ESPOO 2007

VTT RESEARCH NOTES 2373

Nils-Olof Nylund, Kimmo Erkkilä &
Tuukka Hartikka

Fuel consumption and exhaust emissions of urban buses

Performance of the new diesel technology

PLL LTF

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VTT TIEDOTTEITA – RESEARCH NOTES 2373

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ISBN 978-951-38-6922-9 (soft back ed.)
ISSN 1235-0605 (soft back ed.)

ISBN 978-951-38-6923-6 (URL: http://www.vtt.fi/publications/index.jsp)
ISSN 1455-0865 (URL: http://www.vtt.fi/publications/index.jsp)

JULKAISIJA – UTGIVARE – PUBLISHER

VTT, Vuorimiehentie 3, PL 1000, 02044 VTT
puh. vaihde 020 722 111, faksi 020 722 4374

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Technical editing Leena Ukskoski
Text preparing Kirsi-Maarit Korpi

Edita Prima Oy, Helsinki 2007

Nylund, Nils-Olof, Erkkilä, Kimmo & Hartikka, Tuukka. Fuel consumption and exhaust emissions of urban buses. Performance of the new diesel technology. Espoo 2007. VTT Tiedotteita – Research Notes 2373. 48 p. + app. 1 p.

Keywords public transport, urban transport, vehicles, buses, diesel engines, fuel consumption, exhaust emissions, performance, measurements, operating expences

Abstract

The research was carried out by the Finnish Public Transport Association. Altogether seven vehicles were measured, two two-axle Euro 3 -class vehicles as references, three new two-axle Euro 4 -class vehicles and two new three-axle vehicles. The measurements were carried out on a chassis dynamometer, using three cycles describing actual driving. In addition to fuel consumption, exhaust emissions were also recorded for these vehicles.

The differences in fuel consumption and operating expenses were after all smaller than first anticipated. In the case of the Euro 3 -class reference vehicles, the difference between the two vehicles was as high as 7–10%. For new two-axle vehicles the difference in fuel consumption, when simulating urban driving, is only 3–4%. Due to different technical solutions, the results were anticipated to be greater. In suburban driving although, the difference is at its most 11%. In the class of two-axle vehicles, lowest fuel consumption was measured for a SCR vehicle, whereas in the case of the two three-axle vehicles, EGR technology resulted in lowest fuel consumption.

The measurements do not give an unambiguous answer to whether the EGR- or SCR-technology is preferable regarding fuel consumption. The contemplation is hindered by two factors. On one hand, the order of superiority depends on the driving cycle, on the other, the actual exhaust emissions do not match with expectations. The two EGR vehicles (same make) produced higher NO_x -emissions than the manufacturer's Euro 3 -engine. The most fuel efficient SCR -engine is not truly Euro 4 -class what comes to NO_x -emissions. Only two of the new vehicles, both with SCR technology, produce NO_x -emissions genuinely matching their classes.

Both fuel consumption and exhaust emissions have been observed in the study. In case exhaust emissions were completely disregarded, fleet decisions might be directed towards fuel efficient vehicles which after all do not reach the level of emission performance that reasonably could be expected.

Preface

In the fall of 2005, the Finnish Public Transport Association (PLL) contacted VTT. They suggested that VTT would measure the fuel consumption of new Euro 4- and 5 -class diesel busses. The goal of PLL is to offer information on fuel consumption of different technologies and vehicles under real life driving conditions. Member companies can use this information as a guide line in their decision making.

Altogether 7 vehicles were measured in the project. Two two-axle Euro 3 vehicles were measured as a reference. Three new Euro 4 -class two-axle vehicles and two new three-axle vehicles were measured as well. The measurements were carried out on a chassis dynamometer, using three cycles describing actual driving conditions. Fuel consumption and exhaust emissions were recorded for these vehicles. The results are valid for the specific vehicles tested, and may not apply to all vehicles representing equivalent technology.

New technologies awake a group of questions for bus operators. How does fuel consumption change when moving to Euro 4 -technology? Which technology provides lower running costs, SCR or EGR? And what about emissions, are new vehicles clean-running under real life driving conditions? The report pursues to answer these questions, evaluating the most common vehicle types in the Finnish local traffic.

The client has in this project been represented by the executive director of PLL, Mr. Pekka Aalto and the chairman of the technical committee at PLL, Mr. Kari Sulonen.

Espoo 6.2.2007

Nils-Olof Nylund, Kimmo Erkkilä & Tuukka Hartikka

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1. Backround and goals of the project

The largest item of expenditure in service costs of running a bus is, excluding the drivers' salaries, generated by fuel costs. For two-axle urban busses running some 80.000 km per year, the service costs (including capital-, fuel- and service costs) run to some 1.00 €/km. Fuel costs make up some 45% and capital costs some 40% of the total service costs.

The Euro 4 -emission standards for heavy-duty vehicles gradually became effective during 2005 and 2006. Following the first of October 2006, a Euro 4 -exhaust emission certificate is required for all new registered vehicles, apart from a few exceptions.

Figure 1 describes the development of emission regulations for European heavy-duty vehicles. The transition from Euro 3- to Euro 4 -class implies a remarkable tightening of emission values. The limit for particulate emissions (PM) decreases by 80% while the limit for nitrogen oxides (NO_x) decreases more moderately, by 30%. The limit for particulate emissions is the same for Euro class 4 and 5, but this transition will lower the limit for NO_x by an additional 40%. The next phase, Euro 6 is already being discussed, and this class will enter into effect during the next decade.

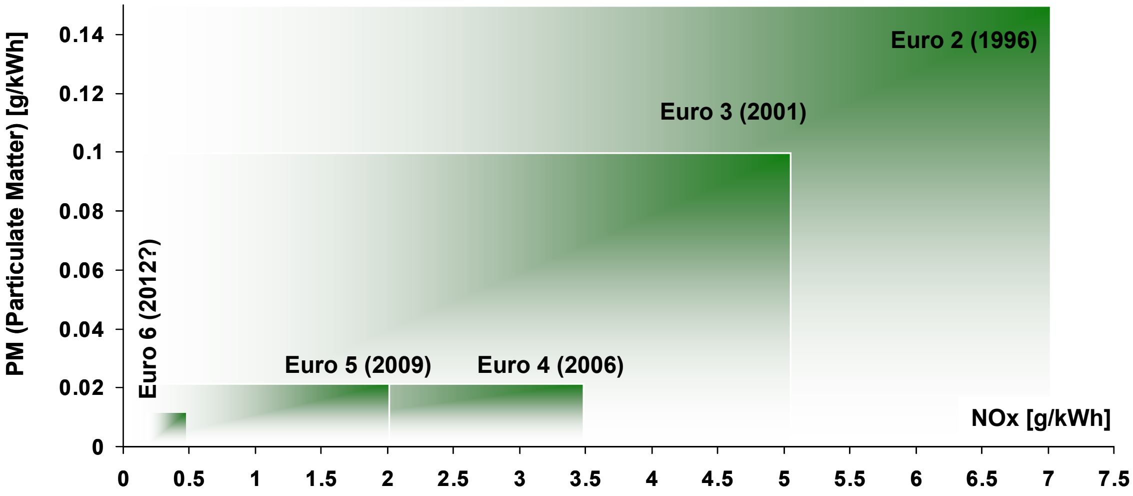


Figure 1. Development of emission regulations for European heavy-duty vehicles. (Danielsson 2006)

In order to meet Euro 4 -standards, the vehicle manufacturers have had to introduce new engine and exhaust cleaning technologies. This reflects on both the price and the fuel economy of the vehicle. The situation is challenging from the buyers' point of view, since the amount of available technologies is increasing instead of decreasing.

Standardised methods for measuring exhaust emissions and fuel consumption on chassis dynamometers exist for light-duty vehicles. Certification measurements for exhaust emissions are made using entire vehicles. Fuel economy is measured simultaneously.

According to current regulations, passenger car manufacturers must provide the buyer with information on the vehicle's fuel consumption. The buyer can use this information during the buying decision.

There are neither official methods nor requirements for measuring fuel economy and exhaust emissions for heavy-duty vehicles using entire vehicles. Official type approval tests for engines are made in an engine bench without considering the features or the purpose of use of the vehicle. Fuel consumption is an auxiliary variable in engine measurements, and it is not even required to announce it. Therefore there are basically no make specific values for fuel economy or emissions for heavy-duty vehicles which would take into account the characteristics of the vehicle (weight, air resistance, engine features and driveline). There are, above all, no comparable values available.

The need for actual consumption figures is great. Bus operators need reliable data on fuel consumption of different vehicle types as a basis for their decisions when acquiring new vehicles. Information provided by different vehicle manufacturers differs although a lot, which means that it is practically impossible to compare the fuel economy of different makes. The influence of the buying decision can be seen through the vehicle's whole life span, thus the importance of the choosing cannot be underrated.

The international organisation of public transportation, UITP, has developed so called SORT-cycles (Standardised On-Road Test Cycles) for measuring the fuel consumption of buses. There are three different cycles, representing urban-, mixed- and suburban driving (UITP 2004). Ambient conditions however affect the accuracy and the repeatability of the on-the-road measurements.

Data on fuel consumption and emissions under real life driving conditions, from various driving situations with different vehicles and levels of load, is also needed for calculating the environmental impact. Therefore the buyers of bus services are interested in mileage specific (g/km) exhaust values representing real life driving conditions. A grading system which caters to official emission certification levels is used in the procurement of bus services in Helsinki metropolitan area. The basic rule is that a cleaner fleet is more generously compensated. The buyers are naturally interested in whether an incentives system really results in a reduction of emissions.

The new emission laboratory for heavy-duty vehicles at VTT, which was completed in 2002, has since its introduction been richly used for measuring heavy-duty vehicles.

Both buses and trucks have been measured on the chassis dynamometer (Nylund & Erkkilä 2005, Nylund (editor) 2006).

VTT has so far measured altogether some 150 vehicles on the chassis dynaometer, of which 70 being trucks and 80 being buses. The vehicles have represented different emission levels, everything from Euro 1 to clean running Euro 5 and EEV -vehicles.

The Finnish Local Traffic Association Ry (PLL) contacted VTT in the fall of 2005. They suggested that VTT should carry out tests for measuring the fuel consumption on new Euro 4- and Euro 5 -class diesel buses. PLL's goal is to offer data to its member companies on fuel consumption of different technologies and vehicle alternatives under real life driving conditions. The data can be used as a base in companies' decision-makings. The promotion of public transportation is in every way remunerative. Therefore VTT accepted PLL's proposal for carrying out the measurement project.

Reporting fuel economy figures only does not come into question, the measurements should also note exhaust emissions. Making fleet decisions based solely upon fuel economy figures could lead to a situation where fuel efficient vehicles were favoured, even though they were not as clean running as expected. Reducing for instance NO_x emissions by means of in-cylinder measures and particulate emissions using exhaust after-treatment devices, usually results in increased fuel consumption.

The official exhaust certifications for heavy-duty vehicles are done using stand-alone engines in an engine bench, following certain load cycles. Therefore measurements made on a chassis dynamometer do not have an official status. VTT has, however, the ability to determine based on the chassis dynamometer measurements whether the vehicle's real life driving emissions correspond to the anticipated values of its emission class. For this, VTT leans on its extensive data base. The evaluation is rather simple for urban buses, since these vehicles are technically and shape- and weight wise very similar. The driving speed for urban buses is also so low, that the vehicle's tires and aerodynamic features do not have that big an influence on its emission levels.

The goals of the PLL project are shortly put:

- produce reliable data on fuel consumption in the form of l/100 km for new Euro 4- and Euro 5 -class diesel vehicles for the use of PLL's member companies
- verify the exhaust emissions of new diesel engines under real life driving conditions
- compare the performance of new vehicles against Euro 3 -class vehicles
- announce make specific performance figures.

The responsibilities of the project were divided as follows:

- selecting vehicles, test cycles and test loads and setting the price for fuel and urea in the calculations: The Finnish Local Traffic Association
- technical condition of the vehicles, including transmission settings: Vehicle manufacturer representatives
- performing the measurements and calculating the results: VTT
- interpreting the results and reporting: TEC Trans Energy Consulting Ltd in co-operation with VTT.

2. New technology for heavy-duty diesel vehicles

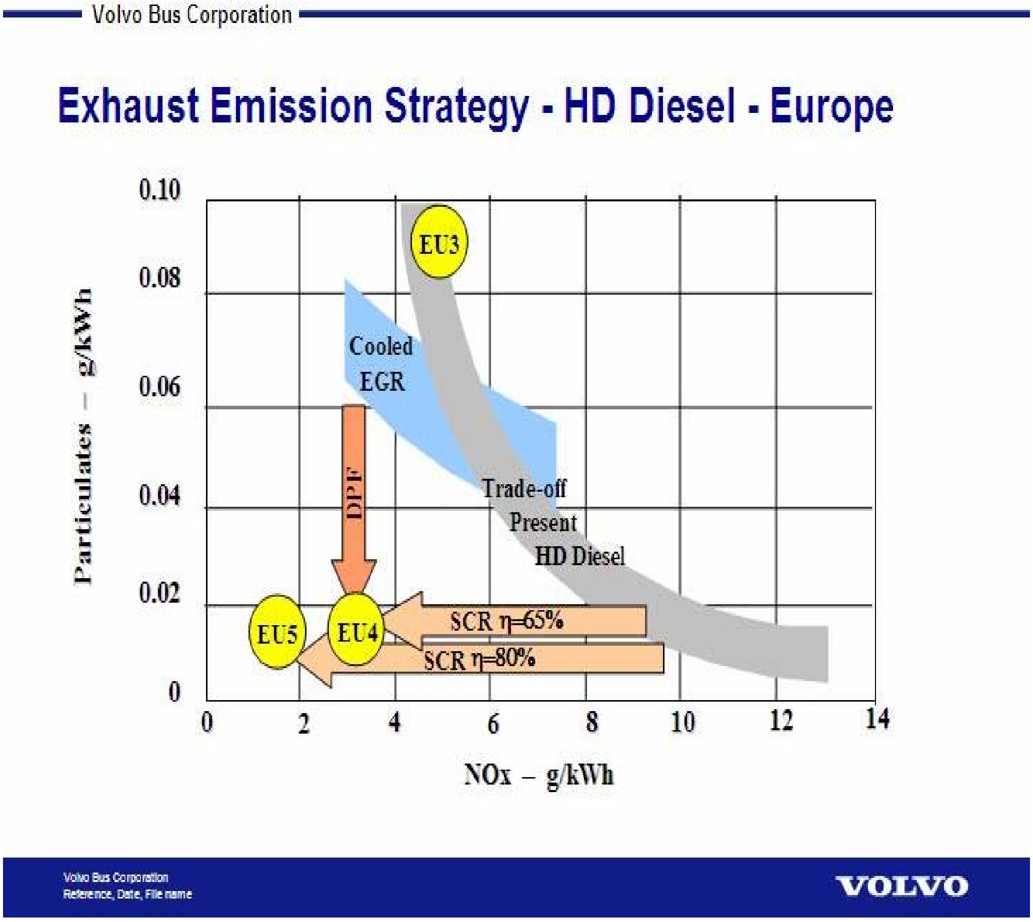
Emission levels for heavy-duty vehicles change fundamentally when Euro 4- and Euro 5 -emission regulations come into effect. Euro class 4 and Euro class 5 have the same limit value for particulate emissions, which is 80% less compared to the Euro 3 -level. The fundamental problem in limiting emissions of heavy-duty diesel engines is to simultaneously decrease both NO_x and particulates. Early injection timing reduces the amount of particulates and fuel consumption, but increases NO_x-emissions. The NO_x-PM dependency can be broken only by using exhaust after-treatment technology.

The key question is which technology to use for reducing NO_x-emissions. The formation of NO_x can be limited either already in the combustion chamber (recirculation of exhaust gas, EGR -technology) or by using exhaust after-treatment technology (urea catalyst, SCR -technology). After-treatment will although most likely be needed for controlling particulate emissions when using EGR -technology (catalyst, particulate catalyst or particulate filter).

Figure 2 illustrates the dependency of NO_x and PM in a Euro 3 engine. It also shows EGR/SCR strategies for reaching Euro 4- and Euro 5 -emission levels. The picture shows an area or a band, which displays how a Euro 3 engine can be adjusted without using any accessory equipment or technology. The operating area of cooled EGR is also marked in the picture.

When using EGR-strategy, NO_x-emissions decrease but particulate emissions increase (movement to the upper left). Particulate emissions can however be reduced using a catalyst or a particulate filter. With an SCR-system, the engine itself is adjusted to a higher NO_x level. This makes it possible to control particulate emissions (movement to the lower right) while simultaneously improving fuel efficiency. By adjusting the amount of urea, and possibly by changing the dimension of the SCR-catalyst, NO_x can be adjusted to either Euro 4- or Euro 5 -level.

The drawback of using an SCR-system is that it requires the use of a separate chemical. This requires a distribution system, as well as separate tanks in the vehicles. The amount of urea needed per every 1 g/kWh reduction of NO_x is about 1% of the amount of fuel. An SCR-catalyst does not either function under low load levels. The temperature of the exhaust gas must be higher than 200 ^{o}C in order for urea to be injected into the catalyst. AdBlue, which is used as the reducing agent, freezes at -11 ^{o}C. This causes additional problems in the Finnish climate. If too much urea is injected into the catalyst, ammonia (NH_3) is formed in the exhaust gas (ammonia slip).



Volvo Bus Corporation

Exhaust Emission Strategy - HD Diesel - Europe

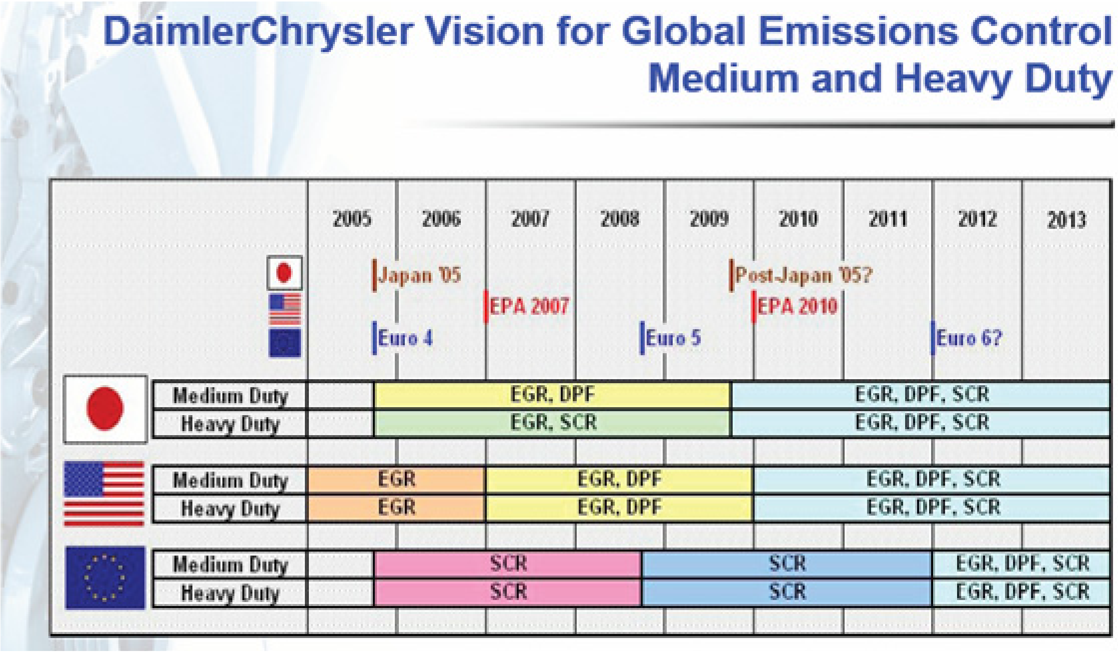
Volvo Bus Corporation
Reference, Date, File name

VOLVO

Figure 2. Alternative strategies for reaching Euro 4- and Euro 5 -emission levels (Danielsson 2005).

Particulates are also critical emission components in diesel engines. No after-treatment for particulates is needed to meet the Euro 3 -limits. The situation changes however along with Euro 4- and Euro 5 -regulations. EGR basically increases particulate emissions, therefore reducing particulates by exhaust gas after-treatment might be needed. An SCR-system decreases also particulates to a certain extent. E.g. Volvo has despite this sold, mainly in the Swedish market, so called Incentive SCR vehicles. These are equipped with both a particulate filter and an SCR-catalyst.

In the future, the situation might well be that diesel engines require EGR, SCR and a particulate filter to fulfil the emission requirements (Figure 3).



DaimlerChrysler Vision for Global Emissions Control
Medium and Heavy Duty

	2005	2006	2007	2008	2009	2010	2011	2012	2013
	Japan '05				Post-Japan '05?				
			EPA 2007			EPA 2010			
	Euro 4			Euro 5				Euro 6?	
Medium Duty	EGR, DPF				EGR, DPF, SCR				
Heavy Duty	EGR, SCR				EGR, DPF, SCR				
Medium Duty	EGR		EGR, DPF			EGR, DPF, SCR			
Heavy Duty	EGR		EGR, DPF			EGR, DPF, SCR			
Medium Duty	SCR			SCR				EGR, DPF, SCR	
Heavy Duty	SCR			SCR				EGR, DPF, SCR	

Figure 3. Daimler-Chrysler's vision for global emission control in heavy-duty vehicles (Puetz 2005).

MAN and Scania are the only European manufacturers who have chosen EGR-technology as their primary option. Most European manufacturers, however, favour SCR-technology (DAF, Daimler Chrysler = Mercedes-Benz, IVECO, Volvo). MAN and Scania do also offer an SCR-option for certain truck engines. Both report that they are developing new Euro 5 -engines based on EGR-technology.

MAN uses a PM KAT -titled particulate catalyst in its Euro 4 -class EGR-engines (MAN 2006). At first Scania proclaimed they would be able to reach Euro 4 -levels without any exhaust gas after-treatment, thanks to advanced fuel injection. It has however been mentioned in some bulletins, that the system includes a maintenance-free oxidation catalyst which primary task is to eliminate odours (Green Car Congress 2005).

3. VTT´s methodology for heavy-duty vehicle measurements

There are no official methods for measuring fuel economy or exhaust emissions of complete heavy-duty vehicles. Official type approval tests for engines are made in an engine bench without catering to the features or the purpose of use of the vehicle.

In default of standardised European measurement methods, VTT started to develop their own method for measuring heavy-duty vehicles on a chassis dynamometer. VTT also started applying for accreditation for their method.

General measuring principles for chassis dynamometer testing are described in the regulations for light-duty vehicles. The official exhaust emission tests for heavy-duty vehicles are made as stand-alone engine measurements. Directives 1999/96/EC and 2005/55/EC describe the so called ETC (European Transient Cycle) -transient test, in which exhaust emission measurements are made using a full-flow CVS-dilution tunnel. ETC –testing is required for all engine types from the Euro 4 -standard onwards. Equivalent measuring methods can also be used in dynamic vehicle measurements.

The American Society of Automotive Engineers, SAE, has published a recommendation for measuring heavy-duty vehicles on roller-type test stands, SAE J2711: Recommended Practice for Measuring Fuel Economy and Emissions of Hybrid-Electric and Conventional Heavy-Duty Vehicles. Furthermore, the U.S. Environmental Protection Agency, EPA, has defined a cycle for measuring heavy-duty vehicles on roller-type test stands (Urban Dynamometer Driving Cycle UDDS). (DieselNet: A)

VTT’s own measuring method, which measures exhaust emissions and fuel economy, is based on both the above mentioned methods and recommendations and on the safety codes for the roller-type test stand at VTT (Figure 4). VTT primarily uses the German Braunschweig –urban bus cycle for the measurement of buses. (DieselNet: B)

VTT prepared a detailed specification for the measurements and applied for accreditation. The Finnish Centre for Metrology and Accreditation, MIKES, checked the measurements and granted accreditation in June 2003 (MIKES T125: In-house method, VTT Code MK02E).

The fuel economy of an entire vehicle is under real life driving circumstances affected not only by the efficiency of the engine, but in addition, the weight of the vehicle, construction and technical details and driving profiles also affect fuel economy. All these factors are taken into account in VTT’s measurements. Fuel economy and emissions are normally reported in proportion to the driving distance, in form of l/100 km or g/km.

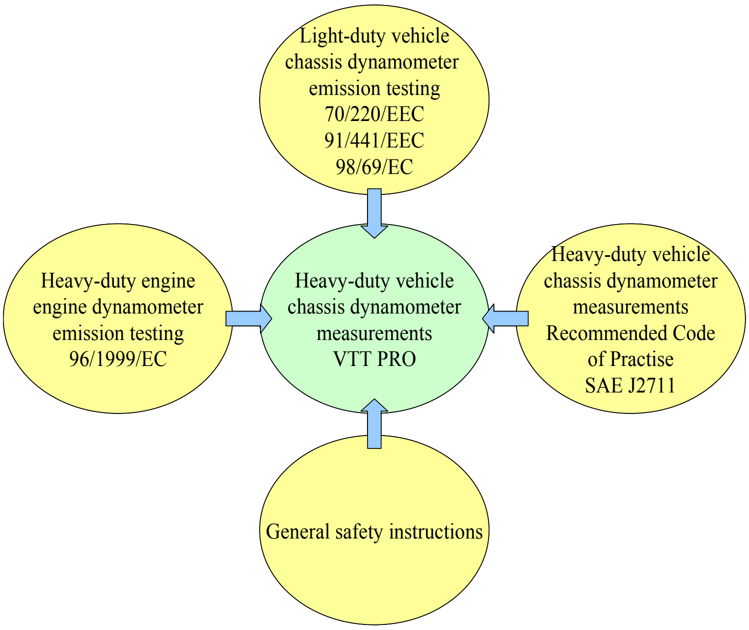


Figure 4. Structure of the method for chassis dynamometer measurements for heavy-duty vehicles at VTT.

Standardised methods make it possible to measure the influence of different factors, such as lubricants, tires, auxiliaries and transmission settings, under conditions similar to real life.

The results can also be reported in proportion to the workload of the driving wheels. In this case the results, in g/kWh, describe the features of the drive train without taking into account for instance the weight of the vehicle.

The quality documentation of a measuring method always contains an estimate of the uncertainty of measurement. When measuring fuel economy, accuracy is affected by the vehicle’s features but also by the accuracy of measuring system (weighing the fuel) and by the accuracy of the test-stand (speed of rotation and generated work value based on torque data). The accuracy of exhaust emission measurements are in addition affected by the accuracy of the exhaust flow measurement and the analysers’ accuracy.

The uncertainty of measuring at VTT’s chassis dynamometer is estimated as follows:

- uncertainty of measuring fuel economy in g/kWh ± 1 %
- uncertainty of measuring exhaust emissions in g/km ± 15 %.

VTT has published the following reports and publications on measurements of heavy-duty vehicles on a roller-type test stand:

Nylund, Nils-Olof, Erkkilä, Kimmo, Lappi, Maija & Ikonen, Markku. (2004). Transient Bus Emission Study: Comparison of Emissions from Diesel and natural Gas Buses. Research Report PRO3/P5150/04. VTT Processes, Espoo, October 2004. http://www.vtt.fi/inf/pdf/jurelinkit/VTTNylund.pdf

Nylund, Nils-Olof & Erkkilä, Kimmo. (2005). Bus emission evaluation. Summary report 2002–2004. Research Report PRO3/P3015/05. VTT Processes, Espoo, April 2005. http://www.vtt.fi/inf/julkaisut/muut/2005/BusEmissionEvaluation.pdf

Nylund, Nils-Olof (editor). (2006). Fuel savings for heavy-duty vehicles “HDEnergy”. Summary report 2003–2005. Project Report VTT-R-03125-06. VTT, Espoo, June 2006. http://www.motiva.fi/attachment/f16d4d543f99d7a59f54560a69063a0e/c73e1f58c9b23276d777bb39a7a66eb2/2006+HDEnergy_summaryreport_eng_final.pdf

Laurikko, J, Erkkilä, K, Nylund, N.-O. Generating Realistic Emission Factors For Heavy-Duty Vehicles – Methods And First Results. Paper F2006P238, Proc. FISITA 2006 World Automotive Congress, Yokohama, Japan, Oct 2006. (On CD-ROM only).

The last-mentioned publication was awarded commendation for best technical presentation at the automotive engineers’ world organisation’s (FISITA) conference. The conference was held in Yokohama, Japan in 2006.

4. Test program and instrumentation

4.1 General

The measurements were made with complete vehicles on VTT's heavy-duty chassis dynamometer. Dynamical cycles, describing real life driving conditions were used. Fuel economy and regulated exhaust emissions were was measured. PLL informed the vehicle manufacturers' representatives about the project in advance. The importers were given the possibility to check the condition of the reference vehicles (Euro 3). The vehicles' air filters were, according to the importers' instructions, replaced before the measurements. The actual test vehicles (Euro 4 and Euro 5) were delivered to the tests through the importers. This left them the responsibility for adjustment and choosing settings. VTT did not perform any specific service operations or adjust the vehicles in any way. The importers were also given the opportunity to comment on the results.

All measurements were repeated at least twice, and average values were used in processing the results.

4.2 Measured vehicles

PLL selected the vehicles to be measured in the project. Altogether seven vehicles were measured, of which two were Euro 3 -class reference vehicles. The measured vehicle models are presented in Table 1. More specific technical data on the vehicles can be found in Appendix A. The weight recorded in the Table 1 is the actual curb weight of the vehicles.

Table 1. Measured vehicles.

Model	Type	Emission level	Cleaning technology	Model year	Curb weight (kg)	Mileage (km)
Brand A	4 x 2	Euro 3	Oxidation catalyst	2005	11 850	26 400
Brand C	4 x 2	Euro 3	-	2005	11 800	48 100
Brand A	4 x 2	Euro 4	SCR	2006	11 860	13 300
Brand B	4 x 2	Euro 4	SCR	2006	11 760	10 800
Brand C	4 x 2	Euro 4	EGR	2006	12 450	12 300
Brand C	6 x 2	Euro 4	EGR	2006	14 250	28 000
Brand A	6 x 2	Euro 5	SCR	2006	14 480	1 800

A load of 1.500 kg was simulated for the two-axle vehicles (roughly quarter load, about 20 passengers) and a load of 2.000 kg (about 27 passengers) for the three-axle vehicles. The client (PLL) selected the load levels to be used in the measurements.

VTT’s conditioned measurement tires were used on the driving wheels of all vehicles.

4.3 Fuel and lubricants

Sulphur-free commercial diesel fuel was used in the measurements. The same fuel batch was used in all vehicles. The fuel was not analyzed separately. The vehicles were measured using the lubricants they arrived with to VTT.

4.4 Instrumentation

All measurements were made in VTT’s research laboratory for heavy-duty vehicles. The chassis dynamometer made by Froude Consine has a roller diameter of 2.5 meters. Its brake power (continuous) is 300 kW. The dynamometer is equipped with a very fast control system and electric inertia simulation, making transient (dynamic) testing possible. The inertia simulation can be adjusted in a range between 2,500 and 60,000 kg.

Regulated exhaust gas components were measured using a full-flow CVS-system (Pierburg CVS-120-WT) and an analyser system (Pierburg AMA 4000), both of these fulfilling Directive 1999/96/EC. The measurements were made using transient driving cycles. The measurement of exhaust gas was therefore carried out principally in the same way as for passenger cars on chassis dynamometers, or as in transient ETC-engine measurements.

Fuel economy and consumption of urea was determined gravimetrically (by weighing).

More information on measuring instruments, and on measuring methods generally, can be found in the reports mentioned in Section 3.

4.5 Test cycles

The driver follows a given speed/time-profile, in other words the driving cycle, during the measurement on the chassis dynamometer. The measurements were made using three dynamical cycles simulating real life driving conditions. Data on the cycles is presented in Table 2. The Braunschweig -cycle, developed in Germany, is a bus cycle describing urban driving. The Helsinki 2 and Helsinki 3 -cycles have been generated to describe driving conditions in Helsinki. The cycles are based on analyses of real driving events. The Helsinki 2 -cycle describes urban driving, whereas the Helsinki 3 -cycle includes elements describing suburban driving. The cycles are graphically presented in Figures 5–7.

All vehicles were also measured using UITP's SORT 2 -cycle. SORT -cycles are defined based on distance and speed, whereas a chassis dynamometer cycle is presented as a function of speed vs. time. This causes problems, because when SORT -cycles are transferred to chassis dynamometer measurements, the realisation depends on the vehicle's characteristics. Therefore results obtained using different vehicles are not necessarily comparable to each other. Due to this reason, the results from the SORT 2 -cycle have not been published in this report. Adjusting SORT -cycles to chassis dynamometer testing would require further development of the processes and measurements of different vehicles types on highways.

Table 2. Data on driving cycles.

	Length (km)	**Duration (s)**	**Average speed (km/h)**	**Maximum speed (km/h)**	**Idling proportion (%)**
Braunschweig (BSC)	10.873	1,740	22.5	58.2	25
Helsinki 2	8.157	1,503	19.7	52.5	28
Helsinki 3	10.334	1,917	41.2	71.7	15

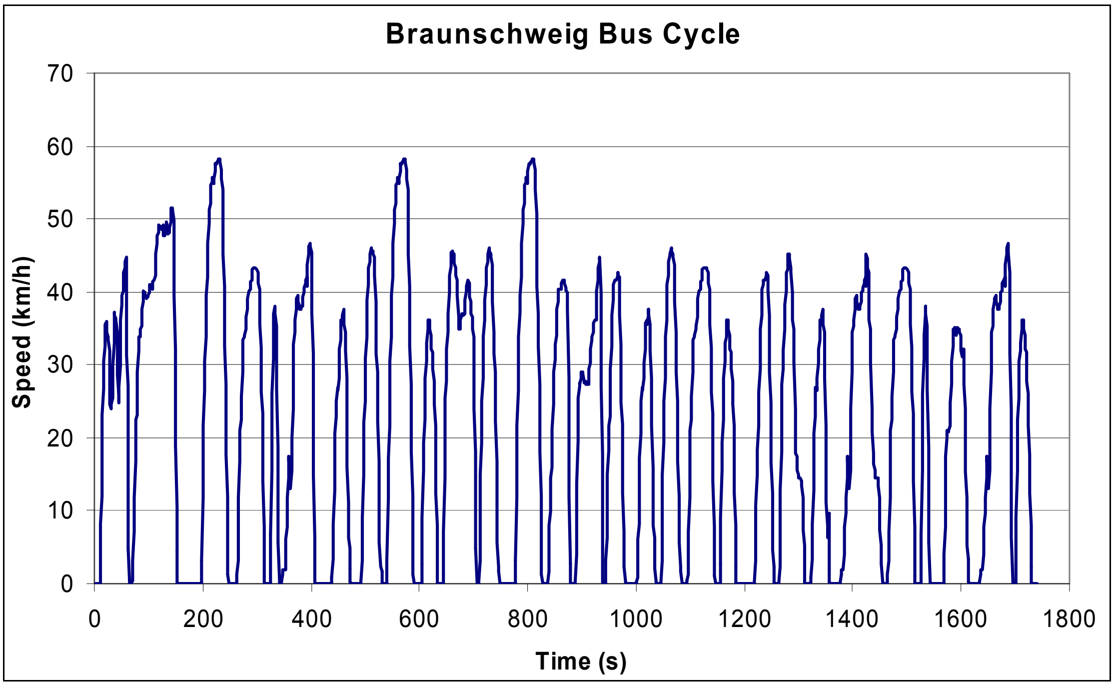


Figure 5. Speed/time profile of the Braunschweig-cycle.

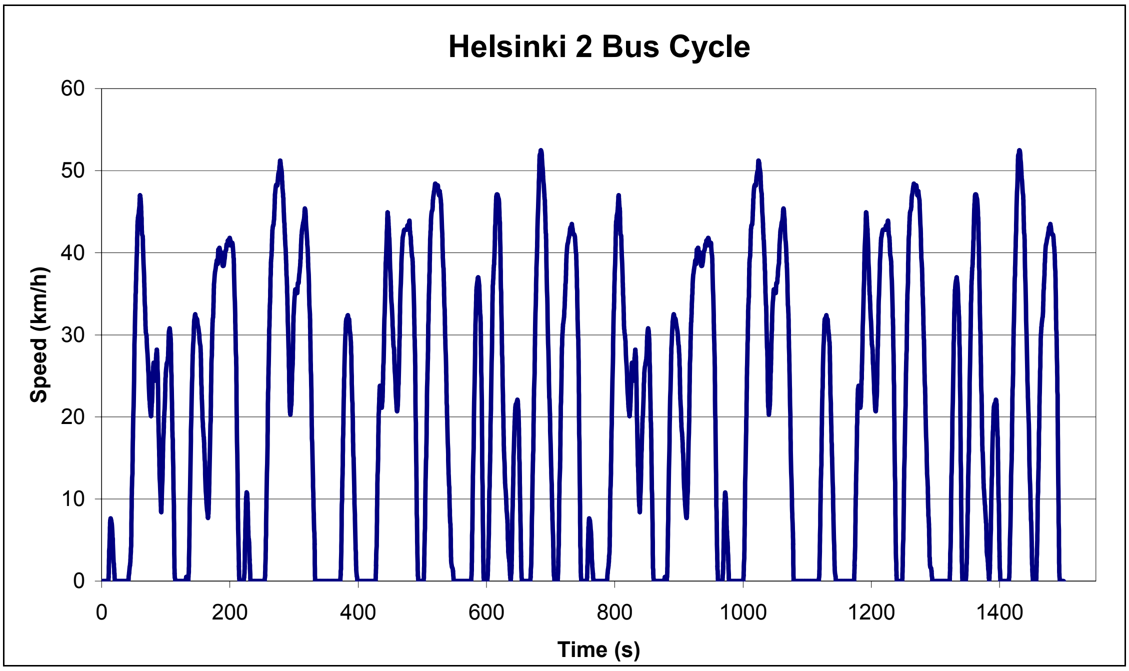


Figure 6. Speed/time profile of the Helsinki 2 -cycle.

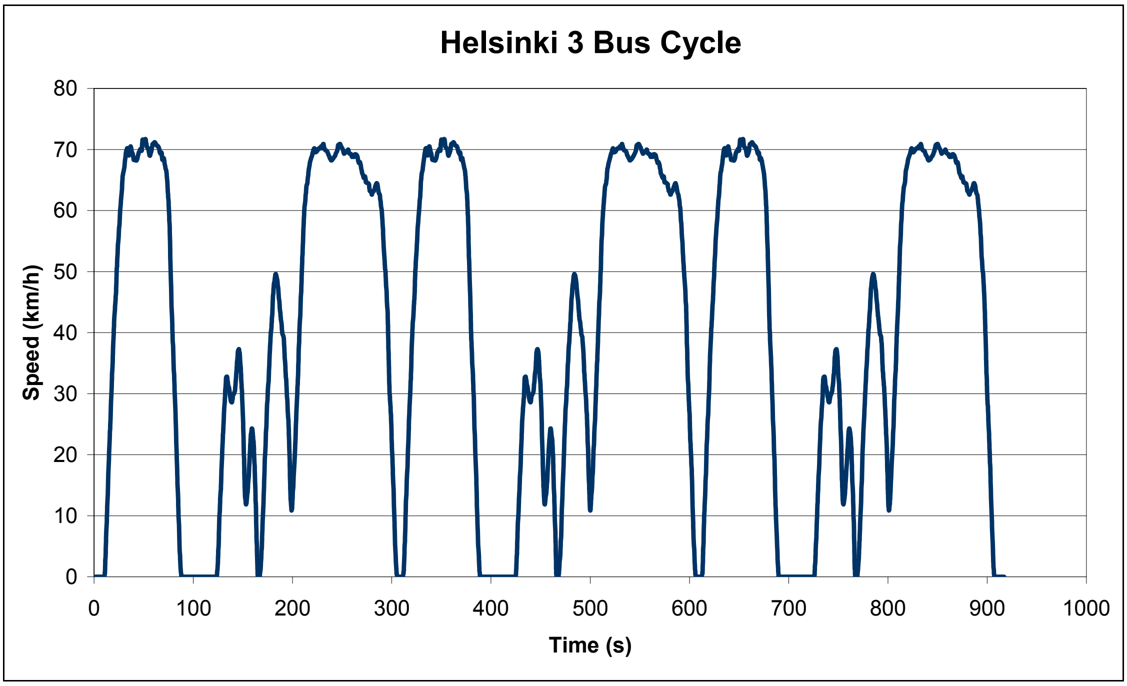


Figure 7. Speed/time profile of the Helsinki 3 -cycle.

5. Calculation principles

5.1 General

The following factors need to be considered in the measurements and when calculating the results:

- tractive resistances of the vehicle in general
  - weight of vehicle
  - how the weight influences the vehicle's tractive resistances
  - how tires affect the vehicle's tractive resistances
- realisation of the test cycle
  - in emission considerations; power losses resulting from tires, transmission and auxiliary equipment.

Measurements and calculations should be implemented in a way, so that features of the vehicle's power-train (engine, transmission, gear ratio, tires and so on), its weight and practical performance reflect its emissions and fuel economy. In practice the latter part means that a vehicle using, for instance a low-ratio final drive or a special programming of the transmission, does not get an advantage in fuel economy if it cannot fulfil the requirements of the test cycle. The test cycles actually do describe real life driving conditions rather well. The actual accumulated work is taken into account in the scaling of the results.

5.2 Defining tractive resistances

Accelerating the weight of the vehicle dominates the need for power in dynamic urban driving. Air resistance on the other hand, does not have that big an impact in urban driving speeds.

VTT has in earlier projects defined different vehicles' tractive resistances by doing coast-down tests on highways. This has also been done for two- and three-axle urban buses. The measurements were made using both zero load and full load (Nylund (editor) 2006).

In this project, computational values were used for the vehicles' tractive resistances. The values are based on the above mentioned coast-down tests.

The equation for tractive resistance under constant speed is:

$F= f_0 + f_1*v + f_2*v^2$, where f_0, f_1 and f_2 are constants, v= speed

The theorem contains a constant term, a term proportional to speed and a term proportional to the square of speed. The latter term mainly describes air resistance. The vehicle's weight directly affects the f_0-term, slightly the f_1-term and marginally the f_2-term.

The force of inertia also needs to be considered in dynamical driving:

F_{dyn}= m*a, where m= weight of vehicle, a= acceleration

The f_0, f_1 and f_2 -terms were defined for both zero load and full load in the coast-down tests. The actual weight of the vehicle was obtained by weighing.

Principles for calculatorily determining tractive resistances were:

- two- and three-axle vehicles were studied separately
- air resistance was estimated to be the same for all vehicles within a class
- the resistance caused by tires was the same for all vehicles (conditioned test-tires, size according to vehicle specification), a static load of 1.000 kg was in all cases added to the rear axle)
- tractive resistances were determined based on vehicle weight
    - the weight directly affects the inertial force
    - the weight's impact on terms f_0, f_1 and f_2 was also noticed by interpolating the values determined in the coast-down tests.

This way tractive resistances, which very closely observe the actual weight of the vehicle, could be modelled.

5.3 Measuring fuel economy

The primary measured variable is the weight of the fuel used during the test. This could in principle be proportioned directly against the distance travelled during the test. This would although not state how the cycle has been realised. Driving at a constant low speed gives a better fuel economy than a varying drive including accelerations and retardations, even though the average speed would be the same.

The consumed amount of fuel can be proportioned to the measured work load on the driving wheels. The result is in this case in the form of g/kWh. The result is reported in the same way as those of engine tests, but the result measured from the driving wheels also includes losses from the engine, the auxiliary equipment, the transmission and the tires. Practically the result describes the effectiveness of the whole power train, but it does not take into account the weight of the vehicle.

The efficiency of the power train, the weight of the vehicle as well as the realised results of the cycle compared to the targeted ones need to be observed when modelling comparable fuel economy figures describing the entire vehicle.

Comparable fuel economy figures are modelled as follows:

- defining the amount of fuel consumed during the test and the actual work accumulated on the driving wheels (“raw data g/kWh on driving wheels”)
- proportioning the raw data for each vehicle category (2- and 3-axle vehicles separately) to the average work load, this way the effect on the specific fuel consumption, due to differences in realised work load, can be observed (see Figure 8)
- modelling, based on the above mentioned values, a fuel economy figure in litres proportioned to the travelled distance (calculated based on the average work load and average travelled speed for the vehicle category)
- the effect of vehicle weight on fuel economy is observed by a cycle specific work load dependency (determined by measuring fuel consumption of a representative vehicle with different loads, see Figure 9)

Table 3 shows the test vehicles’ average work loads for different cycles and the vehicle specific work load realised in the tests. The high number of realised work load for two-axle Brand C Euro 4 -vehicle is primarily due to a difference in weight compared to the other vehicles. This vehicle is able to realise the targeted driving profile.

Table 3. Average work loads and in measurements realized work loads for the test vehicles.

Model	**Test weight (kg)**	**Braunschweig (kWh)**	**Helsinki 2 (kWh)**	**Helsinki 3 (kWh)**
2-axle	Curb weight + 1500	Average 9,91	average 8,42	average 8,39
Brand A Euro 3	13 350	9.788	8.332	7.994
Brand C Euro 3	13 300	9.604	8.153	8.068
Brand A Euro 4	13 360	9.808	8.410	8.476
Brand B Euro 4	13 260	9.640	8.257	8.258
Brand C Euro 4	13 950	10.733	8.935	9.148
3-axle	Curb weight + 2000	12,65	10,51	10,37
Brand A Euro 5	16 480	12.510	10.480	10.526
Brand C Euro 4	16 250	12.792	10.530	10.221

In calculating fuel consumption, the density is estimated to be 840 kg/m^3 and the heat value 42.5 MJ/kg.

Figures 8 and 9 show how the vehicle's work load and weight affect fuel consumption. The illustrated vehicle is a two-axle Brand C Euro 3 -vehicle running the Braunschweig-cycle.

Figure 8 illustrates the dependency between fuel consumption measured from the driving wheels and the realised work load in the Braunschweig-cycle. As the work load increases, the relative share of parasitic losses becomes smaller, which improves the specific fuel consumption. The difference in specific fuel consumption between an unloaded and a fully loaded vehicle is for this reason some 10% (values expressed as g/kWh). This must be taken into account when examining the efficiency of the power train; otherwise the heavier vehicle gains an excess advantage when it comes to its specific fuel consumption.

Figure 9 illustrates how the weight affects the fuel economy in litres per driven distance. An additional weight of 1,000 kg increases fuel consumption by some 2 l/100 km or proportionally by some 5%. The relation has been generated from actual vehicle tests.

The load's (work load) effect on the specific fuel consumption was in the early stages of the calculations compensated (proportioned to average work load), but when calculating fuel consumption per driven distance, the weight of the vehicle and its effects on both total work and specific fuel consumption are accounted for (how the vehicle's weight increases fuel consumption and how the engine's specific fuel consumption decreases when the load increases).

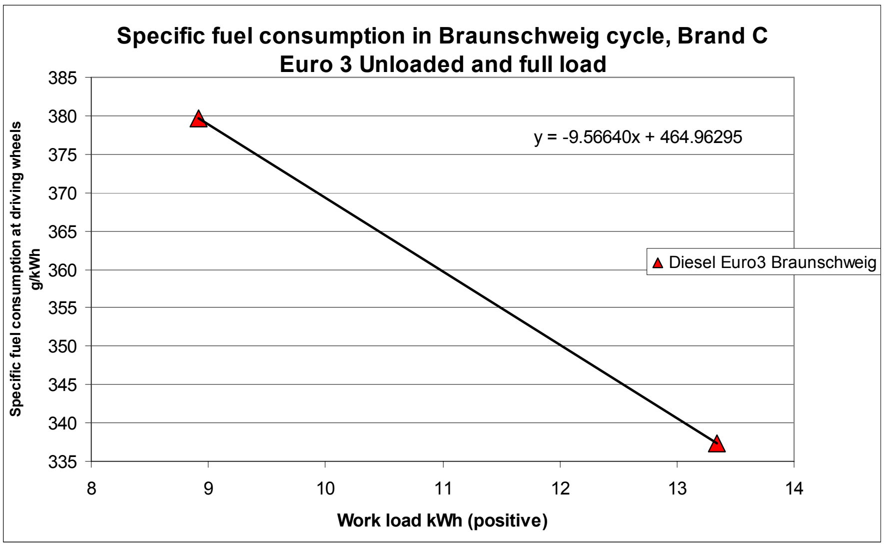


Figure 8. Dependency between fuel consumption measured from the driving wheels and the realised work load in the Braunschweig-cycle.

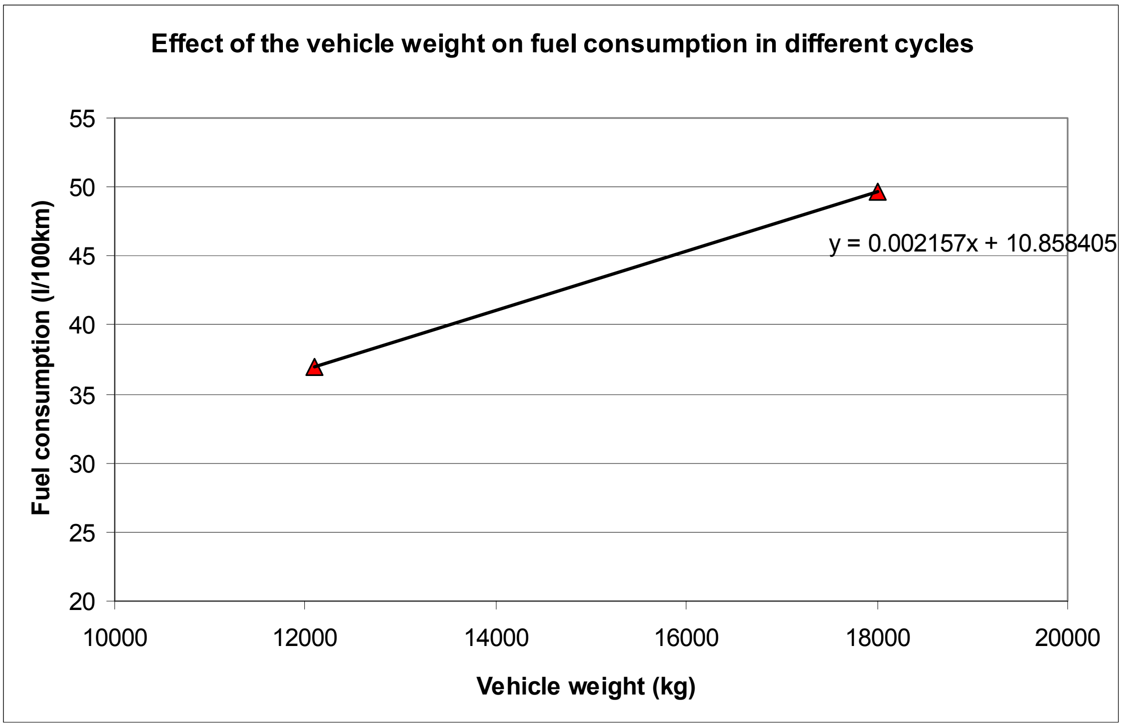


Figure 9. How vehicle weight affects the fuel economy in the Braunschweig-cycle.

5.4 Exhaust emissions

An exhaust emission measurement system in accordance with Directive 1996/96/EC reports the regulated exhaust components' (carbon monoxide CO, total hydrocarbons THC, nitrogen oxides NO_x and particulate matter PM) masses during the test. In engine dynamometer measurements agreeing with the standards, the emissions are proportioned to the work measured from the engine's crankshaft. The results are reported in g/kWh.

In chassis dynamometer measurements the mass of the emission components can be proportioned either to the travelled distance (g/km) or for instance to the work measured from the driving wheels (g/km). Emission figures proportioned to the travelled distance are useful in making emission inventories, since the mileage of buses is generally well known.

Information about different vehicles' emissions under real life driving conditions can be obtained through roller-type test stand measurements. It would be interesting to find out how emissions measured on roller-type test stands correspond with limiting values of different emission categories. In order to do so, a link between engine values and emission values measured from the vehicle needs to be created. When we want to reduce emissions in order to, for instance improve the air quality in urban areas, it is not enough that an engine meets certain emission limits in an engine test stand. Emissions resulting from real life driving conditions should also be reduced when moving to new and cleaner engine types.

Nowadays all new engines have electronic engine control, and therefore also a so called CAN-bus for data trasfer. It is possible to read, for instance, the engine's instantaneous power from the CAN-bus. This way the work produced by the engine in a certain test cycle can be calculated by integrating the power data over the cycle. Emissions can therefore, with a moderate accuracy, be proportioned to the work performed at the crankshaft as in engine test stand measurements.

A bus engine performs the following work load per kilometre in the Braunschweig-cycle (approximate values):

- two-axle vehicle, quarter load (1.500 kg): 1.7 kWh/km
- two-axle vehicle, half load (3.000 kg): 1.8 kWh/km
- three-axle vehicle, quarter load (2.000 kg): 2.0 kWh/km.

The integrated work read from the engine can also be proportioned to the work measured from the driving wheels. Exploring it this way makes the engine work 1.8 times more than the driving wheels, resulting from losses in auxiliary equipment, power train and tires.

These ways of consideration makes it possible to proportion the emission figures of vehicle tests to the certification values of engine tests. In this project emissions have been studied based on scaling specific emissions measured from the driving wheels.

It must although be noticed that the engine load in a standard accordant, so called ETC-transient test for stand-alone engines, differs remarkably from the load of chassis dynamometer cycles which represent real life driving conditions. The ETC-transient test emphasises higher engine speeds than what an engine in an urban bus uses (Figure 10). An engine that has acceptably been certified might in a vehicle test produce clearly more emissions than expected.

The U.S. exhaust gas legislation includes a so called not-to-exceed (NTE) -requirement. This 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: C)

The rationale for increasingly stringent emission regulations is to achieve lower emissions also under real life driving conditions. Therefore NTE-like requirements should be applied in Europe too.

Following above mentioned principles, this research project evaluates how well different vehicles fulfil the limits of different emission classes. The study has been limited to the most essential emissions, in other words nitrogen oxides and particulate matter. The study has been made based on the commonly used Braunschweig-cycle.

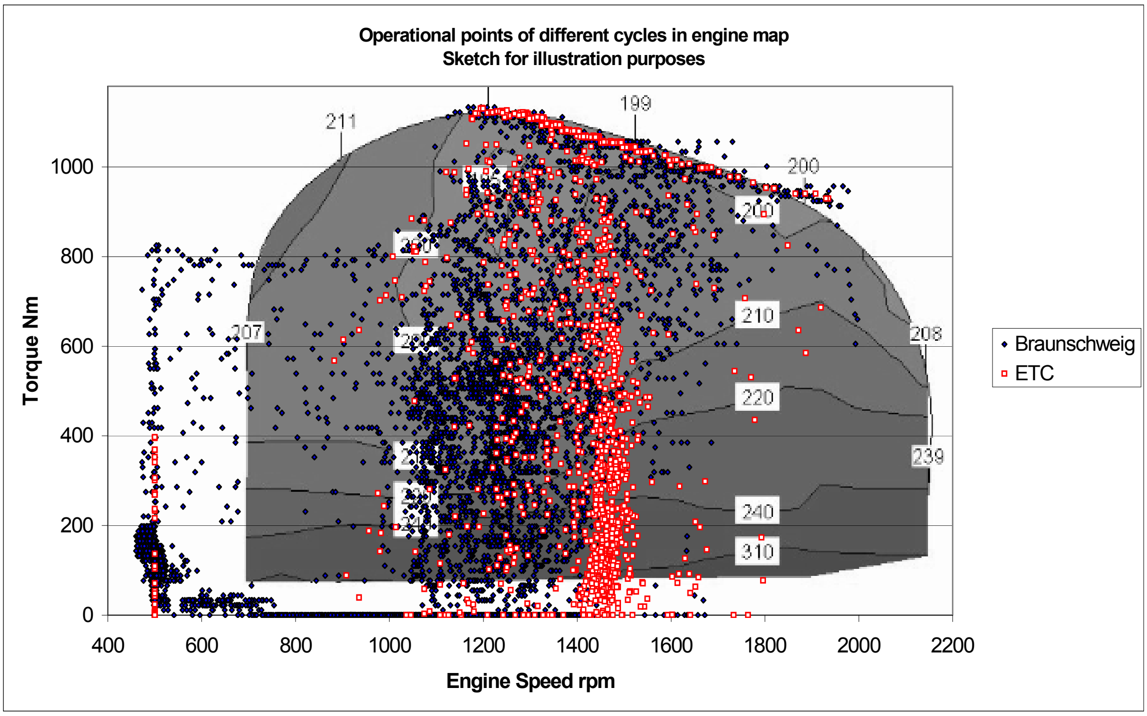


Figure 10. Engine operation in the Braunschweig- and ETC-cycles (suggestive).

Reference values were generated as follows:

- the limit values of the ETC accordant standard engine test are multiplied by a factor taking into account losses in the power train (1.8)
- the limiting value is furthermore multiplied by a factor of 1.25, according to NTE-reasoning
- the overall factor will this way be 2.25
- the limiting value multiplied by that factor is compared against the specific emissions determined from the driving wheels.

Table 4 shows reference values for emissions which have been defined this way.

Table 4. Generating reference values for emissions.

Reference value **ETC * 2,25**	**Euro 3** **(g/kWh)**	**Euro 4** **(g/kWh)**	**Euro 5** **(g/kWh)**
NOx			
limit	5,0	3,5	2,0
observing losses	9,0	6,3	3,6
reference value	11,3	7,9	4,5
PM			
limit	0,16	0,03	0,03
observing losses	0,29	0,05	0,05
reference value	0,36	0,07	0,07

The results show emission values proportioned to both the travelled distance and the work at the driving wheels. Possible differences in work loads have not been taken into account in values proportioned to the travelled distance. The values have only been proportioned to the actual distance driven during the test.

One must call to mind while evaluating the results, that the inaccuracy of measurement for exhaust emissions is some ± 15 %.

6. Results related to fuel economy

6.1 Fuel economy

The vehicles have been presented in the result pictures in the following order:

Two-axle vehicles:

- Brand A Euro 3
- Brand A Euro 4
- Brand C Euro 3
- Brand C Euro 4
- Brand B Euro 4.

Three-axle vehicles:

- Brand A Euro 5
- Brand C Euro 4.

Figure 11 shows the specific fuel consumption measured from the driving wheels for different vehicles. These pictures describe the efficiency of the power train, but do not yet comment the weight of the vehicle.

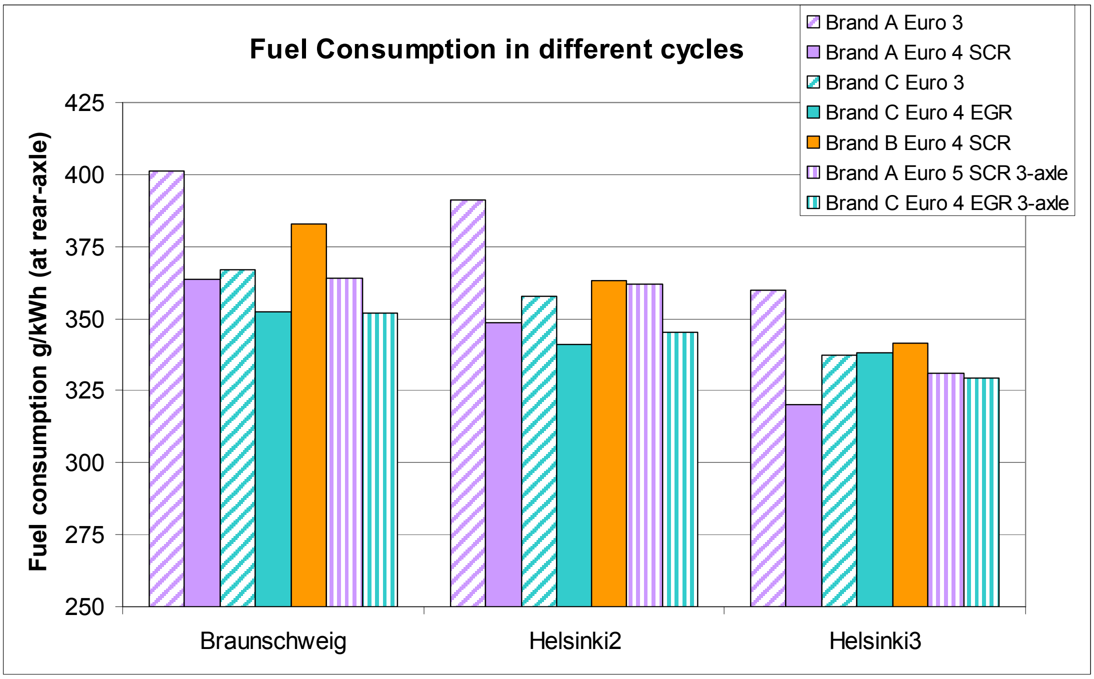


Figure 11. The efficiency of the power train, measured from the driving wheels, describing fuel economy (g/kWh). Values compensated for actual work.

The specific fuel consumption varies between 321 and 400 g/kWh, depending on the vehicle and cycle. The values are in terms of efficiency 26–21%. In other words, only some 25% of the energy contained by the fuel is in dynamic bus cycles transformed into power on the driving wheels moving the bus forward.

Engine manufacturers normally report the lowest fuel consumption to be some 190 g/kWh, which would mean an efficiency rate of some 45%.

Both the Braunschweig- and the Helsinki-cycle gives nearly the same specific fuel consumption values. The Helsinki 3 -cycle has a higher average speed than the other two cycles, which results in a lower fuel consumption. The Helsinki 3 -cycle does although contain rather strong accelerations, which all vehicles cannot fully manage, due to transmission settings.

The differences in fuel economy between the engines are in different cycles at their most 11–13%. Brand A’s Euro 3 -engine gives the highest fuel consumption in all cycles. Brand A’s Euro 4 -class engine and the three-axle Brand C Euro 4 -engine give on average the lowest consumption. Brand A’s Euro 4 -engine is at its best in the Helsinki 3 -cycle, which describes suburban driving. Differences in fuel consumption would at their most be 5–8%, if Brand A’s Euro 3 -engine is not taken into account.

Brand A’s Euro 4 SCR –engine consumes remarkably less fuel than the older Euro 3 -class engine. What comes to Brand C, its Euro 4 -class engines give a 3–5% smaller fuel consumption in the Braunschweig- and Helsinki 2 -cycles than its Euro 3 -class engine, but in the case of two-axle vehicles, the fuel consumption slightly increases (3%) in the Helsinki 3 -cycle.

The Brand B Euro 4 and Brand A Euro 5 -engines consume slightly more fuel than Brand A and C Euro 4 -engines. The difference is some 3% in the Helsinki 2 -cycle. The situation however evens out in the Helsinki 3 -cycle, where the fuel consumption of the Brand B Euro 4 -engine and the Brand A Euro 5 -engine decreases in proportion to the other engines.

Figure 12 shows the vehicles’ fuel consumption in litres relative to travelled distance, taking into account the weight of the vehicle.

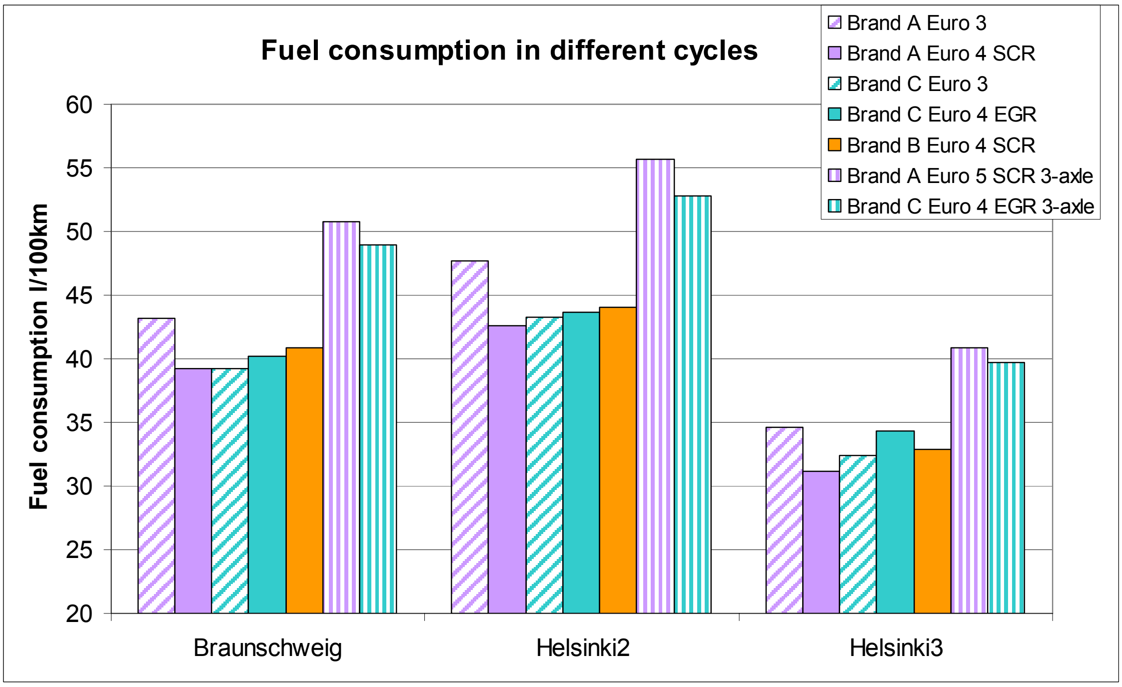


Figure 12. Fuel consumption in litres, observing vehicle weight, proportioned to travelled distance (l/100 km). Fuel consumption in litres describes the actual differences in fuel economy (different power demand caused by dissimilar vehicle weight is not shown in g/kWh-figures.)

The average fuel consumption for two- and three-axle vehicles is in different cycles as follows:

- Braunschweig: 41/50 l/100 km
- Helsinki 2: 44/54 l/100 km
- Helsinki 3: 33/40 l/100 km.

Differences in fuel consumption, measured in litres, are at their most 10–12% for two-axle vehicles, Brand A’s Euro 3 -vehicle having the worst fuel economy. If the Brand A Euro 3 -vehicle is not taken into account, differences are 3–11%. The difference is at its greatest in the Helsinki 3 -cycle. Brand A’s Euro 4 -vehicle consumes on average the least fuel.

Brand C’s Euro 4 -vehicle weighs some 650 kilograms more than its Euro 3 -version, which reflects on the fuel economy values proportioned to the travelled distance. A heavy vehicle invalidates the advantage gained from an efficient power train.

The fuel consumption of Brand C’s Euro 4 -vehicle is in different cycles on average at the same level as that of Brand B. Brand C’s Euro 3 and Brand A’s Euro 4 -vehicle consume the same amount of fuel in the Braunschweig-cycle, some 39 l/100 km. Brand B's Euro 4 and Brand C's Euro 4 -vehicle consume on average 40.5 l/100 km, which is about 3% more.

What comes to fuel consumption, the tree-axle vehicles naturally fall into their own group. The difference in fuel consumption is 3–5% to Brand C's credit.

6.2 Urea consumption

A solution of urea (AdBlue) needs to be used in SCR -vehicles in order for the catalyst to bring down nitrogen oxides. The amount of urea depends on, among others, the engine load and the temperature of the exhaust gas.

The temperature of the exhaust gas is in all driven cycles over 200 °C. Therefore urea can be injected, and the reduction reactions can take place. Figure 13 shows the consumption of urea, measured in litres, in different cycles.

Brand A's Euro 4 -vehicle consumes about 1 litre of urea per 100 km. The consumption of urea is in other words some 2–4% of the fuel consumption. Urea is in proportion most used in the Helsinki 3 -cycle. The Brand B vehicle and the Brand A Euro 5-vehicle consume 2–2.5 litres of urea per 100 km. The proportional part is 5–6% for Brand B's Euro 4 vehicle, and 4–5% for Brand A's three-axle Euro 5 -vehicle.

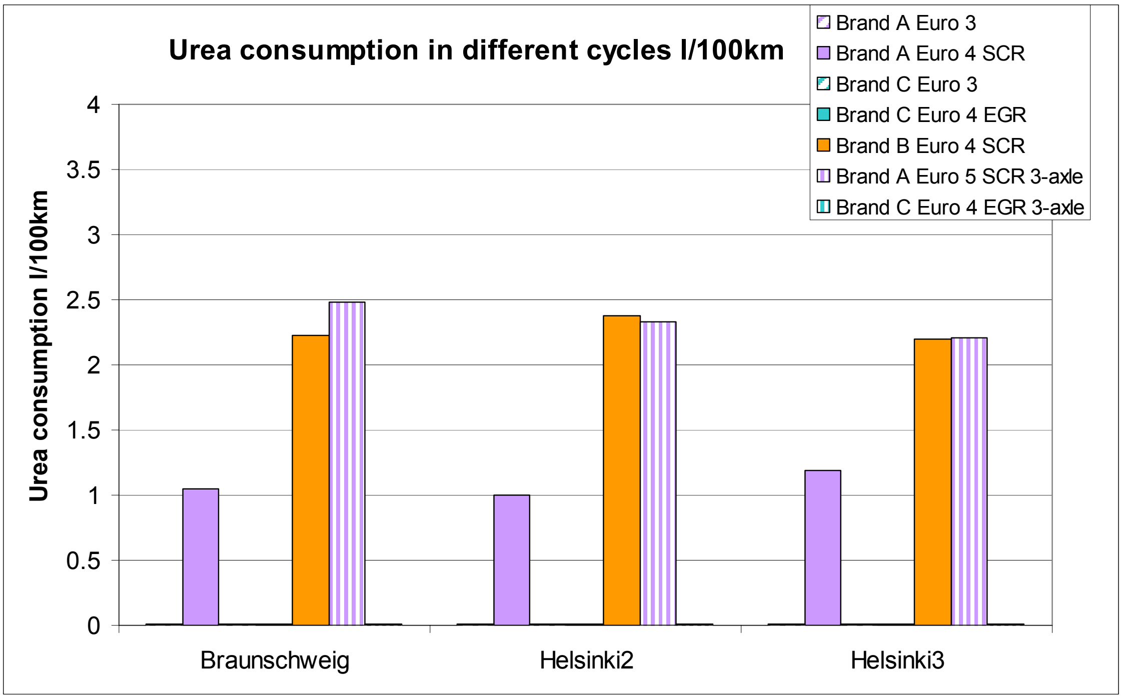


Figure 13. Consumption of urea, measured in litres per 100 km.

6.3 Cost of fuel and urea

Figure 14 illustrates the aggregate cost of fuel and urea, calculated per 100 km. The EGR-vehicles do not use urea. The calculations have been made using the following price estimates (prices without VAT, price levels are presumed to reflect those paid by large bus operators):

- diesel fuel 0,74 €/l (including VAT 0,90 €/l)
- urea 0,55 €/l (including VAT 0,67 €/l).

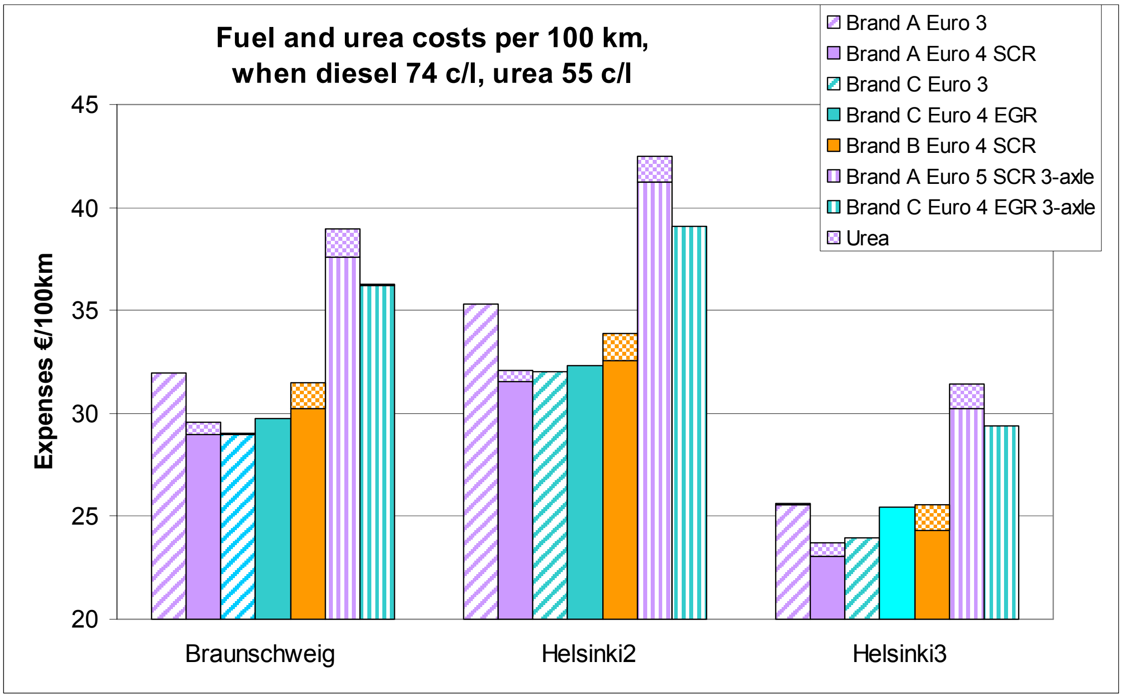


Figure 14. Aggregate cost of fuel and urea.

The aggregate cost of fuel and urea is 24 €/100 km at its lowest (Helsinki 3 -cycle, two-axle Brand C Euro 3 and Brand A Euro 4) and 43 €/100 km at its highest (Helsinki 2 -cycle, three-axle Brand A Euro 5). The cost of urea is at its highest some 4% of the total costs.

Brand A's Euro 3 -vehicle has the highest costs among the two-axle vehicles. The Brand A Euro 4, Brand C Euro 3 and Brand C Euro 4 give nearly the same costs in the Braunschweig- and Helsinki 2 -cycles. Brand B's Euro 4 -vehicle gives 5–6% higher costs than the three above mentioned vehicles. The Brand B Euro 4 -vehicle gives although at all times smaller costs than the Brand A Euro 3 -vehicle.

The study within brands shows, that in Brand C’s case a move to Euro 4 -technology does not alter fuel costs. Brand A’s Euro 4 -vehicle gives a lower combined fuel and urea cost than its Euro 3 -vehicle (without urea).

In the class of three-axle vehicles, Brand A’s Euro 5 -vehicle is 7–9% more expensive to operate than Brand C’s Euro 4 -vehicle.

7. Emission results

The study of emissions is emphasised on, for diesel engines, the most critical emission components, nitrogen oxides and particulate matter.

Figure 15 shows the vehicles' NO_x-emissions proportioned to the travelled distance in different driving cycles. Figure 16 correspondingly shows particulate matter.

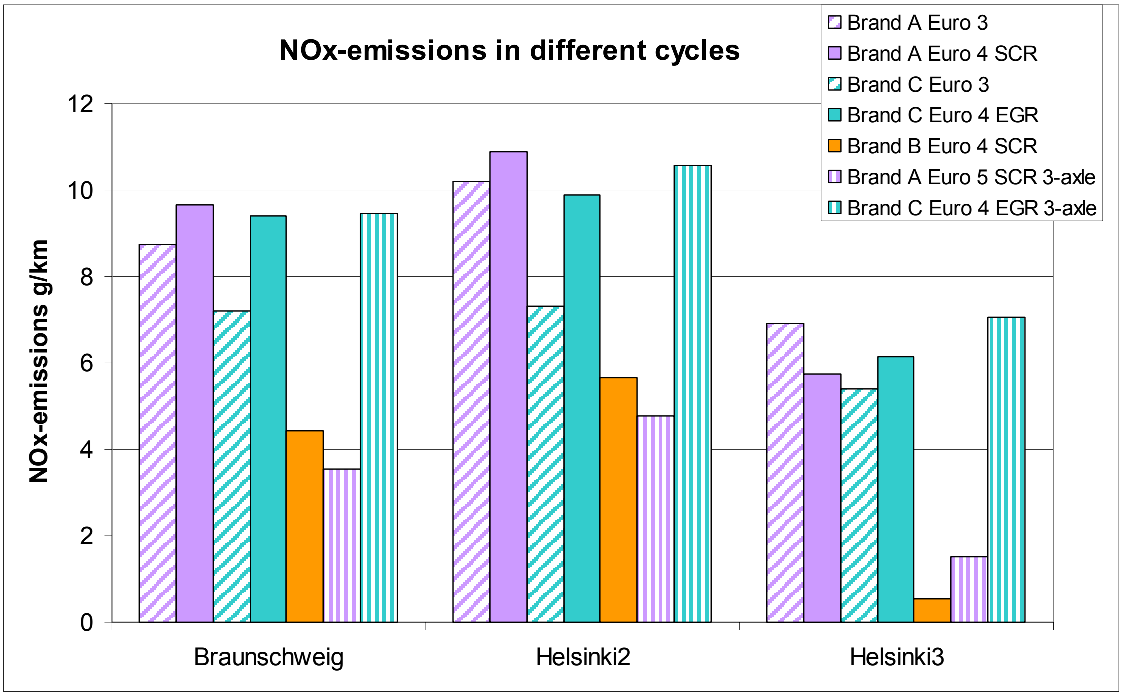


Figure 15. NO_x-emissions in proportion to the travelled distance in different driving cycles.

The dispersion between different vehicles' NO_x-emissions was rather remarkable. The largest value in the Helsinki 3 -cycle was some 15 times greater than the smallest one. The difference was some 2.5-fold in the other cycles.

Figure 15 shows that both Brand A's and Brand C's Euro 4 -vehicles produce more NO_x-emissions in the Braunschweig- and Helsinki 2 -cycle than their corresponding Euro 3 -vehicles (two-axle). The increase is for Brand C's part 30–35%, even though the Euro 4 -class requires a 30% lower NO_x-level than the Euro 3 -class. Brand A's Euro 4 -vehicle gives slightly lower emissions than its Euro 3 -vehicle when driven in the Helsinki 3 -cycle.

The three-axle Brand C Euro 4 vehicle gives slightly higher NO_x-emissions than the two-axle Euro 4 -vehicle of the same brand. The difference in work load in the Braunschweig-cycle is for two- and three-axle vehicles some 18%.

The Brand B Euro 4 vehicle and the Brand A Euro 5 vehicle give clearly lower NO_x-emissions than the other vehicles. These vehicles reach very low NO_x-emission levels, especially in the Helsinki 3 -cycle. They do although consume almost twice as much urea as Brand A's Euro 4 -vehicle. With a sufficient dosing of urea, SCR-technology gives lower NO_x-emissions than what EGR-technology does.

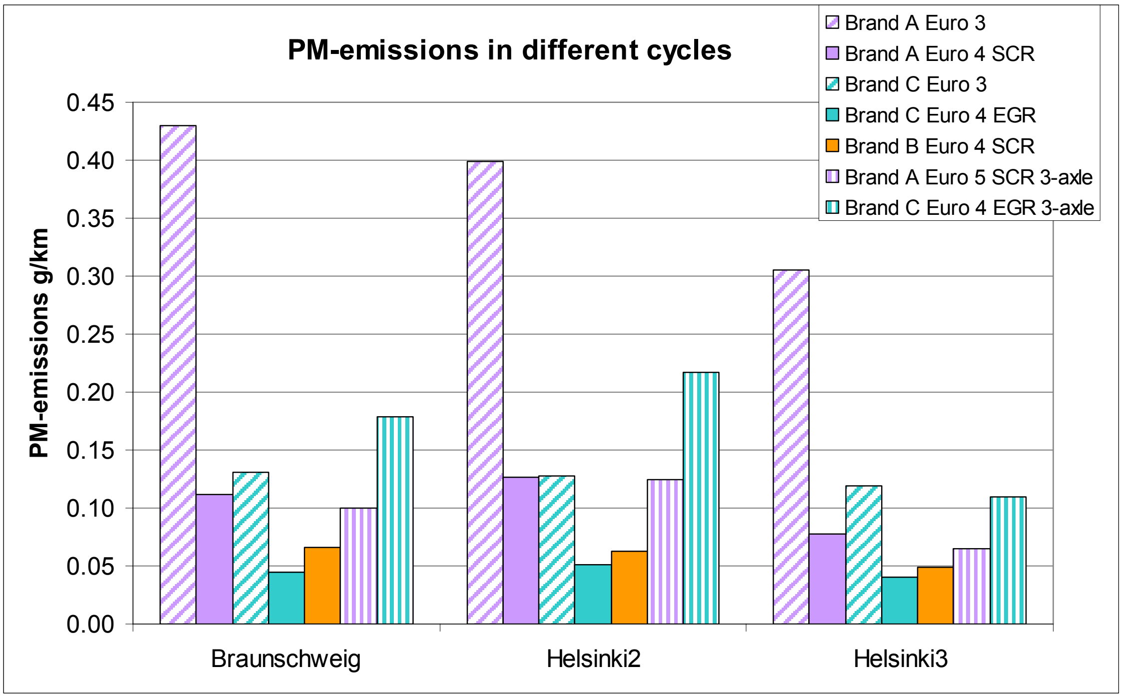


Figure 16. Particulate emissions in proportion to the travelled distance in different driving cycles.

The dispersion of particulate emissions is also significant. Brand A's Euro 3 -vehicle produces by far the most particulate emissions. The difference between the smallest and greatest value is, depending on the cycle, 8 to 10-fold. Both Brand A's and Brand B's two-axle Euro 4 -vehicles give clearly lower particulate emissions than the corresponding Euro 3 -vehicles.

The particulate emissions of Brand C's three-axle Euro 4 -vehicle are rather high. The result is surprising in Brand C's case, because the two-axle Brand C Euro 4 -vehicle has the lowest particulate emissions together with the Brand B Euro 4 -vehicle. Both the Brand C Euro 4 -vehicles have the same 9-litre base engine, but there is a power difference and therefore dissimilarity in the tuning of the engine. The three-axle Brand

C Euro 4 -vehicle produces in proportion more particulates than the Euro 3 -vehicle of the same brand.

Figure 17 shows CO-emissions of the vehicles in different driving cycles. Figure 18 illustrates HC-emissions. The significance of CO- and HC-emissions is in bus fleets minor compared to gasoline fuelled passenger cars. Brand A's SCR-vehicles produce rather high CO -emissions, Brand C's Euro 3 -vehicle on the other hand high HC-emissions compared to the other vehicles.

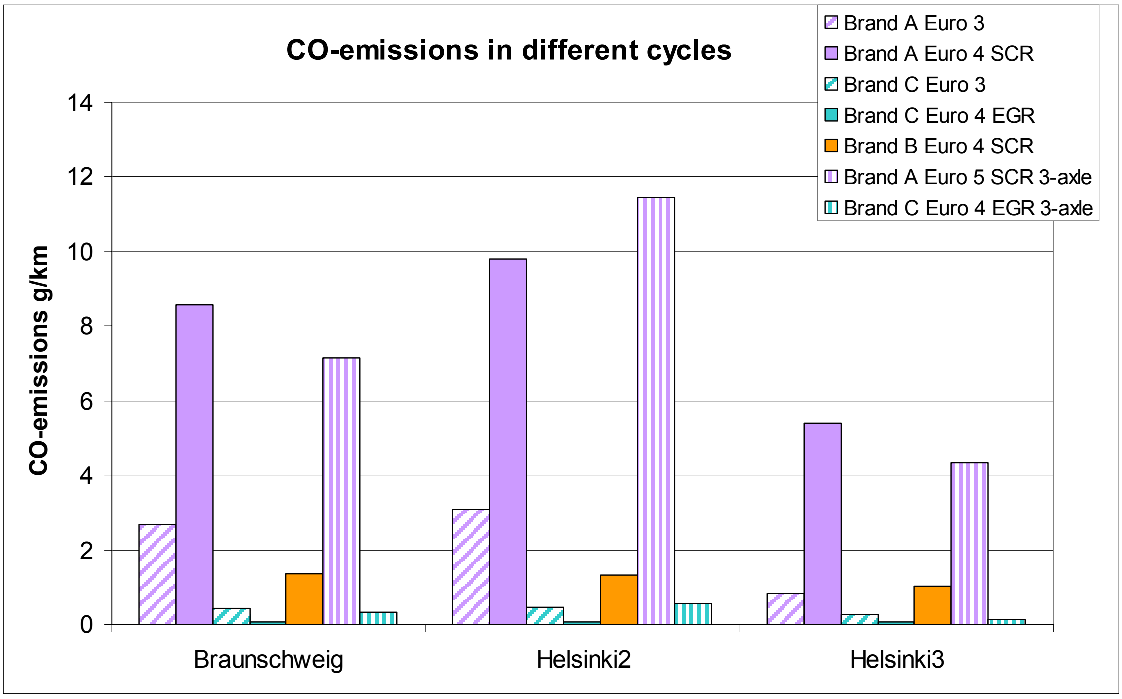


Figure 17. CO-emissions in proportion to travelled distance in different cycles.

Figure 19 illustrates the vehicles' emissions in proportion to the work of the driving wheels in the Braunschweig-cycle. The results are displayed in a NO_x/PM-coordinate system. Based on these values, it is possible to estimate how the vehicles' emissions correspond with the limiting values of the Euro-classes. Reference values for different Euro emission classes (factor 2.25, including NTE-factor, see Table 4, p. 28) are in the picture marked by coloured rectangles. The limit values for Euro-classes, multiplied by only the dissipation coefficient of the power train (1.8), are in the picture marked by dashed lines.

The results are presented in table format in Table 5.

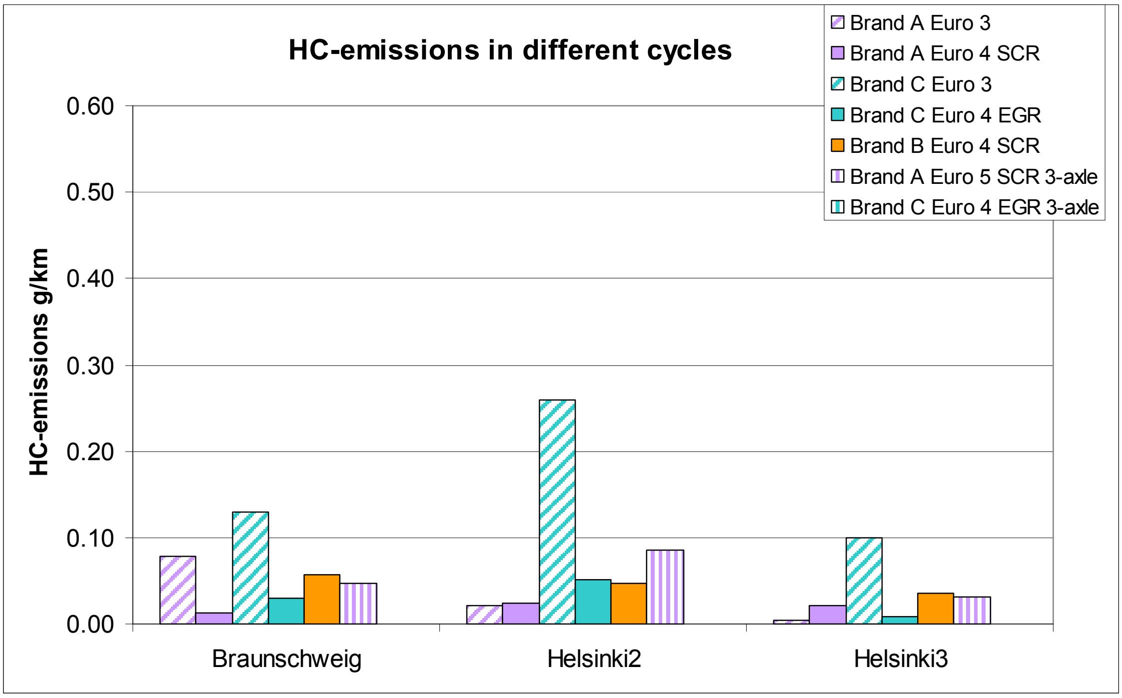


Figure 18. HC-emissions in proportion to travelled distance in different cycles.

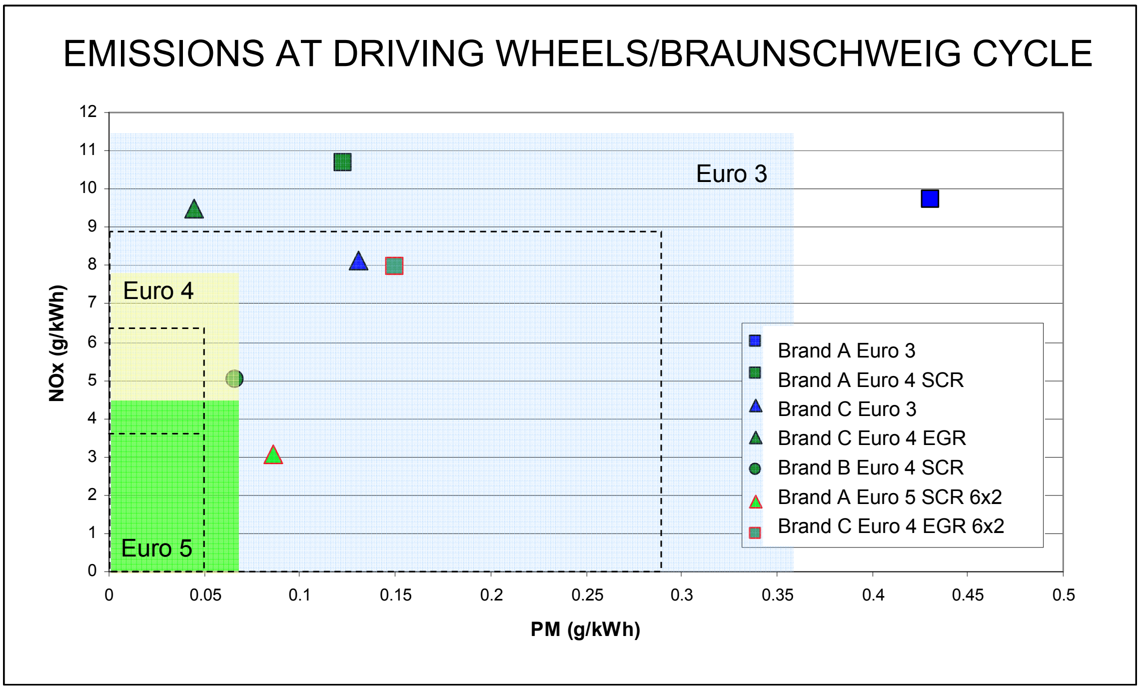


Figure 19. Emissions proportioned to the work of the driving wheels in the Braunschweig-cycle. Coloured rectangles represent Euro-limit values by a factor of 2.25 (including NTE-factor), the dashed rectangles represent Euro-limit values by a factor of 1.8 (power train dissipation).

Only Brand C's Euro 3- and Brand B's Euro 4 -vehicle conform to the requirements of the NTE-accordant Euro-class. Brand C's two-axle Euro 4 -vehicle is easily Euro 4/5-class what comes to particulate emissions, but only Euro 3 -class considering NO_x-emissions. Brand C's three-axle Euro 4 -vehicle is only Euro 3 -class what comes to NO_x- and particulate emissions. The same goes for Brand A's Euro 4 -vehicle. This vehicle is actually very close to Euro 2 -class what comes to NO_x-emissions. Brand A's Euro 5 -vehicle meets Euro 5 NO_x-emission standards, but it emits slightly more particulates than what is allowed according to the shared Euro 4 and Euro 5 -particulate emission level.

Brand A's Euro 3 and Euro 4 -vehicles and Brand C's two-axle Euro 4 -vehicle meet Euro 2 -limit values if the NTE-factor is not taken into account, but only the losses in the power train are noticed. The other vehicles meet in this case the Euro 3 -limit values.

Table 5. Emissions proportioned to the work at the driving wheel in the Braunschweig-cycle and an estimate of meeting emission limits.

Model	**NO_x (g/kWh)**	**PM (g/kWh)**	**NO_x-class (NTE-concept)**	**PM-class (NTE-concept)**	**Total result (NTE-concept)**
2-axle					
Brand A Euro 3	9.7	0.43	Euro 3	Euro 2	Euro 2
Brand A Euro 4	10.7	0.12	Euro 3	Euro 3	Euro 3
Brand C Euro 3	8.1	0.13	Euro 3	Euro 3	Euro 3
Brand C Euro 4	9.5	0.05	Euro 3	Euro 4/5	Euro 3
Brand B Euro 4	5.0	0.07	Euro 4	Euro 4/5	Euro 4
3-axle					
Brand A Euro 5	3.1	0.09	Euro 5	Euro 3	Euro 3
Brand C Euro 4	8.0	0.15	Euro 3	Euro 3	Euro 3

Table 6 presents the corresponding values for the Helsinki 3 -cycle.

Table 6. Emissions proportioned to the work at the driving wheel in the Helsinki 3 -cycle and an estimate of meeting emission limits.

Model	**NOx (g/kWh)**	**PM (g/kWh)**	**NOx-class (NTE-concept)**	**PM-class (NTE-concept)**	**Total result (NTE-concept)**
2 –axle					
Brand A Euro 3	8.9	0.34	Euro 3	Euro 3	Euro 3
Brand A Euro 4	6.9	0.09	Euro 4	Euro 3	Euro 3
Brand C Euro 3	6.9	0.13	Euro 4	Euro 3	Euro 3
Brand C Euro 4	6.9	0.05	Euro 4	Euro 4/5	Euro 4
Brand B Euro 4	0.7	0.05	Euro 5	Euro 4/5	Euro 5
3 –axle					
Brand A Euro 5	1.5	0.07	Euro 5	Euro 4/5	Euro 5
Brand C Euro 4	6.9	0.11	Euro 4	Euro 3	Euro 3

The Helsinki 3 -cycle is emission wise more effortless than the Braunschweig- or Helsinki 2 -cycle. Therefore both Brand B's Euro 4 -vehicle and Brand A's Euro 5 -vehicle meet the Euro 5 -requirements easily in this cycle. The Brand A Euro 5 meets the emission limit for particulates by a whisker, but both vehicles clearly meet the NO_x-limits. The two-axle Brand C Euro 4 -vehicle meets Euro 4 -levels when tested and estimated this way. Both of the Euro 3 -vehicles fulfil the Euro 3 -emission requirements, the Brand A vehicle although the particulate limits only barely.

There are big vehicle-specific differences in the CO- and HC-values. The vehicles' CO- and HC -emissions are Euro 5 -level when examining emissions using the NTE-concept, except for the CO -value for Brand A's Euro 4 SCR -vehicle.

The highest measured CO-value was 9.5 g/kWh (Brand A Euro 4) and the highest measured HC-value 0.3 g/kWh (Brand C Euro 3). The limit values for the ETC-test are for the Euro 4 and Euro 5 -class 4.0 g CO/kWh and 0.55 g HC/kWh. The NTE-reference value is hence 9 g CO/kWh and 1.2 g HC/kWh.

8. Discussion

8.1 General

Per procuration of the Finnish Public Transportation Association, a comparison of different vehicle types' fuel economy and emissions is made when the first Euro 4- and Euro 5 -certified buses hit the market. The situation is outstandingly interesting since different manufacturers have chosen dissimilar technical solutions for lowering emissions in their new vehicles. Of the compared manufacturers, two manufacturers have chosen to use urea catalyst technology (SCR), while the third manufacturer uses exhaust gas recirculation technology (EGR).

The two most popular Euro 3 -class buses (Brand A and C) were used as references in the comparison. Out of these vehicles, Brand C performs better. It consumes less fuel and gives lower NO_x- and particulate emissions. Brand A consumes 7–10% more fuel than Brand C. The evaluation of new Euro 4- and Euro 5 -technology should therefore not be proportioned to the performance of Brand A's Euro 3 -vehicle, but rather to the performance of Brand C's Euro 3 -vehicle. Brand C's Euro 3 -vehicle has in this chapter been the primary point of comparison.

The limit value for NO_x declines by 30% and the limit value for particulate emissions by no less than 80% when moving from Euro 3- to Euro 4 -class. One could therefore assume that emissions in real life driving situations should be reduced as well. It has furthermore been widely estimated that moving to Euro 4 -technology would result in increased fuel consumption.

The results show that moving to Euro 4 -technology does not necessarily result in increased fuel consumption. The results also show that the new technology does not decrease NO_x-emissions as expected for all vehicles.

Both fuel economy and emissions have been observed in this study. If exhaust emissions were completely disregarded it might lead to a situation where fuel efficient vehicles were favoured in fleet buying decisions. These vehicles might although not emission-wise perform the way one could reasonably expect.

8.2 Fuel consumption

In addition to driving cycle and load, the efficiency of the power train and the mass of the vehicle also affects fuel consumption.

The situation is still such that the engine manufacturer can emphasize either low NO_x-emissions or good fuel economy. Manufacturer C has apparently chosen low fuel consumption for its EGR -engines.

Brand C's Euro 4 -engines give a lower specific consumption (measured from the driving wheels in form of g/kWh) than its Euro 3 -engines and other manufacturers' Euro 4- and Euro 5 -engines when measured in cycles describing urban driving (Braunschweig and Helsinki 2). Brand C's Euro 4 -engines do not perform as well in the Helsinki 3 -cycle describing suburban driving. In this cycle Brand C's Euro 4 -engine gives the highest specific consumption of the whole group (excluding Brand A's Euro 3 -vehicle). The difference between the smallest and largest fuel consumption figure is in different cycles between 5 and 8%.

The measurements do not give a univocal answer to whether EGR- or SCR -technology is better in terms of fuel economy. Two factors hinder this study. The order of superiority depends on one hand on the driving cycle, but Brand C's Euro 4 -engines on the other hand give higher NO_x-emissions than its Euro 3 -engines.

Brand C's Euro 4 -vehicle consumes the least fuel in urban driving cycles, but the most in suburban driving (the latter holds true for the two-axle vehicle). The two- and three-axle vehicles have different power versions of the same engine. The two-axle vehicle's less powerful engine responds more strongly to load and duty cycle. The relative fuel consumption of all SCR-vehicles decreases when moving from urban to suburban driving.

If manufacturer C would recalibrate its engines in order to lower NO_x-emissions, both particulate emissions and fuel consumption would increase. Brand B's Euro 4 -vehicle and Brand A's Euro 5 -vehicle give NO_x-emissions which truly correspond to their emission categories.

Brand C's two-axle Euro 4 -vehicle is heavier than the other two-axle vehicles. This fact increases the vehicle's distance proportioned fuel consumption (l/100 km) so that it gives on average the worst volumetric fuel economy in its group, despite its efficient power train. Variation in fuel consumption from vehicle to vehicle is in different cycles 3–11% (two-axle vehicles). What comes to three-axle vehicles, Brand C consumes 3–5% less fuel than Brand A.

Table 7 shows the order of superiority for the volumetric fuel consumption of two-axle vehicles (smallest to largest) in the Braunschweig-, Helsinki 2- and Helsinki 3 -cycles.

Table 7. The order of superiority for the volumetric fuel consumption of two-axle vehicles

Cycle	**Braunschweig Urban**	**Helsinki 2 Urban driving**	**Helsinki 3 Suburban driving**
1.	Brand A Euro 4	Brand A Euro 4	Brand A Euro 4
2.	Brand C Euro 3	Brand C Euro 3	Brand C Euro 3
3.	Brand C Euro 4	Brand C Euro 4	Brand B Euro 4
4.	Brand B Euro 4	Brand B Euro 4	Brand C Euro 4

The lowest fuel consumption figure, 31.1 l/100 km, was reached with Brand A's Euro 4 -vehicle in the Helsinki 3 -cycle. The largest fuel consumption figure, 55.7 l/100 km, was attained by Brand A's three-axle Euro 5 -vehicle in the Helsinki 2 -cycle. Brand A's Euro 4 -vehicle gives on average the best fuel economy.

SCR-vehicles use 1–2.5 litres of urea per 100 km. This is 2–6% of the fuel consumption. Table 8 shows the order of superiority for the aggregate cost of fuel and urea for two-axle vehicles. This angle of view alters the order of the vehicles to some extent, compared to Table 7. The lowest costs are reached using either the Brand C's Euro 3 -vehicle or the Brand A's Euro 4 -vehicle. Brand B's Euro 4 -vehicle gives the highest running costs in all cycles.

This consideration is although unfair. The emission levels of the Brand C's Euro 3 -vehicle and Brand A's Euro 4 -vehicle are in reality Euro 3 -level, whereas the emissions of Brand B's Euro 4 -vehicle are Euro 4- or Euro 5 -level depending on the cycle (see Table 9). External costs caused by emissions should in principle be included in the evaluation of the total costs. Considering the results this way would do justice to the vehicles which are truly clean-running.

Table 8. Order of superiority for the combined consumption of urea and fuel for two-axle vehicles.

Cycle	**Braunschweig Urban driving**	**Helsinki 2 Urban driving**	**Helsinki 3 Suburban driving**
1.	Brand C Euro 3	Brand C Euro 3	Brand A Euro 4
2.	Brand A Euro 4	Brand A Euro 4	Brand C Euro 3
3.	Brand C Euro 4	Brand C Euro 4	Brand C Euro 4
4.	Brand B Euro 4	Brand B Euro 4	Brand B Euro 4

8.3 Exhaust emissions

The actual emission comparison was made based on specific emissions values, in g/kWh, proportioned to the work accumulated on the driving wheels. These values were compared against the limit values of the different Euro-classes. The limit values of the type approval engine test were multiplied by a factor of 1.8, which takes into account the losses of the power train and the auxiliary devices. The values were also multiplied by the so called NTE-factor (1.25). This factor takes into consideration that the duty cycle driven with the vehicle does not load-wise equal that of the normal exhaust test with an engine mounted to an engine test stand. This way a reference value, which is 2.25-fold compared to the actual limit values, was generated. The limit value for NO_x is 5 g/kWh in the Euro 3 -class. The reference value will therefore be 11.3 g/kWh.

The functionality of the vehicles was this way measured in different cycles. When evaluated this way, Brand A's Euro 3 -vehicle is actually Euro 2 -class (high particulate emissions) in the Braunschweig-cycle. Brand C's Euro 3 -vehicle is also in reality Euro 3 -class.

Of the measured Euro 4- and Euro 5 -vehicles, only Brand B's Euro 4 -vehicle corresponds to its declared emission class. Brand A and Brand C Euro 4 -vehicles are Euro 3 -class what comes to their true emissions. This goes for both NO_x and particulate emissions, except for Brand C's two-axle Euro 4 -vehicle which emits particulates in line with the Euro 4/5 -class. The more powerful version of Brand C's Euro 4 -engine produces 2–3 times more particulates than the weaker one.

The NO_x-emissions of Brand A's Euro 5 -vehicle are genuinely of Euro 5 -level, but the particulate emissions slightly exceed the limiting values of the Euro 4/5 -class.

Table 9 shows an estimate of what emission classes the vehicles in reality represent in the Braunschweig- and Helsinki 3 -cycle.

Table 9. The correspondence between Euro-classes of the measured vehicles in the Braunschweig- and Helsinki 3 -cycle, estimated based on the NTE-method.

Model	**Braunschweig NO_x**	**Helsinki 3 NO_x**	**Braunschweig PM**	**Helsinki 3 PM**
Brand B Euro 4	Euro 4	Euro 5	Euro 4/5	Euro 4/5
Brand A Euro 5 3-axle	Euro 5	Euro 5	Euro 3	Euro 4/5
Brand C Euro 4 2-axle	Euro 3	Euro 4	Euro 4/5	Euro 4/5
Brand C Euro 4 3-axle	Euro 3	Euro 4	Euro 3	Euro 3
Brand A Euro 4	Euro 3	Euro 4	Euro 3	Euro 3
Brand C Euro 3	Euro 3	Euro 4	Euro 3	Euro 3
Brand A Euro 3	Euro 3	Euro 3	Euro 2	Euro 3

The emission results confirm that vehicle decisions should not be made solely based on good fuel economy.

9. Summary

Altogether seven vehicles were measured in the project carried out by the Finnish Public Transport Association. In the class of two-axle vehicles, three new Euro 4 -class vehicles were measured, as well as two Euro 3 -class vehicles as references. Two new three-axle vehicles (Euro 4 and Euro 5) were also measured. The measurements were carried out on a chassis dynamometer, using three cycles describing actual driving. Exhaust emissions were, in addition to fuel consumption, also recorded for these vehicles.

The manufacturers have adopted new technology for the Euro 4- and Euro 5 -models. Two of the manufacturers use a urea catalyst (SCR) for reducing nitrogen oxides, while the third one uses an inter-engine method, also known as exhaust gas recirculation (EGR). It has generally been claimed that SCR-technology is better what comes to fuel economy.

Differences in fuel consumption and operating expenses were after all smaller than first anticipated. What comes to the Euro 3 -class reference vehicles, Brand A consumes 7–10% more fuel than Brand C. When simulating urban driving, the difference in fuel consumption between the new two-axle vehicles is only 3–4%. Due to distinct technical solutions, the differences were assumed to be greater. The difference is in suburban driving although 11% at its most. Brand A's Euro 4 -vehicle gives on average the lowest fuel consumption. What comes to emissions and fuel consumption in suburban driving, SCR-technology works better than EGR-technology. Out of the three-axle vehicles, the EGR-vehicle consumes 3–5% less fuel than the SCR-vehicle.

The cost of urea has also to be considered when studying the driving costs. Depending on the vehicle and the cycle, SCR-vehicles consume urea equalling an amount of 2–6% of the fuel consumption. In the two-axle Euro 4 -vehicle group, Brand A's Euro 4 SCR -vehicle gives the lowest operating costs (fuel + urea) in all cycles. In the three-axle -vehicle group the EGR-vehicle gives lower driving costs than the SCR-vehicle.

The measurements do not give an unambiguous answer to whether the EGR- or SCR-technology is preferable regarding fuel consumption. The contemplation is hindered by two factors. On one hand, the order of superiority depends on the driving cycle, on the other, the actual exhaust emissions do not match with expectations. Brand C's Euro 4 -engine produces more NO_x-emissions than its Euro 3 -engine. The fuel efficient Brand A Euro 4 -engine is not truly Euro 4 -class what comes to NO_x-emissions. If manufacturer C would re-calibrate its engines in order to lower NO_x-emissions, both fuel consumption and particulate emissions would increase. Brand B's Euro 4 -vehicle and Brand A’s Euro 5 -vehicle produce NO_x-emissions that truly represent their emission classes.

The dispersion regarding emissions is therefore remarkable. The vehicle’s performance does not either necessarily correlate with its Euro -class under actual driving. SCR-technology works well especially in suburban driving. NO_x-emissions were at their lowest 0.5 g/km (Brand B’s Euro 4), but when using EGR-technology they were 6–11 g/km depending on the cycle. There is significant dispersion also within the SCR-vehicle group. Brand A’s Euro 4 -vehicle produces about 10 times more nitrogen oxides in suburban driving than does Brand B’s Euro 4 -vehicle.

In the Euro 4- and Euro 5 -vehicle group, Brand C’s EGR –engine unexpectedly produces both the highest and the lowest emissions, depending on the power version of the engine. The difference is, depending on the cycle, 3 to 4-fold. The particulate emissions of the other Euro 4- and Euro 5 -vehicles settle somewhere in between these values. The Brand B Euro 4 -vehicle and the two-axle Brand C Euro 4 -vehicle give the lowest particulate emissions.

Brand C’s Euro 3 -vehicle and Brand B’s Euro 4 -vehicle are the only measured vehicles that under real life driving conditions produce emissions responding to their emission class. Brand A’s Euro 5 -vehicle is what comes to NO_x-emissions truly Euro 5 -level, but in cycles describing urban driving its particulate emissions are slightly higher than what they should be in a Euro 4/5 -class vehicle.

The results show that moving to Euro 4 -technology does not necessarily increase fuel consumption, but neither does NO_x-emissions along with new technology decline as expected in all vehicles.

Both fuel consumption and exhaust emissions have been observed in this study. In case exhaust emissions were completely disregarded, fleet decisions might be directed towards fuel efficient vehicles which after all do not reach the level of emissions that reasonably could be expected.

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See also chapter 3 for references.

Appendix A: Technical data

Make and model	**Brand A Euro 4 4x2 (Volvo)**	**Brand A Euro 5 6x2 (Volvo)**	**Brand C Euro 4 6x2 (Scania)**
Engine displacement/Power/Torque	7.2 / 213 / 1200	12,13 / 250 / 1700	8,87 / 199 / 1250
Exhaust system	SCR (Euro4)	SCR (Euro5)	EGR (Euro4)
Vehicle identification	KBG-292	OXI-689	ASG-508
Transmission model	ZF 6HP554 N	ZF 6HP604 N	ZF HP592C N
Transmission setting	SP4 (Economy)	SP6 (Super economy)	-
Final drive	5,29:1	5,63:1	5,57:1
Body length/width	12,86 / 2,55	14,7 / 2,55	14,5 / 2,55
Seating-/standing capacity	43/44=87	58/49=107	51/47=98

Make and model	**Brand B Euro 4 4x2 (Mercedes-Benz)**	**Brand C Euro 4 4x2 (Scania)**	**Brand A Euro 3 4x2 (Volvo)**
Engine displacement/Power/Torque	11,967 / 220 / 1250	8,87 / 169 / 1050	7,284 / 199 / 1195
Exhaust system	SCR (Euro4)	EGR (Euro4)	Oxidation cat (Euro3)
Vehicle identification	MA LK 890	MRG-632	JFU-440
Transmission model	ZF-Ecomat	ZF 6HP502C N	ZF 5HP552 N
Transmission setting	Economy	-	-
Final drive	5,875:1	5,57:1	5,29:1
Body length/width	12,04 / 2,55	12,9 / 2,55	13,0 / 2,55
Seating-/standing capacity	34/67=101	44/39=83	43/36=79

Make and model	**Brand C Euro 3 4x2 (Scania)**		
Engine displacement/Power/Torque	8,97 / 169 / 1100		
Exhaust system	No exhaust after treatment (Euro3)		
Vehicle identification	CYK-183		
Transmission model	ZF 5HP502C N		
Transmission setting	5 speed program		
Final drive	4,22:1		
Body length/width	12,9 / 2,55		
Seating-/standing capacity	43/40=83		

Series title, number and
report code of publication

VTT Research Notes 2373
VTT-TIED-2373

Author(s)
Nylund, Nils-Olof, Erkkilä, Kimmo & Hartikka, Tuukka

Title

Fuel consumption and exhaust emissions of urban buses
Performance of the new diesel technology

Abstract

The research was carried out by the Finnish Public Transport Association. Altogether seven vehicles were measured, two two-axle Euro 3 -class vehicles as references, three new two-axle Euro 4 -class vehicles and two new three-axle vehicles. The measurements were carried out on a chassis dynamometer, using three cycles describing actual driving. In addition to fuel consumption, exhaust emissions were also recorded for these vehicles.

The differences in fuel consumption and operating expenses were after all smaller than first anticipated. In the case of the Euro 3 -class reference vehicles, the difference between the two vehicles was as high as 7–10%. For new two-axle vehicles the difference in fuel consumption, when simulating urban driving, is only 3–4%. Due to different technical solutions, the results were anticipated to be greater. In suburban driving although, the difference is at its most 11%. In the class of two-axle vehicles, lowest fuel consumption was measured for a SCR vehicle, whereas in the case of the two three-axle vehicles, EGR technology resulted in lowest fuel consumption.

The measurements do not give an unambiguous answer to whether the EGR- or SCR-technology is preferable regarding fuel consumption. The contemplation is hindered by two factors. On one hand, the order of superiority depends on the driving cycle, on the other, the actual exhaust emissions do not match with expectations. The two EGR vehicles (same make) produced higher NOx -emissions than the manufacturer's Euro 3 -engine. The most fuel efficient SCR -engine is not truly Euro 4 -class what comes to NOx -emissions. Only two of the new vehicles, both with SCR technology, produce NOx -emissions genuinely matching their classes.

Both fuel consumption and exhaust emissions have been observed in the study. In case exhaust emissions were completely disregarded, fleet decisions might be directed towards fuel efficient vehicles which after all do not reach the level of emission performance that reasonably could be expected.

ISBN
978-951-38-6922-9 (soft back ed.)
978-951-38-6923-6 (URL: http://www.vtt.fi/publications/index.jsp)

Series title and ISSN
VTT Tiedotteita – Research Notes
1235-0605 (soft back edition)
1455-0865 (URL: http://www.vtt.fi/publications/index.jsp)

Project number
15691

Date
May 2007

Language
English

Pages
48 p. + app 1 p.

Name of project
31PLLBUS

Commissioned by
Finnish Public Transport Association PLL

Keywords
public transport, urban transport, vehicles, buses, diesel engines, fuel consumption, exhaust emissions, performance, measurements, operating expences

Publisher
VTT Technical Research Centre of Finland
P.O.Box 1000, FI-02044 VTT, Finland
Phone internat. +358 20 722 4404
Fax +358 20 722 4374

VTT RESEARCH NOTES 2373 Fuel consumption and exhaust emissions of urban buses. Performance of the new diesel technology

Julkaisu on saatavana	Publikationen distribueras av	This publication is available from
VTT	VTT	VTT
PL 1000	PB 1000	P.O. Box 1000
02044 VTT	02044 VTT	FI-02044 VTT, Finland
Puh. 020 722 4404	Tel. 020 722 4404	Phone internat. + 358 20 722 4404
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ISBN 978-951-38-6922-9 (nid.)
ISSN 1235-0605 (nid.)

ISBN 978-951-38-6923-6 (URL: http://www.vtt.fi/publications/index.jsp)
ISSN 1455-0865 (URL: http://www.vtt.fi/publications/index.jsp)