvious reasons (the European values for combustion referred to here are based on JEC):

- Conventional diesel fuel
  - JEC 73.3 g CO_2/MJ
  - GHGenius 75.2 CO_{2eqv}/MJ
  - GREET 75.8 CO_{2eqv}/MJ
- GTL
  - JEC 70.8 g CO_2/MJ
  - GHGenius 72.2 CO_{2eqv}/MJ
  - GREET 73.2 CO_{2eqv}/MJ
- CNG
  - JEC 56.2 g CO_2/MJ
  - GHGenius 58.9 CO_{2eqv}/MJ
  - GREET 57.6 CO_{2eqv}/MJ

The differences arise from the WTT part (the European value for diesel from RED, the values for GTL and CNG from JEC):

- Conventional diesel fuel
  - RED 13.8 g CO_{2eqv}/MJ[9]
  - GHGenius 21.7 CO_2eqv/MJ
  - GREET 19.0 CO_2eqv/MJ
- GTL
  - JEC (remote plant) 22.4 g CO_{2eqv}/MJ
  - GHGenius 32.4 CO_{2eqv}/MJ
  - GREET 41.6 CO_{2eqv}/MJ

[9] The JEC WTW 2011 value 15.9 g CO_2eqv/MJ.

- CNG
  - JEC (remote gas) 22.3 g CO_{2eqv}/MJ
  - GHGenius 10.4 CO_{2eqv}/MJ
  - GREET 25.9 CO_{2eqv}/MJ.

CNG is roughly equivalent to diesel for tailpipe CO_2 emissions. The overall WTW balance depends on the type of gas, local or remote. For Europe, CNG values are for remote (7000 km) natural gas. The values for GTL and DME, on the other hand, are for remote processing and transportation by ship.

For CNG, the GHGenius WTT value is lower than for Europe and USA, due to shorter transports. Using RED and GREET values, CNG gives some 25% higher WTW GHG emissions compared to diesel, using GHGenius equivalent values.

In comparison with conventional diesel fuel, on an average, CNG and GTL increase WTW GHG emissions by some 10–15%, DME slightly less.

In the case of CNG, the result would have been almost identical for the more fuel efficient lean-burn CNG vehicle, as it has higher CH_4 emissions than the stoichiometric CNG vehicle (using RED values 1693 versus 1646 g of WTW CO_{2eqv}/km).

In the case of Europe, DME delivers equivalent GHG compared to GTL when both are based on remote processing, somewhat lower compared to CNG based on remote natural gas. If both DME and CNG are based on remote gas (DME processing in Europe), these fuels deliver equivalent WTW GHG emissions. The higher efficiency of the DME engine is sufficient to compensate for the high WTT emissions of the fossil DME path.

In summary, the WTW CO_{2eqv} emissions for the fossil pathways are:

- Conventional diesel 1324–1473 g CO_{2eqv}/km (EEV SCRT vehicle)
- Oil sands diesel 1564–1639 g CO_{2eqv}/km (EEV SCRT vehicle)
- GTL 1417–1745 CO_{2eqv}/km (EEV SCRT vehicle)
- CNG 1489–1794 g CO_{2eqv}/km (EEV stoichiometric)
- DME 1399–1596 g CO_{2eqv}/km (DME prototype vehicle).

CTL, included in GHGenius, is in a class of its own, with WTW GHG emissions being some 3000 g/km for the EEV SCRT vehicle.

Still, the variation for biofuels is significantly higher. This is due to actual differences in feedstocks and biofuels processing, but also due to differences in the WTT assessment methods, system boundary settings and calculation parameter assumptions. GREET actually presents results with two different methods, the Displacement Method and the Energy Allocation Method.

The biofuel pathways covered in this study fall into three categories for GHG reductions in comparison to conventional fossil diesel (taking into account fuel carbon intensity as well as vehicle efficiency, excluding the GREET ethanol alternatives delivering a negative WTW balance):

1. Biofuels from traditional feedstocks for diesel vehicles:
   - Range of WTW CO_{2eqv} ~ 450 950 g/km
   - Relative reduction ~ 30 70%
2. Conventional biogas in spark-ignition CNG vehicles:
   - Range of WTW CO_{2eqv} ~ 100 500 g/km
   - Relative reduction ~ 65 90%
3. Biofuels from lignocellulosic feedstocks or waste in vehicles using diesel combustion (diesel, ethanol, DME):
   - Range of WTW CO_{2eqv} ~ 25 200 g/km (lowest value GHGenius for tallow FAME)
   - Relative reduction ~ 85 95%.

Comparing FAME and HVO type biodiesel fuels one should observe than the main differences arise from the feedstock, not from the processing. For the same feedstock, in this case rapeseed oil, the RED methodology gives lower production CO_{2eqv} emission values for HVO than for FAME, 44 vs. 52 g CO_{2eqv}/MJ. The values for GHGenius, on the other hand, are the other way around, 6.7 g CO_{2eqv}/MJ for rapeseed oil (canola) based FAME and 10.9 g CO_{2eqv}/MJ for HVO. Please note that the Canadian values for rapeseed are much lower than the European ones, partly reflecting differences in the calculation methodology (GHGenius uses displacement method for biofuels) and parameter assumptions, and partly differences in the conditions for growing the crop. In the case of GREET (soybean), HVO gives significantly higher values than FAME using displacement, which may be caused by by-product types and amount between the two fuel pathways. When energy allocation is used, the results are roughly equivalent for HVO and FAME.

Figures 13.1–13.6 do not account for the CO_{2eqv} emissions either from urea decomposition in the vehicle or from urea production.

In Paragraph 12.1 it was stated that the decomposition of urea in SCR vehicles has no significance for tailpipe CO_{2eqv} emissions (less than 1% contribution). However, in a WTW assessment, the CO_{2eqv} emissions of urea production should be evaluated. The CO_{2eqv} emission of urea production from natural gas via ammonia is 3.28 kg CO_{2eqv}/kg urea (Ecoinvent Database). For the 32.5% solution this means 1.07 kg CO_{2eqv}/kg solution. This again, with a urea solution consumption of 2.5 kg/100 km, means a contribution of some 25 g/km to WTW CO_{2eqv} emissions. This level is of no great significance for diesel vehicles running on conventional fuels, but in the case of the best biodiesel pathways it is as high as 50% of the other WTW GHG emissions.

13.3 Comparison of tabulated and measured end-use TTW data

In EC's measurements, N_2O emissions varied as follows:

- EPA 1998: 14–66 mg/km
- EPA 2007: 11–65 mg/km

- EPA 2007 6.7 L Hybrid: 5–34 mg/km
- EPA 2007 8.9 L Hybrid: 59–78 mg/km
- EPA 2010 8.9 L (1): 97–278 mg/km
- EPA 2010 8.9 L (3): 54–342 mg/km.

The EPA 2007 8.9 L Hybrid was tested using the Manhattan cycle only, the other results include cycle as well as fuel effects (cycle effects are dominating). Normally Manhattan delivers highest and UDDS lowest N_2O values. The 2010 vehicles utilizing SCR give higher N_2O values than the older vehicles. Using an equivalence ratio of 298, the N_2O emissions constitute a CO_{2eqv} emission of 1.5–102 g/km. In relative terms the contribution of N_2O to CO_{2eqv} is in the range on 1–4%.

The highest CH_4 value measured by EC was 0.016 g/km. With an equivalence ratio of 23, this would correspond to 0.4 g CO_2eqv/km, or a negligible number. EC only measured diesel vehicles. EC's total GHG values are presented in Figures 12.22–12.24.

VTT also measured dedicated alternative fuel vehicles. The CNG vehicles, the ethanol vehicle and the prototype DEM vehicle all emitted some amounts of CH_4. Figure 13.7 presents a comparison of measured and calculated CO_{2eqv} values for some of VTT's measurements. For each technology four values are presented:

- MEAS: measured value (tailpipe CO_2 + CH_4 with an equivalence ratio of 23 + N_2O with an equivalence ratio of 298, N_2O values from EC's measurements)
- JEC: value calculated based on measured energy consumption and JEC's value for combustion CO_2 intensity, CH_4 and N_2O with equivalence ratios added
- GHG: value calculated on measured energy consumption and tabulated CO_{2eqv} value from GHGenius
- GREET: value calculated on measured energy consumption and tabulated CO_{2eqv} value from GREET.

Figure 13.7 shows that the differences are not substantial, in all cases less than 10% between highest and lowest value for a given vehicle (inaccuracy of the measurement of tailpipe CO_2 emission being the main source of variations).

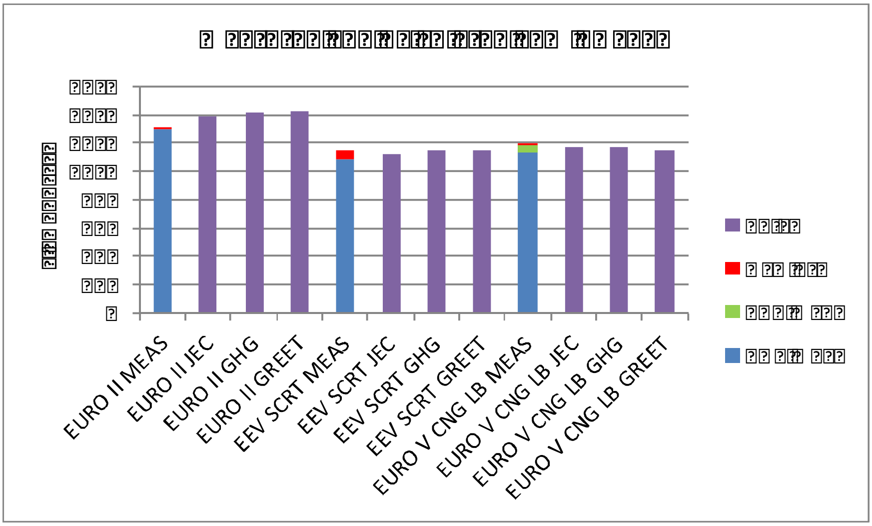


Figure 13.7. A comparison of measured and calculated CO_{2eqv} values for some of VTT's measurements. Braunschweig cycle.

13.4 Total energy consumption

GREET presents values for WTT energy consumption. The RED methodology doesn't encompass energy use. However, the JEC report (JEC WTW 2011, Edwards et al.) present WTT energy use for various fuel pathways.

In general, biofuels pathways are more energy consuming than fossil fuel pathways. However, despite of high energy consumption, biofuel pathways with very low CO_2 intensity, e.g., biomass pathways based on lignocellulosic feedstocks, can deliver low overall CO_2 emissions.

Table 13.2 presents WTT energy use for selected fuel pathways according to JEC (Europe) and GREET. Highest value is 1.83 MJ/MJ (HVO from soy, displacement method) and lowest value 0.15 MJ/MJ (CNG, GREET), a ratio of 12:1. The WTT energy use for biofuels is in the range of 0.87 MJ/MJ (biogas from organic waste, JEC) to 1.83 MJ/MJ (HVO from soy, displacement method). Average value for biofuel chains is some 1.3 MJ/MJ.

Table 13.2. WTT energy use (MJ/MJ) according to JEC and GREET.

FUEL	JEC	GREET
DIESEL	0.19	0.19
OS	-	0.42
GTL	0.63	0.70
FAME (R)	1.09	-
FAME (P1)	1.31	-
FAME (P2)	1.31	-
FAME (S, DISP)	-	1.64
FAME (S, ALL)	-	1.81
FAME (J)	-	-
HVO (R)	1.05	-
HVO (P1)	1.26	-
HVO (P2)	1.26	-
HVO (S, DISP)	-	1.83
HVO (S, ALL)	-	1.58
HVO (J)	-	-
HVO (T)	-	-
BTL (FW)	1.19	-
BTL (WW)	1.19	-
ETOH (SC)	1.81	1.25
ETOH (ST)	1.32	-
ETOH (WH)	1.66	-
ETOH (C)	-	1.41
ETOH (CS)	-	0.96
ETOH (SG)	-	1.03
ETOH (FW)	-	1.31
ETOH (WW)	-	1.08
DME (NG)	0.53	-
DME (FW)	1.07	-
DME (WW)	1.07	-
DME (B)	-	0.92
CNG	0.30	0.15
CBG (WM), CNG (M)	0.97	0.46
CBG (OW)	0.87	-
CLG	-	0.26

Figures 13.8 (JEC) and 13.9 (GREET) show total energy use (WTT + TTW= WTW) for the EEV SCRT diesel and the alternative fuel vehicles (in MJ/km). These Figures take into account the energy needed to produce the fuel and the energy consumption of the vehicle itself. Highest value is 46.5 MJ/km (ethanol from sugarcane, JEC) and lowest 18.1 MJ/km (diesel, JEC and GREET), and in this case the ratio is 2.5:1.

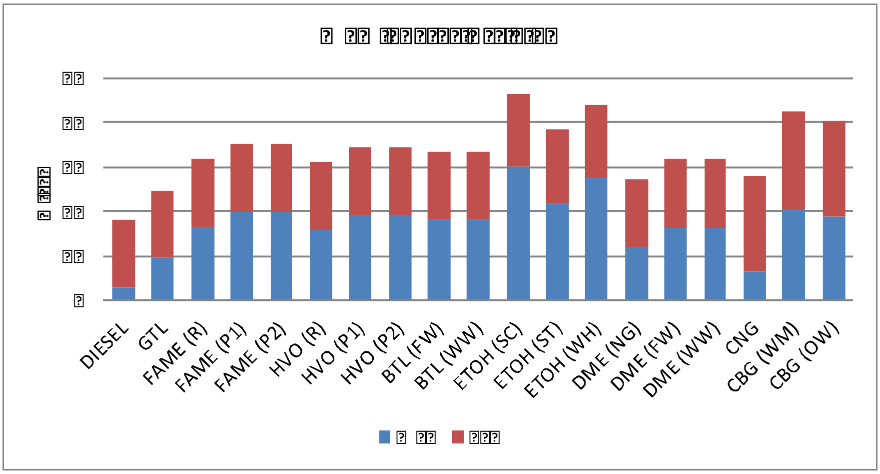


Figure 13.8. WTW energy using JEC values (Europe). Braunschweig cycle.

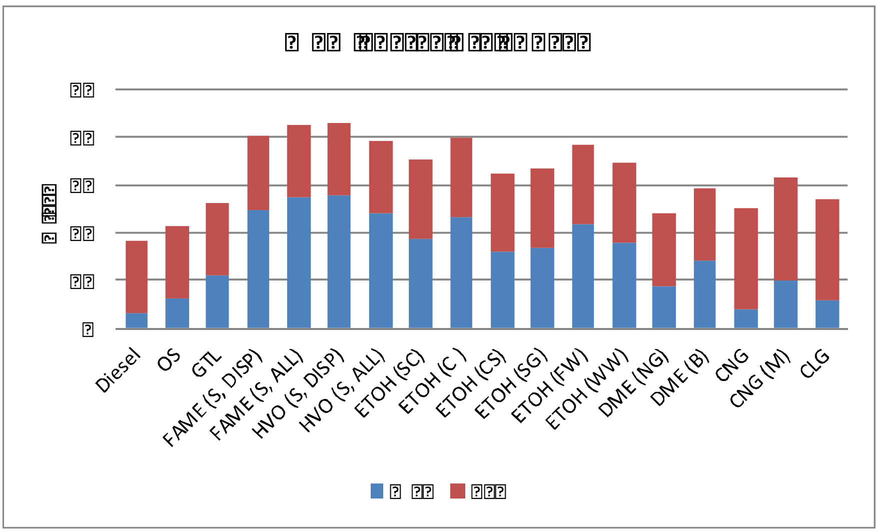


Figure 13.9. WTW energy using GREET values (USA). Braunschweig cycle.

13.5 WTT vs. TTW criteria pollutants

GREET presents energy use, GHG emissions as well as criteria pollutant emissions for fuel production and fuel combustion. The values are given in the format of MJ/MJ or g/MJ. Figure 13.10 shows a comparison of actual measured criteria pollutants for end-use vs. tabulated values. The example is for North-American vehicles, EPA 1998 and EPA 2010 (1), the Manhattan cycle and commercial ULSD fuel (EC's measurements). The results are presented as g/km.

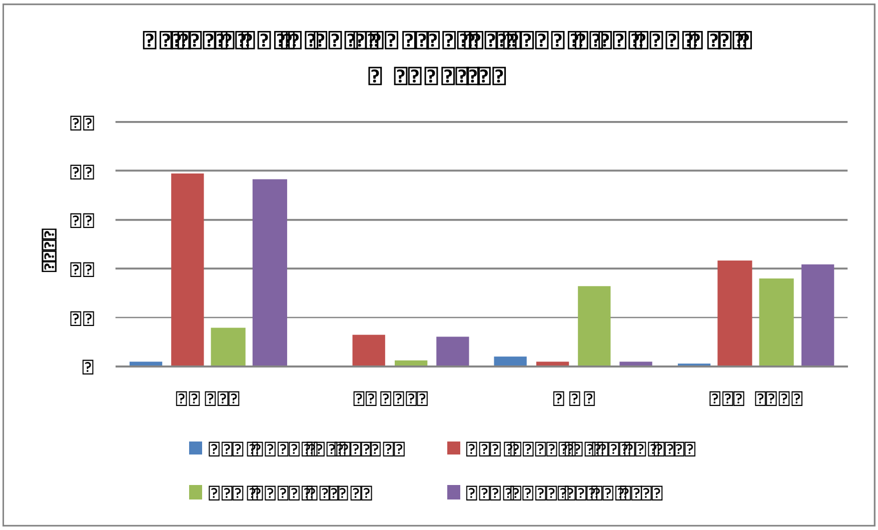


Figure 13.10. Comparison of actual criteria pollutants vs. GREET tabulated criteria pollutants. EPA 1998 and EPA 2010 (1) on commercial ULSD fuel in the Manhattan cycle.

Considering the huge differences in vehicle performance, only one set of tabulated values for combustion cannot fully predict end-use emissions. GREET seems to overestimate CO as well as THC/VOC emissions for both vehicle platforms. The calculated NO_x emission is lower than the actual EPA 2010 (1) emission, and significantly lower than the actual EPA 1998 emission. For TPM, the calculated value is in congruence with the actual EPA 1998 value, and thus much higher than the actual EPA 2010 (1) value.

This clearly indicates that variations in vehicle performance, approaching 1:50 for NO_x as well as particulate emissions, must be taken into account when evaluating end-use emissions.

Figure 13.11 shows criteria emissions for fuel production and end-use. This example is also for EPA 1998 and EPA 2010 (1). Both vehicles have roughly equivalent fuel consumption, so a single value is used for the fuel production part.

Figure 13.11 shows that fuel production is a bigger contributor than end-use for VOC/THC and particulate emissions, whereas in the case of NO_x the situation is reversed. This applies to both vehicles. For CO, with EPA 1998 end-use emissions are higher than fuel production emission, with EPA 2010 (1), end-use emissions are lower.

Table 11.3 and Figures 11.5–11.10 in Chapter 11 present fuel production and fuel combustion emission values for additional fuels.

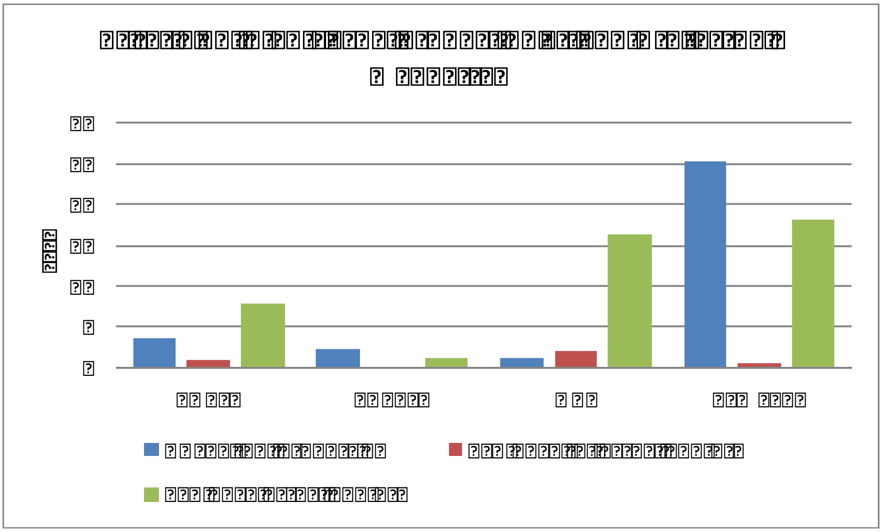


Figure 13.11. Comparison of criteria pollutants from fuel production (GREET tabulated values) and actual end-use criteria pollutants. EPA 1998 and EPA 2010 (1) on commercial ULSD fuel in the Manhattan cycle.

14. Cost assessment results

14.1 General

It was not possible to carry out in-depth cost assessments within this project. External costs of emissions were evaluated using European methodology. Direct costs were estimated by taking into account investment in vehicles, fuel and urea consumption and estimated fuel and urea price. Rough estimates of maintenance costs were made. All results presented in this Chapter, both for external costs and for direct costs, should be considered indicative only

14.2 External costs

14.2.1 Regulated emissions

Table 14.1 presents emission costs according to Directive 2009/33/EC. The regulated emissions accounted for are NO_x, NMHC and particulate matter.

Table 14.1. Cost for emissions in road transport (in 2007 prices). (2009/33/EC)

CO_2	NO_x	NMHC	Particulate matter
0,03-0,04 EUR/kg	0,0044 EUR/g	0,001 EUR/g	0,087 EUR/g

Directive 2009/33/EC gives average costs for emissions in the European Union, and doesn't differentiate where the emissions are generated. However, according to the Directive, higher values may be applied, on condition that the values do not exceed the values set out in Table 14.1 multiplied by a factor of 2.

The European "Handbook on estimation of external cost in the transport sector" (Handbook 2007) differentiates countries and in the case of particulates, also areas or regions:

- Urban metropolitan: cities with more than 0.5 million inhabitants
- Urban: smaller and midsized cities with up to 0.5 million inhabitants
- Outside built-up areas (values also used for the maritime sector).

The idea is that the cost of particulates increases with the size of the exposed population. Appendix 8 presents the cost factors for air pollution according to the "Handbook".

The calculations for this report are done for five different sets of values:

- Finland
- France
- Germany
- 2009/33/EC min. values
- 2009/33/EC max. values (multiplied by a factor of 2).

To cover variations in areas or differences in population density, three different duty cycles were included:

- ADEME (Paris, megacity M)
- Braunschweig (mid-sized city, U)
- UDDS (outside built-up areas, S.

Table 14.2 presents the emission costs used in the calculations.

Table 14.2. Emission costs used in the calculations (SO_2 not taken into account). Values from 2009/33/EC and Handbook on estimation of external cost in the transport sector (2008). The PM values in 2009/33/EC are not for a specified area or population density.

€/ton	NOx	NMVOC	SO2	PM 2.5 M	PM 2.5 U	PM 2.5 S
Finland	800	200	1800	337100	108600	28100
France	7700	1400	8000	392200	126300	78400
Germany	9600	1700	11000	384500	124000	75000
2009/33/EC min	4400	1000			87000	
2099/33/EC max	8800	2000			174000	

As can be seen in Table 14.2, the variations for NMVOC and NO_x by country are substantial. The values for France and Germany are close, whereas the values for Finland are much lower. Baseline 2009/33/EC NMVOC and NO_x values are rather low, but doubling the values brings them close to French and German values.

Variation in metropolitan and urban PM values by country is rather small according to the "Handbook", only the PM value outside build-up areas is much lower for Finland compared to France and Germany. The PM values in 2009/33/EC (average of without and with multiplication factor, 130 500 €/t) are close to the "Handbook's" values for urban areas.

The examples are calculated for 11 vehicle platforms, four conventional diesel vehicles (Euro II to EEV), four diesel hybrids and three alternative fuel vehicles (stoichiometric CNG, ethanol and DME). The results are presented in Figures 14.1 –14.3.

The calculatory external costs vary between 0.001 €/km (stoichiometric CNG, UDDS, Finnish values) and 0.24 (Euro II diesel, ADEME, German values), a factor of some 1:200. The values for Germany are, when comparing the same vehicle and the same cycle, 100–1000% higher than the Finnish ones. The values for Germany are some 10–25% higher compared to the values for France.

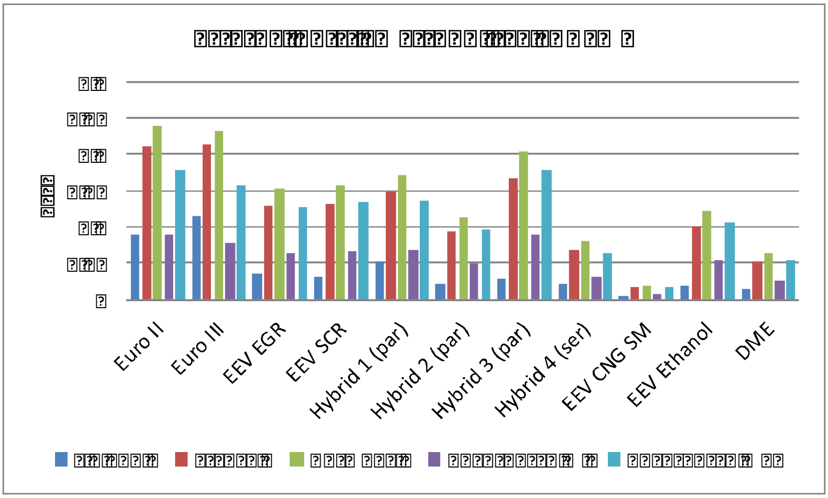


Figure 14.1. External costs. ADEME cycle, metropolitan area.

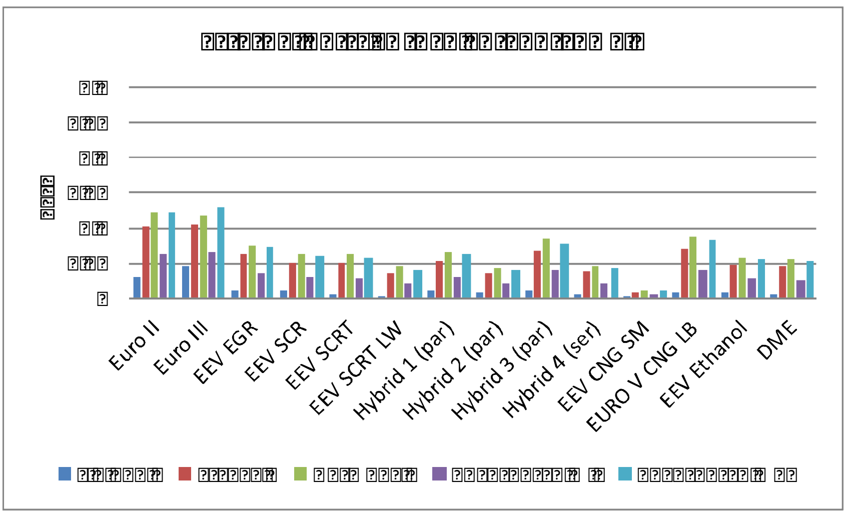


Figure 14.2. External costs. Braunschweig cycle, urban area.

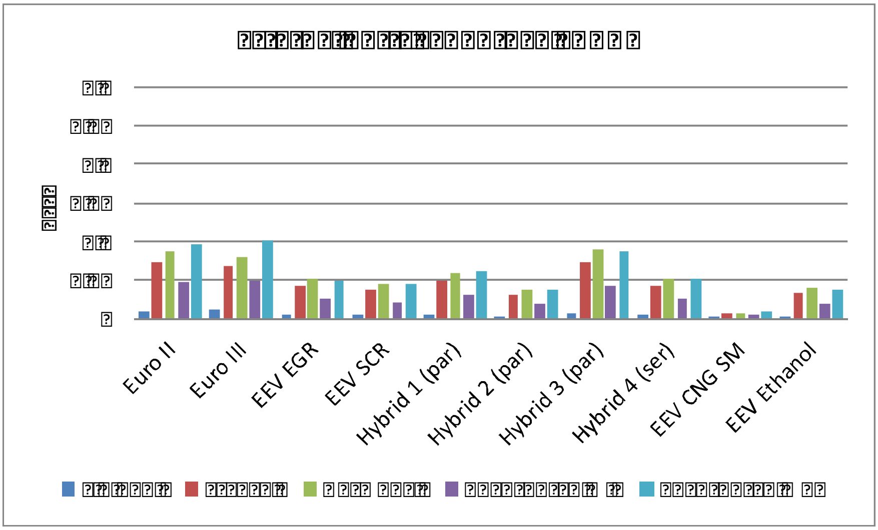


Figure 14.3. External costs. UDDS cycle, metropolitan area.

Looking at the vehicle technologies, Euro II and Euro III have the highest external costs, in the range of 0.01–0.24 €/km. Here it should be noted that the tested Euro III vehicle had rather high PM emission. Stoichiometric CNG has by far the lowest external costs, 0.001–0.02 €/km, 1/10 of older diesels.

Figure 14.4 (ADEME) and 14.5 (Braunschweig) show the emission costs for the calculated using emission cost values for Germany, in this case the most severe combination. The values are presented from highest to lowest.

For ADEME, the vehicles can be grouped into five categories:

- $\geq$ 0.20 €/km: Euro II, Euro III, Hybrid 3 (parallel)
- $\leq$ 0.15 < 0.20 €/km: Hybrid 1 (parallel), EEV SCR, EEV EGR
- $\leq$ 0.10 < 0.15 €/km: ethanol, Hybrid 2 (parallel)
- $\leq$ 0.05 < 0.10 €/km: Hybrid 4 (series), DME[*)]
- < 0.05 €/km: stoichiometric CNG.

[*)] value for DME indicative only.

For Braunschweig, more vehicles are included in the evaluation, and the numbers for emission costs compared to ADEME are roughly cut in half. Again, stoichiometric CNG gives lowest emission costs, some 0.01 €/km. Light-weight EEV SCRT, Hybrid 4 (series) and Hybrid 2 (parallel) qualify below 0.05 €/km. The cost factors accentuate NO_x emissions, and despite very low PM emissions, the lean-burn CNG vehicle delivers third highest emission costs, surpassed only by Euro II and Euro III diesel.

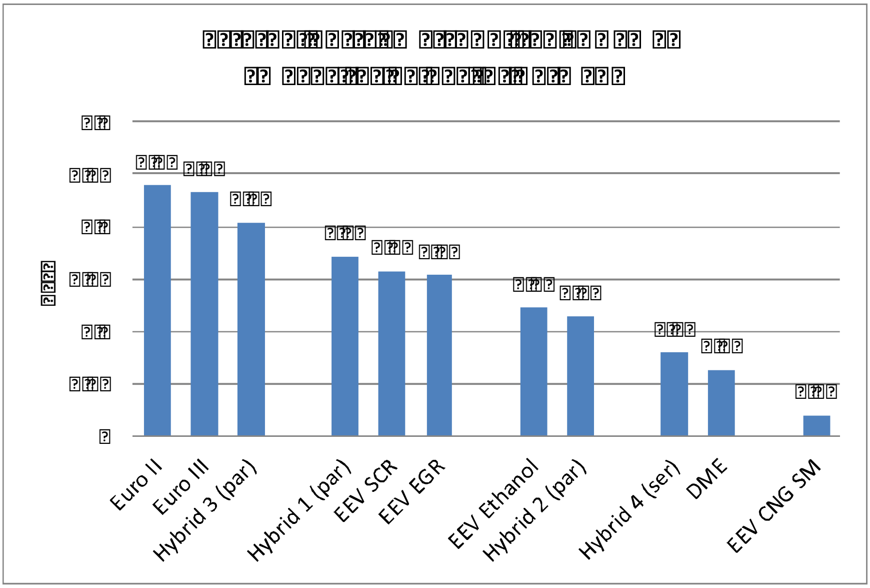


Figure 14.4. External costs. ADEME cycle, metropolitan area, using external costs for Germany (maximum case).

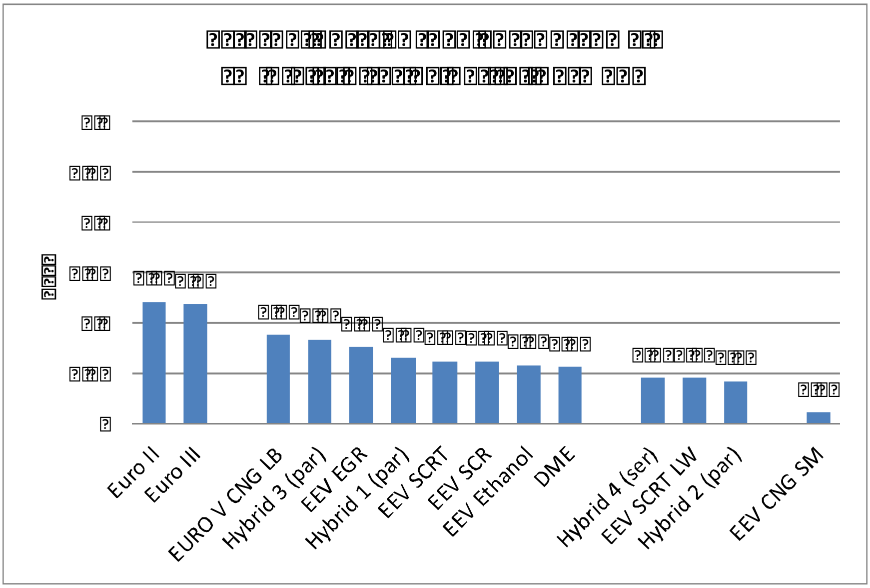


Figure 14.5. External costs. Braunschweig cycle, urban area, using external costs for Germany (maximum case).

Figure 14.6 shows the effect of fuel (commercial EN590 vs. 100% HVO) on external costs. The example is for ADEME and Braunschweig cycles and emission costs for Germany. The vehicles are Euro II and EEV SCR. For both cases, 100% HVO reduced both NO_x and PM emissions.

For the Euro II vehicle the calculatory emission benefit for switching from EN590 to 100% HVO is 0.03–0.05 €/km and for the EEV SCR vehicle less than half of that, 0.01–0.02 €/km. These figures are rather small compared to the difference between Euro II diesel and stoichiometric CNG of 0.11–0.22 €/km (Figures 14.4 and 14.5).

Figures 14.7–14.10 show the split-up on emission costs between NO_x, NMHC/NMVOC and PM. The examples are for Euro II, EEV SCRT, Euro V lean-burn CNG and EEV stoichiometric CNG. The cycle is Braunschweig, and the “Handbook” emission costs are for urban environment.

With the exception of the cases calculated with emission costs for Finland, NO_x totally dominates the aggregate calculatory emission costs. This is even true for the old Euro II diesel with high PM emissions. In the Figures, the contribution of NMHC/NMVOC is invisible.

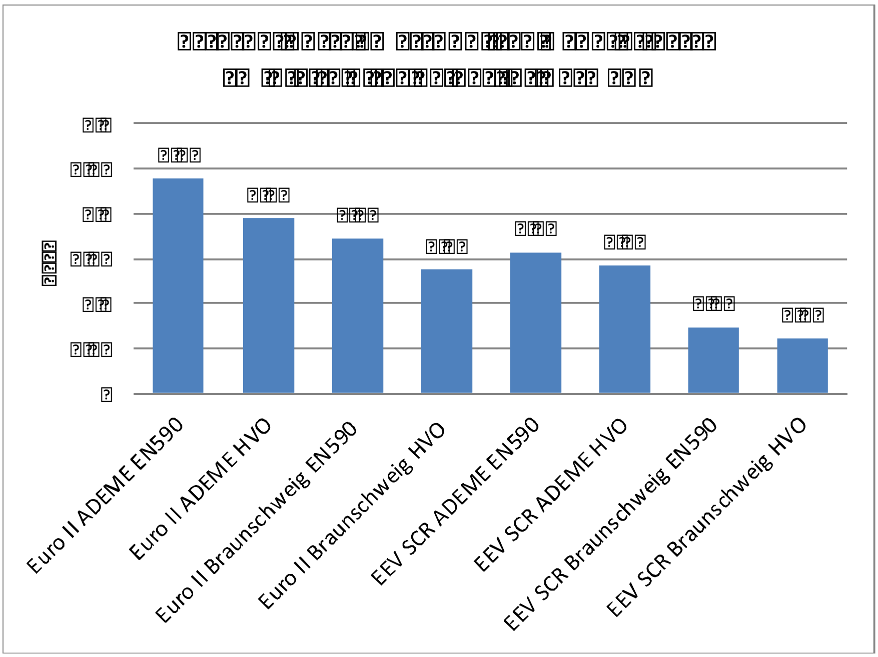


Figure 14.6. Effect of fuel on external costs. ADEME cycle, metropolitan area, using external costs for Germany. Euro II and EEV SCR vehicles, fuels EN590 and 100% HVO.

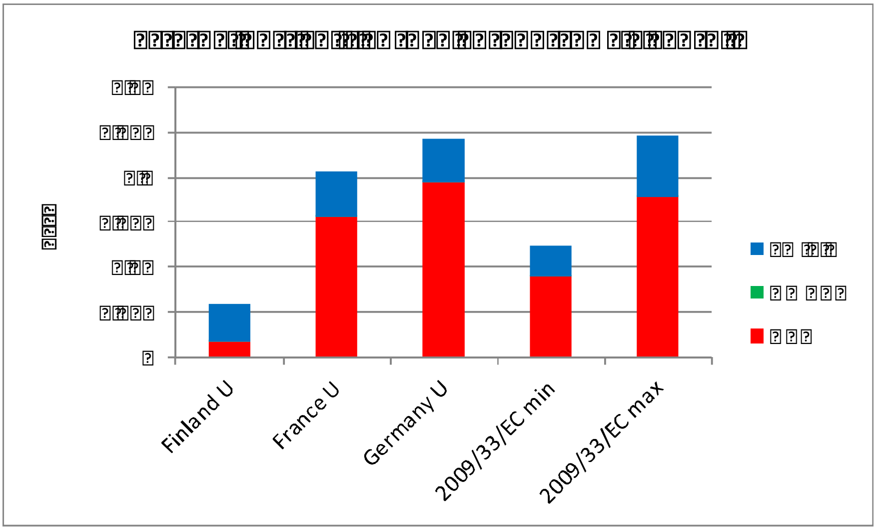


Figure 14.7. Split of emission costs. Braunschweig cycle, Euro II vehicle.

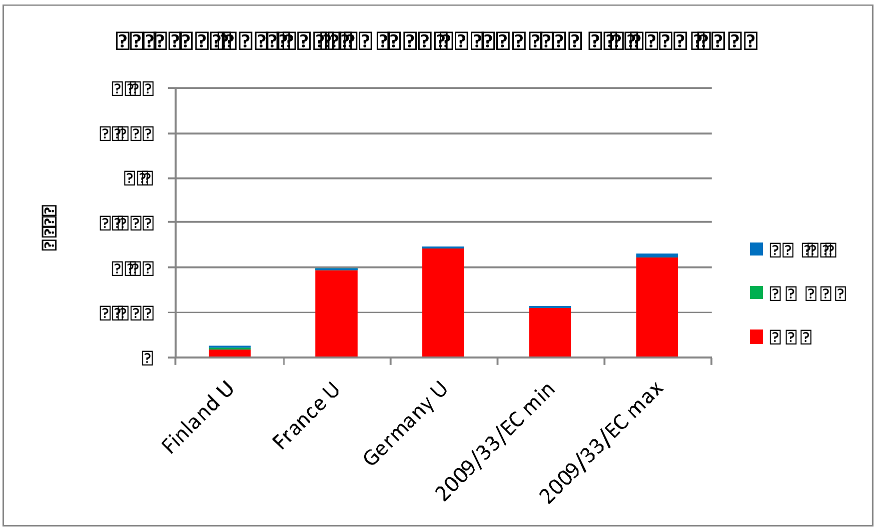


Figure 14.8. Split of emission costs. Braunschweig cycle, EEV SCRT vehicle.

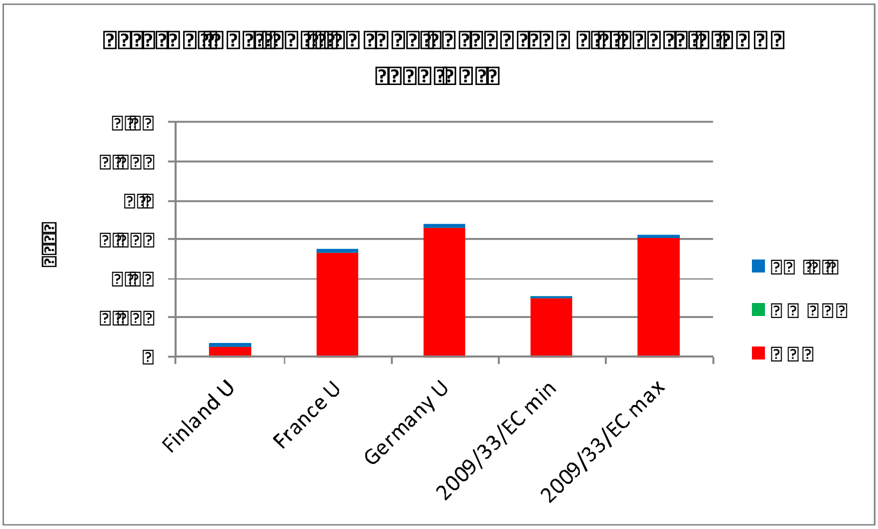


Figure 14.9. Split of emission costs. Braunschweig cycle, Euro V lean-burn CNG vehicle.

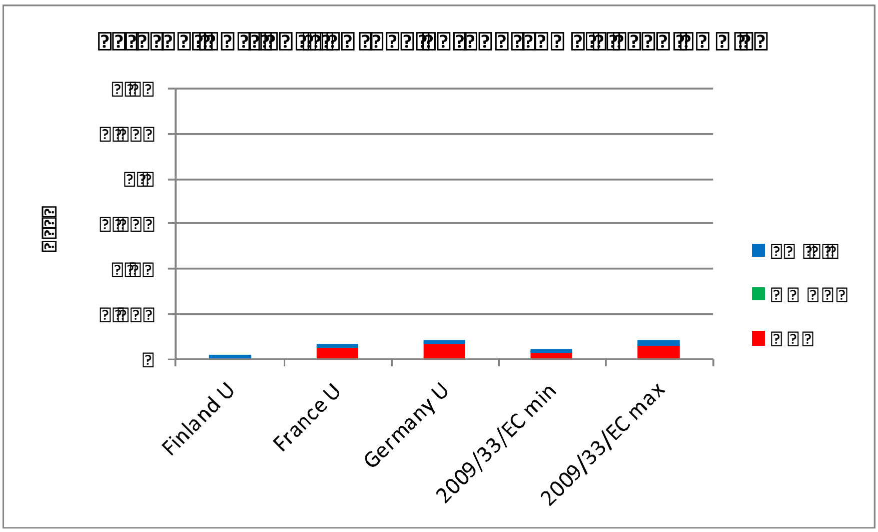


Figure 14.10. Split of emission costs. Braunschweig cycle, EEV stoichiometric CNG vehicle.

14.2.2 Greenhouse gas emissions

Greenhouse gas emissions can also be priced. In December 2011, the price of CO_2 in emission trading is around 10 €/ton (http://www.pointcarbon.com/). Directive 2009/33/EC gives a CO_2 price of 30–40 €/ton, which multiplied by a factor of 2 is 60–80 €/ton.

The "Handbook" also presents external costs of climate change in the form of €/ton CO_2 (Table 14.3). The values depend on the year of application. For the year 2010, the range is 7–45 €/ton, with a central value of 25 €/ton.

Table 14.3. Recommended values for the external costs of climate change (in €/ton CO_2, expressed as single values for a central estimate and lower and upper values. (Handbook 2008)

	Central values (€/tonne CO_2)		
Year of application	Lower value	Central value	Upper value
2010	7	25	45
2020	17	40	70
2030	22	55	100
2040	22	70	135
2050	20	85	180

The effect of CO_2 is not dependent of the location of release, so the costs for greenhouse gas/CO_2 emissions should be looked upon on a well-to-wheel basis, not tailpipe only.

Taking a value of 40 €/ton as basis of assessment could be justified. 40 €/ton is the upper value of 2009/33/EC (without multiplication), and in addition, the upper range for 2010 and central value for 2020 of Table 14.3. This value combined with the data on WTW GHG emissions in Figures 13.4–13.6 renders Figures 14.11–14.13 for the cost of GHG emissions. The results are valid for the Braunschweig cycle.

The costs for greenhouse gas emissions vary from 0.00 to some 0.12 €/km, the highest value is for CTL according to GHGenius.

In the case of diesel vehicles, the costs for GHG emissions are at maximum at the same level as the costs for regulated emissions. For the stoichiometric CNG vehicle running on remote natural gas piped to Europe, on the other hand, the share of regulated emissions of only some 15% of the aggregate costs of regulated and GHG emissions (see Figure 14.5).

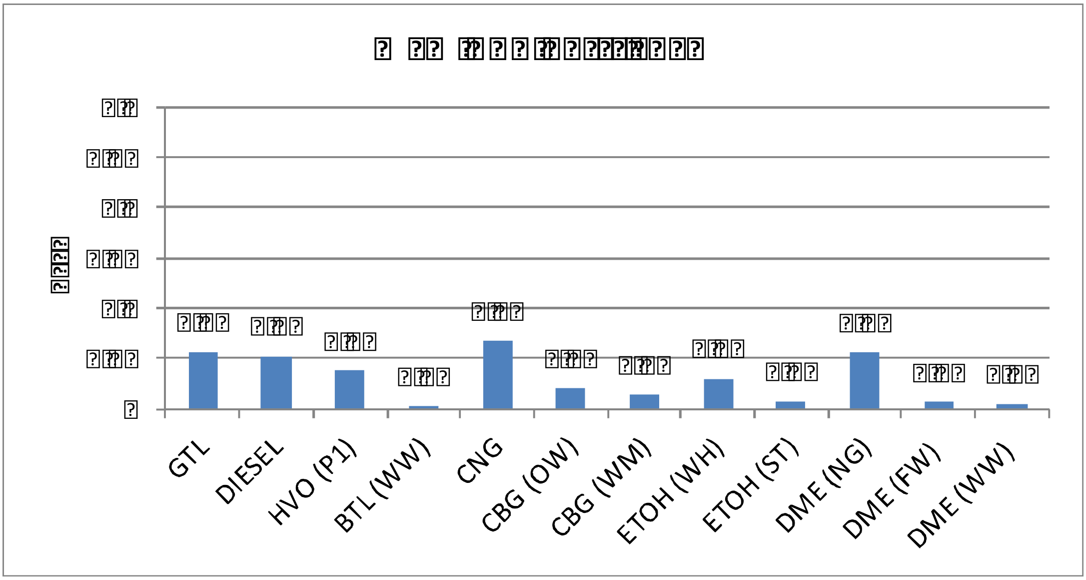


Figure 14.11. WTW GHG costs using RED methodology. Braunschweig cycle. Cost for CO_2 40 €/ton.

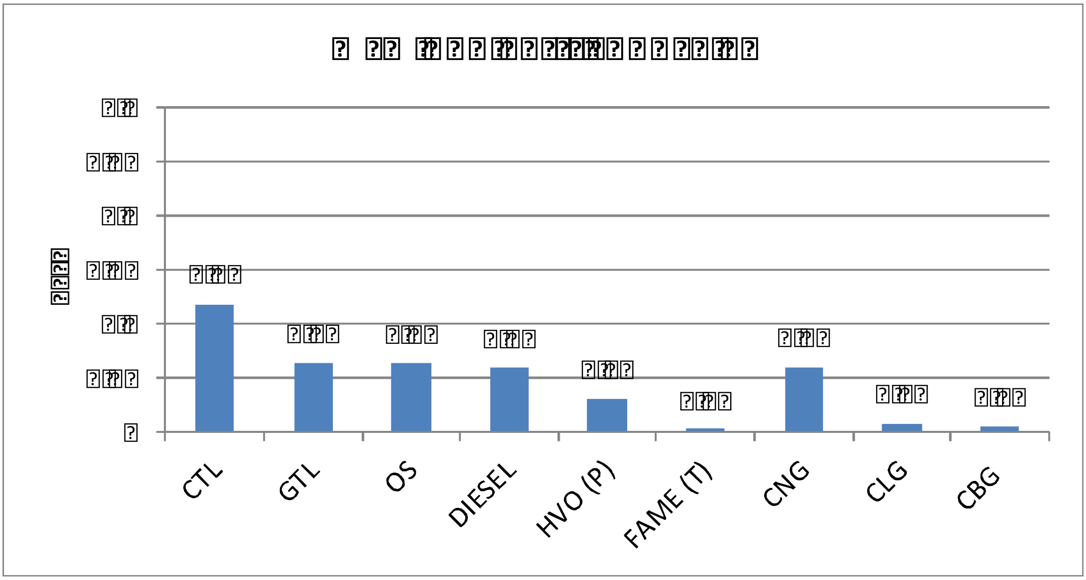


Figure 14.12. WTW GHG costs using GHGenius methodology. Braunschweig cycle. Cost for CO_2 40 €/ton.

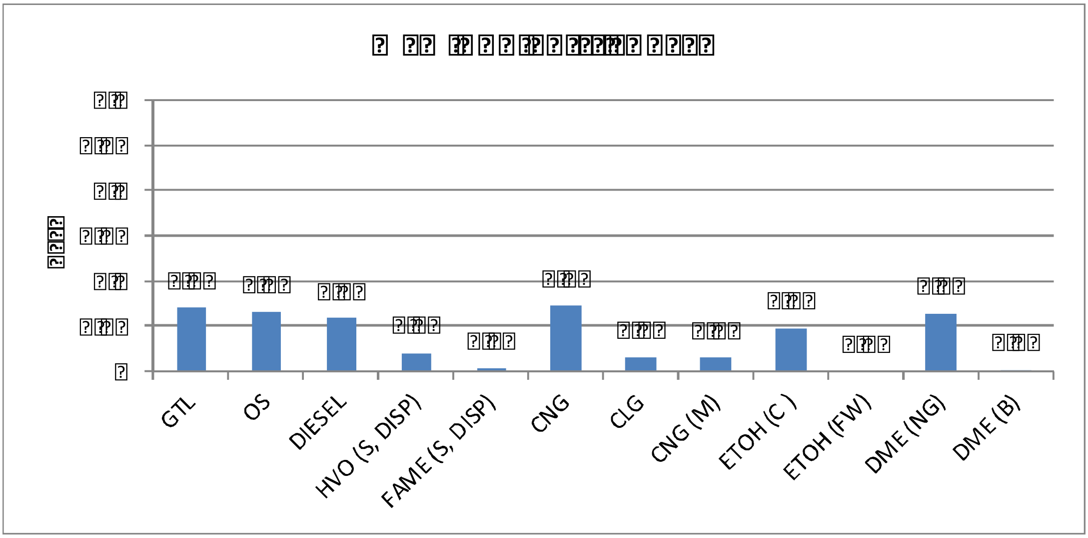


Figure 14.13. WTW GHG costs using GREET methodology. Braunschweig cycle. Cost for CO_2 40 €/ton.

14.3 Direct costs

14.3.1 General

As stated previously, included are vehicle investment costs, costs for fuel and urea and very rough estimates of maintenance costs. The calculations are indicative, as no fixed price lists are available for buses, nor are there universal price lists for fuels.

Taxes and subsidies for fuels and vehicles will vary from market to market. **Please note that no taxes or subsidies are included in the following calculations.** Taxes and subsidies might change the competitiveness of certain technologies considerably.

14.3.2 Vehicle costs

The vehicle alternatives evaluated are:

- EEV SCRT diesel (current baseline technology), 215.000 €
- Light-weight EEV SCRT diesel, +10,000 € (~5%)
- Euro VI diesel (fuel consumption estimated, +25,000 € (~10%)
- Hybrid EEV diesel, +115,000 € (~55%)
- EEV ethanol, +25,000 € (~10%)
- Euro V CNG lean-burn, +50,000 € (~25%)
- EEV CNG stoichiometric, +50,000 € (~25%).

DME was left outside this assessment.

The calculation is made for the Braunschweig cycle, using actual measured fuel consumption values with the exception of the imaginary Euro VI diesel vehicle, which is estimated to consume 5% more fuel and 50% more urea that the baseline EEV SCRT diesel vehicle.

The maintenance costs are estimated as follows:

- EEV SCRT diesel: 0.13 €/km
- Light-weight EEV SCRT diesel: 0.12 €/km (lighter vehicle)
- Euro VI diesel: 0.15 €/km (more complicated than the EEV SCRT vehicle)
- Hybrid EEV diesel: 0.17 €/km (less load on the wheel brakes, smaller ICE, but more complicated vehicle and additional costs for battery renewal)
- EEV ethanol: 0.15 €/km (ethanol more aggressive to materials than diesel)
- CNG vehicles: 0.17 €/km (need for frequent spark-plug renewal, more prone to malfunctioning than diesels).

Pütz (2012) states that for ordinary diesel buses the maintenance cost is typically 50% of the fuel cost. This ratio is also used in this assessment.

The costs for battery renewal of a hybrid vehicle could be estimated as follows. The current cost for Li-Ion battery systems is some 1000 €/kWh. If the battery size is 10 kWh, the service life 5 years and the annual driven distance 80,000 km, then the battery cost per kilometre would be some 0.03 €/km.

The wear of the wheel brakes of a hybrid is less severe than in a vehicle with conventional power train, as the greater part of braking is done electrically. The small ICE is beneficial regarding maintenance costs, but the hybrid vehicle is more complicated than a conventional vehicle, probably requiring more service hours. With factors working in two directions, the maintenance cost of the hybrid is estimated at 0.17 €/km, somewhat higher compared to the imaginary Euro VI diesel vehicle with conventional power train.

14.3.3 Fuel costs

Actual prices for diesel fuel and natural gas at the end of 2011 are used in the calculations.

According to the Energy Information Administration (EIA) of U.S. Department of Energy, the spot price of ULSD fuel was some 3 USD/gallon in December 2011 (Figure 14.14). This is, with the USD/€ exchange rate of 1.30 in December 2011, equivalent to approximately 0.60 €/l. In Europe, the price of diesel fuel at the end of 2011 was around 0.70 €/l (Europe's Energy Portal). In the following calculations, diesel fuel price is estimated at 0.65 €/l (without any taxes). The cost for urea is estimated at 0.5 €/l.

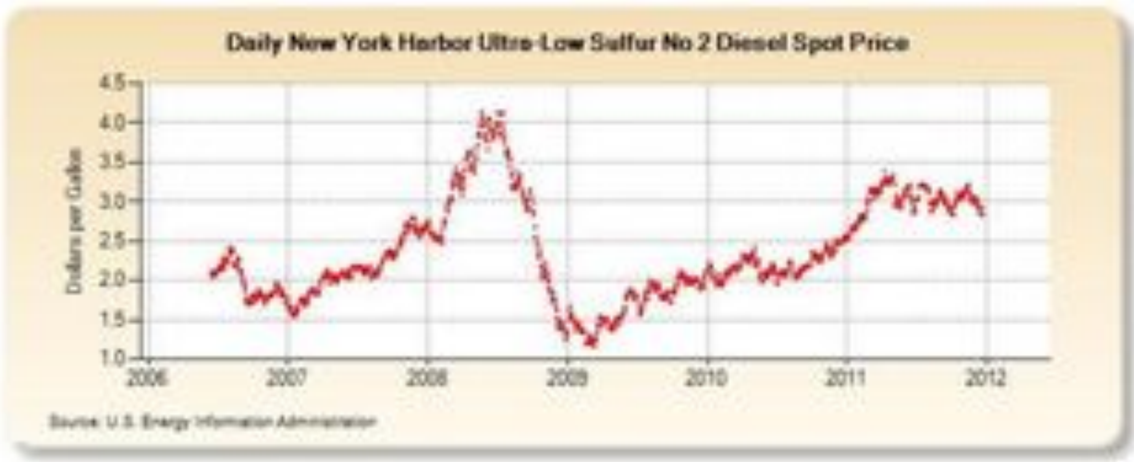


Figure 14.14. Spot price of ULSD diesel in the U.S. (http://www.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=PET&s=EER_EPD2DXL0_PF4_Y35NY_DPG&f=D

EIA also publishes prices for natural gas. The price of natural gas at the end of 2011 is some 4 USD/MMBtu (Figure 14.15), equivalent to some 0.25 €/kg. In Europe, natural gas is significantly more expensive, some 30 €/MWh or some 0.4 €/kg (Europe's Energy Portal). Compression adds to the costs of CNG (capital and operating costs). An average value of 0.65 €/kg or some 0.45 €/liter of diesel fuel equivalent is used for CNG in the following calculations.

In the U.S. the CNG pump price is some 2 USD/gge (gallons of gasoline equivalent), equivalent to 0.45 €/liter of diesel fuel equivalent. In Germany, the average pump price for CNG, including taxes, was 1.0 €/kg in 2011. The tax for diesel fuel is 0.47 €/l and for CNG 0.183 €/kg (Erdgas Fahren 2011). Calculating backwards, the price of CNG without taxes (energy and VAT) was some 0.65 €/kg, or the value used in the calculations. The price of compressed biogas from conventional biogas production is estimated at 0.80 €/kg, or some 25% higher compared to CNG.

Figure 14.15. Spot price of natural gas in the U.S.
http://205.254.135.7/naturalgas/weekly/

Tables 14.4 (diesel fuel) and 14.5 (natural gas) present fuel prices in Europe.

Table 14.4. Gasoline and diesel fuel prices in Europe. The tax free price is the sum of FOB and margin. FOB indicates the purchase price of crude oil and margin comprises refining and bringing the fuel to the consumer. (Europe's Energy Portal, http://www.energy.eu/, date of check 23.1.2012).

FUEL TAXES

A breakdown of the different components that make up the retail (pump) price of Unleaded95 and Diesel.
FOB indicates the purchase price of crude oil. **Margin** is the industry margin: refining, transport, insurance, stockpiling, distribution to petrol stations and sale to consumers. **Excise duties** and Value added Taxes, **VAT**, are taxes that are levied by governments. There is a time lag between a change in crude oil price and its reflection in fuel product retail prices.

Jan. 23, 2012	**Unleaded**					**Diesel**				
MEMBER STATE	FOB	MARGIN	EXCISE	VAT	RETAIL	FOB	MARGIN	EXCISE	VAT	RETAIL
Austria	€ 0.563	€ 0.077	€ 0.513	€ 0.231	€ 1.394	€ 0.613	€ 0.119	€ 0.421	€ 0.222	€ 1.396
Belgium	€ 0.555	€ 0.174	€ 0.645	€ 0.289	€ 1.663	€ 0.595	€ 0.205	€ 0.418	€ 0.258	€ 1.487
Bulgaria	€ 0.558	€ 0.195	€ 0.312	€ 0.213	€ 1.278	€ 0.573	€ 0.221	€ 0.327	€ 0.224	€ 1.345
Cyprus	€ 0.563	€ 0.145	€ 0.368	€ 0.161	€ 1.236	€ 0.563	€ 0.242	€ 0.337	€ 0.171	€ 1.313
Czech Republic	€ 0.560	€ 0.090	€ 0.513	€ 0.234	€ 1.406	€ 0.569	€ 0.163	€ 0.440	€ 0.236	€ 1.439
Denmark	€ 0.559	€ 0.192	€ 0.628	€ 0.345	€ 1.724	€ 0.568	€ 0.265	€ 0.471	€ 0.321	€ 1.635
Estonia	€ 0.559	€ 0.118	€ 0.438	€ 0.222	€ 1.330	€ 0.558	€ 0.166	€ 0.409	€ 0.231	€ 1.366
Finland	€ 0.569	€ 0.140	€ 0.692	€ 0.299	€ 1.699	€ 0.568	€ 0.344	€ 0.349	€ 0.290	€ 1.552
France	€ 0.563	€ 0.127	€ 0.672	€ 0.267	€ 1.629	€ 0.563	€ 0.190	€ 0.471	€ 0.240	€ 1.465
Germany	€ 0.555	€ 0.114	€ 0.645	€ 0.260	€ 1.565	€ 0.555	€ 0.211	€ 0.465	€ 0.233	€ 1.457
Greece	€ 0.559	€ 0.133	€ 0.683	€ 0.318	€ 1.703	€ 0.568	€ 0.266	€ 0.417	€ 0.296	€ 1.527
Hungary	€ 0.573	€ 0.108	€ 0.438	€ 0.301	€ 1.416	€ 0.573	€ 0.193	€ 0.418	€ 0.320	€ 1.504
Ireland	€ 0.573	€ 0.069	€ 0.621	€ 0.288	€ 1.542	€ 0.573	€ 0.147	€ 0.509	€ 0.283	€ 1.512
Italy	€ 0.565	€ 0.140	€ 0.696	€ 0.295	€ 1.702	€ 0.565	€ 0.228	€ 0.571	€ 0.287	€ 1.656
Latvia	€ 0.563	€ 0.114	€ 0.413	€ 0.239	€ 1.327	€ 0.563	€ 0.206	€ 0.329	€ 0.242	€ 1.341
Lithuania	€ 0.566	€ 0.110	€ 0.420	€ 0.231	€ 1.326	€ 0.566	€ 0.224	€ 0.292	€ 0.226	€ 1.312
Luxembourg	€ 0.563	€ 0.141	€ 0.462	€ 0.176	€ 1.241	€ 0.563	€ 0.229	€ 0.292	€ 0.163	€ 1.246
Malta	€ 0.573	€ 0.152	€ 0.469	€ 0.216	€ 1.410	€ 0.573	€ 0.190	€ 0.365	€ 0.201	€ 1.329
Netherlands	€ 0.558	€ 0.131	€ 0.768	€ 0.277	€ 1.735	€ 0.558	€ 0.214	€ 0.456	€ 0.233	€ 1.462
Poland	€ 0.563	€ 0.082	€ 0.362	€ 0.234	€ 1.262	€ 0.563	€ 0.173	€ 0.300	€ 0.239	€ 1.275
Portugal	€ 0.565	€ 0.150	€ 0.613	€ 0.305	€ 1.635	€ 0.565	€ 0.253	€ 0.416	€ 0.285	€ 1.522
Romania	€ 0.559	€ 0.122	€ 0.374	€ 0.248	€ 1.303	€ 0.559	€ 0.195	€ 0.319	€ 0.257	€ 1.329
Slovakia	€ 0.563	€ 0.076	€ 0.573	€ 0.242	€ 1.452	€ 0.563	€ 0.157	€ 0.402	€ 0.233	€ 1.355
Slovenia	€ 0.563	€ 0.092	€ 0.495	€ 0.238	€ 1.390	€ 0.563	€ 0.160	€ 0.369	€ 0.216	€ 1.297
Spain	€ 0.565	€ 0.145	€ 0.452	€ 0.213	€ 1.375	€ 0.565	€ 0.236	€ 0.345	€ 0.207	€ 1.355
Sweden	€ 0.563	€ 0.135	€ 0.659	€ 0.339	€ 1.646	€ 0.563	€ 0.226	€ 0.567	€ 0.337	€ 1.693
United Kingdom	€ 0.559	€ 0.084	€ 0.728	€ 0.274	€ 1.644	€ 0.559	€ 0.169	€ 0.714	€ 0.299	€ 1.729

Table 14.5. Natural gas prices for industrial consumers in Europe. (Europe's Energy Portal, http://www.energy.eu/, date of check 23.1.2012).

NATURAL GAS INDUSTRY

End-user energy prices for industrial consumers.
Two consumption levels are identified. Research methodology. Price data for other consumption levels, please enquire.
Price data mentioned may not reflect the latest insights found in the commercial editions.

Reference month: June, 2011.

Historical price data going back to the year 2000, visit EU Energy History

Consumption: 0.25 GWh/year		Consumption: 5 GWh/year	
EU-member state	**€ per kWh gas**	**EU-member state**	**€ per kWh gas**
Austria	€ 0.0595	Austria	€ 0.0392
Belgium	€ 0.0501	Belgium	€ 0.0309
Bulgaria	€ 0.0352	Bulgaria	€ 0.0315
Cyprus	NO DATA	Cyprus	NO DATA
Czech Republic	€ 0.0430	Czech Republic	€ 0.0365
Denmark	€ 0.0904	Denmark	€ 0.0658
Estonia	€ 0.0330	Estonia	€ 0.0293
Finland	€ 0.0355	Finland	€ 0.0345
France	€ 0.0495	France	€ 0.0360
Germany	€ 0.0489	Germany	€ 0.0478
Greece	NO DATA	Greece	NO DATA
Hungary	€ 0.0439	Hungary	€ 0.0369
Ireland	€ 0.0435	Ireland	€ 0.0331
Italy	€ 0.0485	Italy	€ 0.0303
Latvia	€ 0.0376	Latvia	€ 0.0320
Lithuania	€ 0.0370	Lithuania	€ 0.0347
Luxembourg	€ 0.0457	Luxembourg	€ 0.0445
Malta	NO DATA	Malta	NO DATA
Netherlands	€ 0.0382	Netherlands	€ 0.0346
Poland	€ 0.0416	Poland	€ 0.0339
Portugal	€ 0.0558	Portugal	€ 0.0347
Romania	€ 0.0229	Romania	€ 0.0227
Slovakia	€ 0.0471	Slovakia	€ 0.0380
Slovenia	€ 0.0584	Slovenia	€ 0.0445
Spain	€ 0.0423	Spain	€ 0.0301
Sweden	€ 0.0636	Sweden	€ 0.0492
United Kingdom	€ 0.0372	United Kingdom	€ 0.0231

The estimates for biofuels prices is based on the 2011 IEA publication "Technology Roadmap: Biofuels for Transport" (Biofuels for Transport 2011). This report presents 2010 prices for ethanol, synthetic biogas (via gasification of biomass), conventional biodiesel and advanced biodiesel (BTL). The prices are expressed as USD/litre of gasoline equivalent (lge, Figure 14.16). IEA predicts increasing prices for petroleum products. For biofuels, there are two scenarios, the low-cost scenario and the high-cost scenario. The first one predicts falling prices for all biofuels.

For biofuels, the calculation at hand is based on the 2010 low-cost scenario prices. Corrected for energy content and converted to €/l or €/kg the prices are:

- sugarcane ethanol: 0.31 €/l, estimate with diesel additive +20%= 0.38 €/l
- conventional biodiesel (FAME): 0.78 €/l
- advanced biodiesel (BTL): 0.90 €/l
- synthetic natural gas/biogas (SNG, through gasification): 1.04 €/kg).

In the IEA Biofuels report the price of petroleum gasoline is estimated at 0.53 USD/lge, meaning a diesel price of some 0.45 €/l, or lower than the actual diesel price at the end of 2011.

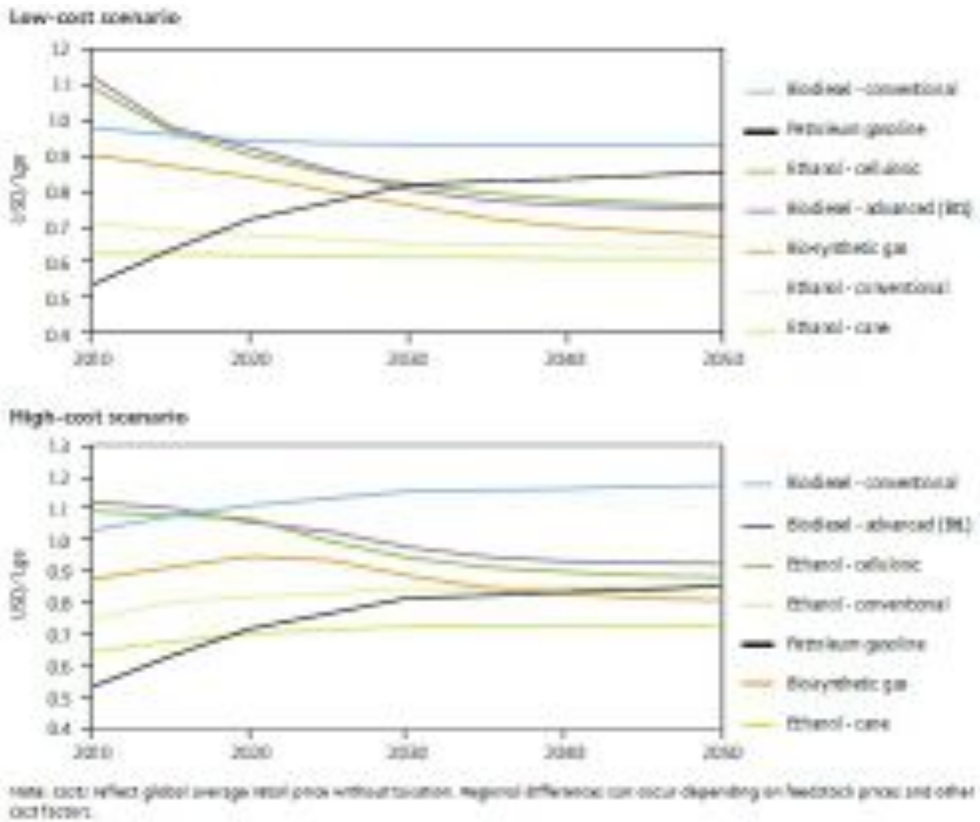


Figure 14.16. Cost estimates for biofuels. (Biofuels for Transport 2011)

Table 14.6 summarizes the parameters used in the cost calculations.

Table 14.6. Parameters for the cost calculations.

Common values	Service life (years)	Residual value (€)	Interest rate (%)	Mileage (km/a)	Urea price (€/l)
	15	0	5	80 000	0.5
Vehicle specific	Vehicle price (€)	Fuel cons. (l/100 km or kg/100 km)	Fuel price (€/l or €/kg)	Urea cons. (% of FC)	Maintenance costs (€/km)
Baseline EEV diesel (SCRT)	215 000	42.5	0.65	4	0.13
Light-weight EEV diesel (SCRT)	225 000	35.5	0.65	4	0.12
Hybrid EEV diesel	330 000	29.9	0.65	4	0.17
Euro VI diesel (imaginary)	240 000	44.6	0.65	6	0.15
EEV ethanol	240 000	79.1	0.38 (€/l)	0	0.15
Euro V GNG lean-burn	265 000	41.7	0.65 (€/kg)	0	0.17
EEV CNG stoichiom.	265 000	43.9	0.65 (€/kg)*)	0	0.17

*) compressed biogas 0.80 €/kg

14.3.4 Aggregate costs for vehicles, fuels and maintenance

The results of the base case cost calculations are presented in Figure 14.17. With the chosen assumptions, the variations in operational costs are in fact surprisingly small, from 0.63 €/km (light-weight EEV SCRT diesel) to 0.77 €/km (EEV hybrid and stoichiometric CNG). Two groups are formed: vehicles with operational costs of some 0.65 €/km (baseline EEV SCRT diesel and light-weight EEV SCRT diesel) and vehicles with operational costs of some 0.75 €/km (hybrid, Euro VI diesel, natural gas and ethanol). On an annual basis, with a mileage of 80,000 km, the difference in operational costs is at maximum some 12,000 €.

The stoichiometric CNG vehicle delivers actual Euro VI emission performance. Therefore it would fair to compare this technology with Euro VI diesel, and in this comparison CNG is at roughly the same cost level as diesel using baseline assumptions.

For Figure 14.18 the following parameters have been changed: price of diesel fuel +40% (0.65 -> 0.90 €/l) and the price of the hybrid vehicle has been reduced 40,000 € (330,000 -> 290.000 €). This would reflect a situation in which the competiveness of alternative fuels has increased due to increase in diesel fuel price and in which hybrid technology has matured resulting in reduced costs.

The changes are not that dramatic. Operational costs are in the range of 0.72–0.85 €/km. Light-weight EEV SCRT diesel is still the cheapest option, and Euro VI is now the most expensive option. The hybrid is now roughly equivalent to baseline EEV SCRT diesel, and natural gas and ethanol are competitive with the diesel options, with the exception of the light-weight diesel.

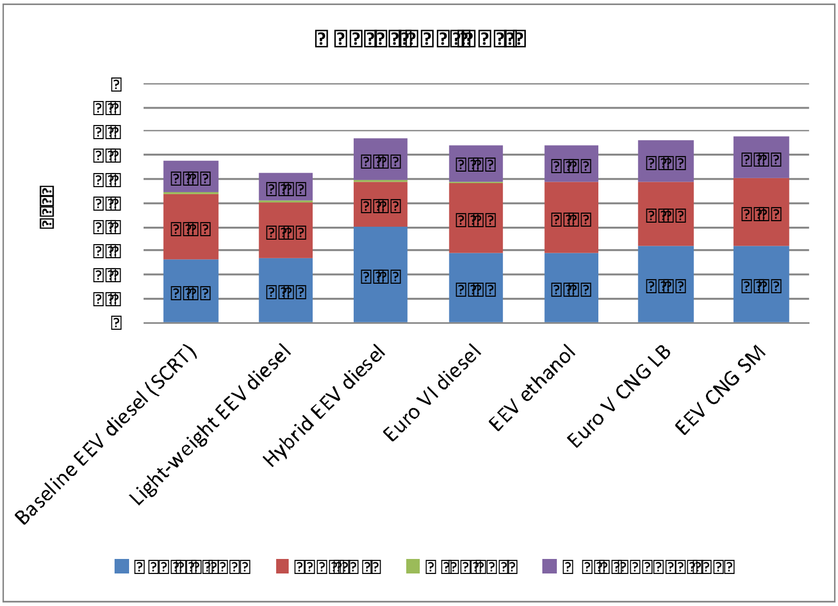


Figure 14.17. Operational costs (indicative) for various vehicle options. Baseline assumptions.

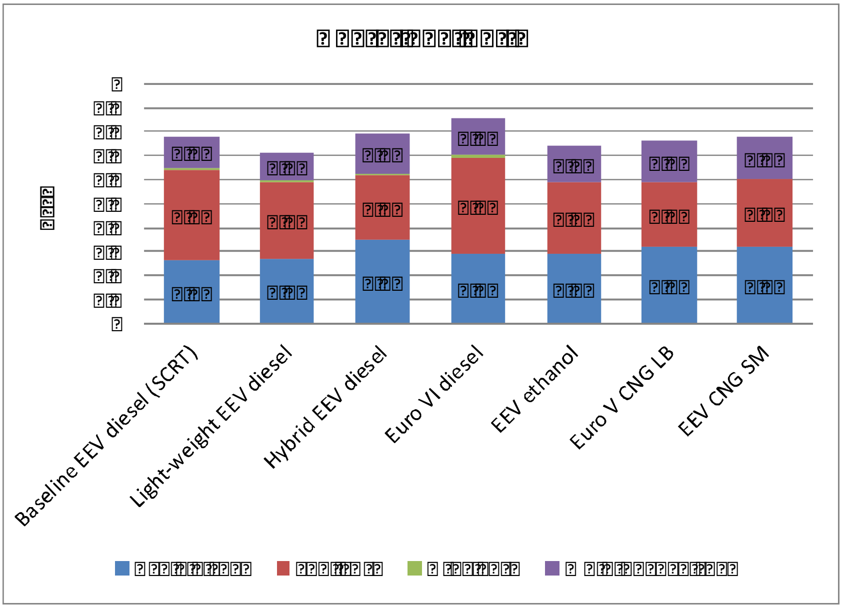


Figure 14.18. Operational costs (indicative) for various vehicle options. Diesel price 0.90 €/l, price of the hybrid vehicle 290,000 €.

Figure 14.19 presents operational costs when operating on diesel (0.65 €/l), FAME (0.78 €/l), BTL (0.90 €/l), natural gas (0.65 €/kg) and biogas (0.80 €/kg). The vehicles are the EEV SCRT diesel and the Euro V lean-burn CNG vehicle. Going from conventional diesel to BTL would increase operational costs some 20% and going from natural gas to biogas some 10%.

In Figure 14.20, the price of diesel fuel is set at 0.90 €/l. For this case the operational costs with diesel would fall in between FAME and BTL, and BTL would be only some 3% more expensive than diesel.

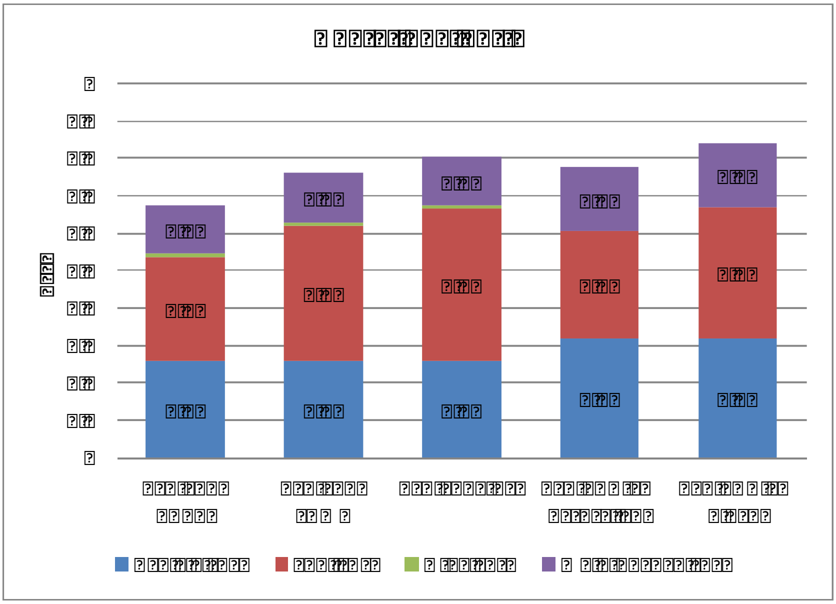


Figure 14.19. Operational costs (indicative) for EEV SCRT diesel and EEV CNG stoichiometric on fossil fuels (diesel, natural gas) and biofuels (FAME, BTL and SNG). Diesel price 0.60 €/l.

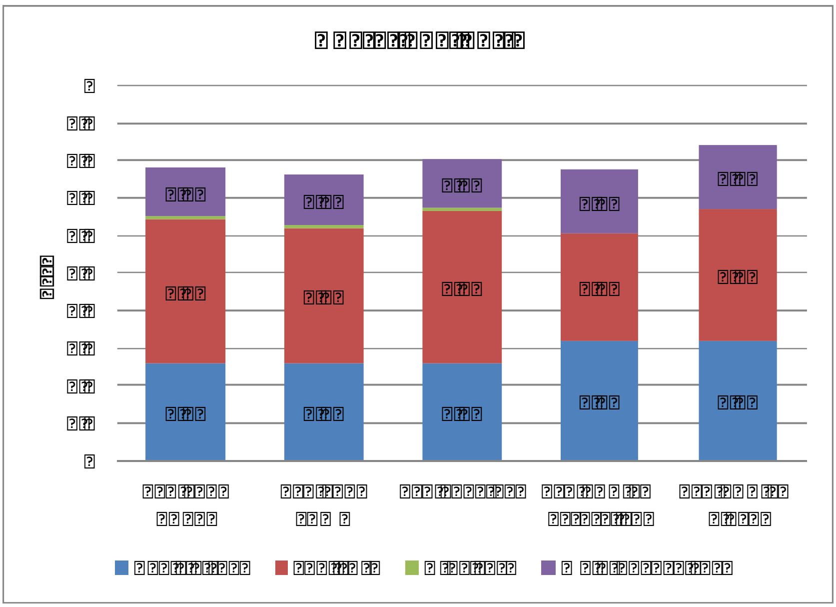


Figure 14.20. Operational costs (indicative) for EEV SCRT diesel and EEV CNG stoichiometric on fossil fuels (diesel, natural gas) and biofuels (FAME, BTL and SNG). Diesel price 0.90 €/l.

In the case of external costs, the calculatory emission benefit of choosing stoichiometric CNG instead of EEV SCRT diesel is some 0.05 €/km for regulated emissions (Figure 14.5). Correspondingly, the GHG benefit of choosing BTL instead of diesel or biogas instead of remote natural gas is also some 0.05 €/km. Figure 14.21 shows total costs taking into account direct as well as indirect costs.

For the base case (Figure 14.19), taking external costs into account reduces the cost difference between diesel and BTL from 0.13 €/km to 0.06 €/km (EEV SCRT) and the cost difference between natural gas and biogas from 0.07 €/km to 0.01 €/km (EEV CNG stoichiometric). Figure 14.21 presents total costs (the sum of direct and indirect costs).

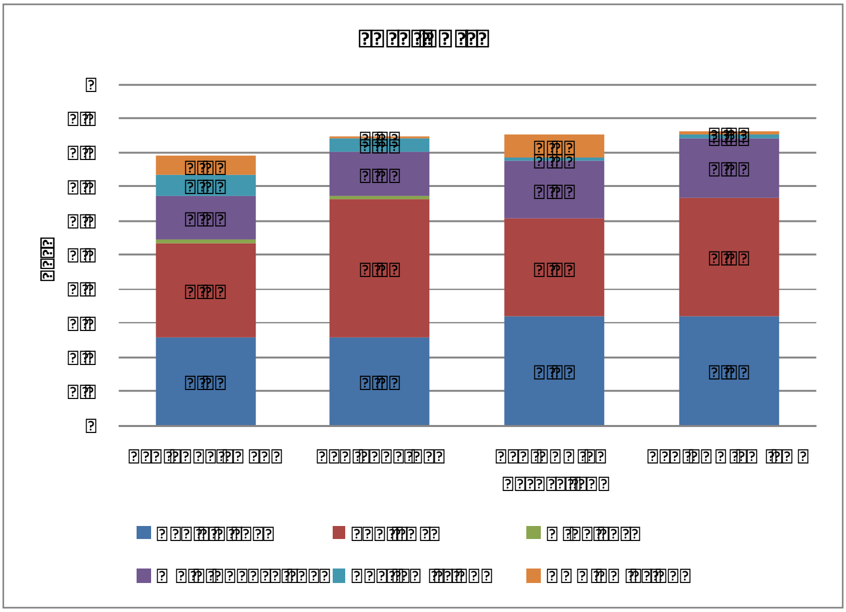


Figure 14.21. Total costs (direct cost and external costs, indicative) for EEV SCRT diesel and EEV CNG stoichiometric on fossil fuels (diesel, natural gas) and biofuels (BTL and SNG). Diesel price 0.60 €/l.

14.3.5 Infrastructure costs

At a bus depot, switching from one liquid fuel to another will in most cases not imply any significant costs. BTL and HVO are fully compatible with existing storages and dispensers designed for diesel. Switching from regular diesel to FAME type fuels might require replacement of certain seals and gaskets and a complete rinsing of the system as FAME is an effective solvent. However, equipment originally designed for diesel fuel is not necessarily compatible with ethanol. Thus switching from diesel to ethanol might require fuel tanks and dispensers to be replaced.

In the cost calculation presented above, the cost of refuelling equipment and the compression costs are included in the price of CNG (CNG price estimated at 1.5 times the energy price of natural gas). The investment costs for a fast-fill CNG station suitable for refuelling buses is in the order of 1 M€. For DME, the refuelling equipment would be similar to that for LPG (the fuel is in liquid phase, pressure level some 10 bar), and significantly cheaper than the equipment needed for CNG.

Workshops designed for repair and maintenance of diesel buses might not be suitable for DME, methane or ethanol vehicles. Flammability of diesel fuel is low, whereas DME, methane and ethanol are highly flammable. This means special requirements on electrical equipment, ventilation and gas detection in the workshops. DME is heavier than air whereas methane is lighter than air, and this must be taken into account when designing workshops for alternative fuelled vehicles. Ethanol resembles gasoline in many ways. However, ethanol is even more challenging than gasoline from a safety point of view. In the fuel tank, gasoline normally forms an oversaturated un-ignitable mixture, whereas the vapours in an ethanol tank in many cases are ignitable.

15. Validation of results

15.1 General

As discussed previously, the WTT results are based on a series of assumptions, while TTW energy consumption and tailpipe exhaust emissions can be measured objectively with relatively high accuracy. The estimation on indirect emission is again based on assumptions. The calculations of direct costs also contain some assumptions, as vehicle prices, fuel prices and the costs for vehicle maintenance vary from location to location.

15.2 Validation of WTT results

The impact of different calculation methodologies, different system boundaries used, and different calculation assumptions made is significant when it comes to results of a WTT assessment of biofuels. Also the timeframe used in the calculations may have an important effect on the results. The results can also vary because of regional differences in the agricultural conditions and processes, energy sources used in the production and differences in technologies used for biofuel production. This variation can also be seen from the results of this study. To better understand the scale of this variation, the WTT results of this study can be compared to other WTT results.

During recent years, numerous studies have been made concerning the greenhouse gas emissions of various biofuel production chains. Soimakallio and Koponen (2011) made a review of chosen studies, which showed how notably the results for one biofuel chain may vary due to the assumptions made in the assessment and differences in the conditions. In this review 25 different LCA studies or sustainability criteria for biofuels were analyzed and WTT emission estimates were collected concerning 14 different biofuel chains (Table 15.1). Also the results from GREET calculation for some biofuel chains made by Kamarat Jermsirisakpong, who stayed at VTT as a visitor researcher at fall 2009, were included in the review.

Figure 15.1 shows the variation of the WTT results. In some of the reviewed studies, the emissions of indirect land use change (ILUC) are taken into account.

In these cases the variation of the WTT results is even more significant. For cellulosic ethanol there are several results showing negative GHG values.

Table 15.1. The studies and biofuel chains assessed in the literature review (based on Soimakallio and Koponen, 2011).

Reference	Year	Biofuel chains studied*	Allocation method**	ILUC***
ADEME	2006	1	MA	
California Air Resources Board	2009	2, 7, 12, 13	EA	
Department for Transport (Britain)	2008	1, 2, 3, 4, 5, 6, 11, 12	S,VA	
EU (RED)	2009	1, 2, 3, 4, 5, 7, 9, 11, 12, 13	EA	
Fargione et al.	2008	2, 3	EA	X
Farrel et al.	2006	13	?	
Fehrenbach et al. (IFEU)	2008	2, 3, 4, 5, 6, 11, 12	EA	
Fritsche & Wiegmann	2008	1, 3, 8, 9, 10, 13	EA	X
Gnansounou et al.	2009	11	EA,VA,MA,CA,S	
Huo et al.	2009	2	EA,VA,S	
JEC-Study	2008	1, 2, 4, 5, 11, 12, 13	S	
Kalogo et al.	2007	14	S(?)	
Koponen at al.	2009	14	EA	
Majer et al.	2009	1, 2, 3, 8	S + several	
Nikander	2008	4, 5, 7	S,EA,MA	
OECD	2008	1, 3, 9, 11, 12, 13	several	
Ou et al.	2009	2, 8	?	
Sheehan et al.	1998	2	MA	
Soimakallio et al.	2009	1, 9, 10, 11	S	
Spatari et al.	2010	13	S, ?	
Stichnothe & Azapagic	2009	14	S	
Thamsiriroj & Murphy	2009	1, 3	S	
UNEP	2009	1, 2, 3, 9, 11, 12, 13	several	X
Wicke et al.	2008	3	S	
Yan & Crookes	2009	1, 2, 11, 12	several	
+GREET calculations	2009	2, 4, 9, 10	EA	

* 1=FAME rapeseed, 2=FAME soya, 3=FAME palmoil, 4=HVO palmoil, 5=HVO rapeseed, 6=HVO soya, 7=HVO animal fats, 8=BTL jatropha, 9=BTL wood residues, 10=BTL energy crops, 11=ETOH grain based, 12=ETOH sugarcane, 13=ETOH cellulosic, 14=ETOH waste

** EA= energy allocation, MA=mass allocation, VA=value allocation, CA=carbon content allocation, S=substitution method, ?=not clearly defined

*** Emissions of indirect land use change included

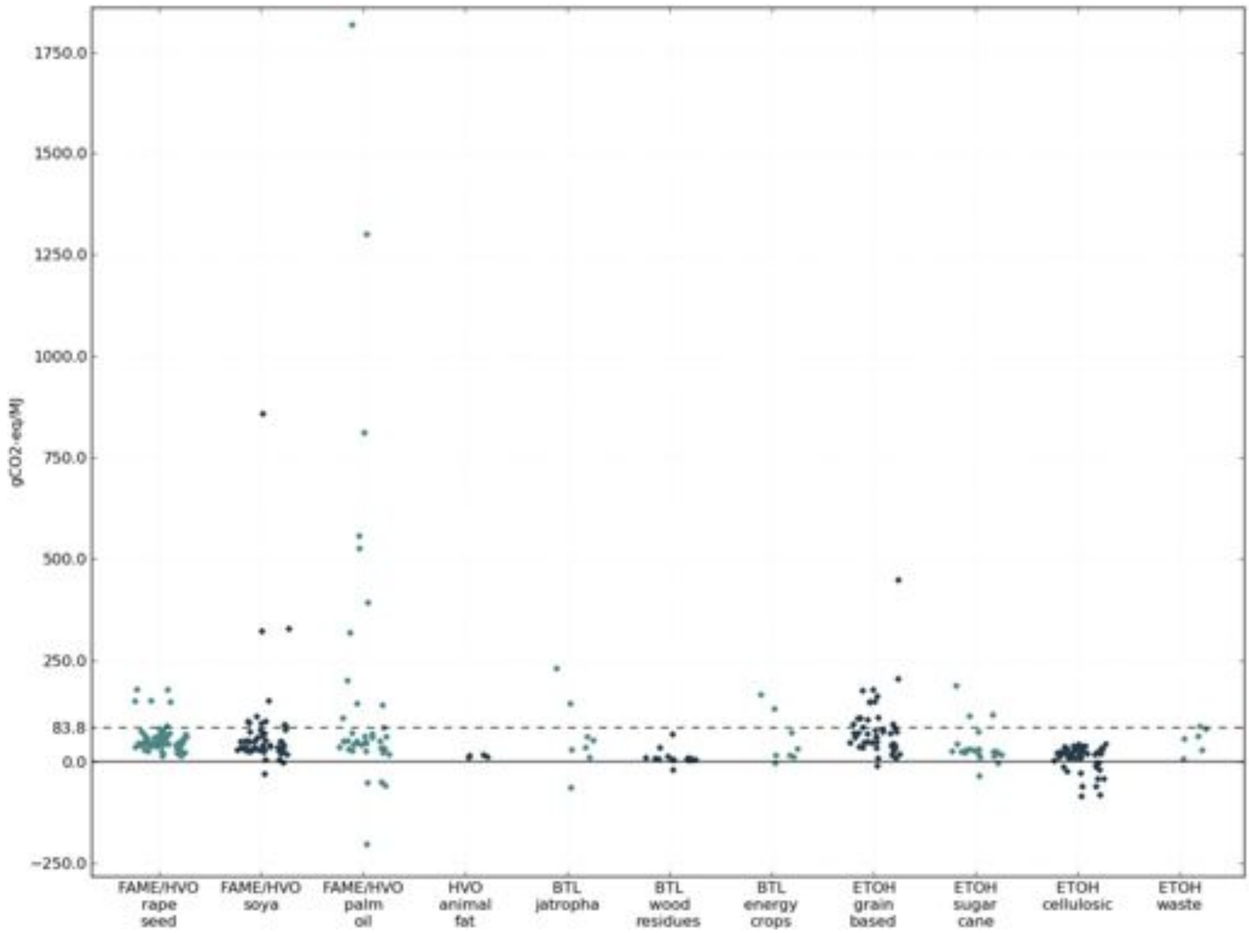


Figure 15.1. Well-to-tank emissions of 14 biofuel chains studied, based on review of 25 LCA studies. The dashed vertical line (y=83,8gCO2-eq/MJ) shows the emission of fossil fuel comparator according to the RED. (Based on Soimakallio & Koponen 2011, GREET calculation results by Kamarat Jermsirisakpong are added to the figure)

15.3 Validation of TTW results

The results for the TTW measurements can be considered quite accurate. VTT estimates the inaccuracy of gravimetric fuel consumption measurements at some ±1%. When the heating value of the fuel is known with adequate accuracy, the same applies to vehicle energy consumption. However, the accuracy for emission measurements is not as good. For measurements of regulated emissions and tailpipe CO_2 emissions VTT has estimated inaccuracy to be at the level of ±15%.

All results are based on the average of at least two individual measurements, and this narrows down the error margins.

When calculating WTW energy use or emissions, the biggest uncertainties are thus related to the WTT part, not the TTW part.

The accuracy of the TTW measurements is definitely sufficient to distinguish different vehicle generations, different vehicle technologies, the effects of driving cycle and also fuel effects for alternative fuels (methane, ethanol, DME) and 100% replacement diesel fuels (FAME, HVO, GTL). However, accuracy is really not sufficient to verify the effects of low-level fuels blends.

Although Environment Canada and VTT conducted testing using common test cycles, the results are not fully comparable due to, e.g., differences in procedures and equipment. Round robin testing was not within the scope of the project. The results indicate higher energy consumption for the North American vehicles compared to the European ones. This difference could arise from the fact that the North-American vehicles deliver lower emissions than their European counterparts but also from differences in methodology and equipment. However, it was deemed that the US 2010 certified vehicles could depict what can be expected for regulated emissions from future Euro VI certified European vehicles.

The vehicles measured had traveled various distances, from only a couple of thousand kilometers to close to a million kilometers. The newest vehicles were low-mileage vehicles in prime condition. There is no guarantee that these vehicles really will maintain the very low emissions over a full service life of some 15 years or more.

By definition, there are no legally binding limit values for unregulated emission components. However, it is clear that measuring regulated components only is not enough when evaluating the full performance of new fuel qualities. In the absence of limit values, the assessment of unregulated components will be mostly qualitative or comparative to conventional technology (diesel). With urea-based SCR becoming increasingly common limit values for ammonia slip are needed.

15.4 Validation of cost assessment results

As in the case of the WTT assessments, the cost assessment is based on a number of assumptions, especially the assessment of indirect costs. As for the direct cost, the fuel consumption of the vehicle is the parameter which can be determined with high accuracy. All other parameters (vehicle price, fuel price, maintenance costs) will vary from site to site. Thus the cost assessments should be considered indicative only.

16. Conclusions

Based on the findings of the project it is possible to establish the effects of various parameters on bus performance. The largest variations and also uncertainties can be found for WTW CO_{2eqv} emissions, or in fact the WTT part of the CO_{2eqv} emissions.

The WTT CO_{2eqv} emissions were defined for various biofuels and fossil fuels. The CO_{2eqv} results of biofuels varied depending on the technology and raw material used for the production. Also the calculation model or methodology used had an effect on the results. The WTT emissions were defined by two different models: GREET and GHGenius, and by the RED methodology of the EU. The differences between these calculation methodologies were also studied. The models/methods have their own calculation assumptions and the data related to different biofuel chains might vary by region, by technology used, etc. The WTT results represent average biofuel chains rather than specific biofuel products, as the data used in the assessment often is average data. The results of any GHG emission assessment are vulnerable to various assumptions, uncertainties, and sensitivities. This report helps to better understand the nature of the WTT assessment and the different tools that can be used for it. The comparison made among the different calculation methods shows, that there are some differences, but also many similarities in the models and methods used in the US, Canada and the EU.

For fossil fuels, WTW CO_{2eqv} intensity varies with a factor of around 3, between 65 g CO_{2eqv}/MJ (natural gas) and 185 g CO_{2eqv}/MJ CTL). In the Braunschweig cycle, energy consumption varies from 10 to 22 MJ/km, giving a WTW range of 1000 g CO_{2eqv}/km (European hybrid with conventional diesel) to 4000 g CO_{2eqv}/km (US 2010 diesel bus with CTL).

In the case of biofuels, the extreme WTW CO_{2eqv} intensity values range from nil to close to 2000 CO_{2eqv}/MJ (Figure 15.1). The latter value with an energy consumption of 22 MJ/km would mean a figure of some 40,000 g CO_{2eqv}/km. For the biofuels included in the actual WTW assessment in this study the WTW values vary with a factor of 40 (excluding those GREET ethanol alternatives giving a negative GHG balance). In the case of the EEV SCRT vehicle the range is 24 g CO_{2eqv}/km (tallow to FAME/GHGenius) to 943 g CO_{2eqv}/km (palm oil HVO, process not specified/RED). Comparing tallow based FAME to CTL, the factor is some 120.

WTW energy use varies with a factor of 2.5:1 for vehicles with conventional power train. Using European JEC values diesel delivers lowest overall energy consumption and sugarcane ethanol the highest. The values are 18 MJ/km for the EEV SCRT diesel and 46 MJ/km for the ethanol vehicle. In the case of diesel the WTT is some 16% of the total energy use, for ethanol some 64%.

Over the last 15 years, tightening emission regulations and improved engine and exhaust after-treatment technology have reduced regulated emissions by a factor of 10:1 and particulate numbers with a factor of 100:1. The most efficient way to reduce regulated emissions is to replace old vehicles with new ones. Clean burning fuels such as methane, ethanol and DME can still provide some advantages over diesel, but regulated emissions are first and foremost determined by the sophistication of the engine and the exhaust control system. Natural gas in combination with stoichiometric combustion and three-way catalyst delivers low regulated emissions, NO_x and PM. All natural gas engines, independent of combustion system, deliver low particulate emissions, equivalent to particulate filter equipped diesel engines. The drawback of current spark-ignited gas engines is high energy consumption in comparison with diesel engines. Additive treated ethanol as well as DME deliver diesel-like efficiency but with lower engine-out particulate emissions.

Hybridization or light-weighting reduce fuel consumption 20–30%, but otherwise the improvements in fuel efficiency have not been that spectacular. In the case of diesel engines sophisticated engine controls and injection systems in principle reduce fuel consumption. Emission control systems such as EGR and particulate filters, on the other hand, tend to increase fuel consumption. As a consequence, at Environment Canada, the US 1998 diesel bus tested had the same fuel consumption as the three US 2010 diesel buses on an average. For Europe, fuel consumption went down going from mechanically controlled Euro II vehicles towards more sophisticated vehicles, with EEV SCR delivering lowest fuel consumption. The introduction of Euro VI is expected to increase fuel consumption somewhat.

The driving cycle affects regulated emissions and fuel consumption by a factor of 5:1. The benefits of hybridization depend on the driving cycle. In a severe low-speed cycle such as the NYBUS cycle hybridization saves close to 40% fuel, whereas the benefit of hybridization is marginal for UDDS and WHVC, below 10%.

Emission performance and fuel quality are interconnected. Sophisticated diesel engines, especially those equipped with exhaust gas after-treatment require high-quality practically sulfur-free fuels. High aromatic and sulfur content increase exhaust toxicity and/or particulate emissions. In all measurements in this project, the reference fuel was high quality commercial diesel with a sulfur content less than 10 or 15 ppm. If the reference fuel had been low-quality high-sulfur diesel, the effects of fuel replacement would have been more accentuated.

Now the fuel effects for diesel replacement fuels were at maximum 2.5:1 for regulated emissions (particulates). FAME type biodiesel is effective for PM reduction. Paraffinic diesel fuels have a potential for simultaneous reductions of NO_x and PM. Paraffinic diesel also delivered significant reductions in exhaust toxicity and mutagenicity.

Some older engines have been approved for 100% FAME type biodiesel. However, most manufacturers do not approve the use of 100% FAME in newer engines with sophisticated exhaust after-treatment systems such as particulate filters. Paraffinic diesel, whether BTL, CTL, GTL or HVO, are drop-in type fuels which in principle can deliver 100% replacement without any modifications to the refueling infrastructure or the vehicles. When applying biofuels, the fuel requirements of the local bus fleet on one hand and the local availability of biofuels on the other hand have to be taken into account. Therefore the optimum solution for Europe and Euro VI vehicles can be a different one compared, e.g., to Thailand and older vehicles.

Both external (emissions) and direct costs were calculated for the various technology and fuel options. The estimates of external costs were done according to the principles laid out in the European "Handbook on estimation of external cost in the transport sector". The external costs (unit costs) are differentiated by countries and in the case of particulates, also by areas or regions. Most of the calculations were done for the Braunschweig cycle.

The external costs for regulated emissions vary between 0.001 €/km (stoichiometric CNG, UDDS, Finnish values) and 0.24 €/km (Euro II diesel, ADEME, German values), a factor of some 1:200. The methodology emphasises NO_x emissions, not particulates, so even for the old Euro II vehicle NO_x dominates the emission costs. For the Braunschweig cycle, the emission costs are 0.01–0.12 €/km (German mid-size city values). The calculatory emission benefit in switching from regular diesel to GTL or HVO is 0.01–0.05 €/km. For the newest vehicles with low emissions the benefit is rather limited.

At a CO_2 price of 40 €/ton, the calculated WTW CO_2 costs are 0–0.12 €/km.

The direct costs, including investment cost for the bus, fuel costs and maintenance costs is 0.63–0.77 €/km for new European vehicles (diesel, diesel hybrid, CNG, additive treated ethanol) using baseline assumptions. In the base case going from conventional diesel to BTL would increase operational costs some 20% and going from natural gas to biogas some 10%. Taking into account external costs for regulated emissions and CO_2 would increase the competiveness of the bio-alternatives.

17. Summary

City buses are the backbone of many public transport systems, and therefore they constitute a very important element of the transportation system. Procurement of bus services is often handled by municipalities or local governments in a centralized manner.

So far conventional diesel buses and conventional diesel fuel have dominated the market, with some contribution from natural gas buses. Now we are in a situation in which the technology options are increasing rapidly. This goes for vehicle technology as well as fuels. Advanced diesel vehicles producing very low emissions are entering the market, and hybrids are becoming commercially available. On the fuel side, various biofuels are offered as blending components or to be used as such. Natural gas and biogas can still deliver emission benefits over diesel. Additive treated ethanol is available for captive fleets such as city buses, and DME has progressed into the field testing phase. The diversification in technology increases the challenges in decision making.

In 2009–2011, a comprehensive project on urban buses was carried out in cooperation between IEA's Implementing Agreements on Alternative Motor Fuels (AMF) and Bioenergy, with input from additional IEA Implementing Agreements. The objective of the project was to generate unbiased and solid data for use by policy- and decision-makers responsible for public transport using buses. Within AMF, this was the largest collaborative project so far.

The project comprised four major parts: well-to-tank (WTT) assessment of alternative fuel pathways, assessment of bus end-use (tank-to-wheel, TTW) performance, combining WTT and TTW data into well-to-wheel (WTW) data and cost assessment, including indirect as well as direct costs.

<u>WTT</u>

Experts at Argonne National Laboratory, Natural Resources Canada, and VTT worked on the WTT part. In the WTT assessment, the total emissions of different fuels were assessed from the raw material production until the distribution of the final product. The assessment was done using RED methodology and GHGenius and GREET models. All these methods are based on life cycle assessment (LCA) approachs. The LCA is a commonly used tool for environmental impact assessment of different products. The framework of LCA is presented in two ISO standards, ISO 14040 and ISO 14044.

Argonne National Laboratory calculated the WTT emissions of 5 fossil fuels and 13 biofuels by using the GREET model. They reported the $CO_{2\text{-eq}}$. emissions, total and fossil energy consumption per MJ of biofuel, as well as the VOC, CO, NO_x, PM_{10}, $PM_{2.5}$, and SO_x emissions. The GREET model is a tool developed with support from the U.S. Department of Energy and is available free of charge for anyone to use (http://greet.es.anl.gov/).

Natural Resources Canada calculated the WTT emissions of 6 fossil fuels and 12 biofuels with the GHGenius model. They reported the $CO_{2\text{-eq}}$. emissions, and separately the CH_4 and N_2O emissions. Also VOC, CO, NO_x, PM, and SO_x emissions were reported. The GHGenius model has been developed by Natural Resources Canada and is available free of charge for anyone to use (http://www.ghgenius.ca/).

VTT reported the WTT emissions of 4 fossil fuels and 19 biofuels according to the RED methodology, published in the Renewable Energy Directive (2009/28/EC) of the European Union. The default values of the directive were used to present the average European GHG emission values for these fuels. The RED does not cover other emissions than the GHGs, so no other emissions were reported.

In co-operation, the institutes made a comparison of the different calculation models and methodologies used for the WTT assessment. The most important calculation principles and assumptions were presented in a table and can easily be compared to each other. The models have many similar calculation assumptions but also differences in their approach to the WTT assessment. The most important difference between the GREET model and the RED methodology is that in the GREET model the carbon absorption of growing biomass is taken into account and consequently the WTT emission may be negative, if more CO_2 is absorbed than released during the biofuel production. Consequently, the GREET model takes into account the real emission of the biofuel combustion. On the contrary, the RED assumes that the amount of carbon absorbed in the growing biomass used as biofuel raw material, is similar to the carbon released when biofuel is combusted, and consequently the emission of biofuel use is zero. Also the GHGenius considers the CO_2 emissions due to biofuel combustion as zero (as the RED), but calculates the CH_4 and N_2O emissions for combustion.

The results of any WTT assessment are vulnerable to various calculation assumptions. Special attention should be put for example on the allocation principles chosen for the WTT assessment as they have an important effect on the final result. In the RED methodology, the emissions are allocated between the main product (biofuel) and possible co-products based on the energy content (in terms of LHV) of the products. The GREET lets the user to choose between co-product displacement, or energy / market value allocation, and the GHGenius uses system expansion and displacement for biofuels and process allocation for petroleum fuels.

The assumptions related to the system boundary of the WTT assessment are also very important, as the results might change significantly if the system boundary changes. In this report, the system boundary of the assessment was set so that for example the possible indirect effects on land use due to biofuel raw material production (ILUC) were left outside from the assessment. However, these impacts were presented in a separate section.

The results of the WTT assessment show that the impacts of the region of biofuel production, the raw material used and the technology choices made for the biofuel process are crucial to the GHG impacts. In addition, many case specific characteristics, e.g. available energy sources or transportation distances, may cause variation of the results. The results may also vary depending on the calculation assumptions, data uncertainties, and sensitivities. The WTT tank part has the most important effect on the variation of the total GHG emissions of biofuels.

TTW chassis dynamometer

In the TTW part Environment Canada (EC) and VTT generated emission and fuel consumption data by running 21 different buses on chassis dynamometers, generating data for some 180 combinations of vehicle, fuel and driving cycle. EC and VTT used congruent instrumentation and methodology. Three driving cycles were common for both laboratories, ADEME, Braunschweig and UDDS. However, as intercalibration was not possible, the results should not be primarily used for comparing European and North-American vehicles, but rather to see what progress tightening emission regulations have brought forwards and how different types of vehicles respond to changes in driving patterns and fuels. The primary test cycles were Manhattan at EC and Braunschweig at VTT.

The fuels covered included diesel, synthetic diesel, various types of biodiesel fuels, additive treated ethanol, methane and DME. Six different hybrid vehicles were included in the vehicle matrix. The TTW work was topped up by on-road measurements (AVL MTC) as well as some engine dynamometer work (von Thünen Institute).

EC tested altogether 7 vehicles representing EPA 1998, 2007 and 2010 emission regulations. The 1998 vehicle and the three 2010 vehicles had conventional powertrains. Of the three 2007 vehicles one had conventional powertrain and two had hybrid powertrains. EC used 7 different cycles to assess vehicle performance. The fuels tested by EC were three different kinds of ultra-low sulfur diesel ULSD (commercial, oil-sands derived and certification fuel) and biodiesel blends with FAME from canola, soy and tallow. In addition, EC tested HVO as a blending component and as such. The number of combinations evaluated was 68.

EC's measurements clearly demonstrated the tremendous reductions in regulated emissions with tightening emission regulations; at maximum a reduction of some 97% for NO_x as well as PM comparing the 1998 vehicle with 2010 vehicles. Already the EPA 2007 platforms deliver significantly reduced PM emissions, thanks to DPFs. NO_x emissions are brought to from EPA 2007 going to EPA 2010 by implementing SCR technology.

For fuel consumption, the changes are small, as the 1998 vehicle has a fuel consumption equivalent to the average of the 2010 vehicles. Hybridization, on the other hand, reduces fuel consumption some 30–35% for the Manhattan cycle. No unambiguous trend of hybridization on regulated emissions could be seen.

Six of the seven vehicles at EC were tested with more than one cycle. Of the cycles used at EC, Manhattan is the most severe one for fuel consumption, PM and in most cases also for NO_x. The "extreme ends" tested Manhattan and UDDS. Going from UDDS to Manhattan, the increase in fuel consumption is some 60–80% for the vehicles with conventional power trains and some 30% for the hybrids. For ADEME, Manhattan and OCTA, hybridization saves 30–35% fuel. In the UDDS cycle the benefit is smaller, some 20%.

With the exception of the EPA 1998 bus, the use of the emission control technologies overshadowed or masked the effects of the varying fuel properties on the measured emissions. However, the results for the EPA 1998 bus were also somewhat inconclusive as both oil sand s derived ULSD and 100% HVO increased particulate emissions.

EC measured several unregulated components, including carbonyl compounds, N_2O and particulate numbers. Emissions of carbonyls from the oldest technology bus compared to all the other buses, especially the 2010 technologies, were significant. The 2010 buses using SCR technology, on the other hand, gave higher N_2O emissions compared to the other bus technologies. Particle number emission rates from the buses with DPF are orders of magnitude lower compared to bus without DPF. Comparing the EPA 1998 bus to the EPA 2010, mass emission rates have been reduced by more than 99%.

Work at **VTT** encompassed 14 vehicle platforms, 6 test cycles and 14 different fuel alternatives, producing a total of 110 different combinations. The vehicle matrix included four diesel hybrids and one light-weight diesel bus. In addition to diesel and diesel replacement fuels, VTT also tested natural gas (CNG), additive treated ethanol and di-methyl-ether (DME) in dedicated vehicles. The DME vehicle was a prototype heavy-duty truck, simulated as a bus. Therefore the results for DME must be considered indicative, at the most. The emission certification of the vehicles ranged from Euro II (late 90s) to EEV (current regulation).

For European diesel vehicles, the progress in regulated emissions has not been as remarkable as for North American vehicles. In round figures NO_x emissions have been cut some 40% and PM emissions some 80% going from Euro II to EEV.

For alternative fuel vehicles the variation in regulated component emission is quite significant. CNG delivers lowest (stoichiometric) as well as highest (lean-burn) NO_x emissions, with a ratio of some 1:10. Both ethanol and DME delivers slightly lower NO_x compared to diesel average. For PM ethanol delivers performance equivalent to average diesel but lower than EGR diesel. CNG gives lowest PM emissions, some 0.015 g/km, i.e. half of diesel average and equivalent to wall-flow filter equipped diesel. DME comes quite close to CNG. Stoichiometric CNG delivers lowest aggregate NO_x + PM emissions, in fact lower than the North-American EPA 2010 certified diesels.

In the case of European vehicles, the oldest vehicle (Euro II) gives the highest fuel consumption. Within the EEV class, the EGR vehicle has some 10% higher fuel consumption compared to vehicles with SCR technology. In the case of European vehicles and the Braunschweig cycle, hybridization reduced fuel consumption (and CO_2) on an average 27% (19   32%) compared to EEV average without hybridization. No clear benefits of hybridization on regulated emissions could be seen. For fuel consumption, the light-weight came close to the fuel consumption values of the hybrids.

When evaluating alternative fuel vehicles, a fair comparison of fuel consumption is done on energy basis, not on volumetric or gravimetric basis. Here the differences are much smaller than for the regulated emissions, but still quite substantial. Diesel is the most fuel efficient option. The CNG vehicles consume 32–39% more energy compared to EEV diesel average. Tailpipe CO_{2eqv} emissions for the CNG vehicles are 5–10% higher than for EEV diesel average. The energy consumption of the ethanol vehicle is some 6% higher compared to EEV diesel average, but in comparison with the EEV EGR diesel, the ethanol vehicle delivers the same energy efficiency. The energy consumption of the DME vehicle was equivalent to EEV diesel average. However, it must be pointed out that the results for the DME vehicle are indicative.

VTT used at maximum six driving cycles in its bus evaluation. The extreme cycles were NYBUS and WHVC. The EEV EGR and EEV SCR vehicles and the hybrids were tested on all six cycles. For diesel vehicles with conventional power train going from WHVC to NYBUS, fuel consumption increases some 250%, and NO_x as well as PM emissions increase some 500–700%. For hybrid vehicles, on an average, fuel consumption increases some 140%, NO_x emissions some 450% and PM emissions increase some 180% going from WHVC to NYBUS. Thus the variations are smaller than for the vehicles with conventional powertrain. In the NYBUS cycle hybridization saves close to 40% fuel, whereas the benefit of hybridization is marginal for UDDS and WHVC, below 10%.

There are significant variations in performance within the group of hybrids, especially regarding emissions. The demanding cycles, NYBUS, ADEME and Braunschweig, accentuate the differences

The stoichiometric CNG vehicle consistently shows low emissions and little variation in emissions from cycle to cycle. PM emissions were more or less constant regardless of the cycle. The performance profile of the ethanol vehicle resembles the one of the EEV EGR diesel. However, the ethanol vehicle delivers lower PM emissions for all cycles, average -50%.

VTT tested four 100% replacement fuels (neat fuels), GTL, HVO, JME and RME. Fatty acid methyl esters (in this case JME and RME) are known to be effective in reducing PM emissions, but the drawback is increased NO_x emissions. Compared to EN590 diesel the PM emission reductions were some 40–75% and the increase in NO_x some 20–45%. HVO and GTL were tested in parallel in Euro III, EEV EGR and EEV SCR. As could be expected, both fuels delivered almost identical NO_x and PM emissions. For all vehicle platforms, paraffinic diesel (GTL, HVO) reduced NO_x 3–4%. PM was reduced 20–50%, the EEV EGR vehicle showing the lowest and the EEV SCR vehicle showing the highest response for PM.

The blended fuels basically perform as can be expected on basis of the performance of the neat fuels. RME, even in blends, increases NO_x and reduces PM. In the Euro II vehicle, a blend of 70% HVO and 30% RME gives only a slight increase in NO_x, but a substantial reduction in PM, demonstrating that some hybrid blends could be of interest.

VTT also carried out some measurements of unregulated components. As for particulate numbers, the vehicles fall into three categories: highest particulate numbers for diesel Euro III, EEV EGR, EEV SCR and ethanol, lowest numbers for CNG and DME in between. In the smallest size class measured (20 nm) CNG delivers almost two orders of magnitude lower numbers than the other technologies. The assumption is that the diesels with wall-flow filters would produce particulate numbers comparable to CNG (SCRT was not covered in the particulate number measurements).

VTT's measurements confirm the observations from Environment Canada; the main parameter affecting the regulated emissions is the vehicle itself. Switching old vehicles to new ones, whether fuelled by diesel or alternative fuels, will deliver huge reductions in local emissions.

The findings can be summarized as follows:

- Old vs. new vehicles
  - 10:1 and even more for regulated emissions
  - 100:1 for particulate numbers
  - close to neutral for fuel efficiency (improvement from Euro II to EEV, but Euro VI is expected to increase fuel consumption over EEV)
- Hybridization and light-weighting
  - 20–30% reduction in fuel consumption
  - not automatically beneficial for regulated emissions
- Effect of driving cycle
  - 5:1 for fuel consumption and regulated emissions
- Fuel effects (when replacing regular diesel)
  - 2.5:1 at maximum (particulates)
- Alternative fuels (in dedicated vehicles)
  - low PM emissions but not automatically low NO_x emissions
  - fuel efficiency depends on combustion system (compression or spark-ignition).

Engine dynamometer work

von Thünen Institute of Germany carried out detailed evaluations of both regulated and unregulated exhaust emissions using a Euro III level heavy-duty diesel engine installed in an engine dynamometer. The engine didn't have any exhaust after-treatment devices, and therefore accentuates the fuel effects on emissions.

The testing was done with four fuels: commercial diesel fuel corresponding to EN590, RME, JME and HVO.

The oxygenated fuels increased NO_x emissions whereas HVO reduced NO_x 15% relative to diesel fuel. As for PM, the oxygenated fuels delivered a reduction of 35% and HVO a reduction of 8% in comparison with diesel fuel. JME and RME reduced particulate numbers, whereas HVO produced particulate numbers equivalent to diesel fuel. The results for mutagenicity were interesting. HVO delivered significantly lower mutagenicity compared to diesel fuel, whereas both JME and RME increased mutagenicity compared to diesel. HVO also produced lowest PAH emissions.

On-road measurements

At VTT, two on-road emission measurement campaigns were carried out. The first one, aimed at demonstrating emission performance in real traffic conditions was carried out in cooperation with **AVL MTC of Sweden**. Three vehicles were measured: Euro III diesel, EEV diesel (EGR) and stoichiometric CNG. The second campaign was aimed at studying the start-up performance of the emission control systems, and was carried out in cooperation **JRC VELA (Italy)**. This campaign encompassed three EEV diesel vehicles: EGR, SCR and SCRT. Testing was carried out using the Braunschweig cycle and the SORT 2 cycle by UITP.

In general, the results of the first on-road measurement campaign were well in line with the results of the chassis dynamometer measurements for NO_x and CO_2. AVL's soot measurement system was sufficient to separate out the vehicle types, but not accurate enough to bring out the effects of driving cycle. The findings were summarized as follows. No NO_x benefit was seen going from Euro III to EEV EGR diesel, whereas the CNG vehicle delivered very low NO_x and soot (PM) emissions independent of driving cycle. The Euro III diesel had high soot emissions, and in this case EEV EGR delivered much lower soot emissions.

In the cold start tests temperatures were in the range of ± 0 to -5 ^oC. After a cold start, the NO_x emission stabilizes after two to four repetitive Braunschweig cycles. Temperature has little effect on the NO_x emissions of the SCR vehicle, with all results in the range of 6–10 g/km. In the case of the SCRT vehicle, cold start increases NO_x with a factor of 3, for the EGR vehicle with a factor of some 4. The pre-supposition was that the SCR equipped vehicles would display greater temperature dependence than the EGR vehicle in the cold start phase. For all vehicles, the stabilized NO_x level, whether on the road or on the chassis dynamometer, is 5–7 g/km. This is an indication of two things. Firstly, the on-road measurements and the chassis dynamometer measurements correlate rather well. Secondly, when warmed up, all three vehicles deliver roughly equivalent NO_x performance.

WTW

The findings of the WTT part were combined with actual bus performance data to form WTW figures.

The specific CO_2 emission of diesel fuel combustion is typically some 75 g CO_{2eqv}/MJ, and the WTT emission some 20 g CO_{2eqv}/MJ, an overall WTW value of some 95 g CO_{2eqv}/MJ. With an energy consumption of 16 MJ/km (typical European vehicle, Braunschweig cycle), the WTW GHG emission is some 1500 g CO_{2eqv}/km.

It is clear that for WTW greenhouse gas emissions fuel is more decisive than vehicle. Within diesel vehicles and diesel hybrids, the ratio between highest and lowest WTW value is 2:1, proportional to fuel consumption. As for fuels, the ratio between highest and lowest WTW value is 120:1 (CTL from coal versus tallow FAME, values from GHGenius). Combining fuel and vehicle, the extreme values for WTW have a ratio of 240:1.

In comparison with conventional diesel fuel, on an average, natural gas based CNG GTL and CNG will increase WTW GHG emissions by some 10–15%.

In the case of Europe, DME delivers equivalent GHG compared to GTL when both are based on remote processing, somewhat lower compared to CNG based on remote natural gas. If both DME and CNG are based on remote gas (DME processing in Europe), these fuels deliver equivalent WTW GHG emissions. The higher efficiency of the DME engine is sufficient to compensate for the high WTT emissions of the fossil DME path.

The biofuel pathways covered in this study (which do not include the extreme values shown in Figure 15.1) fall into three categories for GHG reductions in comparison to conventional fossil diesel (taking into account fuel carbon intensity as well as vehicle efficiency, excluding the GREET ethanol alternatives delivering a negative WTW balance):

1. Biofuels from traditional feedstocks for diesel vehicles:
   - Range of WTW CO_{2eqv} ~ 450 950 g/km
   - Relative reduction ~ 30 70%
2. Conventional biogas in spark-ignition CNG vehicles:
   - Range of WTW CO_{2eqv} ~ 100 500 g/km
   - Relative reduction ~ 65 90%
3. Biofuels from lignocellulosic feedstocks or waste in vehicles using diesel combustion (diesel, ethanol, DME):
   - Range of WTW CO_{2eqv} ~ 25 200 g/km (lowest value GHGenius for tallow FAME)
   - Relative reduction ~ 85 95%.

Variations in WTW energy consumption are much smaller than for WTW GHG emissions. For vehicles with conventional powertrain (diesel and alternative fuel vehicles) highest value is 46 MJ/km (ethanol from sugarcane) and lowest value 18.1 MJ/km, a ratio of 2.5:1. Hybridization or light-weight construction could bring down these values some 30%.

GREET presents criteria emissions for fuel production as well as and end-use. Comparing GREET's estimates for fuel production and actual end-use emissions it can be seen that fuel production is a bigger contributor than end-use for VOC/THC and particulate emissions, whereas in the case of NO_x the situation is reversed. Using the GREET methodology, some ethanol options (corn stover, switchgrass and farmed wood) render negative GHG values.

Cost assessments

External costs of emissions were evaluated using European methodology. Direct costs were estimated by taking into account investment in vehicles, fuel and urea consumption and estimated fuel and urea price. All results presented should be considered indicative only, as there was no possibility for in-depth cost assessments.

The European "Handbook on estimation of external cost in the transport sector" differentiates countries and in the case of particulates, also areas or regions. The idea is that the cost of particulates increases with the size of the exposed population. Values were calculated for Finland, France and Germany.

Values were calculated for 11 European vehicle platforms, four conventional diesel vehicles (Euro II to EEV), four diesel hybrids and three alternative fuel vehicles (stoichiometric CNG, ethanol and DME). The calculatory external costs vary between 0.001 €/km (stoichiometric CNG, UDDS, Finnish values) and 0.24 (Euro II diesel, ADEME, German values), a factor of some 1:200. The values for Germany are, when comparing the same vehicle and the same cycle, 100–1000% higher than the Finnish ones. The values for Germany are some 10–25% higher compared to the values for France.

Euro II and Euro III have the highest external costs, in the range of 0.01–0.24 €/km. Stoichiometric CNG has by far the lowest external costs, 0.001–0.02 €/km, 1/10 of older diesels. The methodology emphasises NO_x emissions, not particulates, so even for the old Euro II vehicle NO_x dominates the emission costs.

Using German "megacity" emission costs for the ADEME cycle, the external costs are 0.02–0.24 €/km, For the Braunschweig cycle and German "mid-size city" the values are cut in half, 0.01–0.12 €/km. For the Barunschweig cycle, the calculatory emission benefit in switching from regular diesel to GTL or HVO is 0.01–0.05 €/km. For the newest vehicles with low emissions the benefit is rather limited.

At a CO_2 price of 40 €/ton, the calculatory WTW CO_2 costs is 0–0.12 €/km.

Estimates of **direct costs** were calculated taking into account vehicle investment costs, costs for fuel and urea and very rough estimates of maintenance costs. The calculations are indicative, as no fixed price lists are available for buses, nor are there universal price lists for fuels. Taxes and subsidies for fuels and vehicles will vary from market to market. **Please note that no taxes or subsidies are includ-**

ed in the calculations. Taxes and subsidies might change the competitiveness of certain technologies considerably.

Calculations were made for seven European vehicle platforms, EEV SCRT diesel, light-weight EEV SCRT diesel, Euro VI diesel (imaginary, roughly equivalent to US 2010), hybrid EEV diesel, EEV ethanol, Euro V CNG lean-burn and EEV CNG stoichiometric. DME was left outside this assessment.

The calculation was made for the Braunschweig cycle, using actual measured fuel consumption values with the exception of the imaginary Euro VI diesel vehicle, which is estimated to consume 5% more fuel and 50% more urea that the baseline EEV SCRT diesel vehicle.

Using baseline assumptions (diesel fuel 0.65 €/l, CNG 0.65 €/kg, additive treated ethanol 0.38 €/l), the direct costs, including investment cost for the bus, fuel costs and maintenance costs is 0.63–0.77 €/km. Light-weight diesel and baseline SCRT are at some 0.65 €/km and the rest of the vehicles at some 0.75 €/km. On an annual basis, with a mileage of 80,000 km, the difference in operational costs is at maximum some 12,000 €. Stoichiometric CNG, which deliver actual Euro VI performance, is roughly competitive with the imaginary Euro VI diesel.

Calculating with a high diesel price of 0.90 €/km would increase the cost of the diesel options some 0.10 €/km. Operational costs are in the range of 0.72–0.85 €/km. Light-weight EEV SCRT diesel is still the cheapest option. Natural gas and ethanol are now competitive with the diesel options, with the exception of the light-weight diesel.

For the baseline case, the additional cost for the hybrid was estimated at some 55%. With a diesel price of 0.60 €/l, the hybrid is not cost competitive. A combination of a diesel price of 0.90 €/l and an additional price of 35% for the hybrid systems makes the hybrid cost competitive.

In the base case going from conventional diesel to BTL would increase operational costs some 20% and going from natural gas to biogas some 10%. Taking into account external costs for regulated emissions and CO_2 would increase the competiveness of the bio-alternatives.

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2009/33/EC. Directive 2009/307/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of clean and energy-efficient road transport vehicles. http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:120:0005:0012:en:pdf

List of Appendices

Appendices related to the main report:

1. WTT methodology
2. Vehicle test cycles
3. Test fuels at Environment Canada
4. Test fuels at VTT
5. GREET tables for energy consumption and criteria pollutants
6. Vehicle test data for Environment Canada
7. Vehicle test data for VTT
8. Cost factors for air pollution according to the “Handbook”

Contributions (outlook reports) by the transport related IEA Implementing Agreements:

A. Bioenergy: Outlook for biofuels
B. Advanced Fuel Cells and Hydrogen Implementing Agreement: Outlook for fuel cell transit buses
C. Advanced Materials for Transport: Outlook for materials technology
D. Hybrid and Electric Vehicles: Technology projection for hybrid and electric buses
E. Combustion: Alternative fuels in combustion

Appendix 1: WTT methodology

This Appendix presents the models and methods used in the WTT assessment of the chosen biofuels are presented in detail.

GREET model

The use of motor vehicles involves two different energy cycles: production and use of motor fuels (fuel cycle) and production and use of motor vehicles (vehicle cycle). The fuel cycle for a given transportation fuel includes the following processes: primary energy (i.e., energy feedstock) production, transportation, and storage (T&S); fuel (i.e., energy source) production, transportation, storage, and distribution (T&S&D); and vehicle operations that involve fuel combustion or other chemical conversions. The vehicle cycle includes material recovery and fabrication, vehicle production, vehicle operation, and vehicle disposal/recycling. (Vehicle operation is included in either the fuel cycle or the vehicle cycle.) The processes that precede vehicle operations are often referred to as upstream activities; actual vehicle operations are referred to as downstream activities.

To evaluate various motor vehicle technologies, both cycles should be considered, because in many cases, use of an alternative transportation fuel or an advanced vehicle technology involves changes in both upstream fuel production activities and in production of materials and vehicles. In energy and emission analyses for consumer goods, researchers often refer to studies of the "cradle to grave" cycle of a product as life-cycle analysis (LCA). A so-called total energy-cycle analysis (TECA) or cradle to grave analysis for transportation technologies includes both the fuel and the vehicle cycles. When TECA results for ICEV-based technologies are separated into three groups — fuel-cycle upstream activities, vehicle production and disposal, and vehicle operations— energy use and emissions from vehicle operations are the largest, those from upstream activities are second, and those from vehicle production and disposal are the smallest.

The GREET model has been developed to calculate per-mile energy use and emission rates of various combinations of vehicle technologies and fuels for both fuel cycle and total energy cycle. Since the development of GREET 1.0 (which was a fuel-cycle model only), the model has evolved to include two components, with a third covering heavy-duty vehicles now in development. The first – the Series 1 component (GREET 1.0, 1.1, 1.2, 1.3, and so on) – calculates fuel-cycle energy use and emissions of light-duty vehicles (passenger cars, vans, and light-duty trucks [LDTs]). This series is the continuation of GREET 1.0. The second – the Series 2 component — calculates vehicle-cycle energy use and emissions of light-duty vehicles. The Series 2 component was developed through Argonne's effort on total energy-cycle analysis for HEVs. During calculations, the Series 2 model draws data from the Series 1 model to estimate vehicle-cycle energy use and emissions. Energy and emission results of fuel cycle (calculated in Series 1) and vehicle cycle (calculated in Series 2) analyses are combined in Series 2. So, the Series 1 model presents fuel-cycle results only, and the Series 2 model presents both fuel-cycle and total energy-cycle results.

To estimate fuel-cycle energy use and emissions, GREET first estimates energy use (in British thermal units [Btu (or MJ)]) and emissions (in grams) per million Btu (or MJ) [g/106 Btu (or MJ)) of fuel throughput for a given upstream stage. The model then combines the energy use and emissions from all upstream stages for a fuel cycle to estimate total upstream fuel-cycle energy use and emissions. The aggregation takes into account, among other factors, loss of a fuel during the fuel cycle. Because fuel-cycle fossil fuel and petroleum consumption, as well as total energy consumption, are of interest, GREET is designed to calculate both of these values as well as fuel-cycle total energy consumption, all at the primary energy level. Total energy includes fossil energy and renewable energy such as solar energy, wind, and geothermal energy. Therefore, the model can estimate the amount of fossil fuel and petroleum displaced as a result of using alternative transportation fuels and advanced vehicle technologies instead of conventional vehicles fueled with gasoline.

The most recent GREET version is GREET1.2011 and is available online: http://greet.es.anl.gov/. GREET model formulation and calculation details are available on line in the following published reports:

ANL/ESD/TM-163: Development and Use of GREET 1.6 Fuel-Cycle Model for Transportation Fuels and Vehicle Technologies by Michael Wang
(http://www.transportation.anl.gov/pdfs/TA/153.pdf)

General Motors Corp., Argonne National Laboratory, BP, Exxon Mobil and Shell: Well-to-Wheel Energy Use and Greenhouse Gas Emissions of Advanced Fuel/Vehicle Systems, North American Analysis, vol. 2
(http://www.transportation.anl.gov/pdfs/TA/164.pdf)

ANL/ESD/05-3: Operating Manual for GREET: Version 1.7 by M. Wang, Y. Wu, and A. Elgowainy (http://www.transportation.anl.gov/pdfs/TA/353.pdf).

A complete listing of published monographs, presentations and technical papers on GREET may be found at: http://greet.es.anl.gov/publications.

GHGenius model

Lifecycle emissions calculated in GHGenius are calculated in the following stages: vehicle operation; carbon in end use fuel from CO_2 in the air (carbon credit for biofuels); fuel dispensing; fuel storage and distribution; fuel production; feedstock transport; feedstock recovery; feedstock upgrading; land-use changes (direct) and cultivation; fertilizer manufacture; gas leaks and flares; CO_2 and H_2S removed from natural gas; emissions displaced by co-products; vehicle assembly and transport; and materials in vehicles.

The results in this report are presented as two stages: fuel combustion and fuel production. The fuel combustion stage actually includes the vehicle operation and carbon in end use fuel from CO_2 in the air (carbon credit for biofuels) sub-stages. The vehicle operation stage includes CO_2 from fuel combustion, other GHG emissions from combustion (based on IPCC 2007 100-year CO_2 equivalency factors), the carbon from non-GHG pollutants and fuel leakage and evaporation (which is assumed to ultimately oxidize to CO_2), and CO_2 from lube oil consumption. The carbon credit for biofuels is equal to the total carbon content of biofuels.

The fuel production stage in this report contains the following stages: fuel dispensing; fuel storage and distribution; fuel production; feedstock transport; feedstock recovery; feedstock upgrading; land-use changes (direct) and cultivation; fertilizer manufacture; gas leaks and flares; CO_2 and H_2S removed from natural gas; emissions displaced by co-products.

In this report, emissions from the last two stages, vehicle assembly and transport and materials in vehicles, were omitted, as they tend to be independent of the fuel in most cases (i.e. using diesel or biodiesel in the same bus has no impact on emissions due to material used in the bus once it has been produced). Differences also tend to be small, and when they are more significant, for example the difference between a standard bus and a hybrid bus, the difference is still only a small fraction of the full lifecycle emissions.

Though GHGenius does not calculate indirect land use changes, it does estimate direct land use and cultivation emissions. This includes emissions from changes in the carbon stock of the land (IPCC methodology), N_2O emissions from fertilizer application and nitrogen content of biomass on the land (IPCC methodology), and emissions from conversion to cropland amortized over 20 years.

GHGenius uses an extensive dataset that has been compiled from many different sources to calculate the energy used and emissions released for each of these different stages of the lifecycle. For further information, GHGenius and its accompanying reports are available online at www.GHGenius.ca.

RED methodology

The European Union Directive on the promotion of the use of energy from renewable sources (RED) provides a list of default values of the emissions saving results for certain biofuels. In this report we used these default values. The RED also introduces a methodology for calculating greenhouse gas impacts of biofuels, as well as the greenhouse gas emission reduction compared with fossil fuels to be replaced. The default values provided in the RED may be used under certain conditions. If the default value for greenhouse gas saving of a production pathway is not presented, producers wishing to demonstrate their compliance with this minimum level are required to calculate the actual emissions from their production process. Also, if the default value presented lies below the required minimum level of greenhouse gas emission saving, the producers can show that the actual emission saving from the biofuel process is higher than the one assumed in default values. The default value can be used if it is presented for the specific biofuel production chain and if the emissions from the carbon stock changes caused by land use change are equal to or less than zero (see equation 3).

The calculation of the actual greenhouse gas emission savings follows the methodology presented in the part C of Annex V of the RED. This methodology is based on the LCA approach, as the greenhouse gas emissions of the whole life cycle of biofuels are evaluated. Part C of Annex V of the RED defines the relative emission reduction in greenhouse gas emissions achievable by replacing a fossil fuel comparator by certain biofuels as:

$$\text{EMISSION SAVING} = (E_F - E_B)/E_F, \qquad (1)$$

where
E_B = total emissions from the biofuel or other bioliquid; and
E_F = total emissions from the fossil fuel comparator.

Total emission from the biofuel or other bioliquid is calculated as:

$$E = e_{ec} + e_l + e_p + e_{td} + e_u - e_{sca} - e_{ccs} - e_{ccr} - e_{ee}, \qquad (2)$$

where
E = total emissions from the use of the fuel;
e_{ec} = emissions from the extraction or cultivation of raw materials;
e_l = annualised emissions from carbon stock changes caused by land-use change;
e_p = emissions from processing;
e_{td} = emissions from transport and distribution;
e_u = emissions from the fuel in use;
e_{sca} = emission saving from soil carbon accumulation via improved agricultural management;
e_{ccs} = emission saving from carbon capture and geological storage;
e_{ccr} = emission saving from carbon capture and replacement; and
e_{ee} = emission saving from excess electricity from cogeneration.

Greenhouse gas emissions are expressed in terms of gCO_2-eq./MJ (LHV). Emissions from the manufacture of machinery and equipment shall not be taken into account. For waste and residue-based raw materials, the calculation of greenhouse gas emissions starts from the collection of the raw material.

Annualized emissions from carbon stock changes caused by land-use change, e_l, shall be calculated by dividing total emissions equally over 20 years period. Here the land use change means a change in the status of the land use (e.g. a change from a forest to a field). For the calculation of those emissions the following rule shall be applied:

$$e_l = (C_{SR} – C_{SA}) \times 3{,}664 \times 1/20 \times 1/P – e_B \qquad (3)$$

where
e_l = annualized greenhouse gas emissions from carbon stock change due to land-use change (measured as mass of CO_2-equivalent per unit biofuel energy);
C_{SR} = the carbon stock per unit area associated with the reference land use (measured as mass of carbon per unit area, including both soil and vegetation). The reference land use shall be the land use in January 2008 or 20 years before the raw material was obtained, whichever was the later;
C_{SA} = the carbon stock per unit area associated with the actual land use (measured as mass of carbon per unit area, including both soil and vegetation). In cases where the carbon stock accumulates over more than one year, the value attributed to C_{SA} shall be the estimated stock per unit area after 20 years or when the crop reaches mturity, whichever the earlier;
P =the productivity of the crop (measured as biofuel or bioliquid energy per unit area per year); and
e_B =bonus of 29 gCO_2eq/MJ biofuel or bioliquid if biomass is obtained from restored degraded land under the conditions provided for in point 8.

The CO_2 emission from the use of biofuel is considered to be equal to the amount of CO_2 that is captured to the growing biomass. That is why the capture of CO_2 in the cultivation is excluded from the calculation and consequently the emission from the use of biofuel, e_u, is considered as zero.

The RED states that the allocation of emissions between the products inside the system boundary should be carried out in proportion to the energy content of the products (determined by a lower heating value in the case of co-products other than electricity). However, the RED does not directly state how emissions from a CHP plant should be allocated between power and heat, when the plant produces power and/or heat to the biofuel process. However, point 18 of Part C of Annex V indicates that energy allocation should be used, if electricity is not produced from agricultural crop residues for which a substitution method is used as regards to electricity.

The RED states that if the electricity used in the biofuel process is not produced within the fuel production plant, greenhouse gas emissions should be evaluated as equal to the average emission intensity of the production and distribution of electricity in a defined region. However, if the power plant producing electricity for the biofuel process is not connected to the grid, greenhouse gas emissions should be assessed as an average production of the particular power plant.

Appendix 2: Vehicle test cycles

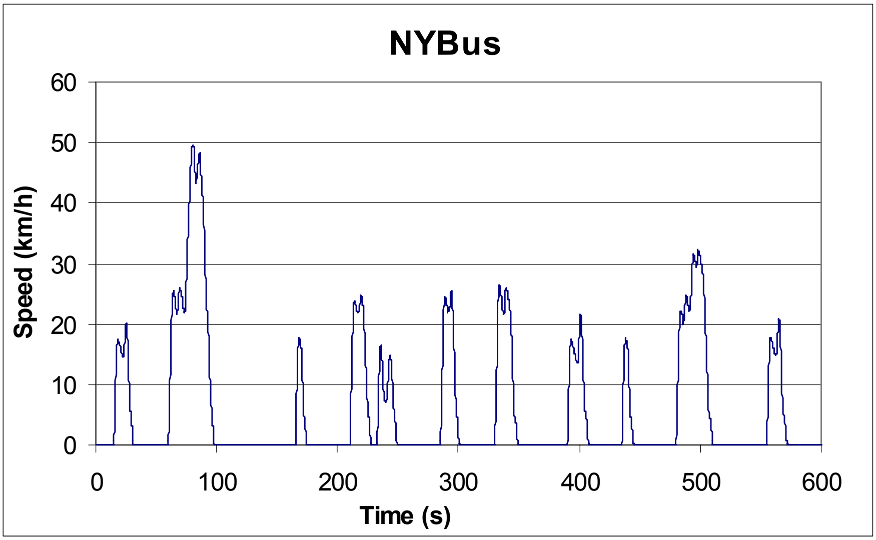


Figure 1. New York Bus Cycle.

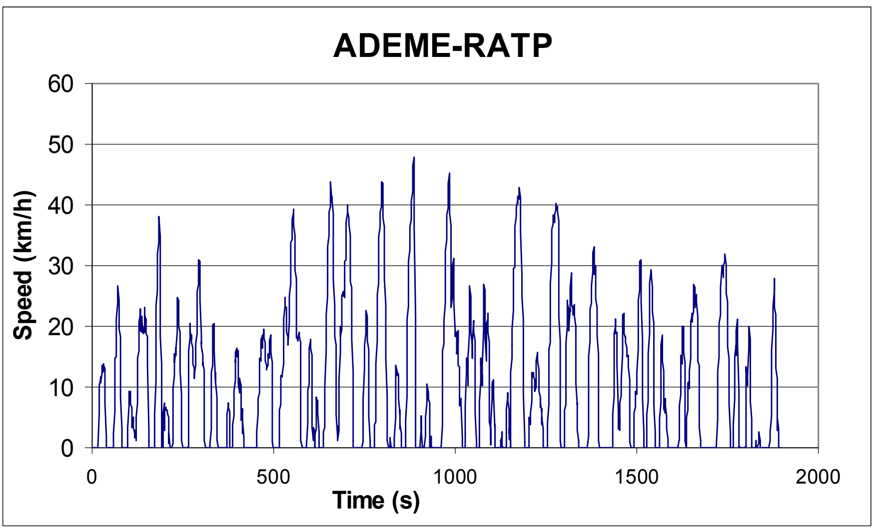


Figure 2. ADEME-RATP (Paris) Bus Cycle.

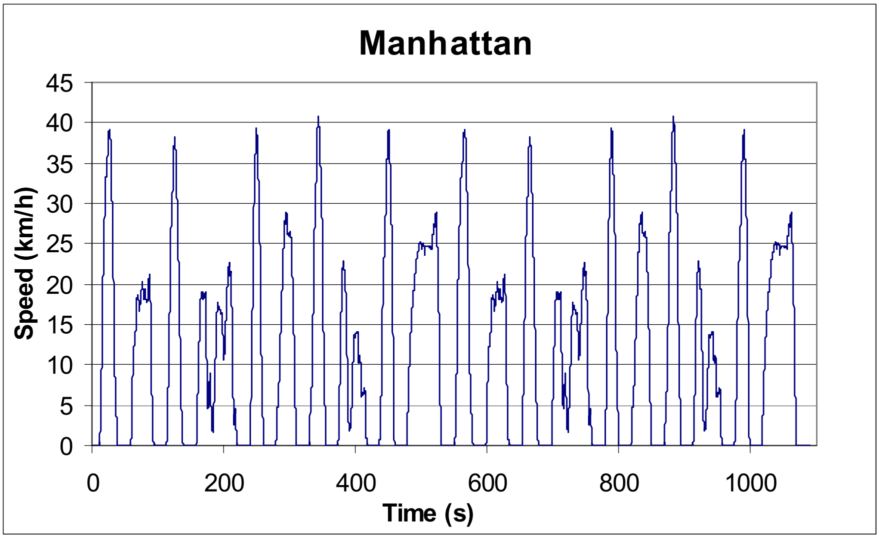


Figure 3. Manhattan Bus Cycle.

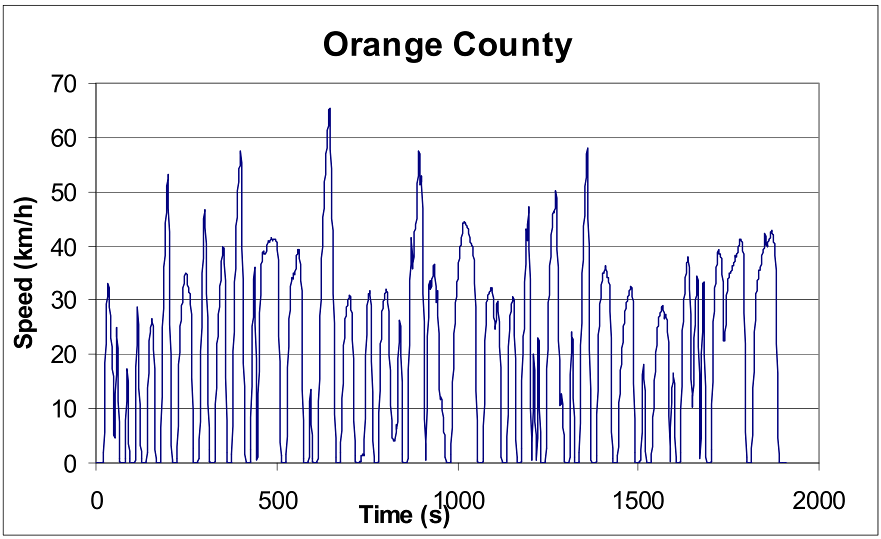


Figure 4. Orange County Bus Cycle.

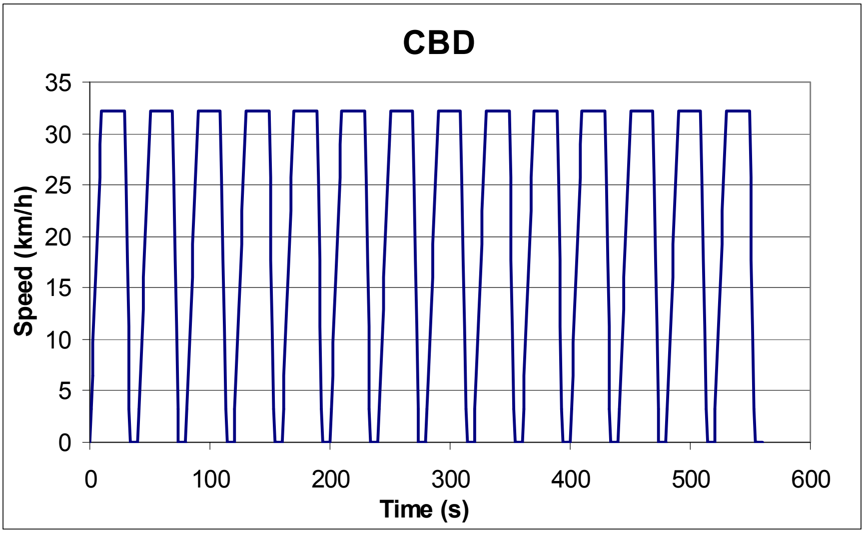


Figure 5. Central Business District Cycle.

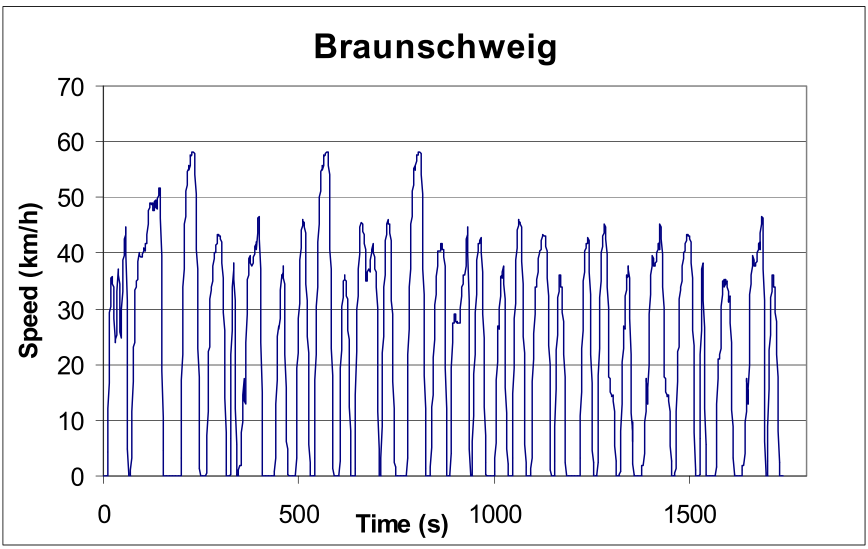


Figure 6. Braunschweig Bus Cycle.

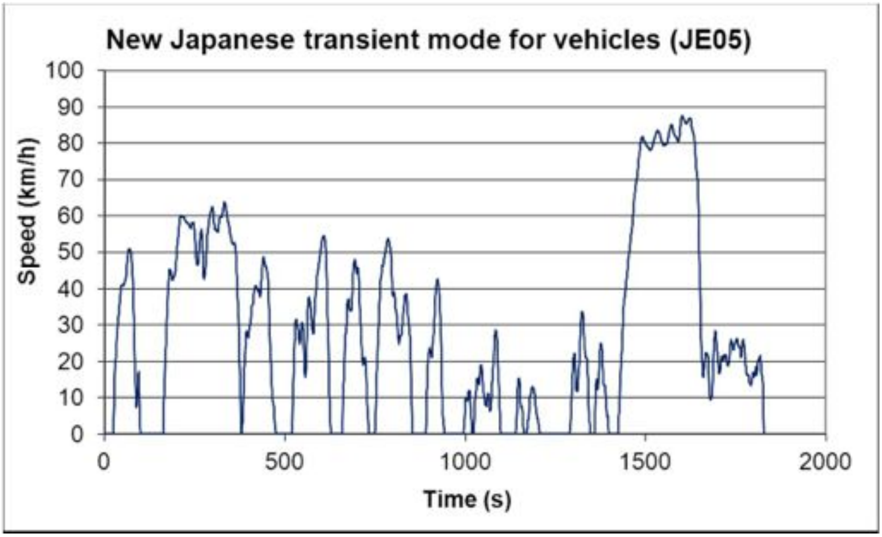


Figure 7. The Japanese JE05 HD cycle.

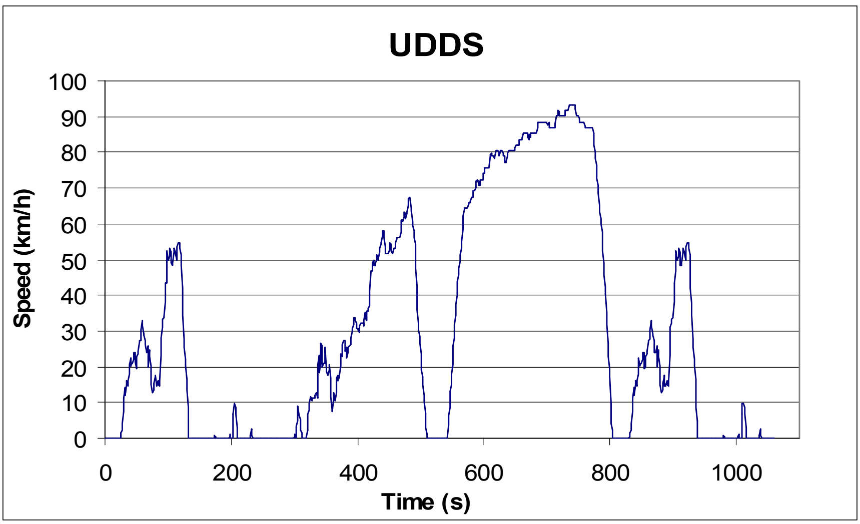


Figure 8. Urban Dynamometer Driving Cycle.

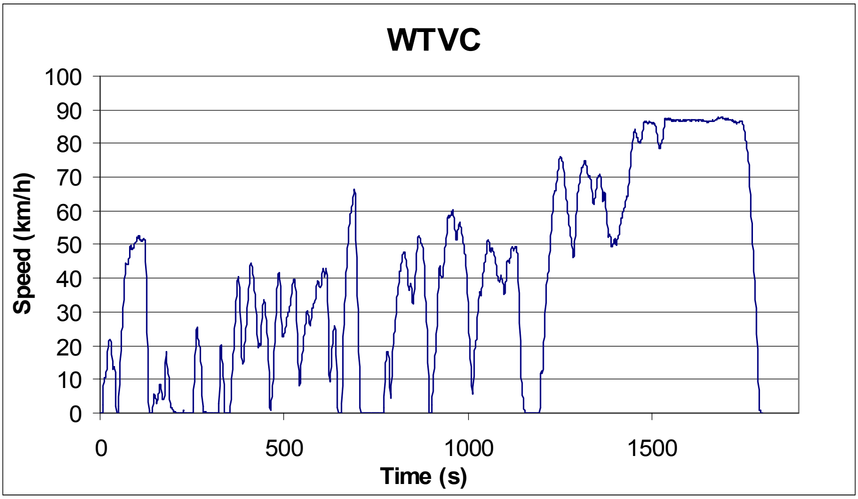


Figure 9: World Transient Vehicle Cycle.

Appendix 3: Test fuels at Environment Canada

Specification	ASTM Method	Units	ULSD COM	ULSD CERT	ULSD OS	HVO	B20 CME COM	B20 HVO COM	B5 CME CERT	B5 SME CERT	B5 TME CERT	B20 SME CERT	B20 TME CERT	B5 CME OS	B20 CME OS
Density	D4052	(kg/m^3@15^{o}C)	829.6	855.3	835	775.1	831.6	809.8	856.6	856.6	856.2	860.7	859.4	844.8	850.9
Specific Gravity	D4052	(kg/L, 60/60oF)	0.819	0.856	0.843	0.775	0.832	0.81	0.857	0.857	0.857	0.861	0.86	0.845	0.851
Cetane Number	D613	-	53.2	43.3	43.5	-	-	-	-	-	-	-	-	-	-
Carbon (wt%)	D5291	-	86.03	87.04	86.12	84.74	84.34	85.84	86.34	86.33	86.32	84.88	84.82	86.03	84.66
Hydrogen (wt%)	D5291	-	13.66	12.96	13.63	15.2	13.76	14.37	12.79	12.78	12.82	12.66	12.8	13.49	13.28
Total Sulphur	D5453	ppm	6	11	5.6	-	7.8	-	8.2	8	8	7.2	7.2	5.8	6.2
Cloud Point max	D5773	^{o}C	-13	-32.1	-34.2	-26	-21.8	-26.8	-22.1	-21.7	-21.4	-17.24	-15.9	-28.5	-24.1
Net Heating Value	D4809	(btu/lb)	18624	18391	-	-	-	-	-	-	-	-	-	-	-

Appendix 4: Test fuels at VTT

Diesel fuel and HVO

At VTT, the testing was carried out over an extended test period. Two different batches of diesel fuel as well as of HVO were used. The variations from batch to batch were minor. Both the diesel fuel and HVO was supplied by Neste Oil

Fuel properties, batch 1

	EN590 (s)	HVO
Density at 15 °C (kg/m^3)	844	780
Cetane number	55	89
Distillation 5 vol-% (°C)	204	266
Distillation 50 vol-% (°C)	290	286
Distillation 95 vol-% (°C)	359	302
Heating value, lower (MJ/kg)	43.1	44.1

Fuel properties, batch 2

	EN590 (s)	HVO
Density at 15 °C (kg/m^3)	836	776
Cetane number	57	76
Distillation 5 vol-% (°C)	207	215
Distillation 50 vol-% (°C)	283	275
Distillation 95 vol-% (°C)	349	293
Heating value, lower (MJ/kg)	43.2	44.0

GTL

The GTL fuel was supplied by Shell International Petroleum Company Limited/Shell Global Solutions (UK). An analysis certificate is available.

Analysis (Test Method)	Component	Result	Unit
Visual Appearance (visuell*)	Visual Appearance	klar	
Density at 15°C (DIN EN ISO 12185)	Density at 15°C	779.4	kg/m³

Analysis (Test Method)	Component	Result	Unit
Destillation (DIN EN ISO 3405)	IBP	207.5	°C
	5 % v/v	227.6	°C
	10% v/v	234.4	°C
	20% v/v	242.8	°C
	30% v/v	251.6	°C
	40% v/v	261.5	°C
	50% v/v	272.2	°C
	60% v/v	282.7	°C
	70% v/v	293.8	°C
	80% v/v	305.2	°C
	90% v/v	320.1	°C
	95% v/v	333.4	°C
	FBP	343.8	°C
	Residue & Loss	2.0	%vol
	E250	29.3	%vol
	E300	76.6	%vol
	E350		%vol
Flash Point (PM) (DIN EN ISO 2719)	Flash Point	93.0	°C
Cetane Engine Method (DIN EN ISO 5165)	CN	74.4	

FAME-type fuels

The RME fuel was delivered by Lantmännen Ecobränsle Ab in Sweden. For this fuel an analysis certificate is available. The JME fuel was supplied by the Petroleum Authority of Thailand (PTT) through the National Metal and Materials Technology Centre of the National Science and Technology Development Agency (NSTDA), Thailand. No analysis certificate is available for this fuel. In the calculations, the heating value for RME is also used for JME.

ASG Analytik-Service Gesellschaft mbH
Trentiner Ring 30 • D-86356 Neusäss / Germany

Lantmännen Ecobränsle AB
Västra Kajen 8B
SE-374 31 Karlshamn

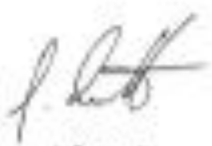
your reference	:	Sigurdsson
your order-no.	:	-
date of order	:	8/12/2009
sample receipt	:	8/14/2009
sampling	:	Customer
report date	:	8/17/2009
page	:	1 of 1

Report-No. : 174777

Sample Designation : FAME C100 20090810 Additiv
Sample Appearance : yellowish, limpid, no free water visible, no contaminations visible, characteristic odour
Sample Container : 2 x 900 ml PE-bottle
ASG-ID : 152865 Seal : -

Parameter	Method	Result	Specification DIN EN 14214 min.	max.	Unit
Ester Content	DIN EN 14103	98,9	96,5	-	% (m/m)
Density at 15 °C	DIN EN ISO 12185	882,6	860	900	kg/m³
Viscosity at 40 °C	DIN EN ISO 3104	4,516	3,5	5,0	mm²/s
Flash Point	DIN EN ISO 3679	166,0	120	-	°C
CFPP	DIN EN 116	-15	-	*	°C
Sulfur Content	DIN EN ISO 20884	2,3	-	10,0	mg/kg
Carbon residue (10%)	DIN EN ISO 10370	0,14	-	0,3	% (m/m)
Cetane number	DIN EN 15195	55,3	51,0	-	-
Sulfated Ash	ISO 3987	<0,01	-	0,02	% (m/m)
Water Content	DIN EN ISO 12937	416	-	500	mg/kg
Total contamination	DIN EN 12662	6	-	24	mg/kg
Copper Strip Corrosion	DIN EN ISO 2160	1	1		Corr. Degree
Oxidation stability at 110 °C	DIN EN 14112	9,9	6,0	-	h
Acid value	DIN EN 14104	0,163	-	0,5	mg KOH/g
Iodine value	DIN EN 14111	114	-	120	g Iodine/100g
Linolenic Acid Methylester	DIN EN 14103	10,4	-	12,0	% (m/m)
Methanol Content	DIN EN 14110	0,02	-	0,20	% (m/m)
Free Glycerol	DIN EN 14105	<0,01	-	0,020	% (m/m)
Monoglyceride Content		0,54	-	0,80	% (m/m)
Diglyceride Content		0,10	-	0,20	% (m/m)
Triglyceride Content		0,01	-	0,20	% (m/m)
Total Glycerol		0,16	-	0,25	% (m/m)
Phosphorous Content	DIN EN 14107	<0,5	-	10,0	mg/kg
Metals I (Na + K)	DIN EN 14108/109	3,2	-	5,0	mg/kg
Metals II (Ca + Mg)	DIN EN 14538	<0,5	-	5,0	mg/kg

*according to application



J. Bernath

Deutscher Akkreditierungs Rat
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General Manager
Dr. Thomas Wilharm
Amtsgericht Augsburg HRB [illegible]

Compressed natural gas (CNG)

The natural gas used in Finland is high-quality Siberian natural gas. The gas utility Gasum states than minimum methane content is 98 % by volume. The web-page of Gasum (http://www.gasum.com/products/naturalgas/Pages/default.aspx) states:

"Natural gas is a low-emission fuel with a high rate of efficiency. Its net calorific value (NCV) is 10 kWh/m³n, so one cubic metre of natural gas corresponds to one litre of domestic fuel oil in terms of the quantity of heat released during combustion.

The composition of natural gas varies slightly depending on its area of origin. The natural gas imported to Finland from Western Siberia is extremely pure and consistent in quality. It contains 98% of methane and 2% of both ethane and nitrogen as well as very small amounts of propane, carbon dioxide and oxygen. Natural gas contains virtually no sulphur and no dust or heavy metals at all."

Additive treated ethanol

The additive treated ethanol for diesel engines corresponds to the Etamax D grade by the Swedish company SEKAB.

The composition of the blends is (SEKAB):

- Hydrous (95 %) ethanol: 92.2 % m/m
- Ignition improver: 5.0 % m/m
- MTBE (denaturant): 2.3 % m/m
- Isobutanol (denaturant): 0.5 % m/m.

An analysis of the fuel was carried at the laboratories of Neste Oil out to determine the net heating value (date 23.9.2010).

Parameter		Unit	Method
Effective heating value	25.472	MJ/kg	ASTMD240
Calometric heating value	28,082	MJ/kg	ASTMD240
Organically bound nitrogen	393	Mg/kg	ASTMD4629
C content	47.8	wt-%	ASTMD5291
H content	12.3	wt-%	ASTMD5291
Density at 15 °C	825.2	kg/m^3	ENISO12185
Water coulometric	5.80	wt-%	ENISO12937
Sulfur	4.5	Mg/kg	ENISO20846

DME

The DME used in the testing was delivered by Volvo Trucks. Fuel was delivered both in the tanks of the vehicle and in a separate container. The fuel was not analyzed. Data for DME was taken from the EU priject on Bio-DME, with Volvo as coordinator (http://www.biodme.eu/about-dme).

Properties of various fuels including DME. (http://www.biodme.eu/about-dme)

Comparison of DME and other fuels

	Energy content (MJ/kg)	Density (kg/m3)	Cetane number	Octane number	C/H/O (mass %)	Boiling point (°C)
Ethanol	28.43	790		110	52/13/35	78
Methanol	19.5	790		110	38/12/50	65
Diesel	43.09	800-845	50-55		86/14/0	180-360
FTD	44.00	760-790	55-75		85/15/0	180-320
RME	37.48	880	50		78/13/9	380
DME	28.43	668	60		52/13/35	-25
Methane	50.00	0.81		122	75/25/0	-162
Hydrogen	119.88	0.089		>125	0/100/0	-253
LPG	46.30	540		90-96	82/18/0	-30
Gasoline	42.70	715-765		90-100	86/14/0	0-210

Heating values used in the calculations

Energy consumption was calculated from fuel consumption. The following table lists the heating values used in the calculations.

Fuel	Lower heating value (MJ/kg)	Reference	Comment
diesel	43.1	analysis	avg. of 2 batches
HVO	44.0	analysis	
GTL	44.0	Shell	
FAME	38.0	Directive 2009/28/EC	
JME	38.0		assumption = FAME
CNG	49.0		50 MJ/kg for pure methane assumption 98 % CH_4 + 2 % inert
Additized ETOH	25.5	alalysis	
DME	28.4	http://www.biodme.eu/about-dme	

Appendix 5: GREET tables for energy consumption and criteria pollutants

[illegible]		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
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Appendix 6: Vehicle test data for Environment Canada

BUS	Test No.	Test Cycle	Fuel Type	CO [g/km]	NO_x [g/km]	THC [g/km]	NO_2 [g/km]	TPM [mg/km]	FC [L/100 km]	CO_2 [g/km]	N_2O [mg/km]	CH_4 [g/km]
[illegible]	[illegible]	MAN	ULSD OS	0.119	7.78	0	4.71	28.3	60.3	1609	78	0
	[illegible]	MAN	B5 CME-OS	0.077	7.5	0	4.13	25.2	59.5	1585	69.1	0
	[illegible]	MAN	B20 CME-OS	0.106	7.78	0	3.71	23.6	60.3	1591	58.9	0
[illegible]	[illegible]	MAN	B5 CME-OS	0.065	14	0	6.24	10.1	59.5	1583	26.7	0.001
	[illegible]	MAN	B20 CME-OS	0.069	14.2	0	5.11	19.1	59.3	1565	15.6	0.001
	[illegible]	MAN	ULSD OS	0.052	14	0	3.98	13.4	57.9	1545	33.6	0.001
	[illegible]	MAN	ULSD COM	0.065	14.2	0	3.49	7.88	60	1553	25.6	0
	[illegible]	OCTA	ULSD COM	0.031	8.65	0	4.5	4.41	45.5	1179	10.1	0
	[illegible]	ADEME	ULSD COM	0.059	13.1	0	4.03	5.3	54.5	1412	19.8	0
	[illegible]	UDDS	B5 CME-OS	0.019	5.62	0	2.46	6.8	42.1	1121	11.2	0.001
	[illegible]	UDDS	B20CME-OS	0.023	5.63	0	2.28	8.8	43.8	1156	4.9	0
	[illegible]	UDDS	ULSD OS	0.019	5.48	0	2.05	9.12	42.3	1129	5.71	0
	[illegible]	UDDS	ULSD COM	0.018	5.61	0	2.04	10	43.5	1127	10.2	0
[illegible]	[illegible]	MAN	ULSD CERT	0.169	5.06	0.137	1.84	12.4	87.5	2378	42.9	0.009
	[illegible]	MAN	ULSD OS	0.17	4.9	0.116	1.74	10.6	87.7	2340	37	0.011
	[illegible]	MAN	ULSD	0.149	4.99	0.172	1.53	13.8	90	2348	36.1	0.006
	[illegible]	OCTA	ULSD CERT	0.062	3.54	0.099	1.28	16.7	65.4	1777	28.3	0.005
	[illegible]	BRAUN	ULSD CERT	0.046	3.07	0.075	1.05	12.7	63.1	1715	30.2	0.009
	[illegible]	BRAUN	ULSD OS	0.03	2.96	0.067	1.12	5.82	62.8	1675	18.4	0.006
	[illegible]	BRAUN	B20 SME-CERT	0.045	3.21	0.078	1.21	6.28	63.6	1701	19.5	0.004
	[illegible]	BRAUN	ULSD COM	0.046	2.97	0.074	1.32	9.08	64	1671	22.3	0.006
	[illegible]	CBD	ULSD COM	0.216	4.06	0.14	1.66	14.7	62.3	1626	36.2	0.009
	[illegible]	JE05	ULSD CERT	0.047	2.5	0.078	1.13	5.79	49.1	1335	21.3	0.005
	[illegible]	ADEME	ULSD CERT	0.2	5	0.206	2.04	13.2	84.2	2289	22.9	0.007
	[illegible]	ADEME	B5 TME-CERT *	0.21	4.76	0.13	1.47	9	84	2273	65.2	0.008
	[illegible]	ADEME	ULSD OS *	0.245	4.34	0.003	1.62	8.18	79.4	2119	46.2	0.012
	[illegible]	ADEME	B20 SME-CERT *	0.169	5.15	0.064	1.57	n/a	86.2	2304	60.3	0.01
	[illegible]	ADEME	ULSD COM	0.223	4.78	0.122	1.72	13.5	83.8	2187	55.6	0.01
	[illegible]	UDDS	ULSD COM	0.044	2.31	0.074	0.785	14	55.6	1450	23.3	0.009
	[illegible]	UDDS	ULSD CERT	0.038	2.37	0.092	0.884	7.86	53.4	1452	17.4	0.005
	[illegible]	UDDS	B5 TME-CERT	0.025	2.43	0.084	0.901	6.8	52.9	1431	17.4	0.003
	[illegible]	UDDS	B5 SME-CERT	0.015	2.44	0.09	0.849	5.22	53.5	1449	14.1	0.003
	[illegible]	UDDS	B5 CME-CERT	0.021	2.46	0.113	0.885	4.7	53.6	1452	12.8	0.004
	[illegible]	UDDS	B20 SME-CERT	0.025	2.44	0.074	0.836	0	54.2	1450	15.9	0.002
	[illegible]	UDDS	ULSD OS	0.035	2.14	0.049	0.749	0	50.3	1343	18.8	0.004
	[illegible]	UDDS	B20 TME-CERT	0.02	2.4	0.077	0.818	5.27	54.1	1444	11.1	0.002
	[illegible]	UDDS	B5 CME-OS	0.029	2.36	0.057	0.816	6.82	54	1436	14.4	0.003

* last series of tests before the occurrence of a DPF regenration - high standard deviation assoicated with TPM

BUS	Test No.	Test Cycle	Fuel Type	CO [g/km]	NO_x [g/km]	THC [g/km]	NO_2 [g/km]	TPM [mg/km]	FC [L/100 km]	CO_2 [g/km]	N_2O [mg/km]	CH_4 [g/km]
[illegible]	[illegible]	MAN	ULSD COM	0.087	2.07	0	n.a.	5.33	87.9	2270	278	0.002
	[illegible]	MAN	ULSD OS	0.086	2.18	0	n.a.	n.a.	83.6	2231	233	0.002
	[illegible]	MAN	B20 HVO-COM	0.073	1.73	0	n.a.	5.39	86.9	2210	161	0.004
	[illegible]	OCTA	ULSD COM	0.057	1.27	0	0.26	2.79	61	1574	368	0
	[illegible]	BRAUN	ULSD COM	0.044	1.46	0	n.a.	1.83	60	1548	218	0.001
	[illegible]	BRAUN	ULSD OS	0.037	1.21	0	n.a.	0.93	57.5	1536	177	0.001
	[illegible]	BRAUN	B20 HVO-COM	0.043	1.17	0	n.a.	3.68	59.2	1506	207	0.001
	[illegible]	UDDS	ULSD COM	0.031	1.21	0	0.671	2.02	50	1291	125	0
	[illegible]	UDDS	ULSD OS	0.028	1.02	0	0.557	0.886	49.5	1322	112	0.001
	[illegible]	UDDS	B20 CME-OS	0.031	1.25	0	0.535	1.9	50.2	1324	145	0.001
	[illegible]	UDDS	B20 HVO-COM	0.029	1.02	0	0.539	2.62	51	1297	129	0.001
	[illegible]	UDDS	B20 CME-COM	0.029	0.809	0	0.34	4.52	51.3	1317	120	0.001
	AVG	UDDS	HVO	0.025	0.753	0	0.394	2.19	50.5	1215	97.1	0
[illegible]	AVG	MAN	ULSD COM	0.796	16.4	0.128	<DL	181	85.5	2202	66.3	0
	AVG	BRAUN	ULSD COM	0.457	9.74	0.046	<DL	142	55.9	1440	27.8	0
	AVG	ADEME	ULSD COM	1.13	15.5	0.162	<DL	222	80	2060	54.9	0
	AVG	UDDS	ULSD COM	0.372	8.41	0.058	0.04	84.7	47.3	1220	18.3	0
	AVG	UDDS	ULSD OS	0.252	9.27	0.076	0.072	91.6	49	1301	21.5	0
	AVG	UDDS	HVO	0.346	8.28	0.041	<DL	104	51.3	1231	14.3	0
	AVG	UDDS	B20 HVO-COM	0.288	9.02	0.042	0.121	121	50.3	1280	16.3	0
	AVG	UDDS	B20 CME-COM	0.259	9.64	0.011	0.331	84.1	51.4	1318	21	0
[illegible]	AVG	MAN	ULSD CERT	0.068	0.367	0.005	0.102	4.74	82.8	2258	342	0
	AVG	UDDS	ULSD CERT	0.015	1.05	0	0.489	1.14	51.9	1416	53.7	0
	[illegible]	CBD	ULSD CERT	0.047	0.621	0.008	0.174	10.8	58.6	1599	-	0
	AVG	OCTA	ULSD CERT	0.054	0.976	0.013	0.717	3.45	63.4	1730	226	0
[illegible]	AVG	MAN	ULSD CERT	0.099	0.336	0.014		8.95	69.1	1883	462.9	0
	AVG	MAN	HVO	0.062	0.217	0.0037		9.45	69.3	1666	232.4	0
	[illegible]	UDDS	ULSD CERT	0.0249	0.667	0		2.11	42.1	1149	213.1	0
	AVG	UDDS	HVO	0.0311	0.752	0.0006		2.29	44.9	1079	293.3	0
	[illegible]	CBD	ULSD CERT	0.0435	0.298	0		15.1	48.1	1318	109.4	0
	AVG	OCTA	ULSD CERT	0.0559	0.335	0.005		8.58	48.9	1333	333.7	0

Appendix 7: Vehicle test data for VTT

Vehicle	Fuel	Cycle	FC	Urea	FC + urea	Energy	CO	CH4	THC	NOx	CO2	PM
			kg/100 km	kg/100 km	kg/100 km	MJ/km	g/km	g/km	g/km	g/km	g/km	g/km
Euro II												
	EN590 (B0)	Braunschweig	43.5	0.00	43.5	18.8	1.90	0.00	0.21	10.1	1300	0.196
	EN590 (B0)	Ademe	55.8	0.00	55.8	24.0	2.25	-0.01	0.29	15.6	1652	0.232
	EN590 (B0)	UDDS	32.2	0.00	32.2	13.9	1.38	0.00	0.15	8.0	955	0.153
	100% HVO	Braunschweig	43.1	0.00	43.1	18.9	1.14	0.00	0.13	9.7	1272	0.113
	100% HVO	Ademe	54.7	0.00	54.7	24.1	1.38	-0.01	0.16	15.1	1595	0.129
	100% JME	Braunschweig	50.0	0.00	50.0	19.0	1.04	0.00	0.08	12.3	1336	0.094
	100% JME	Ademe	63.6	0.00	63.6	24.2	1.26	-0.01	0.10	19.1	1693	0.144
Euro III												
	EN590 (B0)	Braunschweig	36.7	0.00	36.7	15.8	1.62	0.00	0.26	7.7	1154	0.354
	EN590 (B0)	Ademe	47.6	0.00	47.6	20.5	1.84	-0.01	0.46	11.6	1473	0.313
	EN590 (B0)	UDDS	29.6	0.00	29.6	12.8	1.33	0.00	0.20	6.3	928	0.260
	93 % EN590+7% RME	Braunschweig	36.9	0.00	36.9	0.0	1.59	0.00	0.26	8.1	1157	0.327
	70 % EN590+30 % RME	Braunschweig	38.2	0.00	38.2	0.0	1.34	0.00	0.23	8.5	1167	0.241
	100% RME	Braunschweig	42.4	0.00	42.4	16.1	0.94	0.00	0.13	10.2	1204	0.131
	100% JME	Braunschweig	41.3	0.00	41.3	15.7	0.82	-0.01	0.14	7.8	1155	0.160
	100% JME	Ademe	53.3	0.00	53.3	20.3	1.30	-0.01	0.17	11.9	1461	0.231
	70% EN590+23% HVO+7% FAME	Braunschweig	36.8	0.00	36.8	0.0	1.58	0.00	0.26	8.1	1155	0.333
	70% EN590+30% HVO	Braunschweig	37.4	0.00	37.4	0.0	1.57	0.00	0.26	8.0	1173	0.336
	50% EN590+50 % HVO	Braunschweig	36.4	0.00	36.4	0.0	1.39	0.00	0.24	7.6	1137	0.291
	70% HVO+ 30% RME	Braunschweig	38.4	0.00	38.4	0.0	1.06	0.00	0.17	8.3	1155	0.158
	100% HVO	Braunschweig	36.2	0.00	36.2	15.9	1.14	0.00	0.20	7.5	1121	0.217
	100% HVO	Ademe	46.0	0.00	46.0	20.2	1.20	-0.01	0.22	9.1	1397	0.203
	100% GTL	Braunschweig	35.9	0.00	35.9	15.8	1.18	0.00	0.26	7.5	1112	0.217
EEV EGR												
	EN590 (B0)	Braunschweig	38.1	0.00	38.1	16.4	0.07	0.00	0.01	7.4	1183	0.039
	EN590 (B0)	Ademe	50.1	0.00	50.1	21.6	0.10	-0.01	0.06	12.9	1536	0.076
	EN590 (B0)	UDDS	31.3	0.00	31.3	13.5	0.07	0.00	0.02	5.2	958	0.029
	EN590 (B0)	JE05	26.8	0.00	26.8	11.6	0.04	0.00	0.02	4.9	836	0.029
	EN590 (B0)	WHVC	24.4	0.00	24.4	10.5	0.07	0.00	0.01	4.1	761	0.016
	EN590 (B0)	NYBUS	90.5	0.00	90.5	39.0	0.65	-0.02	0.20	25.1	2682	0.108
	70% EN590+30% HVO	Braunschweig	38.0	0.00	38.0	0.0	0.07	-0.01	0.01	7.7	1173	0.039
	70% EN590+30% HVO	Ademe	50.0	0.00	50.0	0.0	0.14	0.00	0.05	13.3	1526	0.057
	50% EN590+50 % HVO	Braunschweig	37.8	0.00	37.8	0.0	0.08	0.00	0.00	7.3	1175	0.034
	50% EN590+50 % HVO	Ademe	48.7	0.00	48.7	0.0	0.14	0.00	0.00	12.4	1492	0.057
	100% HVO	Braunschweig	37.1	0.00	37.1	16.3	0.07	0.00	0.00	7.0	1139	0.030
	100% HVO	Ademe	49.1	0.00	49.1	21.6	0.09	0.00	0.00	13.4	1473	0.042
	100% GTL	Braunschweig	37.1	0.00	37.1	16.3	0.08	0.00	0.00	7.2	1139	0.031
	100% GTL	Ademe	48.1	0.00	48.1	21.2	0.10	0.00	0.00	12.6	1441	0.051
	70% EN590+23% HVO+7% FAME	Braunschweig	38.5	0.00	38.5	0.0	0.07	-0.01	0.02	7.5	1192	0.038
	70% EN590+23% HVO+7% FAME	Ademe	49.9	0.00	49.9	0.0	0.14	-0.01	0.07	13.0	1520	0.063
	93 % EN590+7% RME	Braunschweig	38.6	0.00	38.6	0.0	0.08	-0.01	0.02	7.3	1204	0.041
	93 % EN590+7% RME	Ademe	50.6	0.00	50.6	0.0	0.12	-0.01	0.08	13.1	1541	0.066
	70 % EN590+30 % RME	Braunschweig	40.3	0.00	40.3	0.0	0.11	-0.01	0.01	7.9	1215	0.028
	70 % EN590+30 % RME	Ademe	51.7	0.00	51.7	0.0	0.21	-0.01	0.06	13.3	1541	0.049
	70% HVO+ 30% RME	Braunschweig	39.5	0.00	39.5	0.0	0.10	-0.01	0.01	7.7	1181	0.025
	70% HVO+ 30% RME	Ademe	51.7	0.00	51.7	0.0	0.10	-0.01	0.05	13.6	1521	0.046
	100% RME	Braunschweig	44.3	0.00	44.3	16.8	0.08	0.00	0.02	8.7	1251	0.024
	100% RME	Ademe	58.6	0.00	58.6	22.3	0.13	-0.01	0.04	14.8	1625	0.039
EEV SCR												
	EN590 (B0)	Braunschweig	34.7	1.86	36.5	14.9	3.77	-0.01	0.02	5.8	1061	0.046
	EN590 (B0)	Ademe	45.7	1.24	46.9	19.7	6.29	-0.01	0.04	14.0	1375	0.059
	EN590 (B0)	UDDS	26.9	1.17	28.1	11.6	2.55	-0.01	0.01	4.6	823	0.028
	EN590 (B0)	JE05	25.1	0.84	26.0	10.8	1.03	0.00	0.02	5.8	770	0.021
	EN590 (B0)	WHVC	23.5	1.14	24.6	10.1	1.01	0.00	0.01	3.7	730	0.018
	EN590 (B0)	NYBUS	79.7	0.16	79.9	34.3	23.66	-0.02	0.05	29.9	2343	0.118
	70% EN590+30% HVO	Braunschweig	34.0	1.97	36.0	0.0	4.18	-0.01	0.02	5.4	1043	0.031
	70% EN590+30% HVO	Ademe	44.9	1.19	46.1	0.0	5.76	-0.01	0.03	13.6	1344	0.045
	50% EN590+50 % HVO	Braunschweig	34.0	2.01	36.0	0.0	4.34	-0.01	0.01	5.4	1043	0.028
	50% EN590+50 % HVO	Ademe	46.2	1.49	47.7	0.0	7.48	-0.01	0.02	13.4	1385	0.046
	100% HVO	Braunschweig	34.1	2.01	36.1	15.0	4.02	-0.01	0.01	5.5	1030	0.022
	100% HVO	Ademe	45.1	1.39	46.5	19.9	6.37	-0.01	0.02	13.6	1331	0.031
	100% GTL	Braunschweig	33.7	2.03	35.8	14.8	4.29	-0.01	0.01	5.6	1028	0.024
	100% GTL	Ademe	44.9	1.31	46.2	19.8	6.33	-0.01	0.03	13.8	1333	0.033
	70% EN590+23% HVO+7% FAME	Braunschweig	34.6	2.01	36.6	0.0	3.96	0.00	0.02	5.7	1057	0.026
	70% EN590+23% HVO+7% FAME	Ademe	46.3	1.42	47.7	0.0	6.50	-0.01	0.03	13.9	1382	0.042
	93 % EN590+7% RME	Braunschweig	34.6	2.01	36.6	0.0	3.88	0.00	0.02	5.7	1064	0.031
	93 % EN590+7% RME	Ademe	45.9	1.22	47.1	0.0	6.24	-0.01	0.04	14.3	1375	0.045
	70 % EN590+30 % RME	Braunschweig	36.4	1.93	38.3	0.0	3.36	-0.01	0.02	7.2	1086	0.020
	70 % EN590+30 % RME	Ademe	47.3	1.32	48.6	0.0	5.15	-0.01	0.03	14.8	1388	0.029
	70% HVO+ 30% RME	Braunschweig	35.3	2.01	37.3	0.0	2.96	0.00	0.01	6.6	1045	0.015
	70% HVO+ 30% RME	Ademe	45.5	1.47	46.9	0.0	6.00	-0.01	0.02	15.0	1323	0.023
	100% RME	Braunschweig	39.5	2.15	41.6	15.0	1.33	0.00	0.00	8.5	1099	0.011
	100% RME	Ademe	51.4	1.41	52.8	19.5	2.85	-0.01	0.02	17.9	1410	0.013

Appendix 7: Vehicle test data for VTT

Vehicle	Fuel	Cycle	FC	Urea	FC + urea	Energy	CO	CH4	THC	NOx	CO2	PM
			kg/100 km	kg/100 km	kg/100 km	MJ/km	g/km	g/km	g/km	g/km	g/km	g/km
EEV SCRT												
	EN590 (B0)	Braunschweig	35.3	2.18	37.5	15.2	0.20	0.00	0.01	6.3	1086	0.013
	100% HVO	Braunschweig	34.7	2.40	37.0	15.3	0.05	0.00	0.00	4.3	1021	0.006
EEV SCRT LW												
	EN590 (B0)	Braunschweig	29.3	missing		12.6	0.13	0.00	0.00	4.6	864	0.005
EEV SCR Hybrid 1 Parallel												
	EN590 (B0)	Braunschweig	29.6	missing		12.7	0.66	0.00	0.02	6.0	921	0.057
	EN590 (B0)	Ademe	33.3	missing		14.4	2.63	-0.01	0.06	13.0	1024	0.121
	EN590 (B0)	UDDS	26.3	missing		11.3	1.04	0.00	0.03	5.7	813	0.058
	EN590 (B0)	JE05	21.6	missing		9.3	0.85	0.00	0.02	5.4	670	0.051
	EN590 (B0)	WHVC	21.2	missing		9.1	0.64	0.00	0.02	4.1	660	0.042
	EN590 (B0)	NYBUS	57.7	missing		24.9	4.39	-0.01	0.12	26.5	1742	0.129
EEV SCR Hybrid 2 Parallel												
	EN590 (B0)	Braunschweig	26.2	1.49	27.7	11.3	0.13	0.00	0.01	3.9	847	0.037
	EN590 (B0)	Ademe	29.2	0.60	29.8	12.6	0.27	0.00	0.01	10.3	1015	0.039
	EN590 (B0)	UDDS	22.2	1.01	23.2	9.6	0.13	0.00	0.01	3.8	681	0.033
	EN590 (B0)	JE05	18.6	0.84	19.4	8.0	0.10	0.00	0.01	3.5	594	0.016
	EN590 (B0)	WHVC	19.6	1.10	20.7	8.5	0.08	0.00	0.01	3.9	613	0.026
	EN590 (B0)	NYBUS	49.1	0.12	45.0	21.1	0.74	0.00	0.02	21.7	1600	0.101
EEV SCR Hybrid 3 Parallel												
	EN590 (B0)	Braunschweig	25.4	1.31	26.7	10.9	2.08	0.00	0.01	8.3	795	0.031
	EN590 (B0)	Ademe	30.1	0.11	30.2	13.0	2.85	-0.01	0.04	19.6	968	0.041
	EN590 (B0)	UDDS	29.2	1.62	30.8	12.6	2.84	0.00	0.04	8.9	908	0.056
	EN590 (B0)	JE05	22.4	0.87	23.2	9.6	2.12	0.00	0.04	8.3	708	0.031
	EN590 (B0)	WHVC	23.4	1.49	24.9	10.1	2.29	0.00	0.04	6.3	731	0.042
	EN590 (B0)	NYBUS	56.1	0.06	56.1	24.2	5.07	-0.01	0.06	37.6	1806	0.068
EEV SCR Hybrid 4 Serial												
	EN590 (B0)	Braunschweig	24.8	1.25	26.0	10.7	1.02	0.00	0.03	4.3	761	0.031
	EN590 (B0)	Ademe	28.3	1.08	29.4	12.2	1.57	0.00	0.06	6.4	862	0.047
	EN590 (B0)	UDDS	28.9	1.99	30.9	12.5	1.12	0.00	0.03	5.3	914	0.032
	EN590 (B0)	JE05	22.8	1.14	24.0	9.8	0.89	0.00	0.02	3.9	700	0.027
	EN590 (B0)	WHVC	23.9	1.39	25.3	10.3	0.87	0.00	0.02	4.0	794	0.024
	EN590 (B0)	NYBUS	49.4	0.33	49.7	21.3	2.87	0.00	0.09	14.6	1522	0.070
EEV CNG 1												
	CNG SM	Braunschweig	43.9	0.00	43.9	21.5	1.41	0.26	0.39	0.8	1223	0.016
	CNG SM	Ademe	59.6	0.00	59.6	29.2	1.61	0.38	0.44	1.5	1677	0.012
	CNG SM	UDDS	36.0	0.00	49.6	17.6	2.65	0.48	0.51	0.7	1428	0.014
EEV CNG 2												
	CNG LB	Braunschweig	41.7	0.00	41.7	20.4	0.06	1.94	2.15	8.6	1138	0.016
EEV Ethanol												
	Ethanol	Braunschweig	64.9	0.00	64.9	16.5	0.00	0.12	0.43	5.5	1145	0.036
	Ethanol	Ademe	90.1	0.00	90.1	23.0	0.00	0.13	1.68	11.2	1568	0.031
	Ethanol	UDDS	51.0	0.00	51.0	13.0	0.00	0.07	0.28	4.1	883	0.010
	Ethanol	JE05	49.4	0.00	49.4	12.6	0.00	0.03	0.48	4.6	869	0.009
	Ethanol	WHVC	42.3	0.00	42.3	10.8	0.00	0.03	0.23	3.0	743	0.007
	Ethanol	NYBUS	141.2	0.00	141.2	36.0	0.00	0.11	2.09	21.8	2405	0.047
DME												
	DME	Braunschweig	54.0	0.00	59.4	15.6	25.61	1.83	2.44	5.1	988	0.020
	DME	Ademe	70.1	0.00	78.9	20.3	21.37	1.41	1.97	5.1	1304	0.028
	DME	NYBUS	110.3	0.00	126.6	31.9	23.12	2.06	2.97	9.6	2067	0.046

Appendix 8: Cost factors for air pollution according to the "Handbook"

(Handbook on estimation of external costs in the transport sector. Produced within the study Internalisation Measures and Policies for All external Cost of Transport (IMPACT). Version 1.1.CE Delft 2008)

	Factor costs in € 2000 prices. Unit: € 2000/t of pollutant								
Pollutant	NO_x	NMVOC	SO_2	$PM_{2.5}$ (exhaust)			PM_{10} (non-exhaust)		
Source	CAFE CBA	CAFE CBA	CAFE CBA	HEATCO	UBA transferred to HEATCO[1]	HEATCO/ CAFE CBA (for maritime)	HEATCO	UBA transferred to HEATCO[1]	HEATCO
CAFE CBA sensitivity	VOLY median (PM/O3)	VOLY median (PM/O3)	VOLY median (PM/O3)						
Unit	€ 2000 (emissions 2010)	€ 2000 (emissions 2010)	€ 2000 (emissions 2010)	€ 2000	€ 2000	€ 2000	€ 2000	€ 2000	€ 2000
Local environment				Urban Metropolitan[2]	Urban[3]	Outside built-up areas	Urban metropolitan[2]	Urban[3]	Outside built-up areas
Austria	6,700	1,700	8,300	415,000	134,300	59,900	166,200	53,700	27,300
Belgium	5,200	2,500	11,000	422,300	136,300	91,100	168,900	54,500	36,500
Bulgaria	1,800	200	1,000	43,000	13,800	11,000	17,200	5,500	4,400
Cyprus	500	300	2,000	243,700	78,700	28,500	97,500	31,500	9,200
Czech Republic	7,300	1,000	8,000	252,600	81,400	62,700	101,000	32,600	25,100
Denmark	4,400	700	5,200	386,800	124,700	45,500	154,700	49,900	18,200
Estonia	800	100	1,600	135,400	43,400	22,500	53,900	17,300	9,000
Finland	800	200	1,500	337,100	108,800	28,100	134,800	43,400	11,200
France	7,700	1,400	8,000	382,300	126,300	78,400	156,900	50,500	31,400
Germany	9,600	1,700	11,000	384,500	124,300	75,000	153,800	49,600	30,000
Greece	800	300	1,400	248,700	80,100	35,000	99,500	32,100	14,000
Hungary	5,400	900	4,800	203,600	65,600	52,300	81,500	26,200	20,900
Ireland	3,800	700	4,800	391,000	126,200	40,900	156,400	50,500	16,400
Italy	5,700	1,100	6,700	371,800	120,100	67,600	148,600	48,000	27,100
Latvia	1,400	200	2,000	115,700	37,200	21,500	46,300	14,900	8,600
Lithuania	1,800	200	2,400	142,100	46,500	28,500	57,200	18,600	11,400
Luxembourg	8,700	2,700	9,800	671,500	216,300	95,700	268,600	86,500	38,300
Malta	700	400	2,200	245,400	78,700	28,400	98,200	31,500	9,200
Netherlands	6,600	1,900	13,000	422,500	136,400	82,600	169,000	54,500	33,000
Norway	2,300	300	2,500	309,800	99,800	38,700	123,800	39,900	12,000
Poland	3,900	600	5,600	174,500	56,300	52,400	69,800	22,400	20,900
Portugal	1,300	500	3,500	259,500	83,800	38,500	103,800	33,500	15,400
Romania	2,200	400	2,000	29,300	9,400	7,500	11,700	3,800	3,000
Slovakia	5,200	700	4,900	194,200	62,100	52,400	77,700	24,900	21,000
Slovenia	6,700	1,400	6,200	262,800	84,500	54,500	105,200	33,800	21,800
Spain	2,600	400	4,300	298,800	96,400	41,200	119,600	38,600	16,500
Sweden	2,200	300	2,500	352,600	113,400	34,300	141,000	45,400	13,700
Switzerland	6,200	1,600	8,800	444,800	143,100	73,500	177,900	57,300	29,400
United Kingdom	3,900	1,100	6,900	389,100	125,300	60,700	155,700	50,100	24,300
EU-25	4,400	1,000	5,600			26,000			
Baltic Sea	2,600	500	3,700			12,000			
Mediterranean Sea	500	300	2,000			5,600			
North East Atlantic	1,600	400	2,200			4,800			
North Sea	5,100	1,900	6,900			28,000			

Source: $PM_{2.5}$/PM_{10} HEATCO, values adjusted to € 2000 values using GDP/cap. PPP. development. Other pollutants: CAFE CBA (CAFE, 2005a).

Notes: 1) Derived based on personal communication with Peter Bickel April 5, 2007.

2) Urban metropolitan: cities with more than 0.5 million inhabitants

3) Urban: smaller and midsized cities with up to 0.5 million inhabitants.

Appendix A: Bioenergy: Outlook for biofuels

IEA Bioenergy

Contribution from IEA Bioenergy, Task 39 to the technology outlook

Jack Saddler

Preface

The information below is forward in response to the request from Nils-Olof Nylund, Vice-Chair, of the End Use Working Party (EUWP) for Task 39 contributions to the outlook of technology section of the “Fuel and Technology Alternatives for Buses” study.

The following specific questions were addressed:

- What are advanced biofuels and what is their potential relevance to city bus transport?
- What are the implications of advanced biofuel use for the existing fuel infrastructure?
- What is the market maturity of advanced biofuels currently and the projection for 2020?
- What is the potential for advanced biofuels to contribute to improvements in emissions and energy efficiency?
- What are the cost implications of using advanced biofuels in city bus transport?

IEA Bioenergy Task 39’s focus is on the technology/policy/sustainability of liquid biofuel production. The responses to the questions below are more of a generic, transportation biofuels perspective, rather than a focus on bus transport in particular. The liquid transportation fuel end uses described are based on recent Task 39 reports and contributions.

- **What are advanced biofuels and what is their potential <u>relevance</u> to city bus transport?**

Advanced biofuels are relevant to city buses since they can help reduce fuel-derived greenhouse gas (GHG) emissions and will also, ideally, prove to be cheaper and more sustainable than fossil derived transportation fuels. Advanced biofuels differ from conventional (currently commercial) biofuels in that they either use lignocellulosic feedstock (a.k.a. 2^{nd} generation biofuels) as opposed to sugar, starch or lipids and are more readily integrated in the existing fuel infrastructure, or are derived from countries such as Brazil, who have been shown to produce sugar derived fuels that are both cheaper and more sustainable than fossil derived fuels. . The use of non-food, more abundant lignocellulosic feedstock and the reduced need for infrastructure changes are viewed as characteristics that will reduce the GHG performance of transport services using advanced biofuels.
In the summary below, two advanced biofuel processes are highlighted; cellulosic ethanol and BtL (biomass-to-liquid using biomass gasification followed by Fischer-Tropsch conversion). These technologies are suggested as being the most relevant advanced liquid biofuels for bus transport since their R&D is quite advanced and various groups are now demonstrating the technology (see Figure 1). Thus, they are more likely to reach the bus fleet in the near term. Algae-derived lipids and sugar-derived hydrocarbons are examples of alternative, more long-term, advanced biofuel technologies.

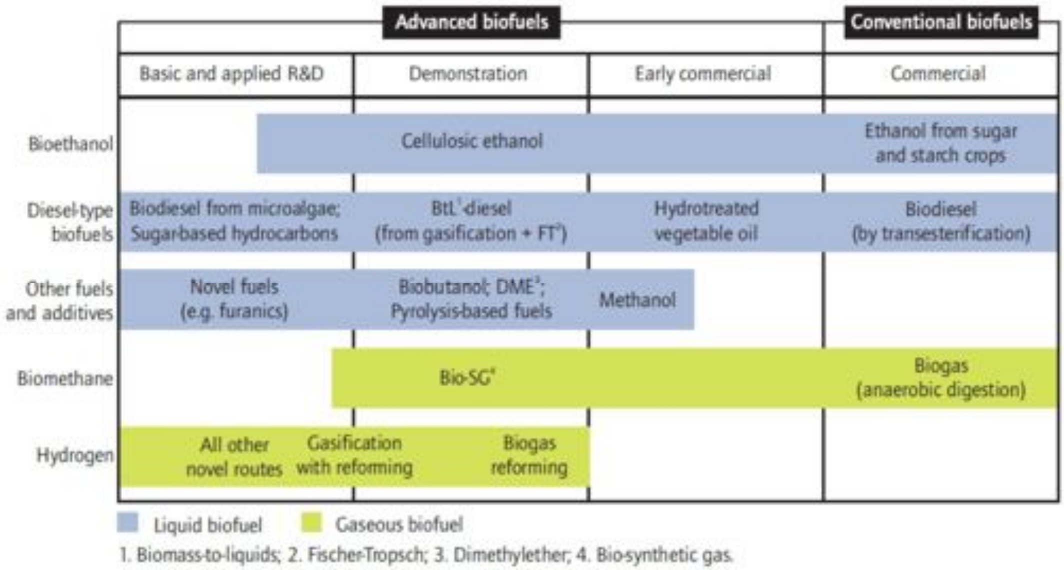
- **What are the implications of advanced biofuel use for the existing fuel <u>infrastructure</u>?**

In a standard petroleum-based fuel infrastructure, BtL-derived diesel can be readily introduced as a petro-diesel analogue while cellulosic ethanol can only be blended up to 15% volume with gasoline (E15). The main reasons that have been suggested for ethanol incompatibility are its higher corrosiveness on storage materials and engines, its hydrophilic nature and its higher volatility and ignition risk as compared to traditional petroleum fuels. In Brazil, the fuel delivery infrastructure and vehicle engines are already largely adjusted to accommodate the requirements of pure ethanol fuel. In other places around the world the infrastructure cannot readily accommodate ethanol blends beyond (typically) 15%. Recently, modern flexi-fuel vehicles (FFVs) which can take up to 85 % ethanol (E85) have made substantial inroads into some automobile markets such as Brazil. Buses operating on ethanol (E95) fuel have been demonstrated in some first-mover cities in Sweden, Italy, Spain and Brazil, with varying degrees of success (BAFF, 2007). The BtL-derived diesel analogue on the other hand, faces no blend-wall or other infrastructure incompatibility issues and can be pumped directly into the already widely used diesel bus engines.Aside from infrastructure issues, ethanol is less energy dense than diesel. While the ethanol engine is as energy efficient as the diesel engine, a bus running on ethanol would need about 60 % more volume of ethanol compared to diesel, due to the lower energy content of ethanol (BAFF, 2007).

- **What is the market maturity of advanced biofuels currently and the projection for 2020?**

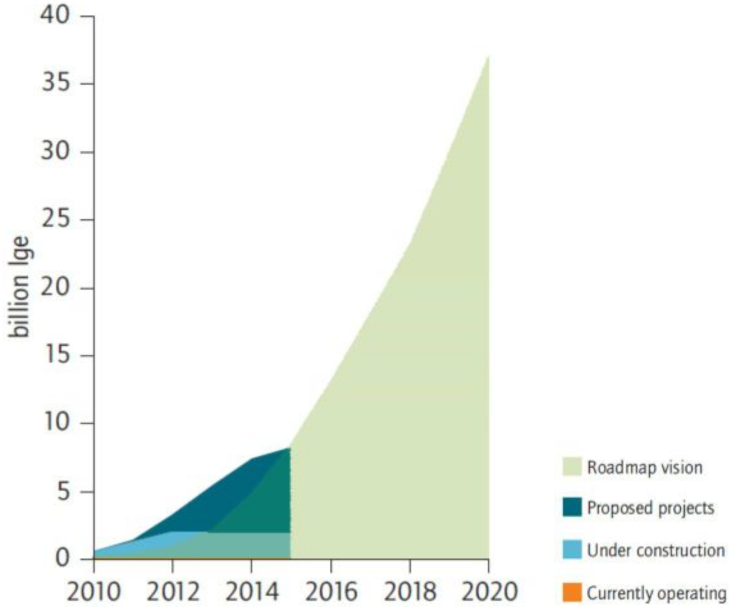
Advanced biofuels are currently at different stages of maturity. Figure 1 depicts the relative maturity of both conventional and advanced biofuels.

Current and projected (2020) market penetration of advanced biofuels is depicted in Figure 2 and compared to the IEA biofuel BLUE Map scenario target (IEA 2011). The IEA biofuel BLUE Map scenario target represents the full potential of biofuels to contribute to the goal of 50% reduction in global GHG emissions by 2050 (a.k.a. “50 by 50”). The majority of demonstration plants for advanced biofuels are currently in North America and Europe while an increasing number of pilot and demonstration plants are being built in non-OECD countries such as China and India. The installed advanced biofuel capacity today is roughly 175 million liters gasoline equivalent (Lge) per year, but most plants are operating below capacity. Another 1.9 billion Lge/yr production capacity is under construction and would be sufficient to meet the IEA roadmap targets until 2013. If the proposed projects are realized, the extra 6 billion Lge/yr of capacity will be sufficient enough to meet the IEA target of 2015. Between 2015 and 2020, however, the challenge for meeting the IEA target becomes much bigger since a 5-fold capacity increase is required within this 5 year time period. Aside from the IEA global goal, country specific targets and mandates have been announced, some of which couple biofuel commitments to minimum GHG emission reductions (LCA basis) and/or advanced biofuel technologies (e.g. the US RFS or the EU RED). Overall, biofuel manufacturing capacity needs to be increased rapidly and substantially, if the existing global targets are to be met.



Source: IEA, 2011, modified from Bowen et al. 2009

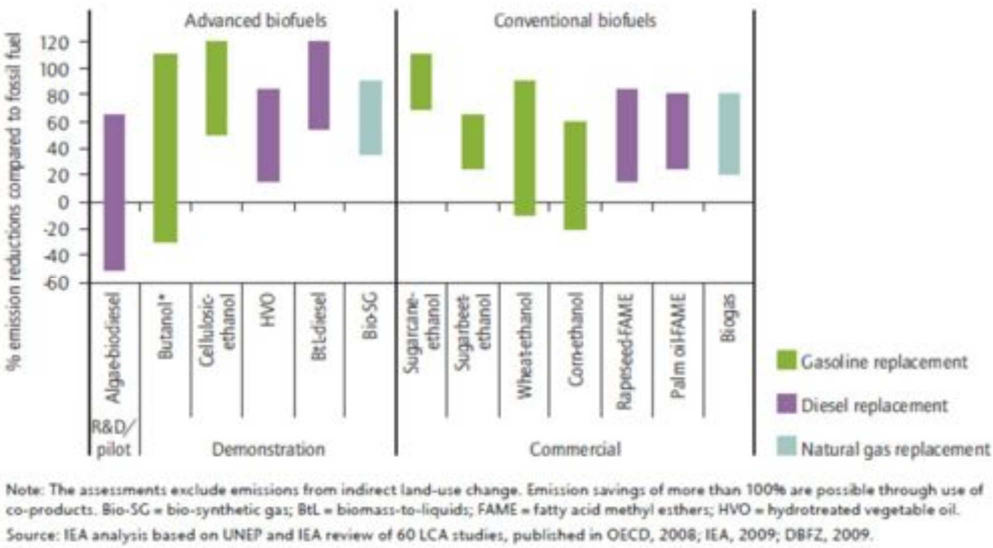
Figure 1: Commercialization status of main biofuel technologies



Source: IEA, 2011 [illegible]

Figure 2: Advanced biofuel production capacity to 2015–2020

- **What is the potential for advanced biofuels to contribute to improvements in <u>emissions</u> and energy efficiency?**



Source: IEA, 2011

Figure 3: Life-cycle GHG balance of different conventional and advanced biofuels, and current state of technology.

The IEA has compiled the GHG reduction results from a number of LCA analyses for main biofuel technologies (Figure 3). BtL-diesel and cellulosic ethanol appear to perform equally well and better than their conventional biofuel counterparts, such as starch ethanol and FAME. The superior GHG performance of sugarcane ethanol as opposed to sugar beet ethanol is an example of the major effect that the choice of feedstock can have on GHG performance of biofuel technologies (This is also one of the major reasons why Brazilian derived fuels can truly claim to be "advanced biofuels"). Another 'hidden' factor that effects GHG emissions is the so-called indirect land use change GHG emissions. These are emissions that have recently been incorporated in LCAs and represent the effect of displacing crops to grow biofuel feedstocks. Typically, these displaced feedstocks would have to be grown elsewhere thus creating a separate GHG impact. This indirect land use change GHG impact analysis is still at early stages and faces numerous complexity challenges. However, some valuable criteria that could indicate biofuels with low indirect land use change GHG impact have been identified:

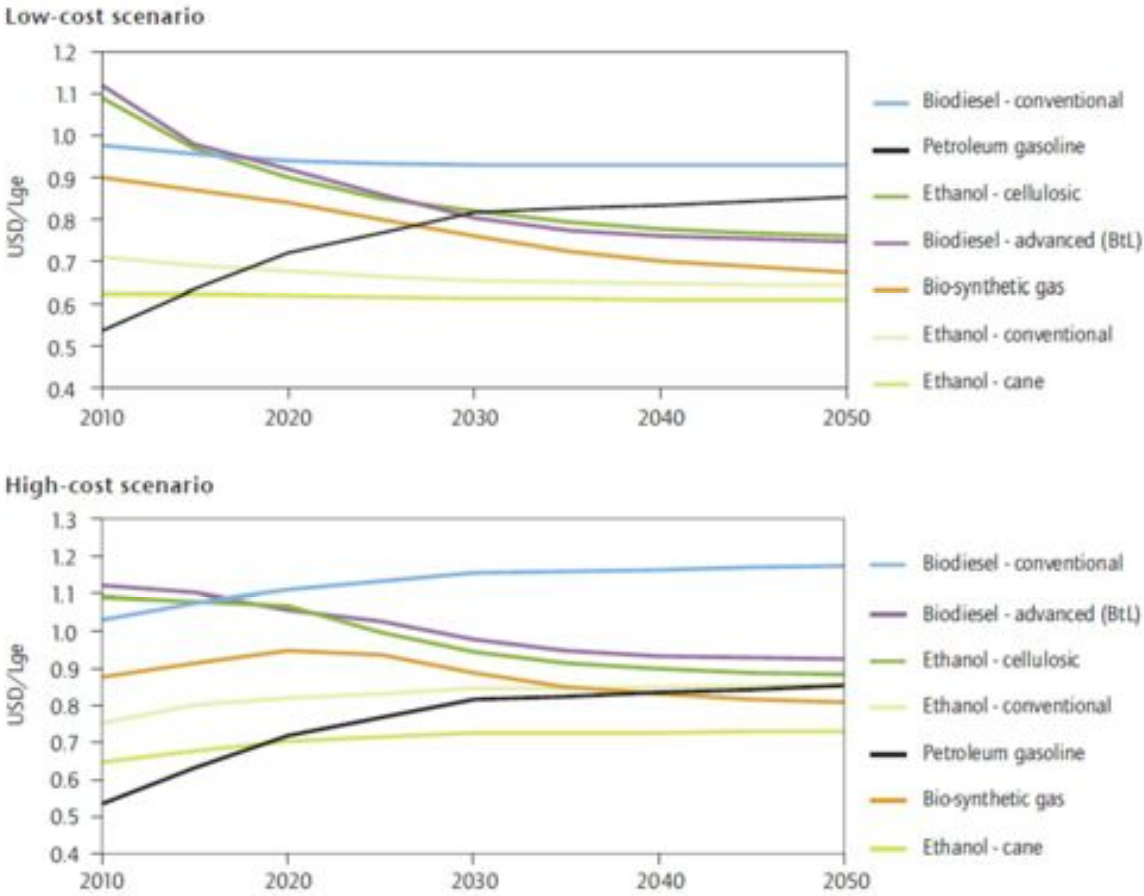
- Focus on wastes and residues as feedstock
- Maximise land use efficiency (higher yields sustainably)
- Use perennial crops on marginal low-carbon soils
- Maximise feedstock use efficiency (at process stage)
- Cascade utilisation of biomass (i.e. linking industrial and subsequent energetic use of biomass)
- Co-production of energy and food crops

About 67 biofuel sustainability certification initiatives are currently under development worldwide (e.g the Global Bioenergy Partnership (GBEP) or the Roundtable for Sustainable Biofuels (RSB)) (Dam, 2010). The extent of adoption and inter-compatibility of these standards are going to play a major role in the commercialization and global trade of advanced biofuels and ultimately their access to city buses.

- **What are the <u>cost</u> implications of using advanced biofuels in city bus transport?**

Sustainable commercialization of biofuels is also highly dependent on their cost of production. The IEA has produced estimates of production costs for different biofuels with projections to 2050 based on bottom-up analysis of supply-chain components. Two different cost analyses have been used (Figure 4) in order to take into account uncertainties such as the dynamic between rising oil prices and biofuel production costs. The low-cost scenario anticipates minimal impact of rising oil prices on biofuel production costs. Biofuel costs fall as scale and efficiency increase over the years. The costs (retail price equivalent, untaxed) of advanced biofuels such as cellulosic ethanol and BtL-diesel reach parity with petroleum gasoline and diesel fuel by about 2030. Sugarcane ethanol remains the lowest-cost biofuel throughout.

In the high-cost scenario, oil prices have a greater impact on feedstock and production costs and most biofuels remain slightly more expensive than gasoline/diesel, with oil at USD 120 /bbl in 2050. Nonetheless, the total cost difference per liter compared with fossil gasoline and diesel is less than USD 0.10 in 2050. In addition, valuing CO_2 savings at around USD 50 per tonne would enable most biofuels to reach or exceed cost parity with their fossil fuel counterparts.



Note: costs reflect global average retail price without taxation. Regional differences can occur depending on feedstock prices and other.

Figure 4: Costs of different biofuels compared to gasoline (BLUE Map Scenario)

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Appendix B: Advanced Fuel Cells and Hydrogen Implementing Agreement: Outlook for fuel cell transit buses

Fuel Cell Transit Buses

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January 31, 2012

Introduction

This report summarizes the current status of the fuel cell bus technology, primarily in the U. S. and North America, but it also includes a brief review of fuel cell bus projects in other countries.

Overview

Fuel cell-powered buses continue to be demonstrated in transit service at various locations in the U. S. and elsewhere. To promote consistency in performance requirements, the U. S. Departments of Energy and Transportation (DOE, DOT) issued a joint request for information (RFI) in May 2011 to seek input from industry stakeholders and the research community on what should be the targets for performance, durability, and cost for transit buses powered by fuel cells, and for the fuel cells in those transit buses. The DOE engages in fuel cell RD&D for a variety of stationary, portable power, and transportation applications; the DOT has established a National Fuel Cell Bus Program (NFCBP) under the Federal Transit Administration (FTA) to promote the advancement of fuel cell electric buses.

Based on the responses to the RFI, DOE and DOT have developed the bus and fuel cell power plant targets shown in Table 1. The 2011 status of fuel cell transit buses being demonstrated is shown in the last column of Table 1. The sections below provide more information on the current status of the various parameters in Table 1.

In mid-2011, there were 25 fuel cell transit buses in operation in the U. S. that included 18 Van Hool buses with UTC Power fuel cells, 1 New Flyer bus with a Ballard fuel cell, 2 Proterra plug-in hybrids with Hydrogenics fuel cells, 3 Ebus plug-in hybrids with Ballard fuel cells, and 1 Daimler/BAE diesel hybrid with a Hydrogenics fuel cell auxiliary power unit (APU). Table 2 shows some of these buses. Seven additional buses are planned to be added to the transit bus demonstration fleet as part of FTA's NFCBP. These buses will use Ballard and Nuvera fuel cells in combination with advanced lithium-ion batteries for energy storage and regenerative braking.

From the U. S. demonstrations, it has been observed that with the next generation of buses entering service, planned service times are increasing (to 19 h/day, 7 days/week), reliability is improving (one FC system has operated for >10,000 h, with two more with >6,500 and >5,500 h) with the MBRC for FC systems being >10,000 for most buses (see Fig. 1). Also, as shown in Fig. 2, fuel economies for the fuel cell buses are consistently better than the baseline buses (diesel buses operated over the same or similar routes). With average fills of 22.5 kg H_2 for FC dominant and 11 kg H_2 for battery dominant buses, more than 101,000 kg of H_2 have been dispensed successfully without any fueling incidents. Challenges remain, however, for the full commercialization of fuel cell buses, primarily in achieving the durability and cost targets.

Table 1. Proposed DOE/DOT targets for fuel cell-powered transit buses in the U.S.

Parameter	Units	Target Value	2011 Status
Bus Lifetime	years / hours	12 / 50,000[a]	TBD
Power Plant Lifetime	years / hours	6 / 25,000[b]	6 / 10,000
Bus Availability	%	90[c]	70
Fuel Fills	per day	1 (<5 min)[d]	1
Bus Cost	$	600,000[e]	2,000,000
Power Plant Cost	$	200,000[e]	1,000,000
Road Call Frequency (All / Power Plant)	MBRC	4,000 / 10,000	1,900 / 2,400
Operating Time	hours per day / days per week	20 / 7	19 / 7
Operating Cost	$/mile	0.38[f]	0.47
Range	miles	300	>300
Fuel Economy	mpgde[g]	8	6.5

[a]Based on RFI responses
[b]Assuming one power plant rebuild during the vehicle's lifetime
[c]For comparison, value for diesel buses is 85%, with 95% achievable by 2020
[d]With an upper bound of 10 min
[e]Cost needed to be competitive with alternatives
[f] Including routine maintenance, but excluding fuel and mid-life overhaul
[g]mpgde: miles per gallon diesel equivalent (lower heating value basis)

Table 2. Some of the fuel cell buses currently in transit service in the U.S.

	Van Hool bus with UTC Power fuel cell
	New Flyer/Bluways bus with Ballard fuel cell
	Proterra bus with Hydrogenics fuel cell (plug-in, battery dominant)

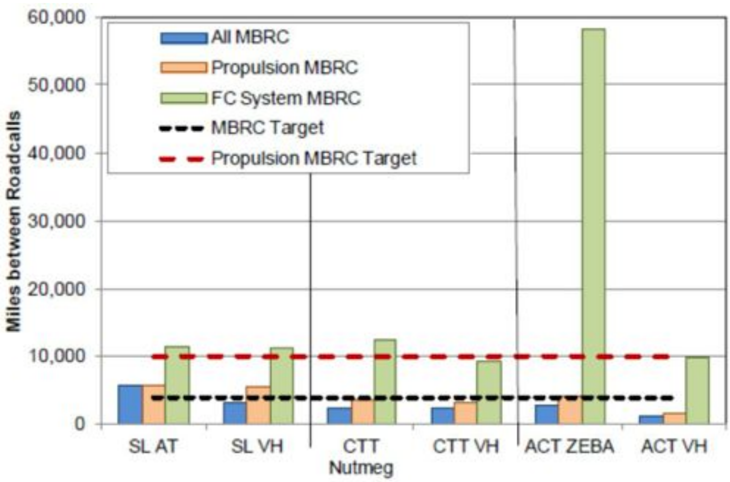

Fig. 1. Miles between road calls (MBRC) experience for fuel cell and baseline buses in the U. S. transit fuel cell fleet (see Abbreviations and Acronyms section for nomenclature).

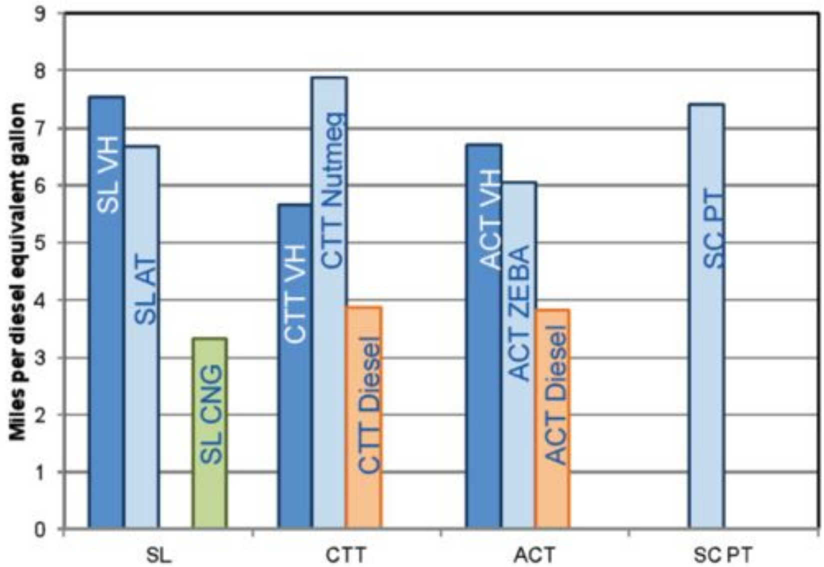

Fig. 2. In the U. S. demonstrations, the fuel cell transit buses have consistently achieved higher fuel economies than the corresponding diesel or CNG baseline buses (see Abbreviations and Acronyms section for nomenclature).

Outside the U. S., BC Transit in Vancouver, British Columbia, Canada, is acquiring the 20 fuel cell bus fleet (and its associated fueling systems) that has been providing transit service in the resort municipality of Whistler, Canada, since the February 2010 Winter Olympic and Paralympic Games. This fleet with Ballard fuel cells has already logged a combined 1,300,000 km, with a minimum of 43,600 km and a maximum of 72,000 km per bus. On some of the mountainous routes in Whistler, the fuel cell buses were unable to maintain highway speeds (≥80 km/h) on >6% grades of one kilometer or longer, with the result that they could not be used on three of the Whistler routes. Performance of the fuel cell buses on the other Whistler routes was very positive, however, with strong driver and user support.

Some of the ongoing and planned Ballard fuel cell bus projects outside North America include 8 buses for Transport for London's CHIC Programme (75-kW FC with ultracapacitors, 2010–2014), 1 bus for EMTU, Sao Paulo, Brazil (150-kW FC, 2010–2012), and 5 buses for Ruter#, Oslo, Norway (150-kW FC, 2011–2016).

In Europe's CHIC (Clean Hydrogen In European Cities) Project, 26 buses will be put into daily passenger service in five locations: Aargau (Switzerland), Bolzano/Bozen (Italy), London (UK), Milan (Italy), and Oslo (Norway). Staged introduction and build-up of the bus fleets and the supporting H_2 fueling stations will facilitate a smooth integration of the fuel cell buses into Europe's public transport system, leading to full commercialization of these buses starting in 2015:

- Phase 0: Hamburg, Cologne, Berlin, Whistler (Canada); a total of 37 fuel cell buses.
- Phase 1: Aargau, Bolzano/Bozen, Milan, London, Oslo; a minimum of 26 fuel cell buses.
- Phase 2: 14 regions in France, Spain, UK, Germany, the Netherlands, Belgium, Italy, Finland, Sweden, Czech Republic, Slovenia, Hungary, and Poland.

In China, a fleet of more than 50 fuel cell buses shuttled athletes and government officials to various venues of the Asian Games in Guangzhou City during November and December 2010. At the 2008 Olympic Games, 2 fuel cell buses transported athletes in Beijing.

In Japan, 3 Toyota-Hino fuel cell buses shuttle passengers between the terminal and the airplanes on the tarmac at Nagoya, Japan's Centrair Airport. In September 2005, 8 Toyota-Hino fuel cell buses were deployed as shuttles at the Aichi Expo.

In Korea, a Hyundai fuel cell bus has operated since 2006 in routine service in metropolitan Seoul and Jeju Island. Hyundai has a contract with Seoul to start supplying multiple fuel cell buses starting in 2013.

Status of Technology

Technology

Fuel cells for transit buses are being developed by many developers, who, working with system integrators and bus manufacturers, are supporting a variety of fuel cell transit bus operations at several different locations around the world. Some technical highlights of these fuel cell systems and the transit buses are given below.

- The Ballard FCvelocity®-HD6 delivers 150 kW (or 75 kW) gross power with a system weight of 400 kg and offers a 12,000-h, 5-year warranty. The system includes air humidification, H_2 recirculation, condenser for water management, and CAN and power supply connections.
- The Ballard HD-6+ available in 2014 will offer 24,000-h durability and 15–20% cost reduction, and HD-7 available in 2015 and later will offer 36,000-h durability and 35–40% cost reduction (which will be needed to meet the FC bus target of $750,000/bus).
- The UTC Power PureMotion™ fuel cell power system delivers 120 kW net with an efficiency of >46% at the rated power. This ambient pressure system has a transient ramp up capability of 24 kW/s.
- The Hydrogenics HyPM® HD 16 fuel cell system (used in the Proterra battery-dominant fuel cell buses)delivers 16 kW at a peak net efficiency of 53%, with a transient capability of idle to peak power in less than 5 s. Hydrogenics has also developed 30-, 90-, and 180-kW systems for buses and other heavy-duty applications.
- For the earlier generation fuel cell buses used in Whistler, Canada, transit service in 2010 and 2011, preventive maintenance requirements were manpower intensive, averaging 2.4 h/1000 km (compared to 0.8 h/1000 km for diesel buses). The batteries in the hybrid power systems needed to be balanced once a month, with up to 8 h of down time, which had a significant impact on bus scheduling.

Efficiency

All fuel cell transit buses have shown higher fuel economies than the corresponding diesel and CNG baseline buses in similar service. The fuel economies are highly dependent on the site's topography and transit duty cycles.

- The projected well-to-wheels efficiencies of various fuel/technology pathways are:
  - Battery EV: 40% from natural gas, 22% from coal
  - Diesel ICE: 26%
  - Fuel cell with H_2 from reformed natural gas: 24%
  - Compressed natural gas ICE: 22%

  - Fuel cell with H_2 from electrolysis: 6%–11% (non-renewable electricity)
- The 12-bus AC Transit HyRoad fuel cell bus project (San Francisco Bay Area) has a target fuel economy of 2 X diesel, and has achieved 1.7 X diesel. Improvements in bus performance have been helped by a 5,000-lb weight reduction in the vehicle and its sub-systems.
- The UTC Power's PureMotion® fuel cell system-based bus fleets have shown 6.5 to 8.0 mpgde in California and 6.0 to 10.0 mpgde in Connecticut, nearly double the fuel economy of corresponding diesel-hybrid buses.
- The Proterra battery-intensive fuel cell hybrid has fuel cell efficiencies of 55% peak and 50% average. The DC-DC converter efficiencies are 94% peak and 90% average, and the complete fuel cell APU is 45% efficient. Combined with >80% efficient drive train (battery 98.5%, traction motor 85%) and 85% efficient hotel loads, the overall system has an efficiency >55% with the 32-kW Hydrogenics fuel cells.
- The fuel cell buses with Ballard fuel cells used in Whistler, Canada, for the 2010 winter Olympics had an average fuel consumption of 13.27 kg/100 km in 2010, and 14.3 kg/100 km in 2011 (with the added weight of 8 H_2 storage tanks for increased range versus 6 tanks during 2010).
- With over 48,000 miles accumulated through mid-September 2011, the CHIC program in London, UK, has observed the day-to-day fuel efficiency for the fleet varying between 8 and 10 kg H_2/100 km, which represents more than a factor of 2 improvement since the CUTE project, and it is also better than the target of 11–13 kg H_2/100 km that was set at the start of the CHIC project.
- In February and March 2008, over 24 days that logged 3,880 miles, the Golden Gate Transit fuel cell bus averaged 8.57 miles/kg H_2 (11.7 kg H_2/100 km) with no road failures; in July 2009, the Marin County Fair fuel cell shuttle bus logged 862 miles with an estimated fuel economy of 7.37 mile/kg H_2 (13.6 kg H_2/100 km).

Maturity (Performance, Durability, and Availability)

Since 2005, fuel cell transit buses have undergone significant evolution in fuel cell technology, bus integration, weight reductions, and performance enhancements. Given below are examples of the continuing maturation of this technology.

- With 12 buses delivered, the AC Transit HyRoad Project in the San Francisco Bay area is showing availability of >90%, and fuel cell stack lifetimes of >10,400 hours and climbing.
- Comment from a 30-year veteran Golden Gate Transit bus driver, after driving the latest Van Hool bus, "They're like Disneyland in the real world."
- Fuel cell buses have been and are being demonstrated in a wide range of climatic conditions, varying from the very hot desert climate of Palm Desert, CA, to the very cold and snowy Chicago, IL (ElDorado buses with 150-kW HD-6 and HD-6+ Ballard fuel cells).
- With fleet experience of over 670,000 miles, the 18-bus UTC Power fuel cell bus fleet is currently in revenue service in California and Connecticut. There have been no fuel cell-related causes for bus unavailability for over 12 months. The overall fuel cell power system availability has exceeded 95% and over 15,000 MBRC. With the new generation of PureMotion® 120 fleet, the MBRC for the fuel cell system is approaching 60,000.
- For the 20-bus fleet in service in Whistler, Canada, in the first year of operations (February 2010 to February 2011), the average daily roll-out availability was 72%, with an all-day availability of 65%, both of which improved slightly during the second year (January to August 2011) to 76% and 68%, respectively. The availability was limited by component failures (control boards, auxiliary heaters) rather than any issues with the fuel cell stack. Operating experience from April 2010 to September 2011 showed brief periods of 100% availability, but also brief dips to 45% availability for the fleet as a whole.

Cost

The results of a cost analysis by BAE Systems are given in Table 3, which shows the approximate premium cost of current fuel cell alternatives over the baseline $325,000 for a conventional diesel bus. Market development and viability studies by BAE Systems show the inverse relationship between fuel cell transit bus cost and the number of buses manufactured, over a project time scale, as shown in Fig. 3. Cost estimates by Ballard, Fig. 4, show a gradual reduction in fuel cell bus capital costs over the years and technology advancements. The corresponding fuel costs are shown in Fig. 5.

Table 3. Cost metrics for fuel cell and alternative transit bus architectures

Architecture	**FC Bus Premium over $325 K Diesel Bus**
Propulsion Fuel Cell	$1,475,000
Battery EV	$575,000
FC APU [Diesel (CNG)]	$375,000 ($425,000)
Hybrid / EA [Diesel (CNG)][a]	$225,000 ($275,000)
Conventional / EA [Diesel (CNG)]	$50,000 ($100,000)
CNG Conventional	$50,000

[a] Electric accessories

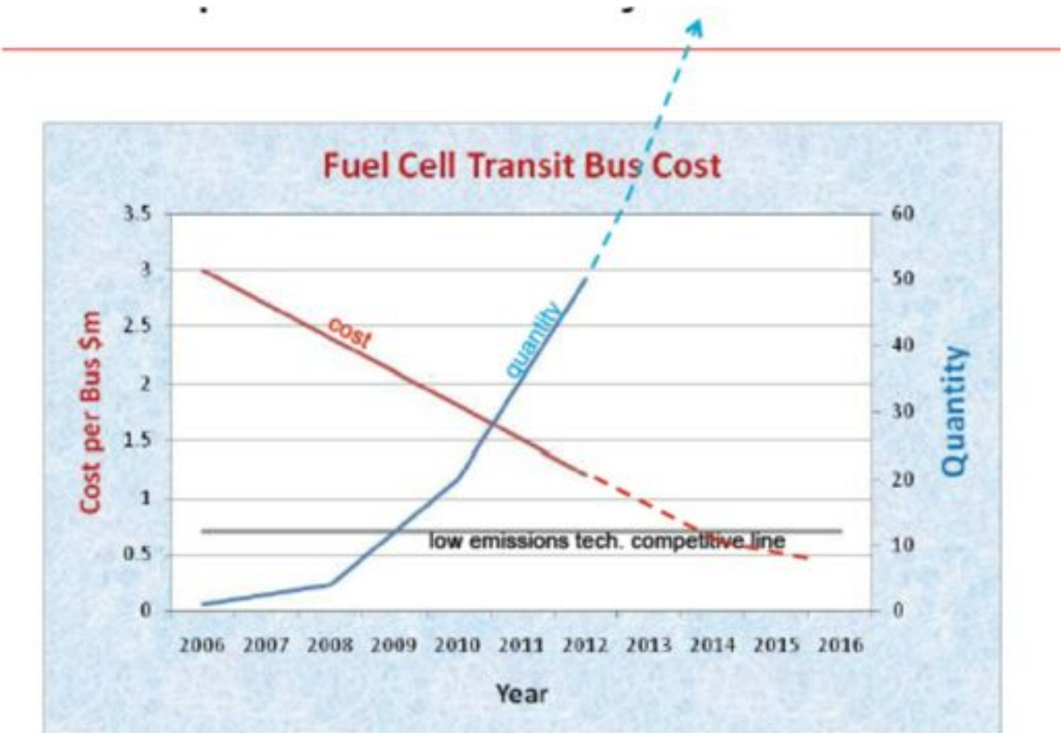

Fig. 3. Fuel cell transit bus cost versus number of buses over time (BAE Systems). Multiple fleets of >100 fuel cell buses will be needed to drive costs to a competitive range. The costs shown are drive-away costs, and they do not include operating and maintenance costs. Current cost, at 20-bus fleets, is approximately $1,200,000/fuel cell bus.

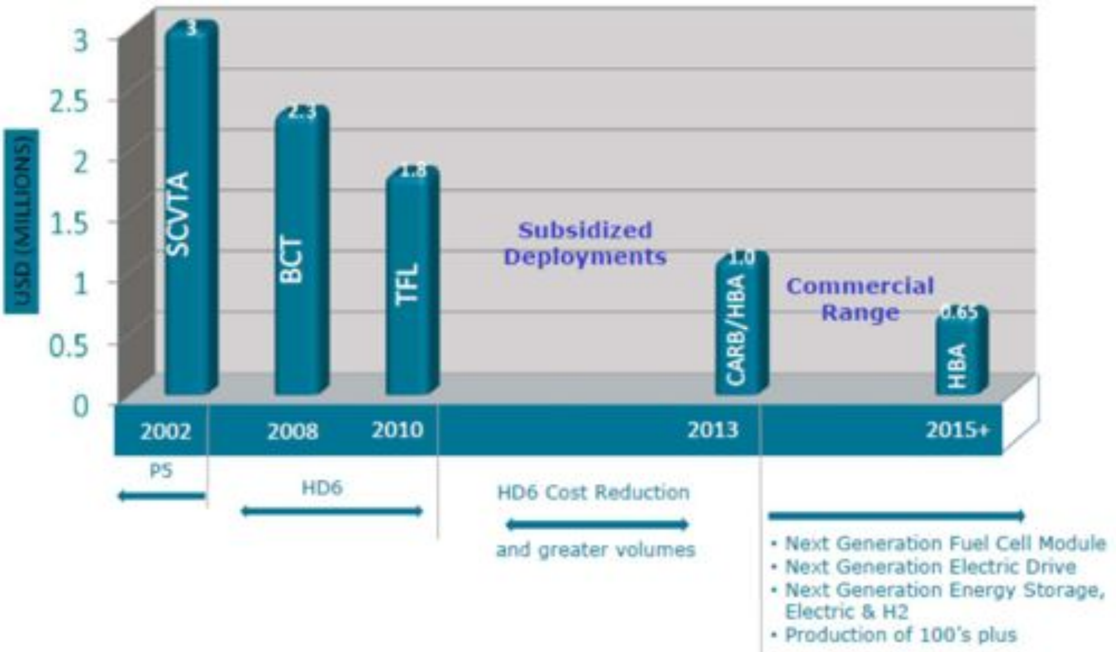

Fig. 4. Capital costs of Ballard fuel cell transit buses over the past decade, and future projections (and improvements needed to meet these projections). Commercial volumes of manufacture are projected to lower costs to $650,000/fuel cell bus.

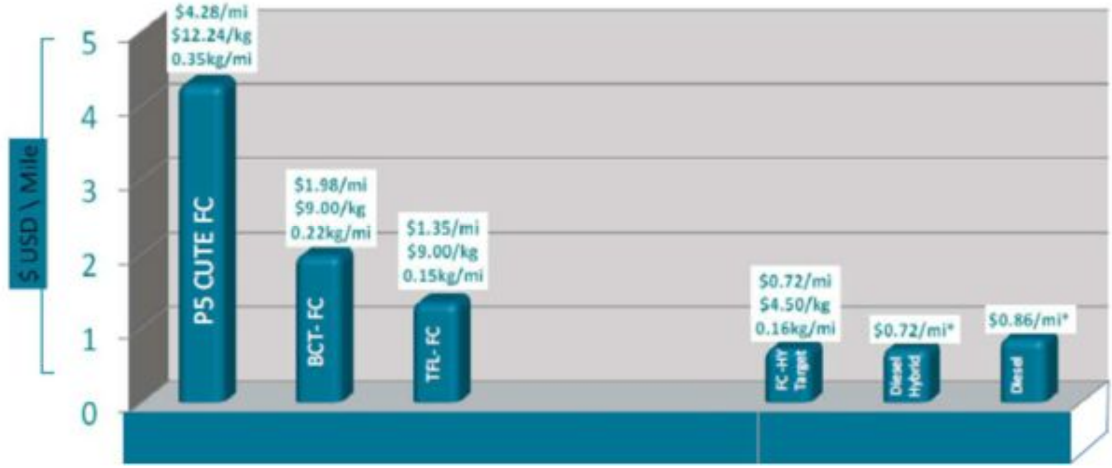

Fig. 5. Fuel costs for fuel cell and diesel/diesel-hybrid transit buses. To become competitive with conventional transit buses will require improvements in fuel cell efficiency and hybridization strategies, and a considerable reduction in the cost of H_2.

Other projections of fuel cell and fuel cell transit bus costs include the following:

- The ElDorado bus with the Ballard HD-6+ fuel cell will demonstrate advanced durability, power density, and fuel efficiency with a state-of-the-art automotive fuel cell stack, and a commercialization target cost of $1 million through design for volume manufacturing.
- The UTC Power bus fleet target is $200–350/kW for the fuel cell power system (stack, BOP, power control system) when manufactured in volumes of thousands per year, based on durability of >18,000 h (in transit service, with its associated load cycling) and 0.3 mg_{Pt}/cm^2 total PGM loading.

Fuels and Infrastructure

From January 2006 to July 2011, the U. S. fuel cell transit buses have been fueled with more than 100,000 kg of H_2 with no fueling safety incidents. Fueling amounts at the major transit sites include:

- AC Transit: 61,321 kg
- CT Transit: 18,217 kg (April 2007 to July 2011)
- SunLine Transit: 21,482 kg

The average fill amount is about 22.5 kg per fueling, with a fill time of about 16 min for fuel cell dominant power plants. For battery dominant power plants, the average fill is about 11 kg.

All of the major industrial gas suppliers have participated in one or more of the fuel cell transit bus demonstration projects. These gas suppliers include Air Liquide, Air Products and Chemicals, Inc. (APCI), and Linde. Fig. 6 shows the Oakland, CA, fueling station of AC Transit, where the H_2 is provided by Linde. The AC Transit fueling stations also use H_2 generated by solar-powered (photovoltaic) electrolysis and biogas.

Fig. 6. The Oakland, CA, fueling station of AC Transit capable of dispensing 360 kg/day.

Air Liquide has provided H_2 for the Project Driveway stations in New York and California, mass transit stations in Whistler, Canada, and Oslo, Norway, and for several materials handling fork-lift truck applications. Hydrogen supply alternatives include liquid trailer, 200–500-bar tube trailer, and on-site production by SMR or electrolysis. Compression technologies for dispensing include liquid pump and vaporization (1000 kg/day), liquid vaporization and gas compression to 1000 bar, by gas booster for up to 10 kg/day or by membrane compressor for 100–1000 kg/day. For transit bus fleets smaller than 25 buses, Air Liquide's analysis indicates that delivered gas is the cheapest option; for larger fleets, SMR may be recommended.

Air Liquide's Vancouver Whistler project for the 20-bus fleet represents one of the world's largest fueling stations. It is capable of fueling 12–15 buses/day at a fill rate of 5 kg/min, with no limitation on successive fills of up to 50 kg in about 10 min. Hydrogen is obtained by SMR, liquefied, and shipped by liquid H_2 tanker; local back-up is provided by electrolysis. At the fueling station, liquid H_2 is stored in two vertical 20,000-gal tanks, each holding 5,300 kg (10 tons); this stored amount represents 10–12 days of usage at the maximum consumption rate. Equipment integrity is monitored by leak-test instrumentation, gas sensors, and flame detectors. All systems are wired with Emergency Stop push buttons. All construction is consistent with NFPA 52, 55, and 2. All equipment conforms to ASME/DOT codes and requirements, electrical equipment is UL listed, and the fuel dispensers are labeled by Intertek.

Air Products has been involved in H_2 energy projects since 1993, with an accumulated experience base of more than 130 H_2 station projects in 19 countries and over 350,000 fuelings/year. For a 200-bus fleet requiring 25 kg/fueling, the challenge would be to dispense 5,000 kg in 6 h, corresponding to an average fill rate of 13.9 kg/min. Industrial customers, by comparison, are more varied: refinery, 283,000 kg/day, 24/7 demand; large liquid H_2 customer, 5,000 kg/day, 24/7 demand; forklift site, 75–200 kg/day, 1 kg/fueling in 3–5 min, 25–100 fuelings/day; Space Shuttle, 130,000 kg/launch (program terminated).

Air Products has developed a dual-phase H_2 tanker by modifying a liquid H_2 tanker to deliver both liquid and gaseous H_2 at up to

7,200 psi. This tanker can supply fuel to a liquid H_2 tank, off-board bulk H_2 storage, a mobile fueler, or tube trailers. This tanker has been deployed in the U. S. and Europe and offers the opportunity to optimize fuel supply logistics and improve fueling economics. For example, for the CHIC project for Transport for London, the 500-kg gaseous H_2 storage is refilled using the dual-phase tanker; most of the refueling equipment is on-board the tanker, leaving little to maintain on the ground. This fueling station is unmanned and monitored remotely.

Linde covers the entire H_2 value chain, including large-scale production, on-site supply and storage, compression/transfer, and dispensing. They have conducted over 10,000 fuelings to-date:

- Up to 100 kg/day for the CUTE project in Amsterdam, the Netherlands; Porto, Portugal; Barcelona, Spain; Perth, Australia; and London, UK;
- 56 kg/h in Shanghai, China, for Shell;
- Up to 140 kg/day for CEP, Berlin, Germany;
- 30 kg/h for the Nuclear Research Institute, Prague, the Czech Republic;
- 5 kg/min at AC Transit's Emeryville and Oakland, CA, stations;
- 70 kg/h for CEP/Vattenfall in Hamburg, Germany; and
- Up to 200 kg/h for Shell in Berlin.

Linde has deployed three different types of H_2 compression technologies for dispensing the fuel to light-duty vehicles and transit buses:

1. Dry Runner: lubricant-free piston compressor, 5–11 kg/h, 350/700 bar.
2. Ionic: ionic liquid as a piston for compression (near isothermal operation), 12–35 kg/h, 420–900 bar.
3. Cryo Pump: high throughput liquid H_2 pump, up to 120 kg/h, 350/700 bar.

Fueling station requirements vary by the project and depend on the location, size of the fuel cell bus fleet, and projections for growth at the site and in the region. Examples of fueling station designs are:

- Proterra fuel cell bus: 66 kg storage capacity with 120 kg/day maximum dispensing amount; 7,000 psi off-board storage pressure for 5,000 psi on-board storage system;

remote operation and monitoring capability, non-communication-based fast-fill dispensing; and designed for expansion to on-site H_2 generation capability.

- The Emeryville, CA, hydrogen fueling station of AC Transit, part of the HyRoad Project that opened in the second half of 2011, offers transit fueling inside the fence, and public fueling outside the fence. Some of the H_2 is obtained by electrolysis of water using solar photovoltaic energy.

Projections

Fuel cell and fuel cell bus technology is proving out, with steady increases in maintainability and reliability. Costs are still a challenge, however, and simply increasing the number of buses and power systems may not be enough to drive the costs down to the target values. "Value Engineering" must be applied to reduce cost and weight, and increase the level of integration of the fuel cell subsystem and the balance-of-plant. Higher vehicle-level integration will also be needed, that includes the fuel system, cooling system, safety systems, and power electronics. According to one developer, the goals of this integration should be to eliminate 50% of the subsystems and 75% of the common parts used in building the buses.

Acknowledgements

The information in this report has been obtained from a variety of published and internet sources. The major such sources are listed in the bibliography, below. If this report or excerpts from it are to be published, or any of its content is to be cited in a public manner, it will be necessary for the author of such a public presentation to obtain copyright clearances from the specific source(s) contained within the bibliography.

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Abbreviations and Acronyms

ACT VH	AC Transit Van Hool buses with UTC Power fuel cells
ACT ZEBA	AC Transit Zero Emission Bay Area Van Hool buses with UTC Power fuel cells
APCI	Air Products and Chemicals, Inc.
APU	Auxiliary power unit
ASME	American Society of Mechanical Engineers International
BC	British Columbia, Canada
BCT	British Columbia Transit (Canada)
BEV	Battery electric vehicle
CARB	California Air Resources Board
CHIC	Clean Hydrogen in European Cities Project (www.chic-project.eu)
CNG	Compressed natural gas
CTA	Chicago Transit Authority
CTT Nutmeg	Connecticut Transit Nutmeg Project Van Hool buses with UTC Power fuel cells
CTT VH	Connecticut Transit Van Hool buses with UTC Power fuel cells
CUTE	Clean Urban Transport for Europe Programme
DOE	U. S. Department of Energy
DOT	U. S. Department of Transportation
EMTU	Empresa Metropolitana de Transportes Urbanos (Sao Paulo, Brazil)
EV	Electric vehicle
FC	Fuel cell
FCB	Fuel cell bus
FCV	Fuel cell vehicle
FCPS	Fuel cell power system
FTA	Federal Transit Administration
GHG	Greenhouse gases (emissions expressed as CO_2-equivalent emissions)
HDV	Heavy-duty vehicle
ICE	Internal combustion engine
LDV	Light-duty vehicle
LH2	Liquid hydrogen
MBRC	Miles between road calls
mpgde	Miles per gallon diesel equivalent
NFCBP	National Fuel Cell Bus Program (U. S.)

NFPA	National Fire Protection Association (U. S.)
RFI	Request for Information
SC PT	South Carolina Proterra battery-dominant bus with Hydrogenics fuel cells
SCVTA	Santa Clara Valley Transit Agency (California)
SL AT	SunLine Transit New Flyer buses with Ballard fuel cells
SL CNG	SunLine Transit CNG buses (compressed natural gas)
SL VH	SunLine Transit Van Hool fuel cell buses with UTC Power fuel cells
SMR	Steam methane reforming (for producing hydrogen)
TBD	To be determined
TFL	Transport for London (UK)
UAB	University of Alabama, Birmingham
UL	Underwriters Laboratories
UTC	United Technologies Corporation

Appendix C: Advanced Materials for Transport: Outlook for materials technology

IEA-IA-AMT.org
Implementing Agreement on Advanced Materials for Transportation Application

AMT technology projection

Stephen Hsu

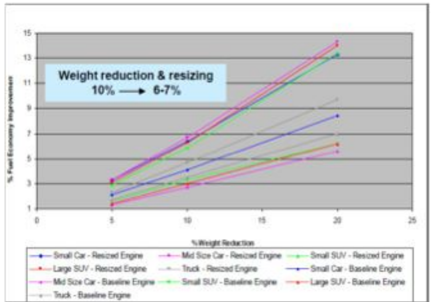
Preface

The Implementing agreement on Advanced Materials for Transportation Applications, in response to the request from Advanced Motor Fuels Implementing Agreement at the urging of the End Use Working Party Vice-Chair for Transport, Mr. Nils-Olof Nylund to contribute an outlook of technology to the "Fuel and Technology Alternatives for Buses" study. The following questions were posed to AMT:

- How much could light-weight materials reduce the weight of city buses and what impact weight reduction has on fuel consumption and at what cost?
- A projection of the development of the weight of a standard 12 metre city bus from now to 2020
- How much can advance in tribology reduce the fuel consumption of internal combustion engines or reduce losses in mechanical drivelines?

Since AMT does not have detailed knowledge of the Bus demonstration program and its design, we are responding in the context of cars and trucks in general and AMT on-going activities.

Lightweighting



Ricardo 07

Weight reduction of vehicles of all kinds will improve fuel efficiency since it takes less energy intensity to accelerate smaller mass. However, Lightweighting is not restricted to the use of light weight materials (implying less dense materials) but to achieve weight reduction of the system using advanced materials while maintaining safety, performance, and cost. The environmental aspects of the materials use also include energy intensity in excavating, manufacturing, and recycling, and to some extent, biodegradability. Depending on the vehicle type, as shown in the figure, a 10% reduction in weight may gain 2%-8% fuel economy. At the same time, reducing weight of a vehicle offsets the increased weight of power accessories, batteries, and generators in hybrid or PHEV without fuel economy penalties.

Materials being considered for weight reduction include aluminum, magnesium, titanium, high strength steel, carbon fiber composites, reinforced nanocomposites of polymers, etc. Some materials are cost-competitive or lower cost and being introduced by OEMs now, some materials have cost penalties and manufacturing consistency issues or performance issues that make them unsuitable at this time. Intense research activities focusing on overcoming these barriers are underway worldwide. This includes the IEA Implementing Agreement on Advanced Materials for Transportation Applications. At the same time, solving the performance and/or consistency issues is insufficient to achieve weight reduction by materials substitutions. Manufacturing cost reduction (raw materials cost, processing cost, fabrication cost), and energy intensity in manufacturing cost and environmental friendliness are also needed to achieve a balanced approach in cost-effective weight reduction goals. Also, reduction in green house gases emission and carbon footprint benefits have to be taken into account. At this stage in the lightweighting effort, cost of substitution is a major barrier.

Of all the lightweighting effort, aluminum is the material being used most frequently in engines, body panels, and other accessory parts to reduce weight. Magnesium and polymeric nanocomposites are selectively used for specific parts. Carbon-carbon composites are introduced in the high end cars for gaining manufacturing experience due to high costs.

Within AMT, we have two Annexes, one on Mg corrosion protection, one on polymeric nanocomposites (clay infiltrated polymer blends). In the Mg corrosion protection, cold spray of aluminum has been found to have a cost-effective protection against the galvanic corrosion of magnesium alloys in contact of iron-based alloys. The study is progressing.

On the polymeric nanocomposite, the issue is consistency in production from batch to batch. Since clay particles (more like platelets, one to two nanometer thick, and about 30-40 microns long, 14-20 microns wide) are minerals, batch to batch variation exist. The clay particles are blended into the polymer matrix using twin-screw extruders before injection molding. In the finished product, the spatial distribution of the nanoparticles within the matrix, the aggregation of the nanoparticles, and interfacial adhesion strength between the particle and matrix all influence the final strength of the composite. In order to tighten the quality, the lack of measurement methods linking the quality of the clay particles to the strength of the composite is a barrier. AMT is currently developing nanomechanical measurement techniques by developing a moduli map of the composite, measuring the enhanced hardness volume surrounding each nanoclay particle. This will provide critical data for predicting the composite strength, as well as pin-pointing specific quality issues associated with clay batches or processing conditions. If the consistency issue can be improved, this class of materials could be introduced as body panels, seats, partitions, providing significant weight savings.

Technology projection: The current lightweighting and multi-materials project in the US has a goal of 50% weight reduction for trucks (buses) within the next ten years. However, overcoming current cost, manufacturing processes, and other challenges may not be sufficient to guarantee significant penetration of new materials into vehicles since market and manufacturing capacity take time to build up. One thing may be sure, the future cars, trucks, and buses may be weighting much less than today's versions. By 2020, a 20% weight reduction may be feasible, thus increasing fuel economy by 10% to 15%.

Fuels and lubricants associated with future multi-fuel engines (including buses)

If an engine is designed to be able to run multi-fuel sources efficiently, the combustion temperature will need to be high enough to eliminate the different energy densities and gum-forming tendencies from various biofuels, etc. Lubricants will have to be specially formulated to cope with the emission regulations, corrosion tendencies, and seal swelling issues.

Based on the projected oil demand and supply in the world, US government has developed a new Corporate Average Fuel Economy (CAFÉ) standard of 54.5 mpg for cars and light trucks by 2025. In addition, a new fuel efficiency standard of 15% to 20% improvement by 2016 for heavy duty trucks is also developed. These standards provide an unprecedented driving force for fuel economy increase in the US. Future fuel economy targets for heavy duty trucks are being negotiated but it is widely expected they will be increasing steadily to lessen the nation's dependence on oil.

Besides lightweighting, increasing the population of electric hybrids, and plug-in hybrids into existing fleet mix is an important factor. However, this is dictated by cost, availability of batteries, consumer acceptance, and crude oil prices.

Another avenue is the use of integrated surface technology (surface textures, diamond-like-carbon films, bonded chemical films) coupled with advanced low viscosity lubricants. AMT is currently engaged in the integrated surface technology to reduce friction in engine components. Our estimate of potential fuel economy improvements of the technologies are 3%-5% from surface technology and 5%-7% from low viscosity lubricants. There is a debate whether the two technology will be additive in nature since the overall frictional loss in engines are about 15% to 17% of the Indicated Mean Effective Pressure (IMEP).

To illustrate the friction reduction potential, Table 1 lists various engine components in a diesel engine. If we have an advanced lubricant which can systematically reduce the friction from the high values down to 0.05, the parasitic energy losses could be cut significantly. It has been known for some time that low viscosity lubricants will improve fuel economy significantly but incur wear and durability penalties.

Table 1. Initial coefficients of friction in a diesel engine (Fox, J. Trib International 38, 265, 2005).

Engine component	Baseline friction coefficient	Friction mechanism
Cam-follower	0.005	rolling and sliding
Cam-cam bearing	0.02	rolling/sliding
Rocker arm-rocker support	0.02	rolling and sliding
Pushrod socket-pushrod	0.05	roll/slide
Rocker tip-valve bridge	0.05	simple
Piston skirt-cylinder liner	0.08	boundary + hydrodynamics
Piston rings-cylinder liner	0.12	boundary + hydrodynamics
Piston pin-piston	0.08	boundary + hydrodynamics
Connecting rod small end	0.12	boundary + hydrodynamics
Connecting rod large end	0.12	boundary + hydrodynamics
Crank shaft main bearing	0.12	Boundary + hydrodynamics

Advanced lubricants are being developed around the world to reduce the friction. Literature reports using nanoparticles as an independent friction and wear modifier in lubricants is gaining ground. If successful, this will allow the use of low viscosity lubricants without wear and durability penalties. Most of the nanoparticle papers have reported measured friction coefficient level of about 0.04. GWU has recently reported a frictional level of 0.02 using actual ring and liner components tested on a Cameron-Plint ring and liner simulation tester.

Surface texturing

Engineering surfaces by design are isotropic and uniform roughness to facilitate surface mating and interface coupling. Recently directionally aligned surfaces, multi-scale featured surfaces, and discrete dimpled (textured) surfaces have been introduced to gain additional functionality. Modern tires use intricate surface texture designs to control traction under various weather conditions. Surface engineering and textural control are increasingly being recognized as potent tools to enhance performance but their use is limited by the cost of texture fabricating versus the benefits to be gained. The lack of a sound science basis for designing surface properties of materials hampers the development of this technology. This project addresses that barrier to development.

Figure 1 qualitatively illustrates the operating regimes of industrial components/systems under various speed and load combinations. Each region represents different degrees of influence by the three basic lubrication regimes: hydrodynamic, elastohydrodynamic (EHL or mixed), and boundary lubrication. Although somewhat arbitrary, the classification scheme in Figure 1 is helpful in the selection of surface texture designs. Prior researchers have shown, the following parameters can be adjusted to achieve friction reduction under various lubrication regimes: (a) shape and aspect ratios of dimples, (b) depth of dimples, (c) dimple arrangement and spacing, and (d) density (area fraction) of dimples.

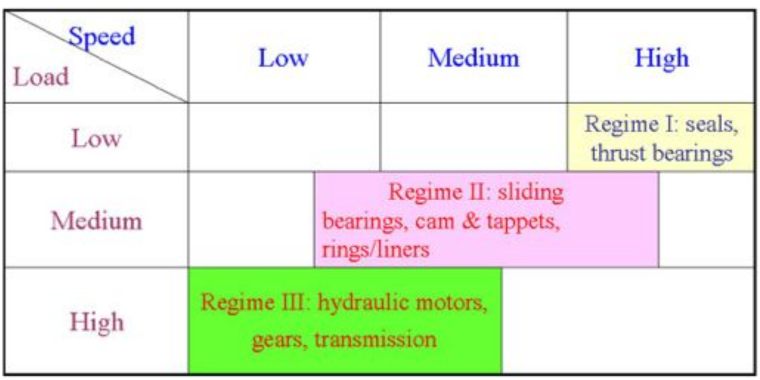


Figure 1. Classification of the textured surfaces used under different operating conditions.

For regime I, under steady state conditions, the load is fully supported by the fluid film pressure. The surfaces are separated by a continuous fluid film and the thickness of the film is controlled by the contact geometry (conformal and non-conformal contacts), speed and load, and the viscosity of the lubricant.

Surface textures in this regime are often used to hasten the onset of the hydrodynamic lubrication mechanism, reducing the friction. The most notable studies in this regime are the pioneering papers by Etsion and his group (1, 2-6). A focused laser beam is used in pulsating mode to generate micro-dimples rapidly on various metal surfaces. These dimples enable durable energy efficient operations of many mechanical seal designs (nominal apparent contact pressures from 0.1 MPa to about 15 MPa and speed range from 0.5 m/s and up). He cited 40%-50% reduction in frictional torques and nearly doubling seal service life by various manufacturers (7). He reported that within this range of speed and load for conformal contacts, the friction reduction mechanisms were: a) enhanced hydrodynamic lubrication by early entry into the hydrodynamic regime (4); b) possible cavitation lift effects for some systems; and c) reverse flow inside the dimples or induced by the dimples (6). Etsion also developed hydrodynamic models for laser textured surfaces with symmetrical circular dimples and proposed several parameters for the design of dimples in this regime (3). The hydrodynamic lift depended on the size, depth, and number of dimples in the contact area. The number of dimples in the contact area can be quantified by the area ratio defined by the area of dimpled surface over the total area in the contact. He suggested that for typical seal applications, a surface texture using circular dimples (100 μm diameter and 10 μm in depth) at 20% area coverage may be a good starting point (5). Further refinements are needed depending on specific operating conditions and surface materials. The ratio of dimple depth over the diameter of the dimple also has significant influence on hydrodynamic lift (4).

There are contradictory reports in the literature on the effects of textures on friction under EHL regime (8-10). Some data suggest when the apparent contact pressure exceeds 180 MPa, friction increased. Both theoretical modeling and experimental results from references (8-10) confirm this observation. This is primarily due to the edge stresses induced by the elastic contacts around the dimple edges. So there is a balance between the number of dimples and edge stress effects. So the density needs to be much lower.

When the speed slows down and the load is further increased, most of the load is supported by the asperity contacts. Under such conditions, local plastic deformation of asperities and wear can occur (boundary lubrication regime). Studies in this regime are characterized by contradictory reports (11-16). Suh reported friction reduction by introducing parallel grooves in relatively poorly lubricated systems such as titanium alloys to trap the wear particles, hence reducing significantly the third body abrasion effects (11-12). Pantelis reported to achieve benefits of increased anti-galling by surface texturing (13). Petersson reported some benefits under very limited conditions using different geometries but also reported instances where friction actually increased (14-15). In this regime, our results suggest that small deep dimples at minimum density are needed to achieve friction reduction.

Because the optimum pattern and size and shape are different for each regime, practical application of surface texture design for each engine component is complicated since some engine components often have a wide variation of speeds and loads through a single duty cycle, e.g. the ring liner interface. Therefore translation of basic texture design for engine components requires detailed understanding of the materials composition, contact dynamics, and motion kinematics, and stress distributions throughout the duty cycle.

Within AMT, Annex IV, we have developed an extensive data base on various surface textures, diamond-like-carbon thin films, and bonded chemical films to achieve friction reduction of engine component interfaces. Current texture designs are being tested with our collaborating OEMs to optimize the technology.

Technology Projection by 2020

Lightweighting and tribological advances in surface technology and advanced lubricants will significantly improve fuel economy of buses by at least 10%-15% in five years. As required by the US fuel efficiency standards, by 2020, fuel economy improvement of 20%-25% may be feasible. However, adaptation of new technologies also depends on availability of advanced materials at reasonable costs and design balance. It would appear that new surface technology and new advanced lubricants will play a significant role in the upcoming fuel efficiency drive.

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Appendix D: Hybrid and Electric Vehicles: Technology projection for hybrid and electric buses

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Contribution by Task XII of IEA Implementing Agreement on Hybrid and Electric Vehicles (HEV)

Prof. Jussi Suomela, Aalto University, with additional input from Mr. Sami Ojamo, Veolia Transport Finland

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The Task XII – Heavy Duty Vehicles of Implementing agreement on Hybrid and Electric Vehicles - HEV, in response to the request from Advanced Motor Fuels Implementing Agreement at the urging of the End Use Working Party Vice-Chair for Transport, Mr. Nils-Olof Nylund to contribute an outlook of technology to the “Fuel and Technology Alternatives for Buses” study. HEV was asked to comment on the following issues:

- Trolley buses
- Hybrid technology in buses
- Current offerings of hybrid buses, FC, parallel and series
- Benefits of hybridization
- Cost of hybridization
- Fuel cell busses
- Battery electric buses.

Figure 1: A light-weight parallel hybrid bus. Photo by Kabus.

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Hybridization and electrification are means to improve the efficiency of vehicles.

Hybridization can be seen as a natural development in vehicle technology. Hybridization makes is possible to recuperate kinetic energy otherwise lost as heat in the wheel brakes. In addition, hybridization enables downsizing and smoothing the operation of the internal combustion engine, factors that also contribute to reduced fuel consumption. An autonomous hybrid (not replenished with electrical energy from the grid) doesn't enable a shift in energy carriers, but reduces overall energy consumption.

Vehicles which use electric energy from the grid, either directly (trolley buses) or through on-board energy storage, enable a shift from oil based fuels to alternative energy sources. Electricity can be generated from a multitude of primary energy sources, some options like hydro, solar and wind providing an opportunity for carbon neutral mobility.

Fuel cell vehicles could be considered a subcategory of hybrid or electric vehicles: the driveline configuration is equivalent of a series hybrid or a battery electric vehicle, but the electric energy originates from a fuel cell, not from an ICE driven generator or a battery. Anyhow a fuel cell vehicle can have energy storage to provide hybridization.

Figure 2 shows the different technical options for the electrification of public transport buses.

Electric powertrains are characterized by high efficiency and favorable torque characteristics. As in the case of hybrids, an electric power train makes recuperation of kinetic energy possible.

Throughout the IEA Bus Report, the Braunschweig bus cycle has been used for comparison of diesel, diesel hybrid and alternative fuel buses. For fuel or energy consumption the Braunschweig cycle is roughly equivalent with the SORT 2 (Standardised On-Road Test Cycle) test cycle developed by UITP, the International Association for Public Transport (SORT 2004). According to UITP, the fuel consumption of a typical 12 meter diesel bus is some 42 l/100 km (~15 MJ/km or 4.2 kWh thermal energy/km) driving the SORT 2 cycle.

Within the project on the European Bus System of the Future (EBSF, http://www.ebsf.eu/), UITP has recently conducted a study called "Options for fully electrified operation of urban bus lines" (Pütz & Schwürzinger 2012). According to Pütz & Schwürzinger, the energy consumption of a 12 meter long battery electric bus is 1.2 kWh/km (without air conditioning). This value is congruent with the value announced by BYD for their 12 meter battery electric bus (120 kWh/62 miles, http://www.byd.com/ElectricBus.html#p2). Thus the energy consumption of a battery electric bus is only some 30 % of that of a conventional diesel bus.

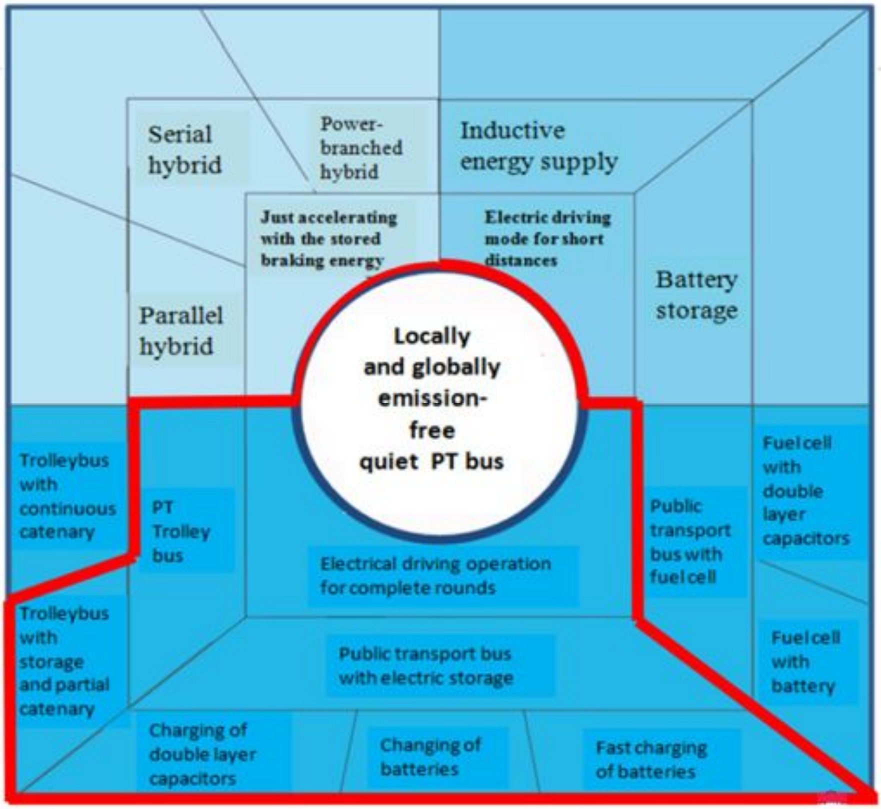

Figure 2: Options for electrified propulsion of public transport buses. (Pütz & Schwürzinger *2012, original source Müller-Hellman, A.)*

However, high efficiency alone doesn't guarantee low carbon emissions, as the carbon dioxide emissions are a product of energy use times carbon intensity of the energy. Figure 3 shows the average carbon dioxide intensity for power generation in various countries.

The values range from some 50 g CO_2/kWh (France) to 900 g CO_2/kWh (Australia).

Grid transmission losses are often estimated at some 5 %. Thus the total energy consumption of a battery electric bus is some 1.25 kWh/km. Well-to-wheel CO_2 emissions will then, using the values of Figure 3 for average CO_2 intensity, range from some 65 to 1150 g CO_2/km. These values should be compared with the WTW values for an ordinary diesel bus, ranging from some 30 g CO_2/km (best biofuel) to some 1400 g CO_2/km (regular diesel fuel, see main report).

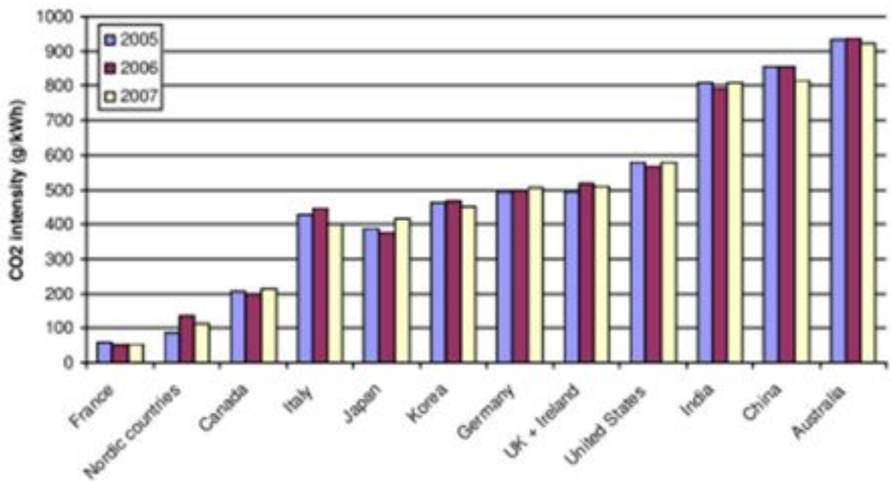

Figure 3: CO_2 intensity (g CO_2/kWh) for total power generation. (Ecofys 2010)

Hybrid systems use two sources of power to propel the vehicle. The hybrid system uses the advantages of the two power sources to attain lower fuel consumption. Typically, the two power sources are a petroleum-fueled internal combustion engine and an electric motor and battery system. However, other systems that combine a petroleum-fueled internal combustion engine with hydraulic accumulators have also gained popularity. There are also some vehicles on the market that uses GNC engines with plug-in hybrid system with possible autonomy of 30-40km with full electric. Also there is LPG hybrids under development. Specifically, increased efficiency is gained by the following:

1. Recapturing a portion of the vehicle's kinetic energy during deceleration, which is known as regenerative braking
2. Unloading harsh transient operations (e.g., launch acceleration and passing maneuvers) from the internal combustion engine
3. Augmenting the engine torque for transient maneuvers (e.g., short accelerations) with the secondary power system, which allows designers to downsize the internal combustion engine so it can operate at higher average loading and higher average efficiency
4. Meeting the accessory (or auxiliary) power demand when stopped by using the secondary power system, which allows the internal combustion engine to turn off.
5. In addition, some hybrid vehicles (and some plug-in hybrid electric vehicles, or PHEVs) are capable of all-electric driving. This capability can be useful for vehicles needing to operate in zero-emission zones.

There are three major hybrid vehicle configuration subtypes:

- series hybrids
- parallel hybrids
- series/parallel (power-split) hybrids.

The major differences between these subtypes relates to how energy flows from the power sources to the wheels. In a series hybrid, energy flows from one power source through all of the components in series (that is, one after another). In a parallel hybrid, each of the on-board power sources can provide energy directly to the wheels. A series/parallel or power-split hybrid can take on aspects of both the series and parallel system. Although hybrids are normally discussed in the context of hybrid electric vehicles, or HEVs, the same designations described above can be used for other hybrid systems, such as hydraulic hybrids.

The primary power source in a hybrid electric system - whether it is a series, parallel, or power-split system - is almost always an internal combustion engine, although other options such as fuel cells or gas micro-turbines have been used in transit buses.

The secondary power source is typically an electric motor connected to a battery system. Lead acid batteries have been used in the past, although more recent hybrids use both nickel metal hydride and lithium ion battery chemistries. Ultracapacitors have been used successfully in some hybrid applications, as well. Although ultracapacitor systems do not have high energy density, they are ideally suited for some hybrid applications. For example, they have been successfully demonstrated in refuse hauling applications in the United States (Business Wire 2006). A refuse hauler makes about one thousand stops per day. In these cases, the ultracapacitor's high cycle life and high power absorption capability are advantages that make it preferable to a battery.

A similar application for ultracapacitors we see today on hybrid city buses. One example of successful demonstration of using ultracapacitors in city bus is hybrid bus seen on Figure 1 (Kabus & VTT & Aalto). Fuel consumption was cut down by ca. 25% with hybridization and around 20 % with light weight construction. Very often the distance between bus stops in a city bus application is between 300 and 500 meter. The permanent stop-and-go between the bus stops is producing a lot of breaking energy and has to be stored in very short time, something a battery never can do. Today's hybrid buses with ultracapacitors can drive zero emission for few hundred meters. If this range has to be extended batteries could be combined.

Hybrid energy storage systems that combine batteries with ultracapacitors achieve the benefits of both: the ultracapacitor's cycle life and power density and the battery's high energy density. However, successful commercial deployments of that technology have not been demonstrated yet. Achieving full benefit from the combination would require separated voltages for the energy storages, which would require some additional power electronics.

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In a series configuration, the internal combustion engine or other prime mover is mechanically decoupled from the road. All power is generated and transmitted to an electric or hydraulic drive to power the wheels. Figure 4 shows a schematic of a series and parallel hybrid electric vehicle power trains. In a series hybrid electric system, chemical energy contained within the fuel (e.g., diesel, hydrogen, ethanol, gasoline, etc.) is released as a result of a chemical reaction such as combustion or that of a fuel cell. This reaction occurs in the power unit, which runs a generator to create electricity.

A commercial application of that principle we see since many years on dual mode trolleybuses. These are trolleybuses which have an extra strong diesel generator on board to produce the electricity on board, which allows to run the electrical driven buses also where no electrical lines are existing.

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In a parallel hybrid system (Figure 4), each power source follows a direct path to supply energy
to the wheels. In an electric hybrid, one path would be through an electric traction motor and
another through the internal combustion engine. In a hydraulic hybrid, the two paths correspond
to an engine and a hydraulic accumulator. Besides of full size hybrid system, parallel systems can also be used as smaller sizing to gain partial benefits of hybridization, called "power assist and "micro/mild" hybrid systems. At the moment, the parallel hybrid is the most common system on hybrid city buses on the markets. Usual

argument behalf of parallel hybrids is their good efficiency on wide range of driving profiles.

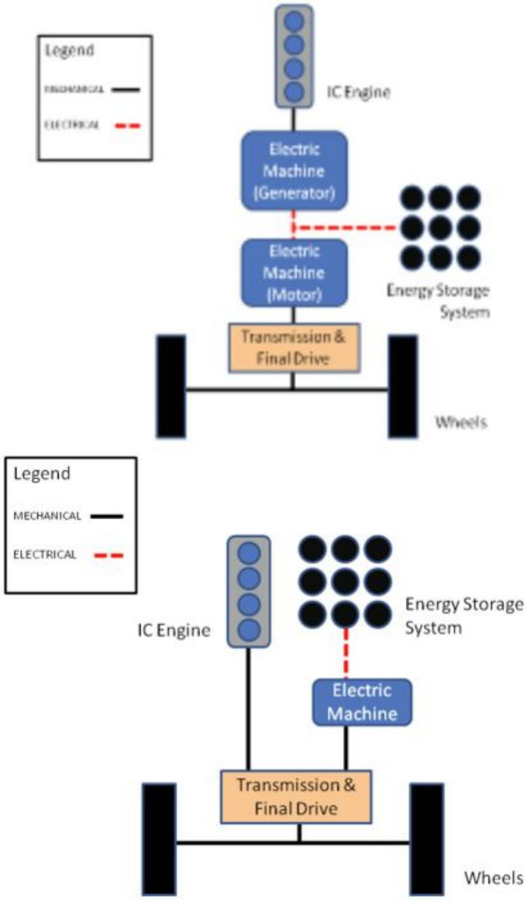

Figure 4: Series and parallel hybrid electric vehicle.

The series/parallel or power-split hybrid system has the advantages of both the parallel and series configurations, but the price is higher due to more complexity. One example of power-split hybrids use sophisticated planetary gear systems along with electric machines to form an “electric continually variable transmission,” or e-CVT. The electric machines play the role of both motors and generators, depending on which way the power is flowing. Figure 5 shows the component setup of two common power-split systems. The system with one planetary gear set is known as an input split system. The system with two planetary gear sets is a compound split system, sometimes also called a two-mode system.

In buses typically either parallel or series topologies have been used. Power-split is considered too high cost solution in heavy vehicles where the production series are also remarkably smaller comparing to personnel cars.

Figure 5: Types of power-split hybrid systems. Left: an input split system; right: a compound split system (also known as a two-mode system).

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BAE Systems' HybriDrive™, a hybrid electric vehicle propulsion system, has been successfully used in Orion buses (Figure 6) that have been deployed in New York City Transit's (NYCT) fleet since 1998 (NAVC et al. 2000). NREL has been tracking the performance of these vehicles in the field periodically since the first 10 buses were sent to NYCT in 1998. NREL conducted an evaluation of the Orion VII low-floor bus over the 12-month period from October 2004 to September 2005. The hybrid buses were part of a larger order of 125 vehicles that included Orion VII hybrid buses with BAE Systems' HybriDrive™ installed. These buses cost $385,000 each. For comparison, during the same years, equivalent CNG and diesel buses were $313,000 and $290,000 each, respectively (Barnitt 2008). The hybrid buses traveled about 5000 miles between road calls, which is better than the minimum 4000 miles required by NYCT. The hybrid electric transit buses had an average fuel economy of 3.19 miles per gallon over the 12-month period. This was 34% to 40% higher than the fuel economy of diesel buses without exhaust gas recirculation units that were operating under similar driving conditions from two different depots over the same period.

Figure 6: Orion VII bus with BAE Systems HybriDrive hybrid propulsion system.

A distinct drop in fuel economy was observed during the summer months; it was believed to be due to the use of the air conditioning system. Maintenance costs were tracked for the hybrid system at $0.367 (U.S. dollars) per mile. Unfortunately, there were no new diesel baseline buses to compare this figure with over the same period. Figure 7 shows the fuel economy of the HEV buses over the year in comparison to that of the diesel buses at the same stations. For details on this study, see Barnitt and Chandler (2006).

BAE Systems is supplying drive systems to many bus manufacturers, including Alexander Dennis Ltd of London (delivery accepted in October/November 2008; see Fleets & Fuels 2008-11-10).

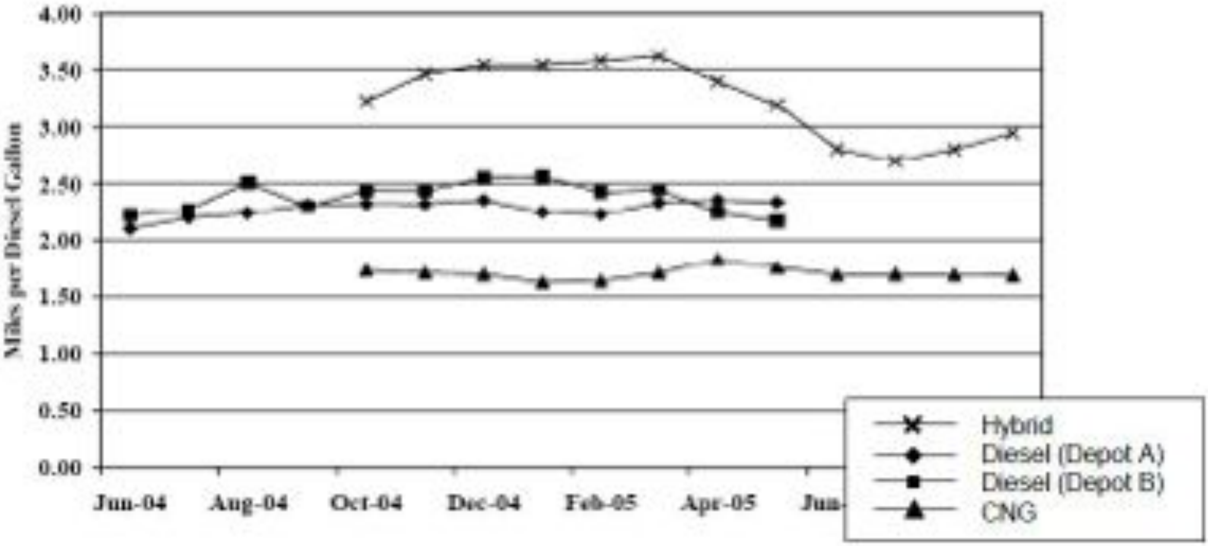

Figure 7: Performance of the BAE Systems HybriDrive on the Orion VII transit bus

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The Allison EV Drive (The EP SystemTM) is a 2-mode power-split hybrid power train currently being sold in 60-foot articulated transit buses. Table 1 lists the specifications of the system (Allison Transmission 2008).

Table 1: Specifications of the Allison EV Drive system. (Allison Transmission 2008)

Component Specification	Value
EV drive weight (kg)	417 (dry) and 428 (wet)
Output power (kW)	261
Dual power inverter module (DPIM) continuous power (kW)	150
DPIM weight (kg)	75

In a study conducted at NREL, two 60-foot articulated transit buses (one conventional and the other a hybrid system) were tested at NREL's ReFUEL heavy vehicle chassis dynamometer test facility (Hayes et al. 2006). The hybrid bus was part of a 235 hybrid bus order by King County Metro, which operates bus service in a 2,134-square-mile area in and around Seattle, Washington (Chandler and Walkowicz 2006).

Both vehicles were 2004 New Flyer buses (Figure 8) powered by Caterpillar C9 8.8 liter engines. The hybrid used the GM-Allison hybrid power train. Four driving cycles, ranging from extreme stop-and-go to more high-speed driving, were used to evaluate the vehicles. The hybrid bus demonstrated a fuel economy improvement of 30% to 75%, depending on the driving cycle.

Figure 8: GM-Allison hybrid transit bus at the NREL ReFUEL Chassis Dynamometer Test Facility

Volvo is offering 12m hybrid buses with a parallel system. One axle is driven and batteries are used on the roof. The concept is mainly designed for a regional transport.

Siemens is offering a serial system and uses batteries to store the energy. One axle is driven. The system is e.g. used by the bus builder Van Hool in 12m and 18m buses.

The HESS buses have two axle electrical driven, which is a result of the serial hybrid system which is using ultracapacitors to store on a short term base the generated energy. The energy management can be adapted to the local route. The buses are 18 or 25m long (Figure 9) and have an electrical operated AC.

Voith is offering a parallel system with batteries. The traction is made on one axel and in use in the 12m buses from Gillig in the USA and Solaris in Poland.

Eaton is offering a parallel system which is in example used on 12m Solaris city buses. The electric system is sized relatively small, as the electric motor maximum power is 44 kW. The Eaton hybrid system is further development from midsize delivery truck version.

Figure 9: Hybrid bus in Luxembourg (photo courtesy of HESS)

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The overall benefits of hybridization include the following:

1. Reduction in the amount of fuel consumed per unit of distance per unit of mass hauled
2. Reduction in emissions per unit distance per unit mass hauled
3. Integrated electrical power generation to run ancillary systems and auxiliary loads as well as the ability to provide off-vehicle power in some applications
4. Ability of hybrid electric systems to be tuned for performance (at the expense of the fuel economy benefit, however)
5. Ability to run using only electricity, in some instances.

Additionally, researchers have observed reductions in the wear of some system components, such as brake pads and braking systems (Barnitt and Chandler 2006).

In addition to fuel savings, heavy hybrid electric vehicles offer other values to the customer. These include noise reduction, reduced emissions, export power capability to use the power train to power off-board systems, and zero-emission capability. Unfortunately, these are not necessarily known to or valued by potential customers. Also, because of the way engines are certified, no additional credit is given to a heavy hybrid electric vehicle over the credit for the engine at component certification time.

A zero-emissions range could be quite valuable in some applications. For example, a zero-emissions capability would allow the engine to turn off when coming to a school bus stop and any other time when children are outside the vehicle. Additionally, a zero-emissions capability can be used in entering areas designated by authorities for zero emissions for pollution mitigation or safety reasons. For example, conventional vehicles cannot typically enter an enclosed space because toxic carbon monoxide emissions could build up.

[illegible]

The main advantage of a battery electric bus in comparison with a trolley bus is that the battery electric bus doesn't need an expensive and sometimes disfiguring catenary system. The battery electric bus is in general more flexible. The main drawbacks of the battery electric bus are the need for a large and expensive energy storage and limited range. However, with improving battery technology, battery electric buses are becoming technically and commercially feasible.

Some limited operations with battery electric buses started already more than a decade ago, mainly with small buses with a capacity of 10-15 passengers (Figure 10). The range of such buses, often with changeable lead-acid batteries was 50-60km. These were mainly used for very specific services and bus lines.

Figure 10: Electric lead-acid bus in France (photo courtesy of Veolia Environnement)

In 2008/2009 the European bus industry started to develop new technology power trains and lithium-based batteries aiming at bigger vehicles and longer autonomy. Capacity was increased to the midibus range (up to 50 seats). But still there were no standard size busses available in Europe. Meanwhile the Chinese manufacturers started producing regular size electric city buses (12m long), but still with low volumes.

Today also the European manufacturers show interest in 12m battery electric buses, although the focus is still mainly on midibuses. It is interesting to note that those companies currently involved in battery electric buses are mostly smaller independent manufacturers, not primarily the major European bus manufacturers. Within a couple of years a much wider selection of battery electric buses can be expected. As a boost to the market, there are demo projects popping up everywhere in Europe to test and evaluate electric buses and alternative charging methods.

Within 2012 there will be more than 2000 electric city busses running in normal operations in China, with large portion (+60%) of those being BYD eBUS-12 full electric 12m city buses (Figure 11). Table 2 presents technical data for the 12 meter BYD bus. Sunwin is another major Chinese brand with more than 200 buses.

Figure 11: The 12 meter long BYD battery electric bus.

Table 2: Technical data for the 12 meter long battery electric bus.

Dimensions	Length	39.37 ft.
	Width	100.4 in.
	Height	126.0 in.
	Wheelbase	20.34 ft.
	Track (F/R)	82.5/72.4 in.
	Curb weight	30423.79lb
	GVWR	39683.21lb
	Seats	27+4 (foldable) +1 (driver)
	Wheelchair position	2
Performance	Top speed	62.1mph
	Urban conditions	≥ 155 mi.
	Power consumption	120kWh per 62 mi.
	Turning radius	<40 ft.
	Min. ground clearance	5.5 in.
	Approach/Departure angle	7°/7°
Chassis	Suspension	Front & rear self-levering air suspension, ECAS system
	Brakes	Front & rear disc-braking, ABS+ASR

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Today the leading battery technology is lithium-iron-phosphate batteries, adopted by most manufacturers. With this technology the autonomy of a full size electric bus can be up to 200km with one charge. Charging power is typically 100 kW, giving a charging time of 2…3 hours. But as the bus should be in operation all the time and not standing connected to charger, fast charging technology is evolving at the same time. The big questions for the future will be:

- inductive charging or connective cable with plug?
- super-fast charging and smaller energy storage with several charging cycles against fast charging and larger energy storage with lower number of charging cycles?

In the USA, Proterra is using lithium-titinate batteries in their battery electric bus (Festner & Karbowski 2012). The bus (Figure 12) is equipped with rather small energy storage, 74 kWh, providing an autonomy of roughly 30 miles or 50 km (includes operation of air conditioning). Fast charging time from 10% up 95% of complete battery charge takes 10 minutes (calculated charging power some 400 kW). The buses also use “top-up” charging along the line at the bus stops (up to 3 minutes), enabling the buses to continuously serve a 17 mile (27 km) long line. Fast-charged up to 80%, the lithium-titinate batteries can take up to 20.000 cycles. In comparison it is said that lithium-iron-phosphate batteries can be expected to last 2000-6000 cycles charged to 80-70% of capacity.

Figure 12: Proterra electric bus in Foothill Transit with super-fast charging at bus stop (photo courtesy of Veolia Environnement)

In addition to fast charging at the bus stops, there are also some concepts of partial catenary systems. The idea is to use catenary wiring e.g. in suburbs where the wiring is not considered as disfiguring as in, e.g., historic city centers.

So the challenge is to evaluate and select the best solution taking into account the following factors:

- weight of the batteries
- longevity/charging cycles
- need for autonomy
- cost of infrastructure
- overall operational costs.

Battery charging, especially when charging several buses simultaneously at high power, will have a significant impact on the local grid. Some types of chargers generate reactive powers and disturbances which must be taken into consideration. Filtering and smart charging controls/smart grids will be needed to cope with high numbers of battery electric buses.

[illegible] – [illegible]

A successful example of an all-electric vehicle is the trolleybus (Figure 13). Every day thousands of trolleybuses around the world transport millions of people and are reducing noise and local emissions in the streets. The electrical traction of a trolleybus gets its energy from the electrical lines. While braking, the electrical driveline can recuperate energy back to the lines or use it on board for other users as heating, AC, etc. The recuperation depends on the topography and the characteristics of a line but is normally between 15 and 35%. Therefore the lines can be considered as an electrical storage system.

As a new development in the industry we see that ultracapacitors are integrated in the line system to avoid load peaks in the electrical energy supply. Trolley bus systems are developing side by side with electric buses so the future should bring more sophisticated trolley bus systems such as combined supercaps and batteries. It seems that the goal is to get rid of overhang wires and only integrate charger into the bus stop. This means that the bus can be quick charged (about 20 sec) in every bus stop without harming the batteries by using the supercaps as energy storage to get from bus stop to another one (maximum distance 1km). Then with batteries the bus can be driven even 35km meaning that it can be driven back to the depot for the night or to the maintenance supplier. This kind of system is under construction in France already. On the other hand battery electric buses could adopt similar fast charging systems, which would practically mean that functionalities of battery electric buses and trolley buses would converge together.

Trolleybuses can have a length of 12 to 25m and carry up to 220 passengers in one vehicle.

Figure 13: Trolleybus.

[illegible]

Fuel cell buses could be considered a subcategory of electric buses. Fuel cell bus technology is described in the contribution by the Implementing Agreement on Advanced Fuel Cells (Appendix B).

[illegible]

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Appendix E: Combustion: Alternative fuels in combustion

IEA Combustion

Contribution of the IEA Combustion Agreement – Collaborative Task on Alternative Fuels in Combustion

Martti Larmi, Kalle Lehto & Teemu Sarjovaara, Aalto University

Preface

This appendix is reporting the main research results of one part of a multinational collaborative task “Alternative Fuels in Combustion” of the IEA Combustion Implementing Agreement. The collaborative task is operated on task sharing principle. The subtask project described here is called “ReFuel” and it has been the contribution of Finland in the collaborative task from 2009 to 2011.

The ReFuel project has been a research task demonstrating the possibilities of utilizing the chemical and physical properties of alternative fuels to improve the efficiency and reduce the emission formation in engine combustion. The chosen combustion type was diesel combustion and the chosen fuel was a paraffinic high cetane number diesel fuel, Ref. 1. The effect of oxygenate addition was further studied, in order to reveal the effect of oxygen without much affecting the other properties of the fuel. The studied fuels are fully applicable in busses. The engine technology needed for combustion modification could be ready for product development phase in the near future. No infrastructure changes are needed.

As revealed by the “ReFuel” project, the modification of combustion could give very good results with respect to emission formation and exhaust gas after treatment. Corresponding research studies has been carried out with DME in South Korea, for example. Moreover, the lean burn dual fuel gas/biogas combustion with pilot injection could be one promising future option. Various alcohols and ethers could be feasible fuels, too.

Future expectation by 2020 is the break-through of new engine technology adaptive for various new fuels with dedicated combustion systems without remarkable cost effects. The greenhouse gas effects are due to the origin of the fuels and its total production chain. Combustion development contributes to the utilization of various environmentally friendly fuels the best possible way.

Introduction

The objective of the ReFuel project was to develop new extremely low emission combustion technologies for new renewable fuels in compression ignition engines. The target was to decrease the engine out emissions at least by 70%. The scope was to utilize the physical and chemical properties of the renewable fuels that differ from properties of the traditional crude oil based fuels and to develop optimum combustion technologies for them.

The project focused firstly, on paraffinic high cetane number fuels i.e. hydrotreated vegetable oil (HVO) fuel as a typical representative of this kind of fuel and secondly, on fuels with high content of oxygenates. This was implemented by blending oxygenate to HVO fuel.

The project consisted of following research paths supporting each other:

- Literature review and reaction scheme evaluations
- Fuel spray studies
- Emission mapping calculations
- Optimum combustion design with CFD
- Engine tests with a high-speed research engine
- Engine tests with a medium-speed research engine
- Extensive emission measurements
- Particle emission analysis.

In this report the main focus is on the high-speed engine tests performed during the ReFuel project.

Fuels

The novel paraffinic diesel fuels have excellent physical and chemical properties. Renewable diesel fuel, HVO, is an example of paraffinic high-cetane, low-aromatic diesel fuel. Paraffinic HVO does not suffer from storage and low temperature problems. The combustion related properties of paraffinic fuels are excellent enabling engine operation with reduced nitrogen oxide emission without suffering from traditional trade-off with increased particle matter emission.

Combination of paraffinic fuel and an oxygenated diesel component could offer further benefits in engine performance and exhaust emissions. A large number of oxygenates were reviewed to find the most promising candidate in this respect. Di-pentyl ether (DNPE) was selected for the tests due to its diesel-like fuel properties and low exhaust emissions reported in literature. Paraffinic HVO as such and with oxygenate were used in this study in comparison with conventional diesel fuel.

The three fuels used in the high-speed engine tests were regular EN590 diesel, HVO, and oxygenated HVO. Oxygenated fuel in the experiments contained 2 wt-% oxygen, which was obtained by blending 20 wt-% DNPE and 80 wt-% HVO. Selected properties of the test fuels are shown in Table 2. Due to the low amount of oxygenated HVO available the test matrix was kept quite small. The reference load points of 50, 75, and 100 % were run. Also moderate EGR points of 2.5, and 5 % with 75 % load were run so the results could be compared with the EGR results using neat HVO.

Table 1 Test fuel properties.

Quantity	Unit	EN 590	HVO	HVO + DNPE
EN590 diesel fuel	%-wt	100	0	0
HVO	%-wt	0	100	80
HVO + DNPE	%-wt	0	0	20

Density	kg/m^3	837,3	779,9	781,2
Viscosity (at 40°C)	mm^2/s	3,587	2,985	2,348
Eff. heating value	MJ/kg	43,173	43,991	43,137
	MJ/l	36,149	34,308	33,699
Cetane number (IQT)		54,7	88,2	93,9

High-speed engine tests

The high-speed engine tests were run using a “LEO” research engine at Aalto University Internal Combustion Engine Laboratory, Fig. 1. The LEO engine is a single cylinder common rail diesel heavy duty research engine based on a commercial 6-cylinder Sisu Diesel 84 CTA, and it’s equipped with an electro hydraulic valve actuator system (EHVA).

Figure 2. LEO research engine used in the ReFuel high-speed engine runs.

The research engine main specifications are found in Table 2.

Table 2. LEO specification.

Parameter	Value	Unit
Number of cylinders	1	#
Cylinder diameter	111	mm
Stroke	145	mm
Compression ratio	17:1	

Reference study

Three reference loads were run using the engine operational parameters directly from the corresponding commercial engine. The reference loads were run with three different test fuels: Regular EN590 diesel, HVO, and HVO+oxygenate.

PM emissions decreases greatly with HVO and HVO+oxygenate compared with EN590. Also significant reduction of elemental carbon was observed, Fig. 2 and 3. There was also a small decrease in organic carbon emission. PAH emissions decreased as well. Aldehyde emissions were lower at 50% load but slightly higher or the same at high engine loads. When comparing HVO with HVO+oxygenate it was found that the oxygenated fuel had smaller PM and PAH emissions but higher aldehyde emissions on high loads.

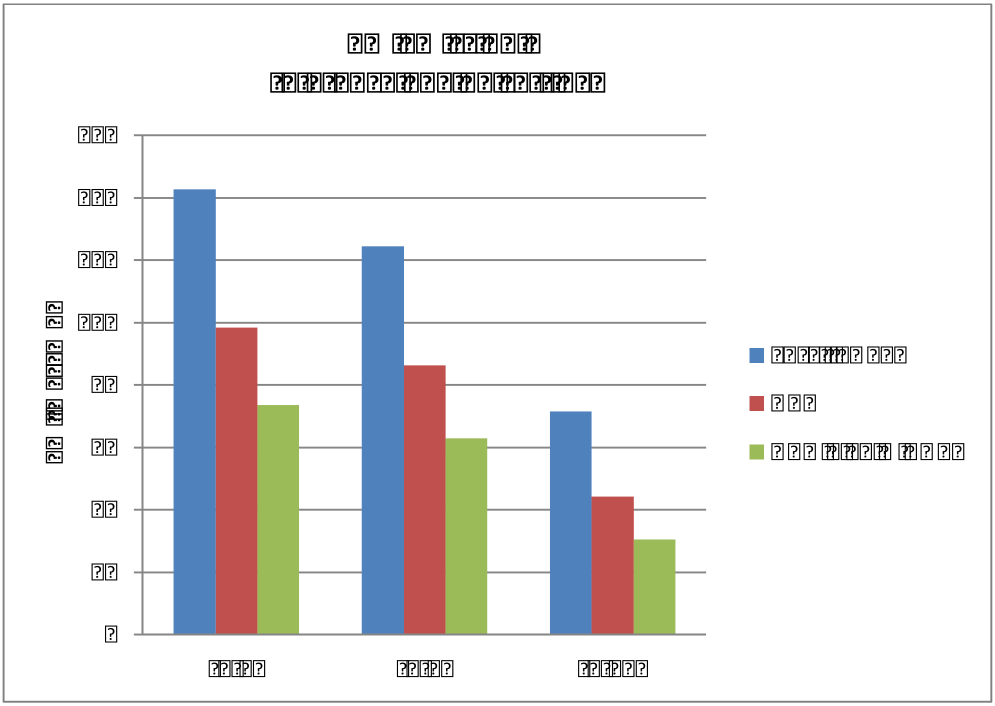

Figure 2. PM emissions with the studied fuels.

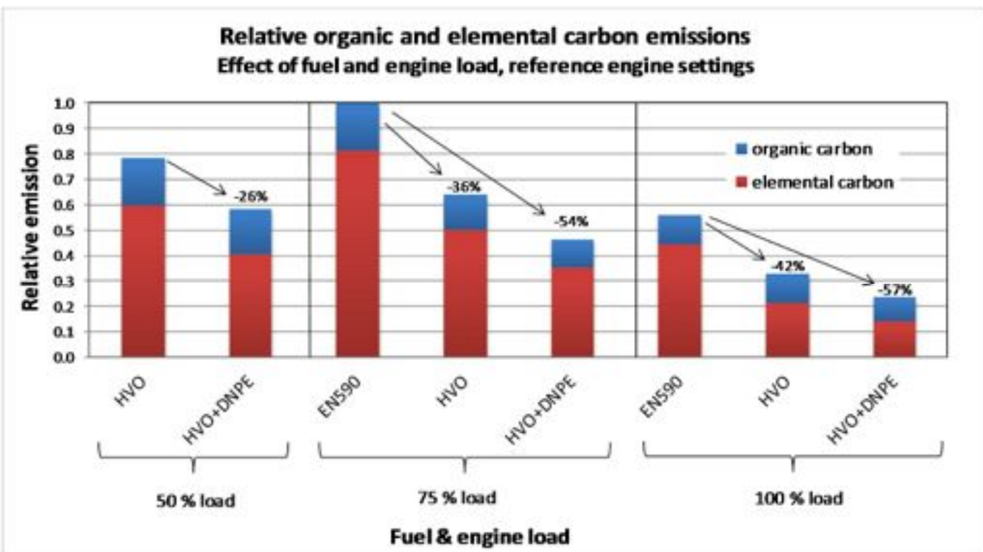

Figure 3. Organic and elemental carbon emissions with different fuels and engine loads.

Even with the substantial drop in PM emissions when using HVO or HVO+oxygenate, the NO_x emissions did not increase, Fig. 4.

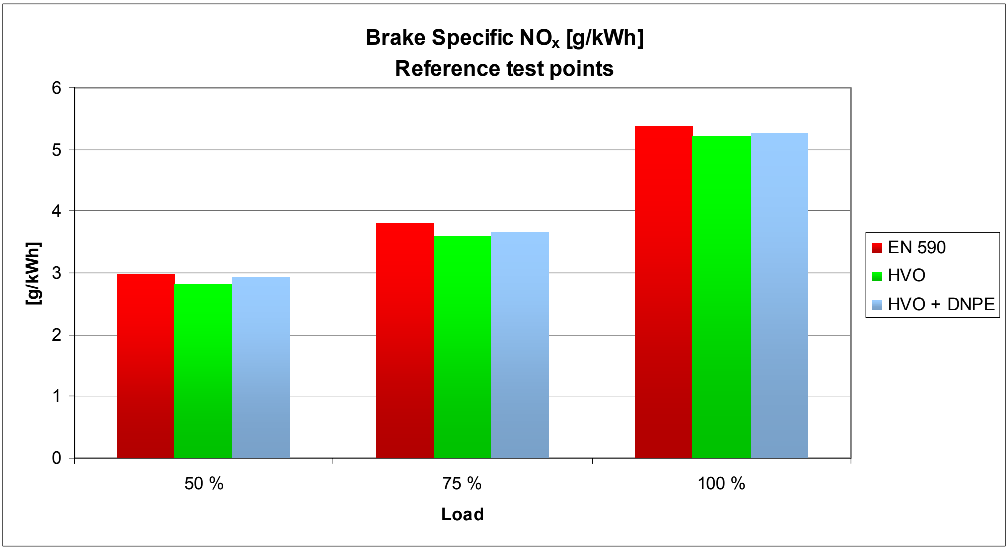

Figure 4. Brake Specific NOx emission at the reference loads

When comparing HVO with HVO+oxygenate it was found that the oxygenated fuel had smaller PM emission but slightly higher aldehyde emission, both being substantially lower than the emissions when using EN590. All in all, the relative decrease in particulate emissions caused by changing the fuel from HVO to HVO-oxygenate blend was of the same order of magnitude than the decrease caused by changing the fuel from fossil EN590 to HVO fuel

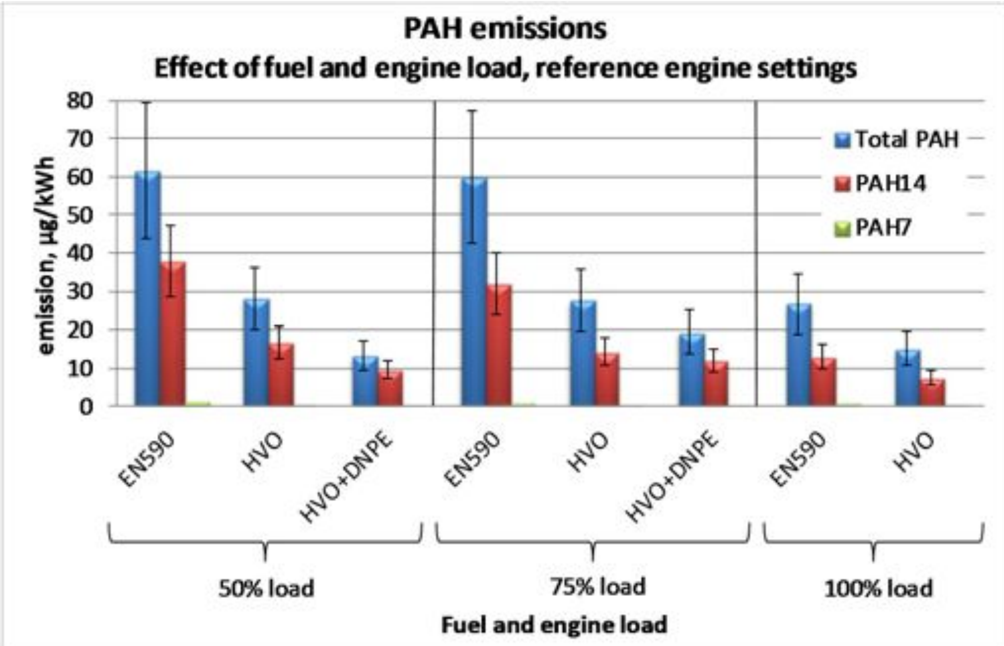

Figure 5. PAH emissions with different fuels and engine loads.

HVO "optimized" engine settings

For the optimized process test runs three different running parameters were created for each load point by varying exhaust gas recirculation (EGR) percentage, miller timing and fuel injection parameters. The different points were named LN (Low NO_x), LS (Low smoke), and opt (Optimum). The idea behind the three different points is as follows:

Opt: A good compromise were both NO_x and smoke emission is reduced .

LN: Adjust the parameters to get the minimum of NO_x emission while keeping the smoke emission below the reference emission of EN590

LS: Adjust the parameters to get the minimum of smoke emission while keeping the NO_x emission below the reference emission of EN590

In the high speed engine tests the set goal of 70 % reduction in NO_x emission with PM emission no higher than the reference and vice versa was achieved or very nearly achieved depending on the load point. Generally it can be said that particle matter emission can be affected or even controlled significantly with the HVO-fuels and engine settings used in this study. The NOx-Smoke trade-off results for 100 % load are shown in Fig. 6. The results were very similar also with other loads run.

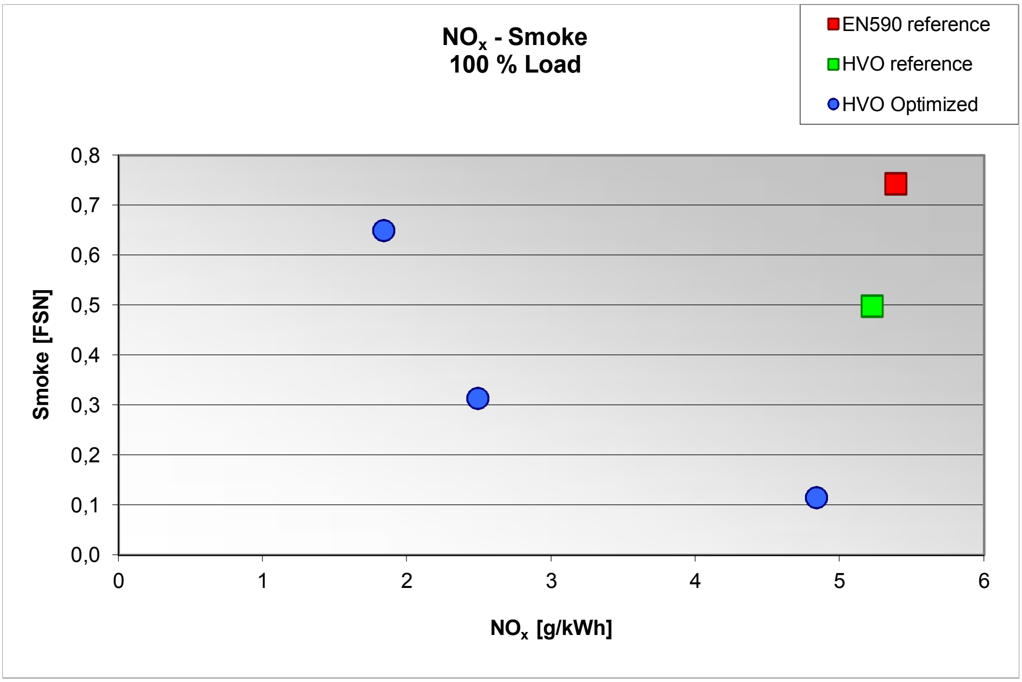

Figure 6. NOx – Smoke trade-off with 100 % load. The reference points with EN590 and HVO and the three HVO "optimized" points.

Conclusions and relevance for city buses

Hydrotreated vegetable oil (HVO) and oxygenated HVO were tested as a drop in fuel in a heavy duty diesel engine. The results showed significant reduction in particle matter (PM) emission without the usual NO_x-penalty that is normally got due to NO_x-PM trade-off. Also it was found that the use of miller valve timing and

EGR together with some fuel injection optimization further emission reduction is possible.

From the city buses point of view, the results of the reference tests with standard engine settings were promising. Just by changing fuels the reduction in PM as well as non regulated PAH emissions are notable. The cost aspect is not too much of an issue when HVO is used as a drop in fuel, as the price of the fuel is the dominating factor. The optimized engine settings used in this study, however, would need changes in engines, mostly due to the relatively high Miller-rates.

From the environmental point of view, the use of HVO could replace the use of fossil fuels and so decrease the green house gas emissions. And as mentioned before, the local exhaust gas emissions would also decrease. With some engine optimization there is potential for even larger emission reduction.

HVO as well as other high cetane number diesel fuels will be more widely available in the near future. HVO could be distributed in the current filling station network, so no new infrastructure is needed. Also the future engines will most likely be able to utilize the benefits of high cetane number fuels.

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Title	**Fuel and Technology Alternatives for Buses** **Overall Energy Efficiency and Emission Performance**
Author(s)	Nils-Olof Nylund & Kati Koponen
Abstract	In 2009–2011, a comprehensive project on urban buses was carried out in cooperation with IEA's Implementing Agreements on Alternative Motor Fuels and Bioenergy, with input from additional IEA Implementing Agreements. The objective of the project was to generate unbiased and solid data for use by policy- and decision-makers responsible for public transport using buses. The project comprised four major parts: (1) a well-to-tank (WTT) assessment of alternative fuel pathways, (2) an assessment of bus end-use (tank-to-wheel, TTW) performance, (3) combining WTT and TTW data into well-to-wheel (WTW) data and (4) a cost assessment, including indirect as well as direct costs. Experts at Argonne National Laboratory, Natural Resources Canada and VTT worked on the WTT part. In the TTW part, Environment Canada and VTT generated emission and fuel consumption data by running 21 different buses on chassis dynamometers, generating data for some 180 combinations of vehicle, fuel and driving cycle. The fuels covered included diesel, synthetic diesel, various types of biodiesel fuels, additive treated ethanol, methane and DME. Six different hybrid vehicles were included in the vehicle matrix. The TTW work was topped up by on-road measurements (AVL MTC) as well as some engine dynamometer work (von Thünen Institute). Over the last 15 years, tightening emission regulations and improved engine and exhaust after-treatment technology have reduced regulated emissions by a factor of 10:1 and particulate numbers with a factor of 100:1. Hybridization or light-weighting reduce fuel consumption 20–30%, but otherwise the improvements in fuel efficiency have not been that spectacular. The driving cycle affects regulated emissions and fuel consumption by a factor of 5:1. The fuel effects are at maximum 2.5:1 for regulated emissions (particulates), but as high as 100:1 for WTW greenhouse emissions. WTW energy use varies by a factor on 2.5:1.
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Experts at Argonne National Laboratory, Natural Resources Canada and VTT worked on the WTT part. The WTT emissions of various fossil fuels and biofuels were assessed by using GREET model from the United States, GHGenius model from Canada and RED methodology of the European Union. All these models follow the frame work of life cycle assessment.

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