

IEA Technology Network Cooperation: Fuel and Technology Alternatives for Buses: Overall Energy Efficiency and Emissions

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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 off 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 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. WTW energy use varies with a factor on 2.5:1.

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INTRODUCTION

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.

The organizations which actively took place in carrying out the project were:

- ADEME (the French Environment and Energy Management Agency)
- Argonne National Laboratory (USA)
- AVL MTC (Sweden)
- Environment Canada
- Natural Resources Canada
- von Thünen Institute and partners (Germany)
- VTT Technical Research Centre of Finland (lead partner)

The full report [1] of the project will be published on the website of Advanced Motor Fuels at www.iea-amf.vtt.fi.

PROCESS AND DESCRIPTION

The various IEA Implementing Agreements within the IEA Technology Network 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 the 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. In addition, all transport related Implementing Agreements submitted outlook reports (timeline 2020) of their respective technologies.

The elements of the projects are shown in Figure 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.

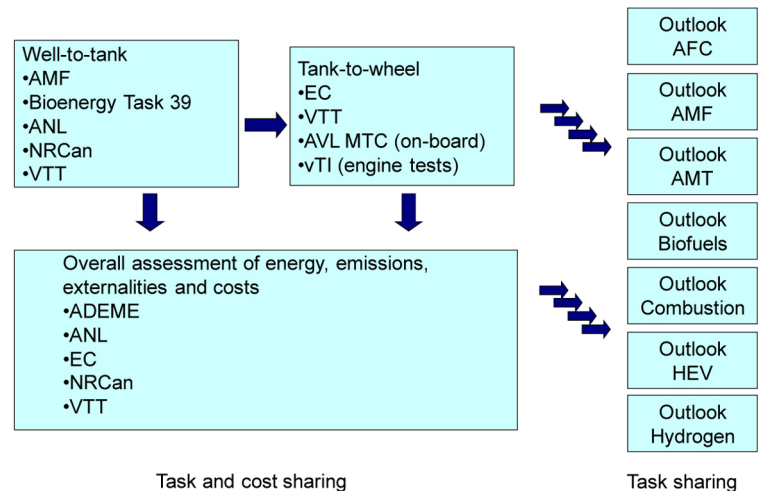


Figure 1. The elements and the actors in the overall project.

In vehicle and engine testing, the following diesel fuels and diesel fuel 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.

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

Table 1. The fuel chains studied with the GREET [2] and GHGenius [3] models and the RED [4] methodology.

	GREET (USA)	Abbreviation used:	GHGenius (Canada)	Abbreviation used:	Renewable energy directive = RED (EU)	Abbreviation used:
Fossil fuels	Conventional diesel	Diesel	Conventional diesel (Canadian average)	Diesel	EU average fossil fuel (comparator)	Diesel
	Oil sand diesel	OS	Oil sands to diesel	OS	Natural gas to GTL (remote plant)	GTL
	Natural gas to GTL	GTL	Natural gas to CNG	CNG	Natural gas to CNG (remote gas)	CNG
	Natural gas to CNG	CNG	Natural gas to LNG	LNG	Natural gas to DME (remote plant)	DME (NG)
	Natural gas to DME	DME (NG)	Natural gas to FT-diesel	GTL		
			Coal to FT-diesel	CTL		
Bio fuels	Landfill gas to CLG	CLG	Landfill gas to CLG	CLG	Biogas to CBG (from wet manure)	CBG (WM)
	Manure to CNG	CNG (M)	Landfill gas to LLG	LLG	Biogas to CBG (organic waste)	CBG (OW)
	Sugarcane to EtOH	EtOH (SC)	Biogas to CBG (anaerobic digester)	CBG	Sugarcane to EtOH	EtOH (SC)
	Corn to EtOH	EtOH (C)	Biogas to LBG (anaerobic digester)	LBG	Wheat to EtOH (NG as process fuel)	EtOH (WH)
	Corn stover to EtOH	EtOH (CS)	Rapeseed to HVO	HVO (R)	Straw to EtOH	EtOH (ST)
	Soybeans to HVO	HVO (S)	Rapeseed to FAME	FAME (R)	Rapeseed to HVO	HVO (R)
	Soybeans to FAME	FAME (S)	Palm oil to HVO	HVO (P)	Rapeseed to FAME	FAME (R)
	Switchgrass to EtOH	EtOH (SG)	Soybeans to HVO	HVO (S)	Palm oil to HVO (1)	HVO (P1)
	Farmed wood to EtOH	EtOH (FW)	Soybeans to FAME	FAME (S)	Palm oil to HVO (2)	HVO (P2)
	Wood residue to EtOH	EtOH (WW)	Wood residue to FT-diesel	BTL (WW)	Palm oil to FAME (1)	FAME (P1)
	Biomass to DME	DME (B)	Wood to FT-diesel (short rotation forest)	BTL (FW)	Palm oil to FAME (2)	FAME (P2)
			Tallow to FAME	FAME (T)	Farmed wood to FT-diesel	BTL (FW)
					Waste wood to FT-diesel	BTL (WW)
					Farmed wood to DME	DME (FW)
					Waste wood to DME	DME (WW)
					Jatropha to HVO	HVO (J)
					Jatropha to FAME	FAME (J)
					Waste/animal oil to HVO (3)	HVO (T)
					Waste/animal oil to FAME	FAME (T)

Explanations: GTL=gas to liquid, EtOH=ethanol, FAME=fatty acid methyl ester, HVO=hydrotreated vegetable oil, FT=Fischer-Tropsch, DME=Dimethyl ether, CNG=compressed natural gas, LNG=liquefied natural gas, CLG=compressed landfill gas, LLG=liquefied landfill gas, CBG=compressed biogas, LBG=liquefied biogas, 1=process not specified, 2=process with CH₄ capture at oil mill 3=estimate based on waste/animal oil to FAME

- 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.

WELL-TO-TANK ANALYSIS

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 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.

TANK-TO-WHEEL MEASUREMENTS

In the TTW part both Environment Canada (EC) and VTT carried out chassis dynamometer measurements. Together 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 buses were 40 foot or 12 meter long

city buses, and the measurements were carried out simulating half load.

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. 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). The outcome of the measurements is distance based performance data, e.g., energy consumption (MJ/km) and emissions (g/km) per driven distance. Transient-type testing was considered imperative to depict the real service of city buses.

The vehicles tested by EC and VTT are presented in [Appendix 1](#).

The TTW work was topped off by on-road measurements (AVL MTC) as well as some engine dynamometer work (von Thünen Institute). The work by von Thünen Institute focused on unregulated emissions.

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. EC's test matrix is presented in [Appendix 2](#).

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 FAME from 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. VTT's test matrix is presented in [Appendix 3](#).

The test fuels are presented in [Appendix 4](#).

RESULTS - WTT ASSESSMENT

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 in the full report 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 sequestration of growing biomass is taken into account and consequently the WTT emission may be negative, if more CO₂ is sequestered 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 sequestered 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 CO₂ emissions due to biofuel combustion as zero (as the RED), but calculates the CH₄ and N₂O 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 of the full report.

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.

The WTT, TTW and WTW GHG emission data of the different calculation models are presented in [Appendix 5](#). 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.

RESULTS - 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). 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.

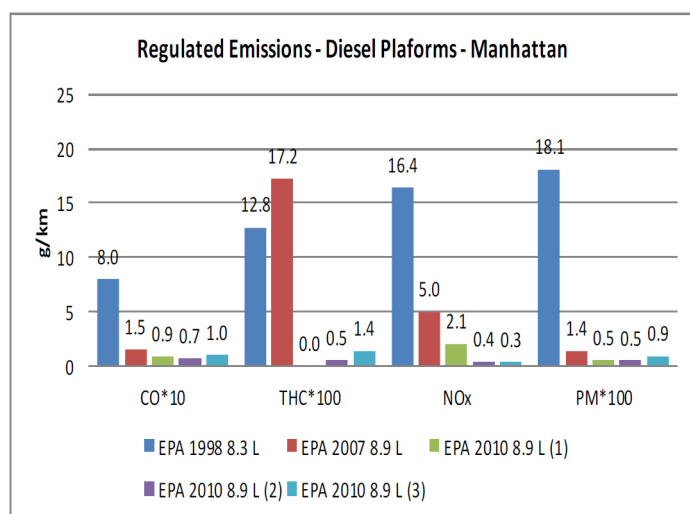


Figure 2. Regulated emissions for diesel vehicles with conventional powertrains. North-American vehicles, Manhattan cycle.

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 3 (NO_x) and 4 (PM) show emission results for European vehicles.

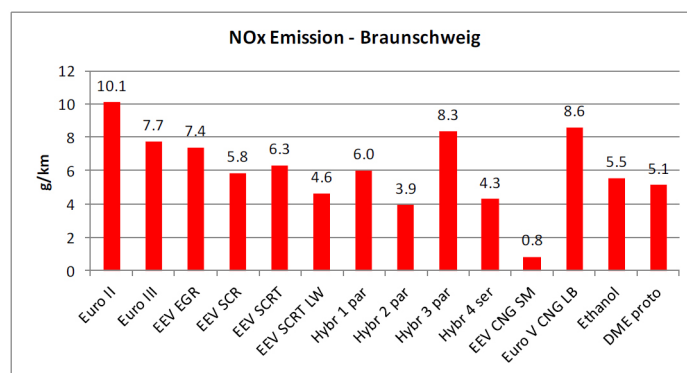


Figure 3. NO_x emissions of all tested European vehicles. Braunschweig cycle.

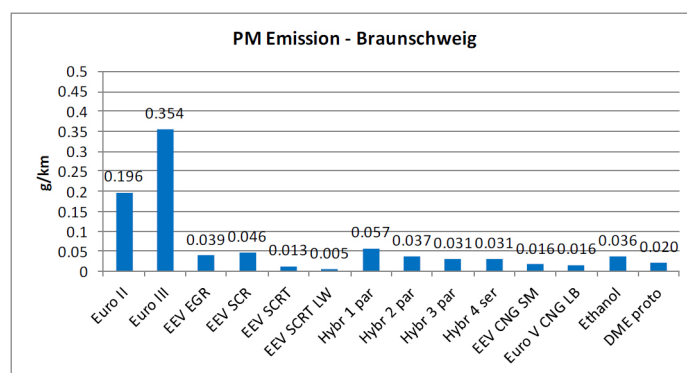


Figure 4. PM emissions of all tested European vehicles. Braunschweig cycle.

Hybridization or light-weighting reduce fuel consumption 20 - 30 % on an average, but otherwise the improvements in fuel efficiency have not been 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 roughly 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 slightly increase fuel consumption. Figure 5 shows energy consumption for European vehicles. Ratio between highest and lowest value is 2:1.

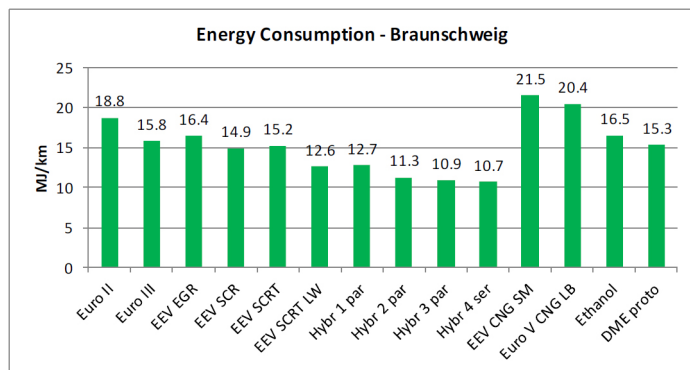


Figure 5. Energy consumption of all tested European vehicles. Braunschweig cycle.

Tailpipe CO₂ emissions (Figure 6) 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.

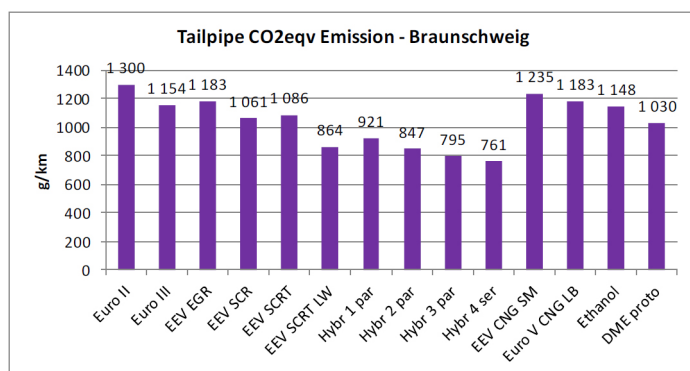


Figure 6. Tailpipe CO₂eqv emissions of all tested European vehicles. Braunschweig cycle. CH₄ taken into account with a factor of 23 for CNG, ethanol and DME.

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 7). The benefits of hybridization depend on the driving cycle. In severe low-speed cycles hybridization saves close to 40 % fuel. Figure 8 shows an example on the effects of driving cycle and hybridization on fuel consumption.

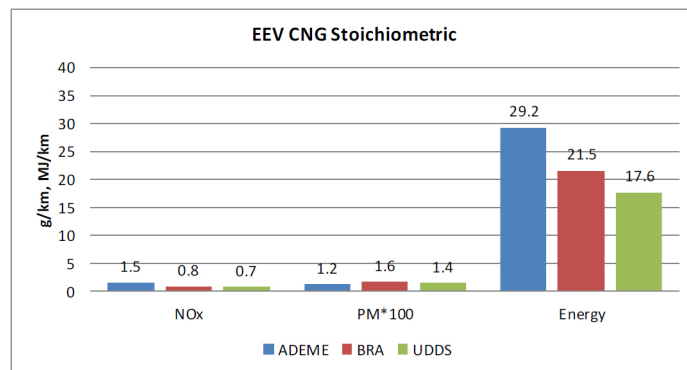


Figure 7. The effect of driving cycle on NO_x, PM and fuel consumption. EEV CNG stoichiometric.

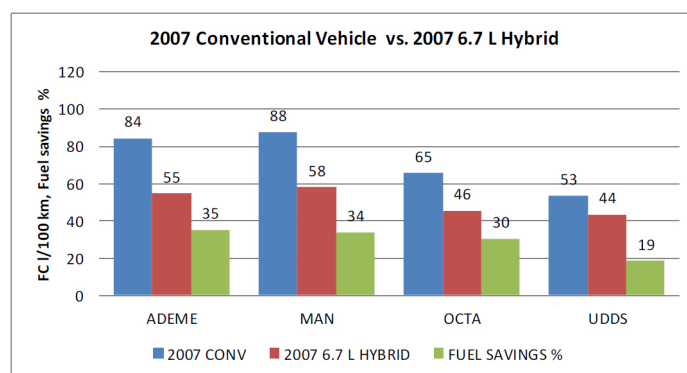


Figure 8. An example of driving cycle and hybridization on fuel consumption.

RESULTS - FUEL EFFECTS ON 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 9).

FAME type biodiesel is effective for PM reduction, but tends to increase NO_x emission (Figure 10). 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 11).