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HEAVY-DUTY VEHICLES: SAFETY, ENVIRONMENTAL IMPACTS AND NEW TECHNOLOGY “RASTU”

Summary report 2006–2008

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Disclosure: Public

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Heavy-duty vehicles: Safety, environmental impacts and new technology, “RASTU”.
Summary report. Edited by Matti Kytö, Kimmo Erkkilä and Nils-Olof Nylund

Abstract

Research on fuel savings for heavy-duty vehicles was carried out within the framework of the three-year (2006–2008) “RASTU” project. The research integrate also included tasks relating to emissions, IT applications and safety. Five research parties and nearly 20 sponsors took part in the project.

During the research period, a total of approximately 140 heavy-duty vehicles were tested using a chassis dynamometer. An overall trend that emerged is a decline in the emissions and fuel consumption of new vehicles (Euro IV, V and EEV). However, there are significant differences between vehicle makes. Emissions of buses in particular vary a lot, and the emissions of only a few diesel vehicles correspond to the class in which the vehicle is certified. In trucks, the actual emission levels correspond, on average, to the emission class stated. The Euro IV emissions regulations brought to market solutions that are based on both EGR and SCR technology. At the beginning of the research period, SCR vehicles, on average, offered both lower exhaust emission and fuel consumption values. At the end of the period, the situation became a bit more balanced, particularly for trucks. Fuel savings of approximately 5-10 % are, however, possible with the right selection of vehicle. The exhaust emission tests also measured emissions not regulated by legislation regarding new low-emission vehicles, such as aldehydes, ammonia, individual gaseous hydrocarbons, NO_2-content, PAH compounds and mutagenicity of particulate matter as well as the quantity and size distribution of particles. Overall, EEV-level diesel powered vehicles were "cleaner" than the Euro III and Euro IV vehicles in terms of emissions other than NO_2. Natural gas powered buses continue to offer emission advantages even when compared to the newest diesel buses.

Several vehicle engineering development subtasks were completed as academic theses. Potential development areas included aerodynamics, tyres, reducing the weight of heavy-duty vehicles by means of light-weight structure technology, axle alignment, stability of the modular combination as well as energy efficiency benchmarking of 40 and 60 ton combinations. A tyre recommendation was developed for actual trailer combinations that ensures safety but also minimises fuel consumption. The project developed vehicle IT applications such as driver aid systems as well as automatic skid detection and load detection. The driver aid system focused on city buses. A driver aid system prototype was installed in a total of 15 buses in the Helsinki metropolitan area and in Jyväskylä. An incentive system for drivers aimed at improving and prolonging the impacts of economical driving style training was demonstrated in the project. In the subtask for evaluating the efficiency of energy-saving measures, calculations to evaluate the measures were developed.

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CONTENTS

1 “RASTU” RESEARCH INTEGRATE OVERVIEW

The research integrate for 2003–2005, HDENERGY, concentrated heavily on the energy savings of heavy-duty vehicles. The RASTU research integrate also worked on the energy saving theme but increased focus was placed on emissions. The previously separate projects on emissions tests for buses and trucks were integrated into the RASTU project. The scope of operations was also expanded to highlight the development of the safety of heavy-duty vehicles, for example, by means of IT technology.

In short, the objectives of the RASTU project were:

- To investigate the actual performance of new vehicle types (Euro IV, Euro V and EEV)
    - Fuel efficiency and exhaust emissions in real-life driving situations
    - Development work aimed at the eco-labelling of heavy-duty vehicles
    - Adapting new vehicle technology to conditions in Finland as effectively as possible
    - Optimising the performance of fuel and lubricants for new vehicles
- To develop IT technology for improved fuel efficiency and better safety and service levels of heavy-duty vehicles
- To develop vehicle engineering for reduced fuel consumption
- To verify energy-saving measures and transfer information to transport companies, to support energy saving agreements in truck and bus operations, and to develop follow-up systems
- To study the impact of new vehicle technology on the quality of urban air (NO_2/PM)

The project objectives are well aligned with EU-level guidelines. In April 2009, a directive (2009/33/EC) was passed on the promotion of clean and energy-efficient road transport vehicles. The directive aims to include the lifetime costs for energy consumption, carbon dioxide emissions and pollutant emissions as award criteria in the procurement of vehicles. In addition, the directive requires that public transportation services that are based on a license, permit or authorisation of a public authority be carried out using transport vehicles that are procured in line with this principle.

The directive defines how the costs should be calculated. The award should be based on values counted per kilometre for fuel consumption, CO_2 and emissions (2009/33/EC):

”Fuel consumption, as well as CO_2 emissions and pollutant emissions per kilometre for vehicle operation shall be based on standardised Community test procedures for the vehicles for which such test procedures are defined in Community type approval legisla-

tion. For vehicles not covered by standardised test procedures, comparability between different offers shall be ensured by using widely recognised test procedures, or the results of tests for the authority, or information supplied by the manufacturer."

In both the previous HDEnergy project and the current RASTU research integrate, data on fuel consumption and emissions has been generated exactly in the form and for purposes set out in the directive. However, VTT is of the opinion that the calculation rules presented in the directive for estimating the vehicle's lifetime fuel consumption and emission costs disproportionately emphasise the energy component in relation to CO_2 and the actual emission components.

Transport ERA-NET Action Group ENT9, with the header "Environmental performance indicators for heavy-duty vehicles", is a network that aims to build international collaboration for the determination of actual energy consumption and environmental emissions of heavy-duty vehicles. In practice, this means standardising the measurements performed on a chassis dynamometer, and in the early stages harmonising the practices of central laboratories engaged in research activities. Including chassis dynamometer tests in the actual norms, or even in type approval regulations, is naturally desirable, but expecting rapid progress is not realistic.

The RASTU project consisted of a total of ten subprojects (nine subprojects with technical content; responsible parties in brackets below):

1. Performance of new Euro IV/V/EEV vehicles (VTT)
2. Fuel and lubricants for Euro IV/V/EEV vehicles (VTT)
3. Development of vehicle technology (HUT, VTT)
4. IT applications for vehicles (VTT, UO)
5. Optimisation of bus and coach operations (VTT)
6. Energy efficiency management and incentive systems for truck operations (TUT, EC Tools)
7. Evaluation of measures for reduced energy consumption (VTT, TUT)
8. Development of methodology (VTT)
9. Research into exhaust emissions (VTT)
10. Coordination and communication (TEC Transenergy Consulting Ltd, VTT, Motiva)

The project reports are available on the project website at www.rastu.fi.

The annual budget of RASTU was approximately EUR 800,000. The main sponsor was Tekes – the Finnish Funding Agency for Technology and Innovation and its ClimBus technology programme. Other sponsors included AKE Finnish Vehicle Administration, Ministry of Transport and Communication, Helsinki City Transport HKL and Helsinki Metropolitan Area Council YTV. The project was also funded by a group of enterprises and transport companies. A complete list of sponsors is provided in Appendix 1.

There were two foreign sponsors, the French Energy Agency ADEME and the Swedish Road Administration Vägverket. The English-language reports with a more limited scope were mainly aimed at these sponsors.

The results for 2008 and a summary of the results of the entire project are presented by subproject starting from Chapter 2.

2 PERFORMANCE OF NEW EURO IV/V/EEV VEHICLES (VTT)

Responsible party: VTT Technical Research Centre of Finland

Text: Kimmo Erkkilä, Petri Laine and Nils-Olof Nylund

2.1 MEASUREMENTS OF CITY BUSES

2.1.1 General

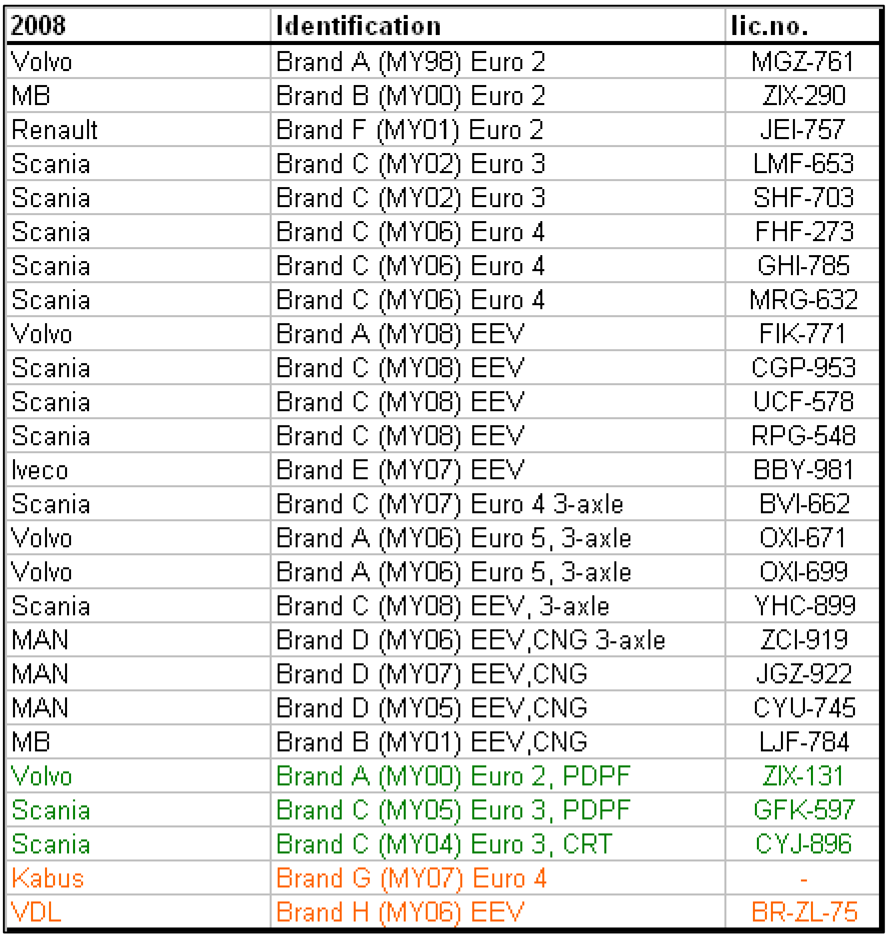
The new "Environmentally Enhanced Vehicle" (EEV) fleet was well represented in the 2008 city bus measurements. In addition to measurement results from the RASTU project, values for vehicles in parallel projects were also included in the database. Considering all measurements, the emission database for city buses grew to more than 100 vehicles (since 2002). The vehicle types measured are presented by emission class in Table 2.1.

Table 2.2 shows the vehicles added in the RASTU project emission database in 2008. The colour-coded special cases have not been used in the calculation of averages for each vehicle type. The special cases include vehicles retrofitted with catalysts, marked with green, and light-weight structure vehicles, marked with red. The vehicles measured include both new vehicle types and older vehicles under ongoing monitoring.

Diesel vehicles:		**CNG vehicles:**	
Euro 1	2 pcs	Euro 2	2 pcs
Euro 2	29 pcs	Euro 3	7 pcs
Euro 3	30 pcs	EEV	16 pcs
Euro 4	17 pcs	**Total.**	**25** pcs
Euro 5	4 pcs		
EEV	10 pcs		
Total.	**92 pcs**		

Table 2.1. Vehicle types in the database by emission class and fuel type

Table 2.2. City buses measured in 2008



2008	Identification	lic.no.
Volvo	Brand A (MY98) Euro 2	MGZ-761
MB	Brand B (MY00) Euro 2	ZIX-290
Renault	Brand F (MY01) Euro 2	JEI-757
Scania	Brand C (MY02) Euro 3	LMF-653
Scania	Brand C (MY02) Euro 3	SHF-703
Scania	Brand C (MY06) Euro 4	FHF-273
Scania	Brand C (MY06) Euro 4	GHI-785
Scania	Brand C (MY06) Euro 4	MRG-632
Volvo	Brand A (MY08) EEV	FIK-771
Scania	Brand C (MY08) EEV	CGP-953
Scania	Brand C (MY08) EEV	UCF-578
Scania	Brand C (MY08) EEV	RPG-548
Iveco	Brand E (MY07) EEV	BBY-981
Scania	Brand C (MY07) Euro 4 3-axle	BVI-662
Volvo	Brand A (MY06) Euro 5, 3-axle	OXI-671
Volvo	Brand A (MY06) Euro 5, 3-axle	OXI-699
Scania	Brand C (MY08) EEV, 3-axle	YHC-899
MAN	Brand D (MY06) EEV,CNG 3-axle	ZCI-919
MAN	Brand D (MY07) EEV,CNG	JGZ-922
MAN	Brand D (MY05) EEV,CNG	CYU-745
MB	Brand B (MY01) EEV,CNG	LJF-784
Volvo	Brand A (MY00) Euro 2, PDPF	ZIX-131
Scania	Brand C (MY05) Euro 3, PDPF	GFK-597
Scania	Brand C (MY04) Euro 3, CRT	CYJ-896
Kabus	Brand G (MY07) Euro 4	-
VDL	Brand H (MY06) EEV	BR-ZL-75

Scania EEV buses with EGR technology offered an interesting comparison to EEV-level SCR technology in 2008. For the most part, the results of the EEV vehicles were satisfactory. Nevertheless, unexpected results that clearly deviated from the normal level of the group were detected among the Scania EEV vehicles.

Table 2.3 shows the emission factors for city centre driving (Braunschweig) and major urban roadways (Helsinki 3), updated with the new results.

Table 2.3. Updated emission factors of city buses.

Emission chart, updated 7.5.2009

Braunschweig	*CO g/km*	*HC g/km*	*CH4* g/km*	*NOx g/km*	*PM g/km*	*CO2 g/km*	*CO2 eqv g/km*	*FC kg/100km*	*FC MJ/km*
Diesel Euro 1	1.39	0.32	0.00	15.59	0.436	1219	1219	38.6	16.4
Diesel Euro 2	1.48	0.19	0.00	12.94	0.202	1270	1270	41.0	17.4
Diesel Euro 3	0.80	0.14	0.00	8.64	0.195	1189	1189	38.2	16.2
Diesel Euro 4	2.84	0.10	0.00	8.35	0.112	1194	1194	38.5	16.4
Diesel Euro 5**	2.84	0.10	0.00	8.35	0.087	1194	1194	38.5	16.4
Diesel EEV	1.12	0.02	0.00	5.87	0.062	1116	1116	36.4	15.5
CNG Euro 2	4.32	7.12	2.33	16.92	0.009	1128	1283	42.1	20.1
CNG Euro 3	0.14	1.67	1.14	9.36	0.011	1257	1295	46.2	22.0
CNG EEV	2.27	1.04	0.87	3.18	0.007	1275	1294	46.3	22.7

* For diesel CH4 = 0
** Euro 5 emission factors are estimated by Euro 4 results

-0.296451 -0.444036 -0.065109 -0.054246
-0.049611
-0.124496

Emission chart, updated 7.5.2009

Helsinki3	*CO g/km*	*HC g/km*	*CH4* g/km*	*NOx g/km*	*PM g/km*	*CO2 g/km*	*CO2 eqv g/km*	*FC kg/100km*	*FC MJ/km*
Diesel Euro 1	1.12	0.26	0.00	12.63	0.353	988	988	31.1	13.2
Diesel Euro 2	1.20	0.16	0.00	10.48	0.163	1029	1029	33.0	14.0
Diesel Euro 3	0.65	0.11	0.00	7.00	0.158	963	963	30.8	13.1
Diesel Euro 4	2.30	0.08	0.00	6.76	0.090	967	967	31.0	13.2
*Diesel Euro 5**	*2.30*	*0.08*	*0.00*	*6.76*	*0.070*	*967*	*967*	*31.0*	*13.2*
Diesel EEV	0.90	0.01	0.00	4.76	0.050	904	904	29.4	12.5
CNG Euro 2	3.50	5.76	1.89	13.70	0.007	914	1039	33.9	16.2
CNG Euro 3	0.11	1.35	0.92	7.58	0.009	1018	1049	37.2	17.8
CNG EEV	1.84	0.84	0.70	2.58	0.006	1032	1048	37.3	18.3

* For diesel CH4 = 0
** Euro 5 emission factors are estimated by Euro 4 results

2.1.2 Nitrogen oxides and particulate matter

Table 2.1 shows the emission results of the latest measurements for nitrogen oxides (NO_x) and particulate matter (PM). The average results of all emission classes used as a comparison are presented as larger triangles and circles. The figure contains the limits based on both ESC (European Steady Cycle) and ETC (European Transient Cycle) engine tests for Euro III vehicles. Before the Euro III level, the limits were based on the results of the R.49 test (a static test that preceded the ESC). The limits for the newer vehicles (Euro IV and Euro V/EEV) are based on the ETC cycle. In both cases, the factor for proportioning the engine tests to the results of the Braunschweig cycle is 1.8. The factor is obtained from the amount of work used in the test in relation to the distance travelled (kWh/km).

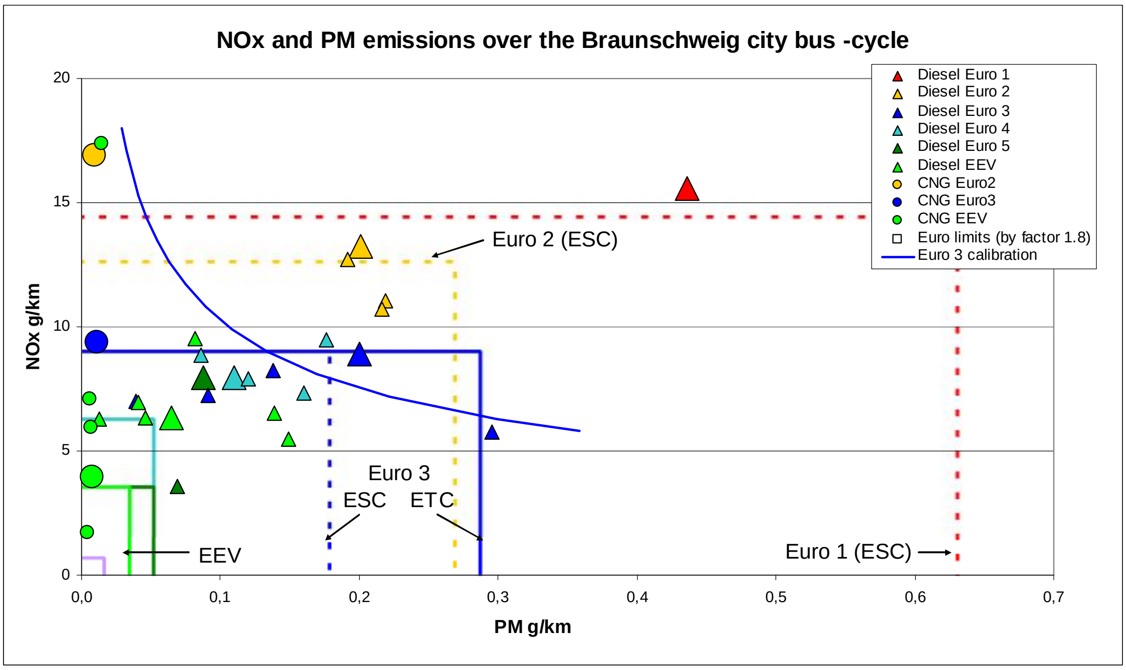


Figure 2.1. The nitrogen oxide (NO_x) and particulate (PM) emissions of a city bus in relation to the distance travelled. The results of the individual measurements of 2008 are presented as small triangles or circles; the averages of all results by emission class are presented as large triangles (diesel buses) or circles (natural gas powered buses).

The results for 2008 are in line with the results of the previous years' measurements. Euro III vehicles follow the calibration curve of Euro III. Two Euro III vehicles provided a significantly better than average particulate emission result. One of the vehicles was equipped with a CRT filter and the other with a pDPF. The emission result of the vehicle equipped with the CRT filter was notably low, even slightly better than the EEV average. However, the vehicle equipped with a pDPF functioned in the same manner as an average Euro V vehicle. Compared to the average Euro III level, the PM emission in a vehicle equipped with a CRT filter was reduced by 80 %. The pDPF in turn reduced the PM emission by 53 %. The results for the Euro IV vehicles are in line with the previous years' results and are at the level of Euro III vehicles, as expected. All new Euro IV results were obtained from measurements carried out in Scania EGR vehicles.

The most interesting set in Figure 2.2 is the diesel EEV series that saw an increase of several vehicles. The NOx emission level in the EEV vehicles in the Braunschweig cycle is, in practice, at the level of the Euro IV limit. Within the group, the NOx emission is at the same level for all vehicle makes. The vast scattering of the vehicles' PM emissions is worth noting. The lowest particulate emissions were measured in Iveco's vehicles equipped with the SCRT system (SCR catalyst + an actual particulate filter). The highest particulate emissions and the vastest scattering within the group, all the way to the Euro III level, were seen in the emissions of the Scania EGR buses.

Of the gas powered vehicles followed up, the MAN EEV operating with a stoichiometric mixture produced an exceptionally high NOx emission (7g/km) and was ranked at the level of the MAN lean mixture buses. Another stoichiometric MAN also produced a result typical of that type of vehicle and ranked clearly within the EEV limits. In 2008, a Mercedes-Benz lean mixture engine vehicle with a Euro 2 → EEV upgrade was also measured. Nevertheless, the upgraded vehicle's result was one typical of the Euro 2 class (Figure 2.1). The result shows clearly that in this case, the impact of the upgrade on emissions was non-existent.

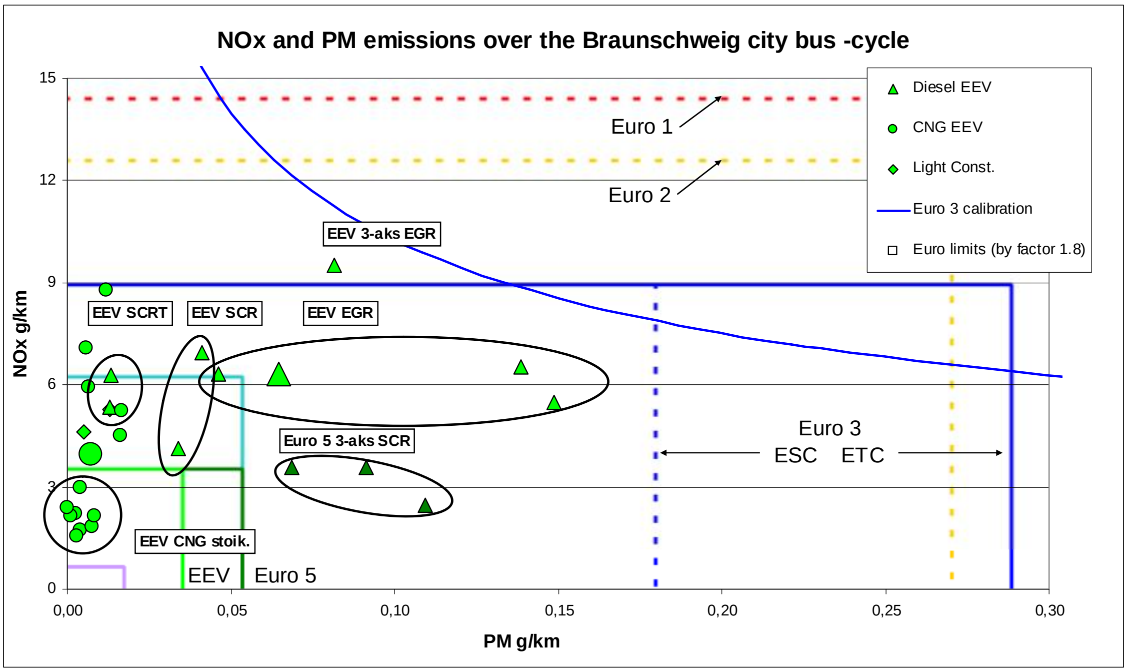


Figure 2.2 The nitrogen oxide (NO$_x$) and particulate (PM) emissions of a city bus in relation to the distance travelled. Measurements 2006–2008

2.1.3 Carbon dioxide emissions and fuel efficiency

Figure 2.3 shows the carbon dioxide (CO$_2$) and nitrogen oxide (NO$_x$) emissions of city buses. The new diesel-powered EEV vehicles rank as follows in terms of energy-efficiency: vehicles equipped with SCR technology give CO_2 results of close to 1,100 g/km, which is a benchmark value for a city bus with a regular structure. For EEV vehicles equipped with EGR technology, the CO_2 result is 1,200 g/km on average.

The results for three-axle vehicles measured in 2008 are in the range of 1,400 g/km, as expected. A new vehicle type was added to the three-axle vehicle group: Scania Euro IV. The NOx and PM emissions of the vehicle measured were typical of the Euro IV class, but its CO_2 emission was high, approximately 1,550 g/km. An average three-axle vehicle is 10 % more energy-efficient than this particular vehicle. The Volvo Euro V and MAN EEV vehicles' results were typical in their classes.

Figure 2.4 shows the CO_2 emissions in relation to the PM emissions. The Iveco SCRT vehicles produced very low particulate emissions, just like gas powered vehicles. The results of the vehicles equipped with SCR technology are promising. The new technology has significantly reduced the emission level of city buses, and at the same time, the vehicles with the new technology are clearly more energy-efficient than their predecessors. Figures 2.3 and 2.4, however, indisputably show the better energy-efficiency of light-weight structure technology compared to traditional buses. The CO_2 readings of diesel powered vehicles shown in the Figures were defined based on the weighed fuel consumption, and due to this the measuring accuracy is good (±1 %). The results of the natural gas powered vehicles are CO_2 emission measurements directly so the variation in measurements is greater, approximately ±15 %.

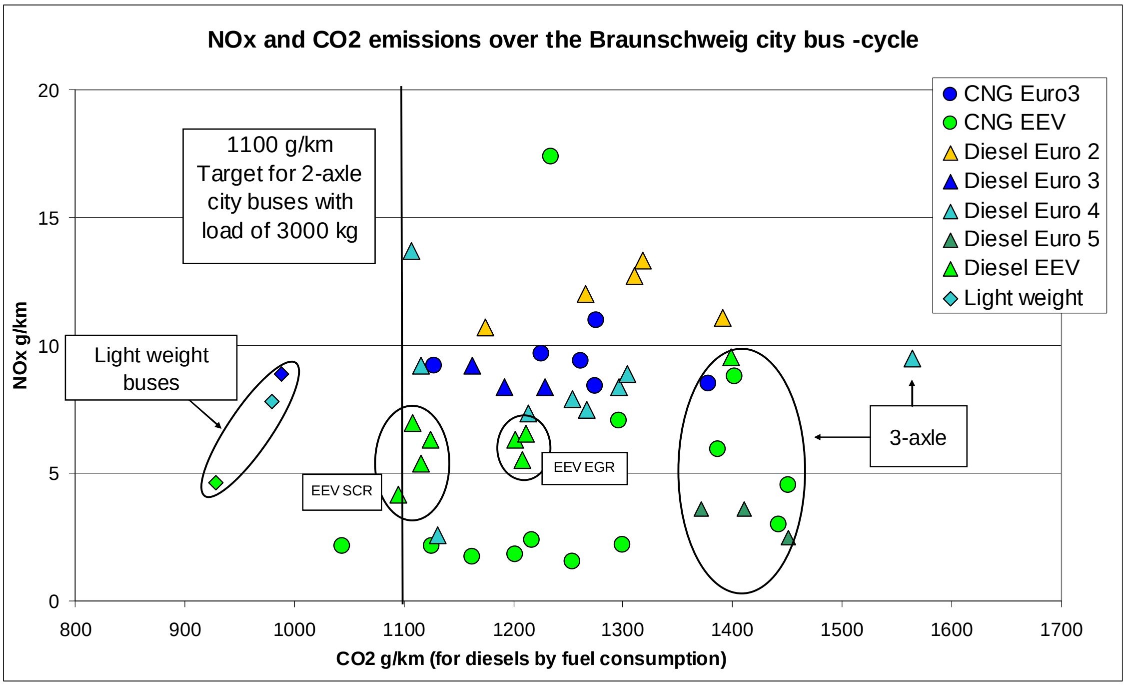


Figure 2.3. Carbon dioxide (CO_2) and nitrogen oxide (NO_x) emissions of city buses.

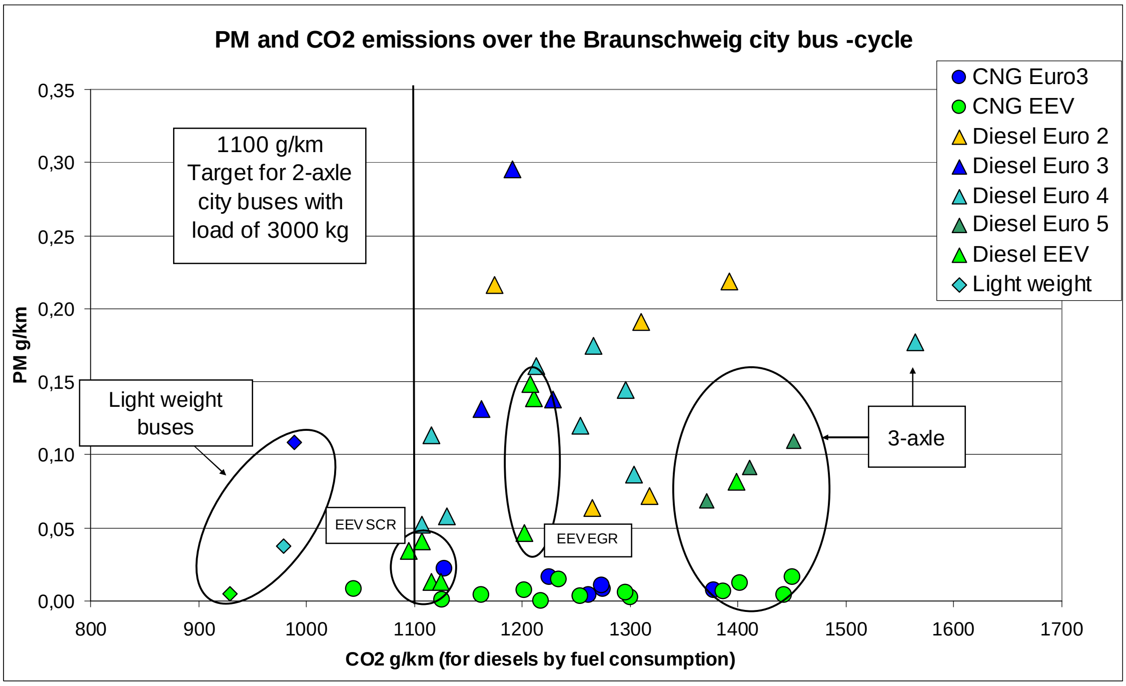


Figure 2.4. Carbon dioxide (CO_2) and particulate matter (PM) emissions.

2.1.4 Follow-up vehicles

Figure 2.5 shows the most recent follow-up result of the Volvo Euro 2 city bus under long-term follow up. The vehicle's emissions have remained at a constant level after the installation of a retrofitted pDPF filter. The follow-up measurement of 2008 does not indicate any kind of increase in the emissions, apart from variations that are typical of the vehicle, and the vehicle is still considered to be in normal operating condition. Please note the variation in the vehicle's annual kilometres travelled.

The monitoring of the 2002 Scania Euro III vehicle (ZOF-209) was discontinued in 2008 due to the decommissioning of the vehicle from the partners' fleet. During follow-up, the performance of the retrofitted oxidation catalyst weakened. In this case, the catalyst should have been replaced after 200,000 to 300,000 kilometres.

The 2008 follow-up measurement of the Euro IV vehicle equipped with EGR technology shows an interesting development in the components of emission. Figure 2.6 shows that the CO emission has increased from the previous year's follow-up by 2.1 g/km, showing an increase of five times the original value. Total hydrocarbon emissions (THC) have also continued increasing after the previous measurement (15 %), and the result has grown threefold from the original level. There has been a reduction of almost 20 % from the original level. The particulate emission did not increase either anymore but returned to the starting level of 0.12 g/km. The vehicle's fuel consumption remained constant during follow-up.

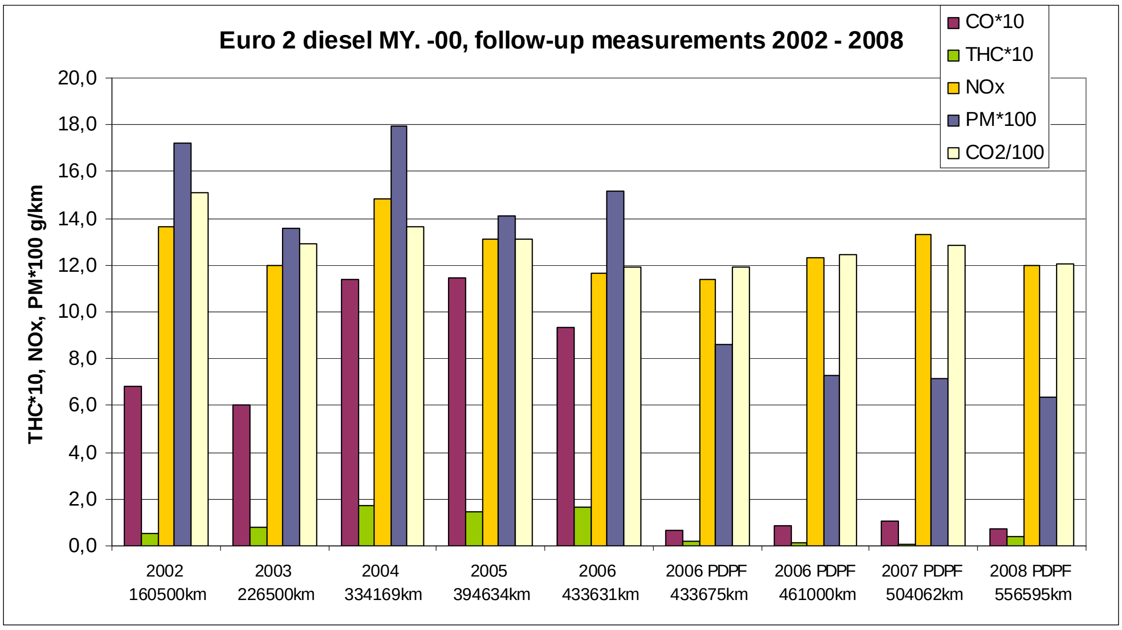


Figure 2.5. The emission results of the Euro 2 follow-up vehicle (ZIX-131, Volvo model year for 2002–2008. A pDPF had been installed in (FK= Proventia pDPF) the vehicle in 2006.

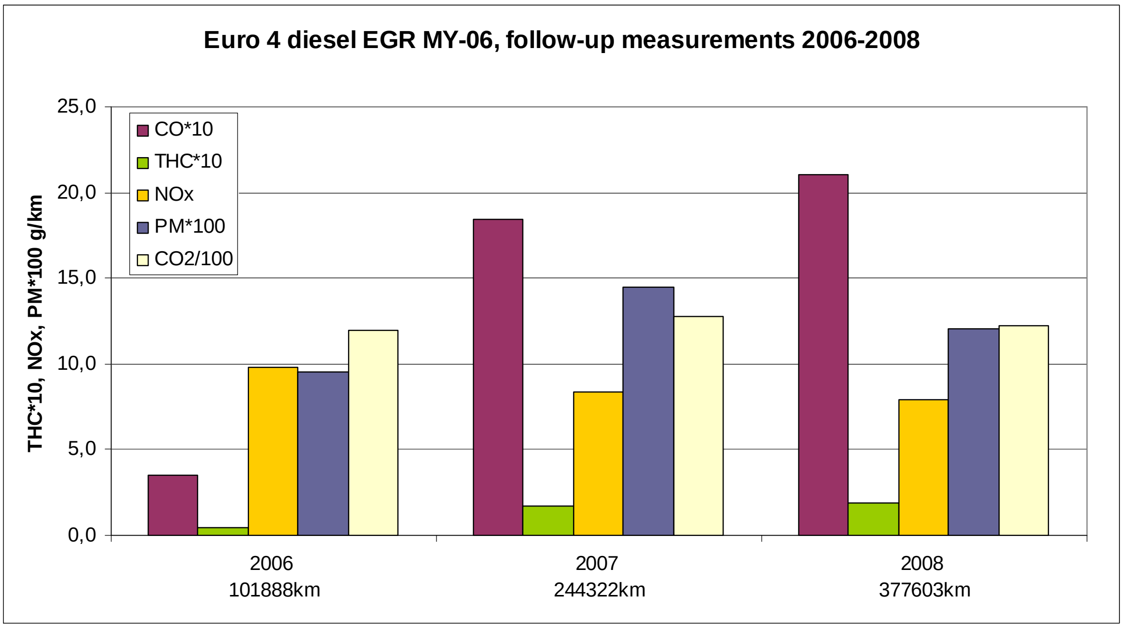


Figure 2.6. The emission results of the Euro IV EGR follow-up vehicle (MRG-632, Scania model year for 2006–2008.

The emissions of the MAN EEV natural gas powered vehicle using a stoichiometric mixture increased significantly compared to the previous results (Figure 2.7). The NOx emissions had nearly tripled compared to their original level. The PM and CO emissions had also grown significantly. The follow-up vehicle's results deviated from a large number of equivalent vehicles, and it is possible that the vehicle in question had a malfunction.

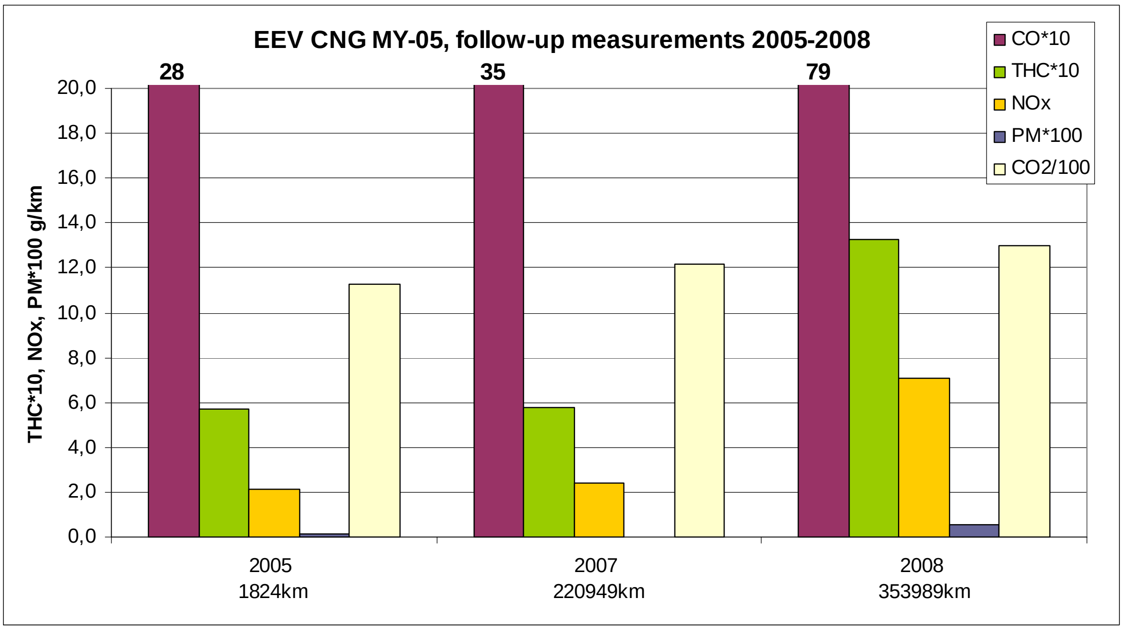


Figure 2.7. The emission results of the EEV natural gas powered (CNG) follow up vehicle (CYU-745, MAN model year 2005) for 2005 and 2008.

2.1.5 Summary

The measurements for the period 2006–2008 indicate that there is a lot of scattering in the actual emission results of the newest EEV diesel powered buses. The best results in terms of the problematic nitrogen oxide and particulate emissions are at the emission limits set for the EEV vehicles, but on average, the situation is worse. The NOx emissions of the majority of the EEV vehicles are near the Euro IV limit. Depending on the technology used, the particulate emissions are at less than half of the limit, or, at the other extreme, the readings are up to four times higher.

On the other hand, although the actual emissions of the EEV vehicles on average settle at the level of Euro IV, these vehicles are still clearly cleaner than the Euro IV vehicles: in reality, they did not reach the set limits either. In accordance with the emission factors shown above in Table 2.3, the NOx emissions of the EEV vehicles were on average 30 % lower and the PM emissions were on average about 45 % lower than the respective averages of the Euro IV vehicles. The vast difference in the particulate emissions can partly be explained by the particulate filter in some EEV bus types and partly by the significant differences between the bus models that were measured.

The measurements during the period also indicate that as the emission regulations are getting tighter, energy efficiency has also improved. In the tests, the newest EEV buses consumed about 5 % less fuel on average than the Euro III and IV buses and more than 10 % less than the Euro II buses.

2.2 MEASUREMENTS OF TRUCKS

2.2.1 General

Truck measurements were performed in different weight categories: 18 ton, 26 ton, 42 ton and 60 ton. The RASTU results make the overall VTT vehicle database for trucks an extensive one, providing excellent representation of the fleet currently in use. The database on the performance of Euro IV-level vehicles is important in evaluating the environmental impacts of the existing fleet. On the other hand, the measurements of follow-up vehicles provide additional information on the stability of performance in these vehicle categories in terms of accumulated kilometres. The importance of the follow-up results is highlighted when the effects of traffic are evaluated over a longer time span.

Previously, vehicle model specific comparisons were carried out in corresponding weight categories for Euro III vehicles in the HDEnergy project, and the earlier Rastu annual reports included information on the Euro IV vehicle measurements. Differences of up to 10 % to 15 % can typically be seen in the fuel consumption results of vehicles designed for the same purpose and with the same emission level.

Research into the 18 ton weight category was supplemented in 2008 by testing four new vehicles in the Euro IV emission class. At the end of the year, a significant amount of new information was added to the database in the 42 ton weight category as well. Three out of four new vehicles were new Euro V vehicles. The summary figures contain the results of the three-year measurements for all of them. The results of the Euro III vehicles are presented as the average of the category in question with three loads. The figures for the Euro IV and Euro V vehicles are for each individual vehicle with three loads as well. As a rule, the emission per work decreases as the vehicle's load increases. However, in the Euro IV and Euro V vehicles equipped with exhaust after-treatment technologies, only the particulate or NOx emission may decrease while the other component remains nearly unchanged.

The emission limits of the Euro classes have been scaled up by a coefficient of 1.5 to simulate emission results measured from the tractive wheel. The coefficient of 1.5 is an estimate of the losses caused by the powertrain, tyres and accessories; typically the losses are smaller. For example, in the Euro 4 class, the emission limits in the ETC engine test are 3.5 g/kWh for NO_x and 0.03 g/kWh for particulates. By applying the coefficient of 1.5 to these values (without a separate NTE factor), the comparison value of the chassis dynamometer measurements of the Euro 4 vehicles is approximately 5 g/kWh for NO_x and 0.05 g/kWh for particulates. This is only a rough estimate since, in reality, the loss coefficient depends on, among other things, the load level and driving cycle.

Under all the vehicle categories there is a chart in which fuel and urea consumptions are presented. In 42 ton class there is also a chart where fuel and urea costs are presented. The price of diesel used in all cost calculations is EUR 1.00 and that of urea, EUR 0.50 per litre. In the text there are comments about the vehicle fuel economy. These comments refer to combined cost calculations of fuel and urea using values above (the percentages also refer to these cost calculations)

2.2.2 Comparison measurements of 42 ton trucks

Several interesting additions were made to the 42 ton weight category in 2008. A new make in the comparison measurements is DAF, which provided a Euro V vehicle equipped with SCR technology for testing. New technology in the series is represented by Iveco and MB SCR as well as Euro V vehicles from Scania relying on EGR technology.

Figure 2.8 shows significant differences in the fuel consumption results in the highway cycle. Considering the costs of urea (5 to 7 % of fuel consumption), MB is the most economical vehicle in this weight category with an average difference of 5 % compared to the most uneconomical vehicle, regardless of the load (Figure 2.9). The other vehicles' compared results were consistent within the limits of the measurement accuracy (± 1 %).

In the freeway cycle, the order of the most economical vehicles remains unchanged but the difference between them is smaller (Figure 2.10). This is partly due to the increased urea consumption in the SCR vehicles (+0.5 %). MB SCR continued to be the most economical option, with a difference of 5 % compared to the weakest one. Scania EGR fell short of the best result by about 2 % -points but was still the second most economical.

In both cycles, the most uneconomical comparison depends on the load level; in other words, none of the vehicles received the worst results with all loads. In particular, in the freeway cycle the vehicles in the Euro IV and Euro V classes were more economical than an average vehicle in the Euro III class.

In terms of exhaust emissions, all makes performed well in the highway cycle and remained within the emission class limits. The result of the Volvo FE240 Euro was even at the level of Euro V (Figure 2.11). The entire new 42 ton category performed well in the freeway cycle as well (Figure 2.12). In the Euro V class, however, only Iveco and in the Euro IV class Volvo remained below the limits in all loads. Compared with the Euro III average, the actual emissions of all makes decreased significantly.

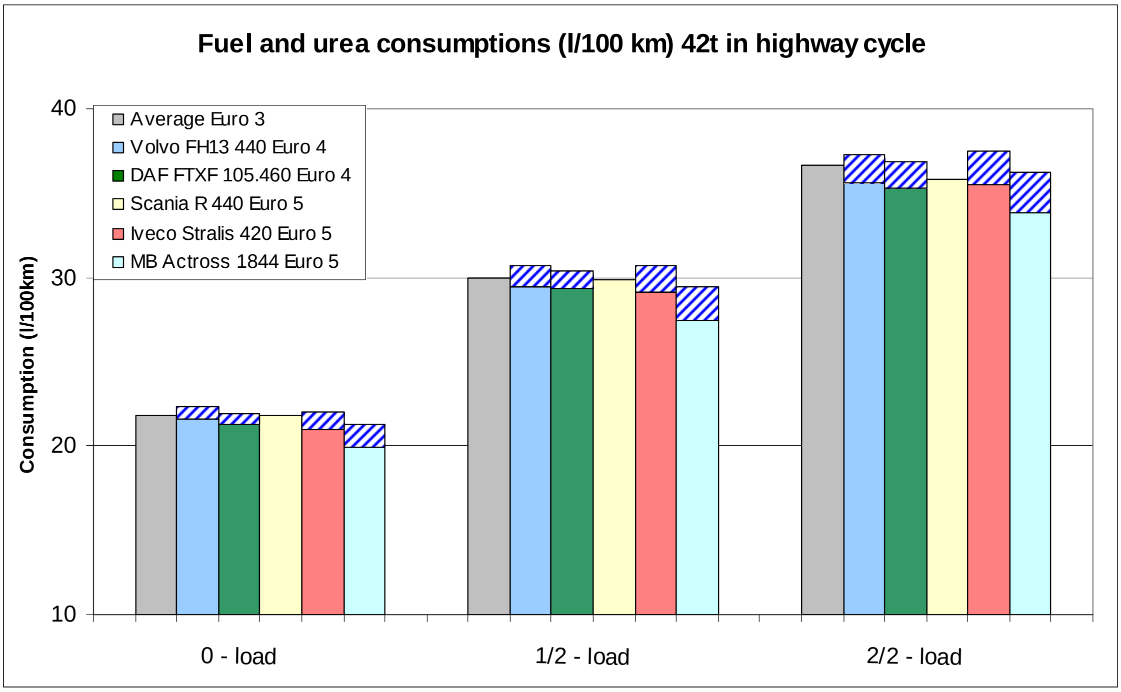


Figure 2.8. Fuel and urea consumption, 42 ton category, highway cycle

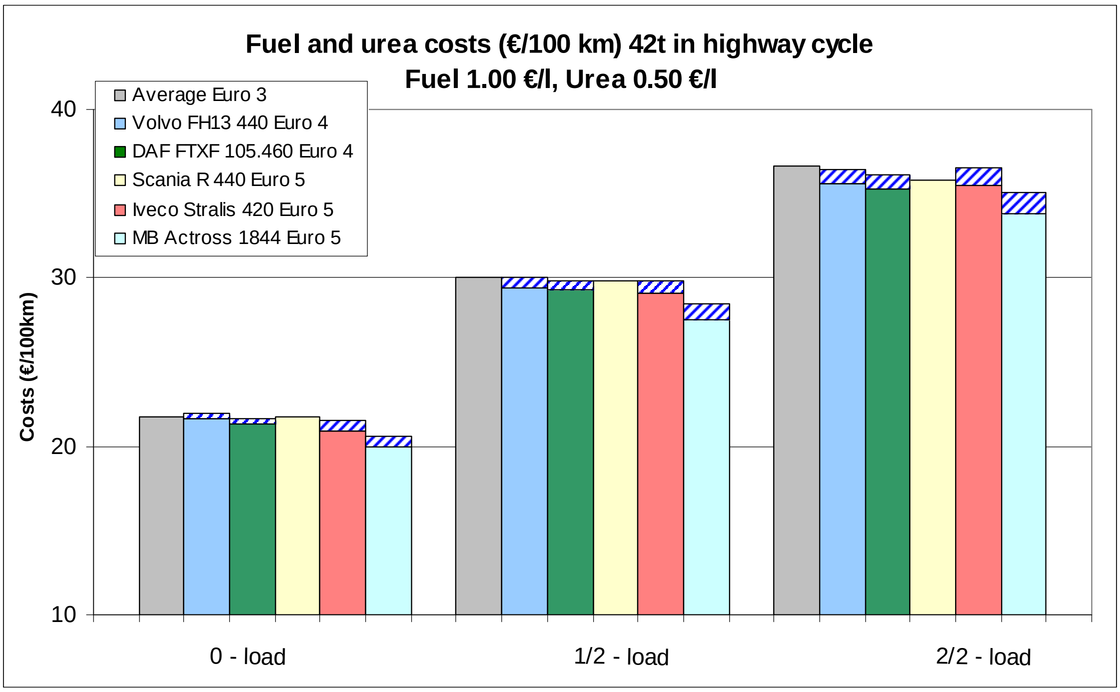


Figure 2.9 Fuel and urea costs, 42 ton category, highway cycle

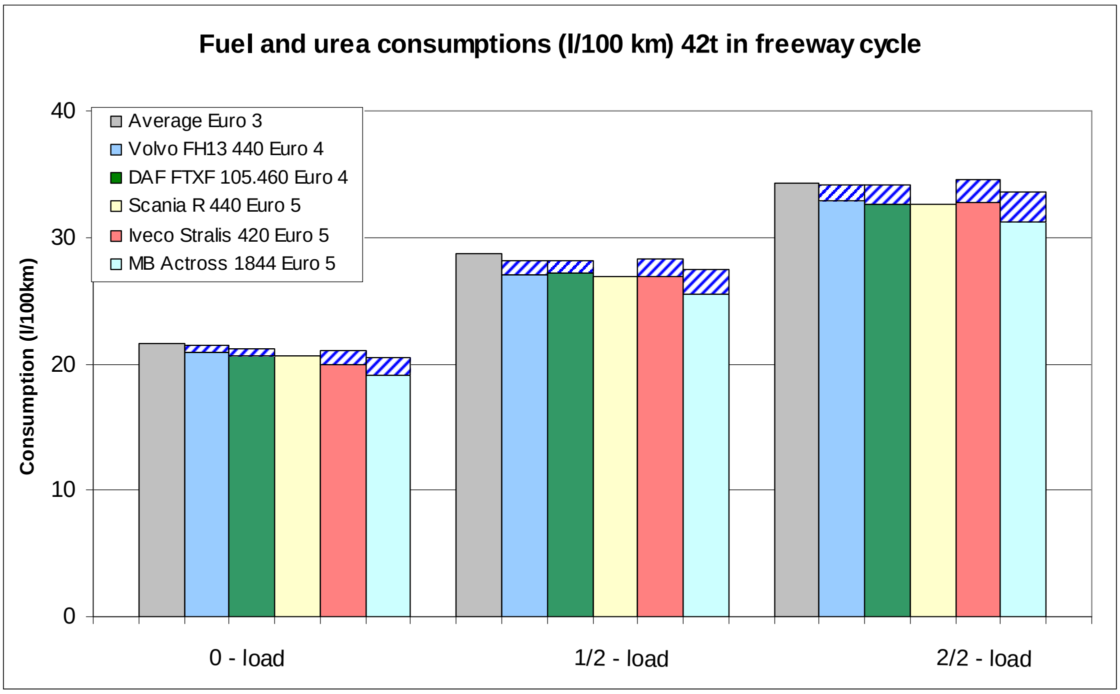


Figure 2.10. Fuel and urea consumption, 42 ton category, freeway cycle

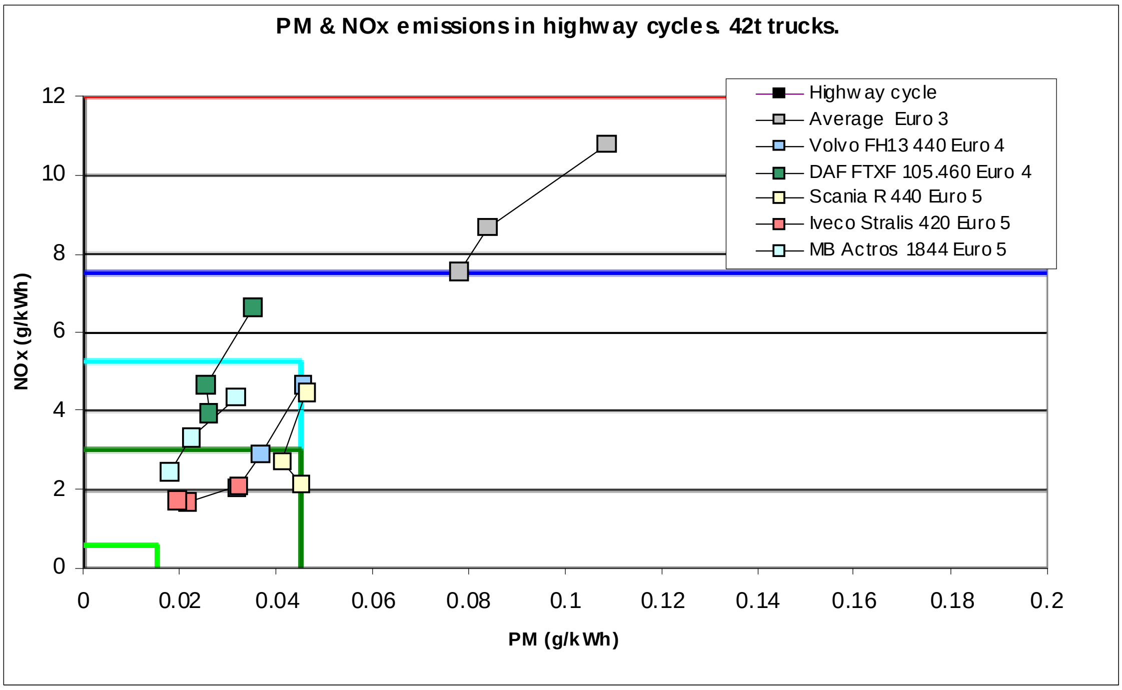


Figure 2.11. NO_x and PM emissions per driven wheel work, 42 ton category, highway cycle

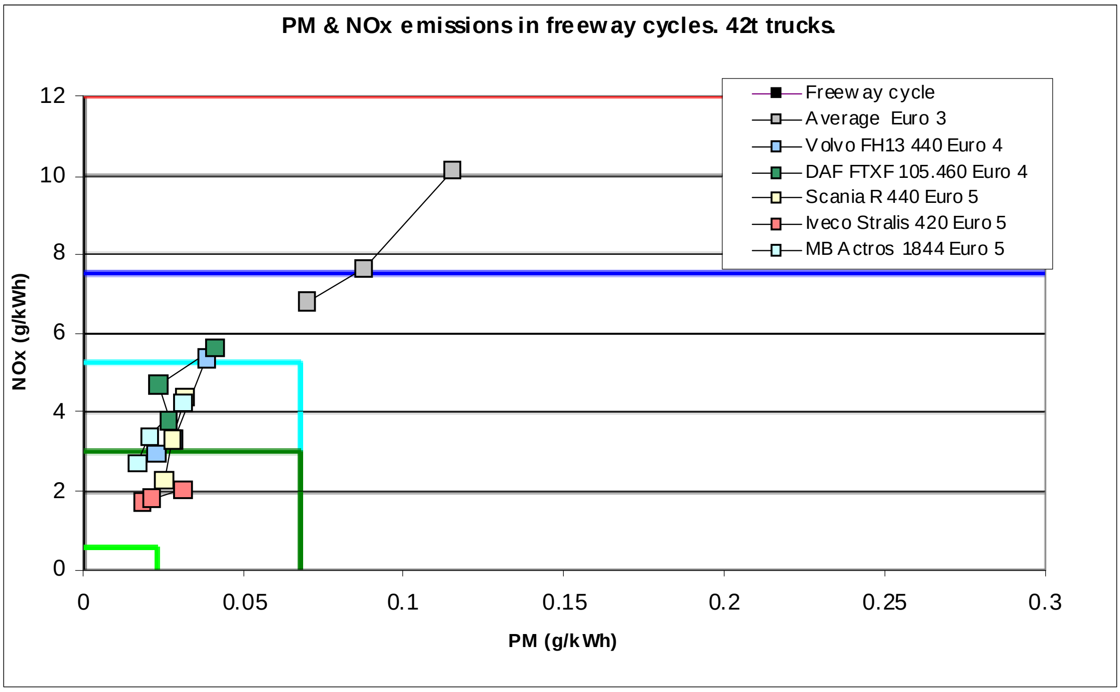


Figure 2.12. NO_x and PM emissions per driven wheel work, 42 ton category, freeway cycle

2.2.3 Comparison measurements of 18 ton delivery trucks

The test series for the 18 ton vehicles grew by four new Euro IV-level vehicles. The older Volvo FE 320 result was replaced with a new Volvo FE 240 with a more suitable power class for the series.

Figure 2.13 shows the fuel consumption results for 18 ton category.. In a consumption comparison of the vehicles, converted into costs, in the delivery cycle, that also took urea consumption into account, Iveco's SCR technology produced an excellent result: the result was, on average, 7 % more energy-efficient than the most uneconomical option in all load categories. Correspondingly, the MAN EGR was the second most economical in all load categories with a 1 % -points weaker result than that of the Iveco SCR.

Figure 2.14 shows the corresponding results in the highway cycle. In the highway cycle, the best result was produced by Iveco Stralis Euro IV. On average, Iveco was 9 % more economical than the most uneconomical option at all load levels.

In terms of exhaust emissions, compared to highway and freeway cycles, the delivery cycle is a challenging task. Volvo FE240 was the only individual vehicle that remained within the Euro IV range in this cycle. MB and MAN performed reasonably well with the exception of an empty vehicle. The results of Iveco and Renault show a strong scattering of NOx that is dependent on load. The results of MB show strong, load dependent scattering in both NOx and PM (Figure 2.15).

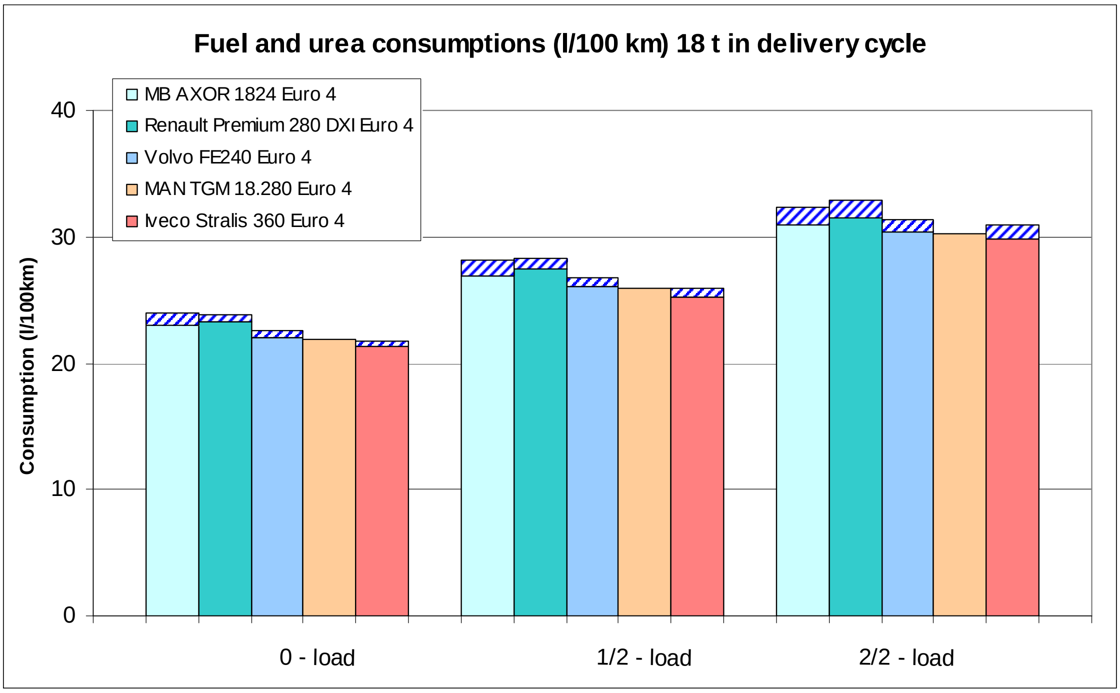


Figure 2.13. Fuel and urea consumption, 18 ton category, delivery cycle

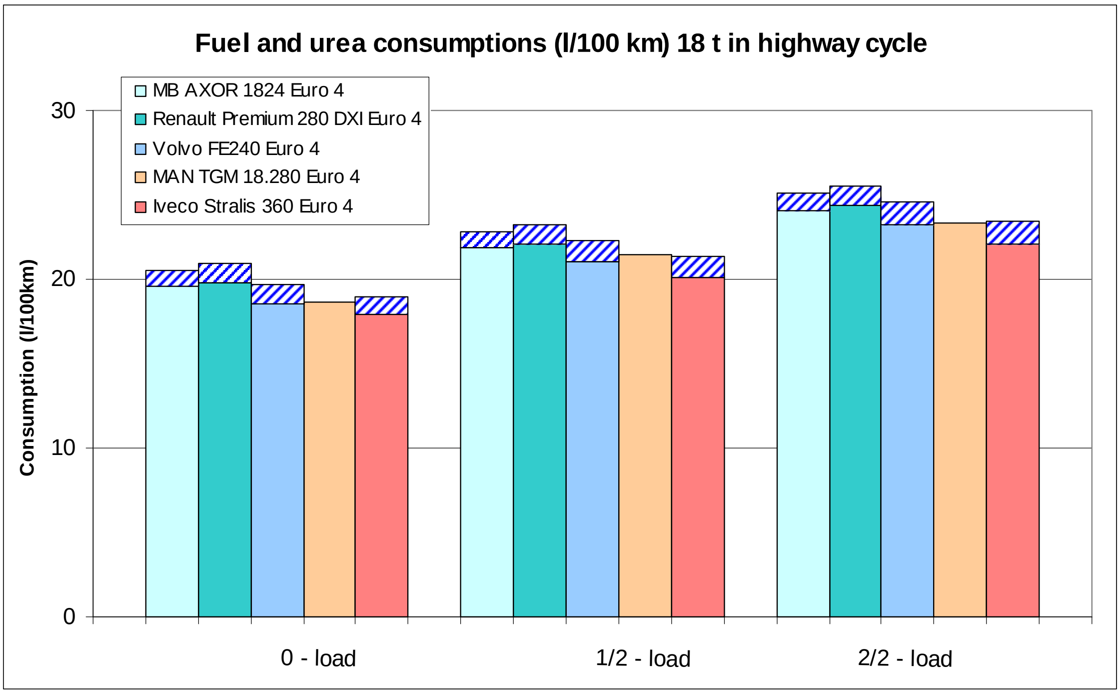


Figure 2.14. Fuel and urea consumption, 18 ton category, highway cycle

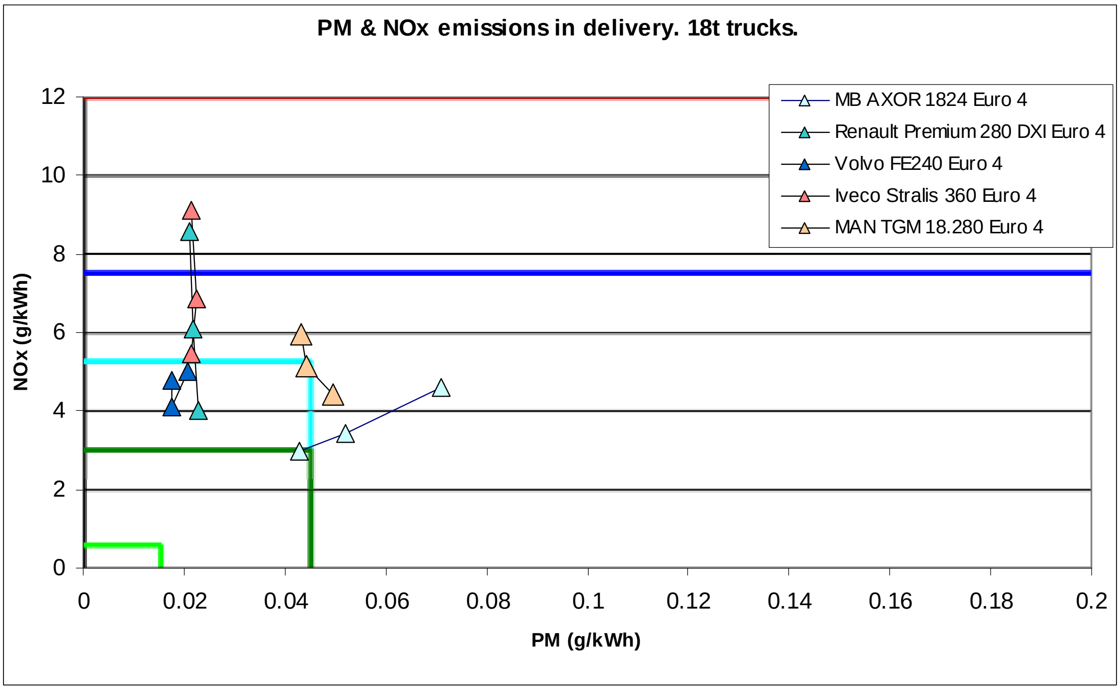


Figure 2.15. NO_x and PM emissions per driven wheel work, 18 ton category delivery cycle

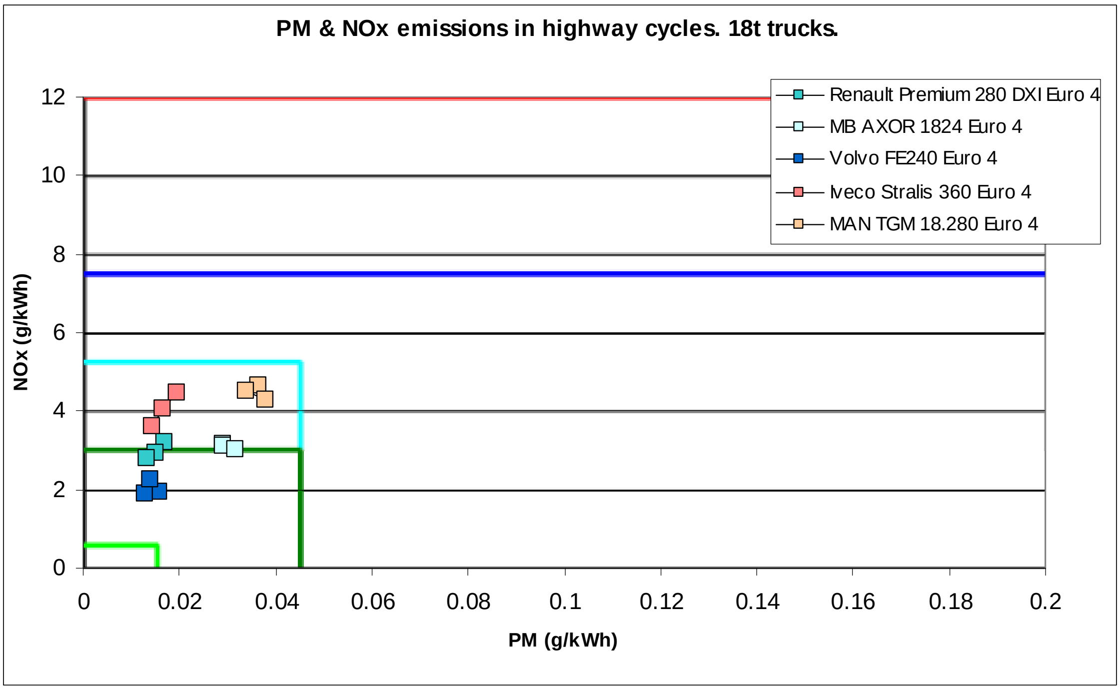


Figure 2.16. NO_x and PM emissions per driven wheel work, 18 ton category, highway cycle

2.2.4 Comparison measurements of 26 ton trucks

The heavy-duty delivery truck class is an interesting group to compare, since it consists of vehicles from both the 42 ton category and 60 ton category.

Figure 2.17 shows quite large differences in fuel consumption between vehicles. MB Euro V stands out as the most economical option with an average difference of 12 % compared to the most uneconomical alternative. Although the differences between makes are remarkably big within the class, the result of all makes are better than the Euro III average level.

In the demanding delivery cycle, heavy-duty delivery trucks do not stay within the range of the Euro IV class. The scattering of the EGR vehicle results due to load in both the 18 ton and 26 ton category was smaller than that for vehicles equipped with SCR technology (Figure 2.18).

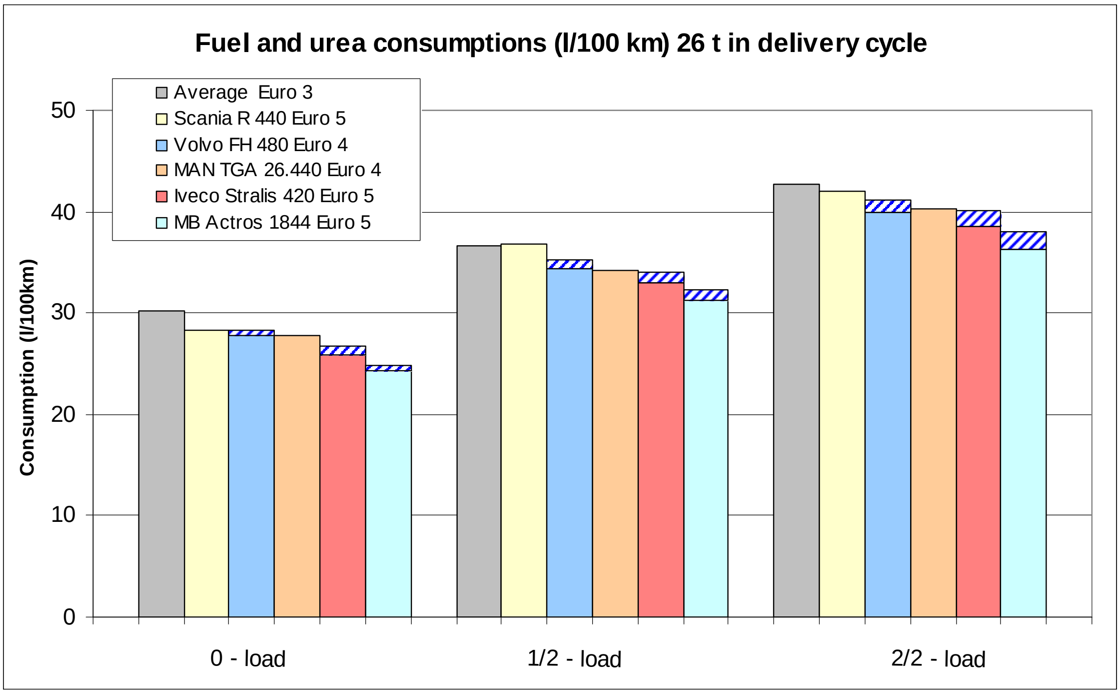


Figure 2.17. Fuel and urea consumption, 26 ton category, delivery cycle

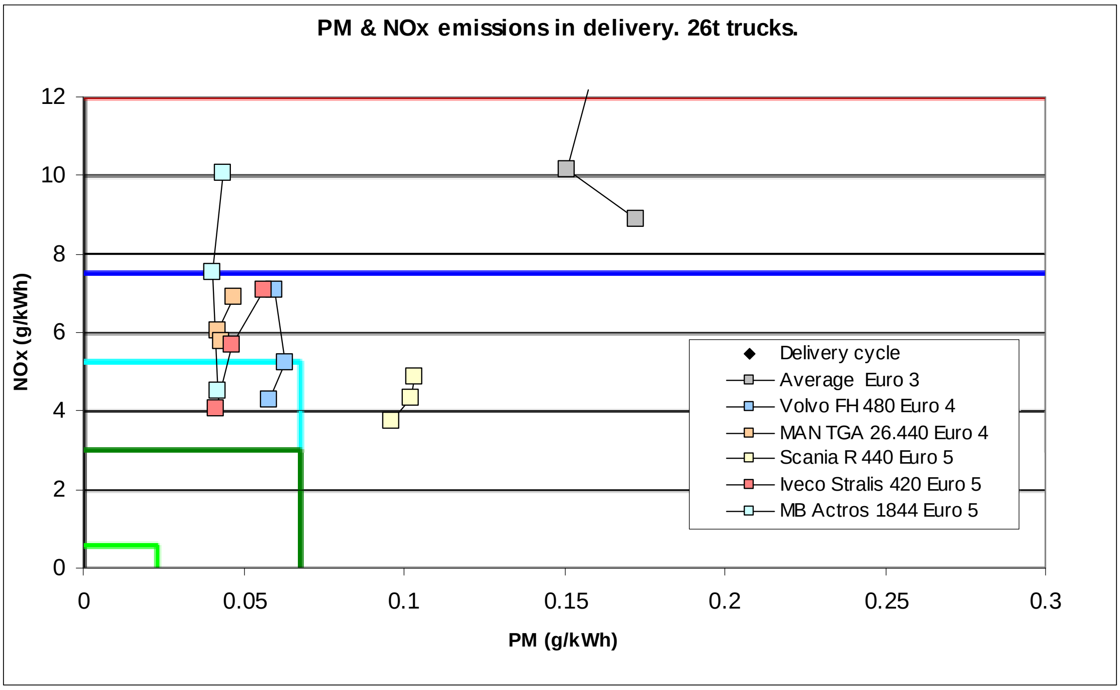


Figure 2.18. NO_x and PM emissions per driven wheel work, 26 ton delivery cycle

2.2.5 Follow-up measurements

During the RASTU project, two 60 ton trucks, Iveco Stralis 420 Euro IV SCR and Scania R420 Euro IV EGR, were tested. Initially, the aim was to perform measurements at sparsing kilometre intervals but due to changes made to the vehicles, the measurement intervals were shortened as needed.

In 2008, Iveco was measured twice, at 90,000 kilometres and again at 140,000 kilometres. In terms of fuel consumption, the vehicle remained constant throughout the entire follow-up period (Figure 2.19).

Emissions varied widely in Iveco. With the accumulated kilometres, the NOx emissions first decreased (-18 %) but in the latest measurements they rose higher than the original level (+5 %). PM emissions were also on the rise. At its lowest, the PM emission was as low as -35 % from the original value. The last measurement, however, indicated a clear increase (+16 %) in the PM emission as well. Nevertheless, it is too early to conclude that this would mean a rising emission trend. Changes in the emission level may still indicate fluctuation that is characteristic to the vehicle, although this fluctuation would be quite significant.

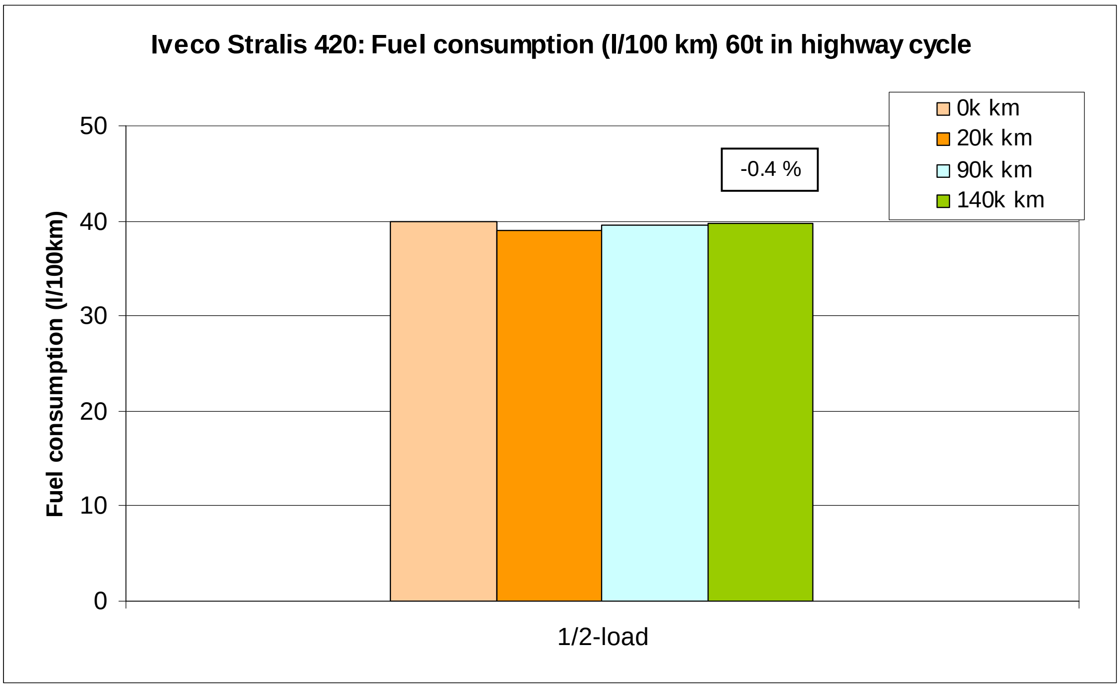


Figure 2.19. Iveco Stralis 420 follow-up, fuel consumption, 60 ton highway cycle. The difference percentage between the latest measurement and the original value

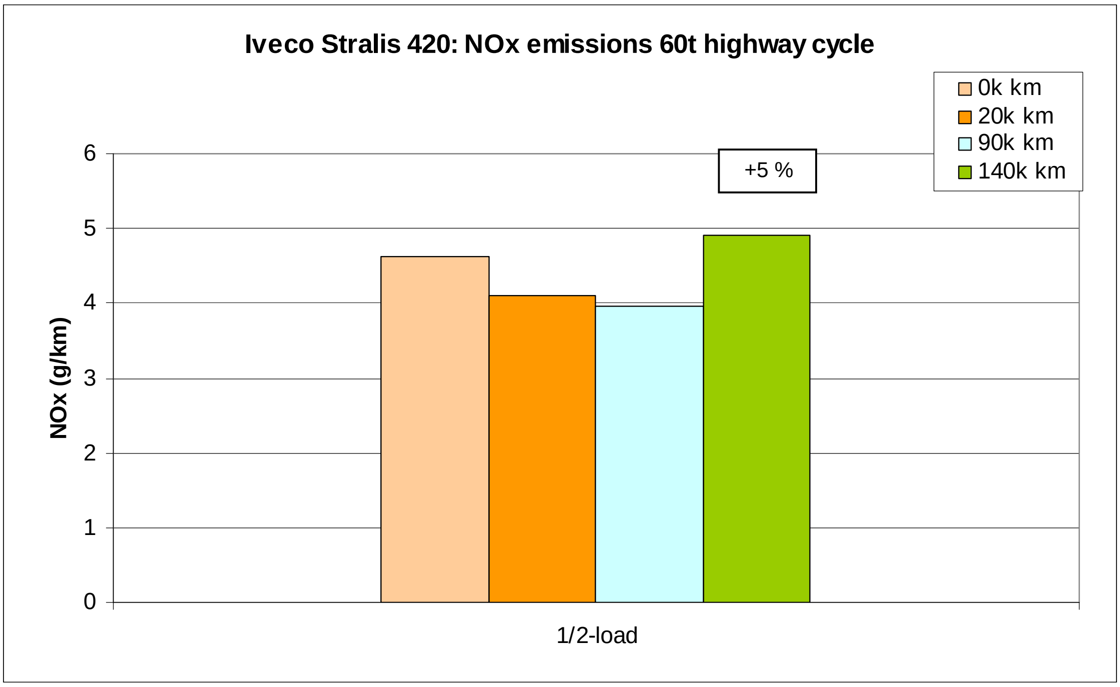


Figure 2.20. Iveco Stralis 420 follow-up, NOx emissions, 60 ton highway cycle

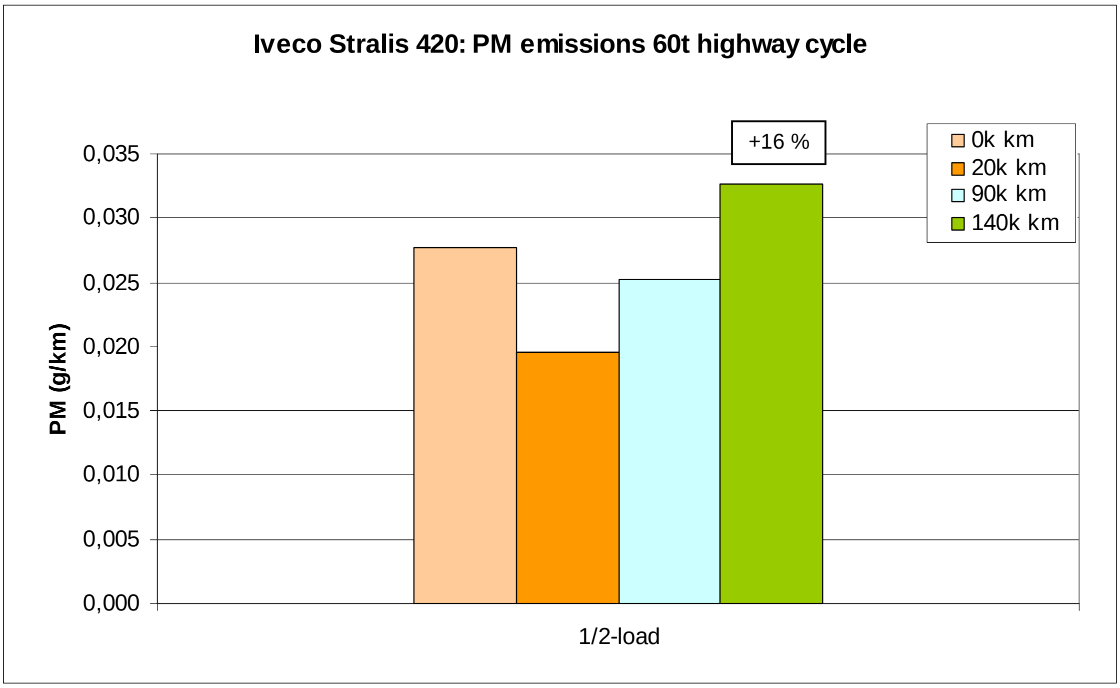


Figure 2.21. Iveco Stralis 420 follow-up, PM emissions, 60 ton highway cycle

The Scania R420 Euro IV vehicle was measured as many as four times in 2008. The follow-up measurements were performed at 50,000, 160,000 and 200,000 kilometres. In addition, the vehicle was tested due to the change of rear gearing at 70,000 kilometres.

Scania's fuel consumption remained very constant until the last measurement, in which an exceptionally large decrease (-3.2 %) was observed. The difference is so significant that a clear change has occurred in consumption (Figure 2.22). All measurements were performed using VTT's measurement tyres on the tractive wheels, in which case, for example, tyre wear does not affect the result.

It seems like Scania's NOx emissions vary in the same way as in the case of Iveco, and it is not possible to determine a clear trend, although the last measurement indicated an emission level that clearly exceeded the starting level (+13 %). The PM emission increased in the latest two measurements, as much as +45 % compared to the starting level. (Figures 2.23 and 2.24)

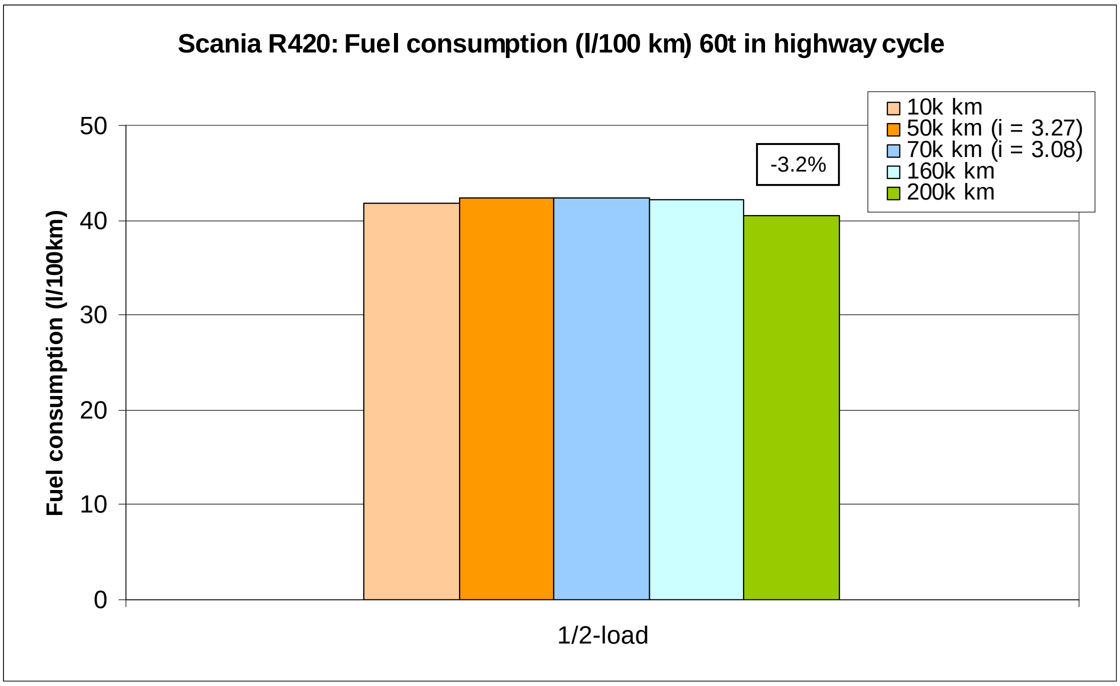


Figure 2.22. Scania R420 follow-up, fuel consumption, 60 ton vehicles, highway cycle.

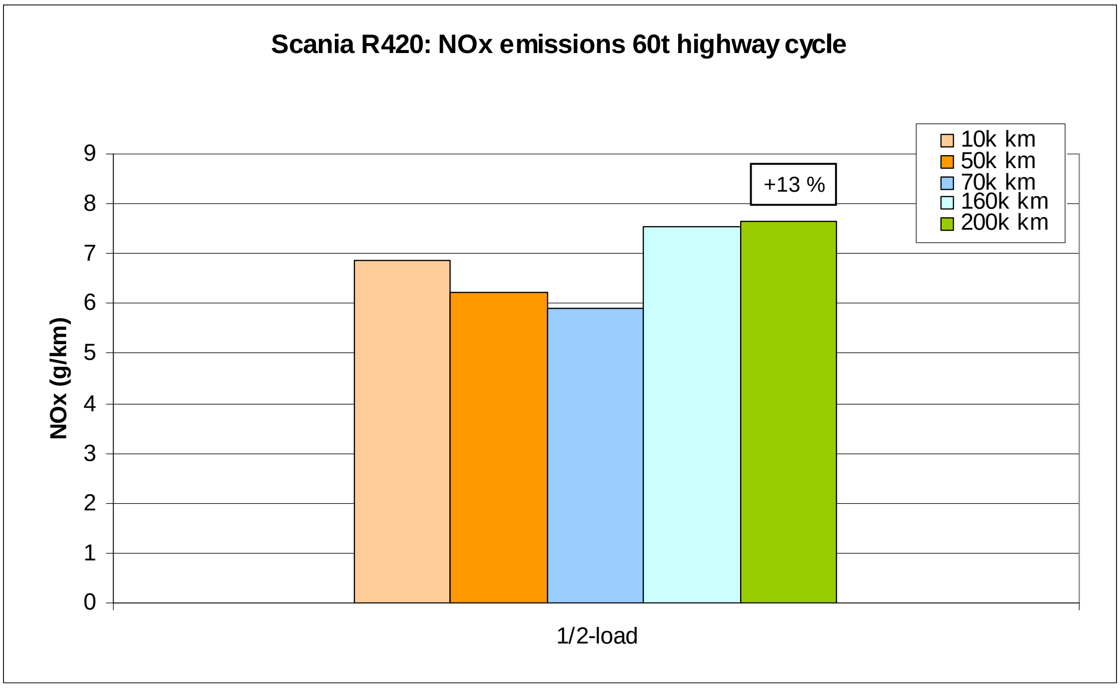


Figure 2.23. Scania R420 follow-up, NOx emissions, 60 ton vehicles, highway cycle.

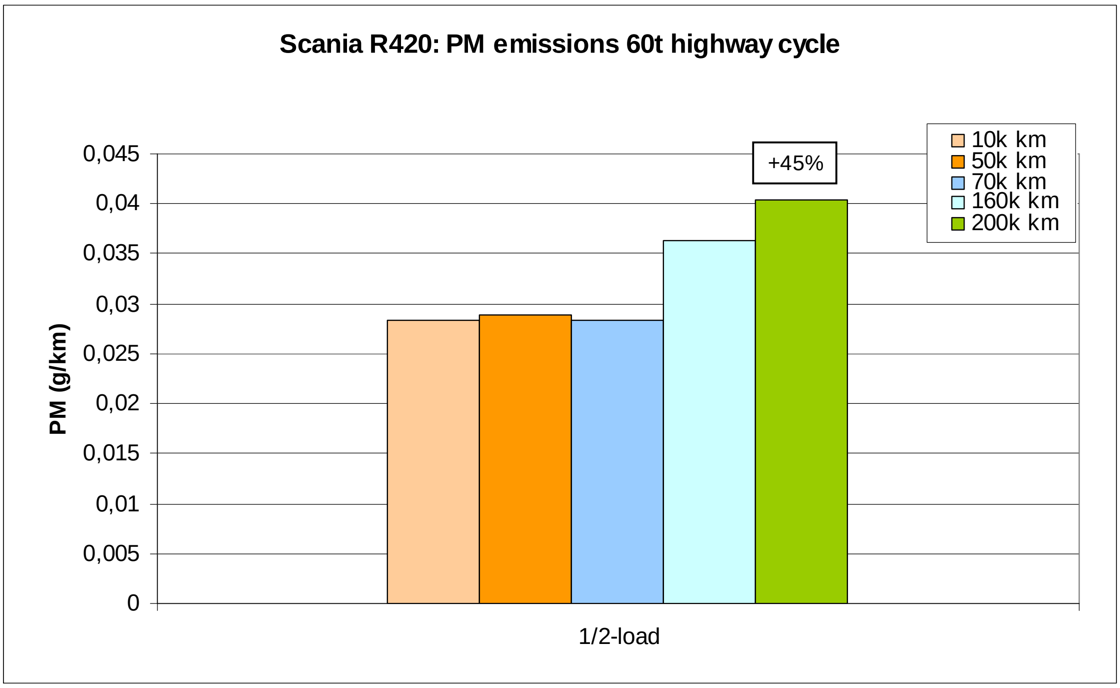


Figure 2.24. Scania R420 follow-up, PM emissions, 60 ton vehicles, highway cycle.

2.2.6 Summary

The conclusion drawn from the 2006–2008 measurements is that the newest Euro IV and Euro V trucks comply with the emission restrictions and are as clean as expected in actual road operations as well. The changes in the engine loads are clearly less varied in truck operations than, for example, in the case of city buses. In addition, the engine transient cycle (ETC) test was originally developed on the basis of the truck load profiles, which partly explains why the emissions are well under control in the actual driving cycles of trucks.

New engine types in trucks, just as in city buses, are more economical than before despite the tightened emission regulations. On the one hand, this is due to the optimisation of engine adjustments for fuel efficiency made possible by SCR systems, and on the other, the introduction of new engine types to the market.

The vehicle equipped with an SCR system was the most fuel efficient and, taking the potential urea expense into account, also most economical in all vehicle classes. The SCR system alone, however, does not guarantee economical operations since an EGR vehicle was the second most economical among both the 18 ton and 42 ton vehicles.

3 FUEL AND LUBRICANTS FOR EURO IV/V/EEV VEHICLES

Responsible party: VTT Technical Research Centre of Finland

Text: Matti Kytö

3.1 GENERAL

During 2006–2008, the test programme contained fuel tests on renewable NExBTL biodiesel, produced by means of hydrogenation technology, conventional RME biodiesel and Swedish low-emission MK1 (Miljö Klass 1) fuel. The impact of lubricants was studied both in a Cummins diesel engine using an engine test bench and in an entire vehicle using a chassis dynamometer. Vehicle measurements were also used to study the effect of automatic transmission oils on fuel consumption, but the scope was relatively limited.

Lubricant measurements supplementing previous measurement series only were carried out in 2008. The results are reported in Chapter 3.3. The central findings from fuel tests performed earlier are summarised in Chapter 3.2.

3.2 FUEL TESTING

In 2007, fuel tests were carried out on vehicles used in postal deliveries and also using delivery cycles primarily describing the operation of these vehicles. The fuels tested were a commercial diesel fuel, methyl ester of rapeseed oil (RME), and hydrogenated renewable diesel fuel NExBTL produced by Neste Oil Ltd. A detailed report on the tests is available in the 2007 annual report. In this document, only the central findings are included. The central findings of the 2006 bus tests (NExBTL vs. Finnish commercial diesel) and truck tests (Swedish low-emission MK1 diesel fuel vs. Finnish commercial diesel) are reported in this document.

3.2.1 Light-duty vehicle tests

The tests were performed using a 2004 Volkswagen Transporter 1.9 TDI-7HK-Kastern van using a postal delivery cycle.

The tests measured regulated exhaust emissions (carbon monoxide, total hydrocarbons, nitrogen oxides, particulate matter and carbon dioxide) and fuel consumption. Fuel consumption was measured on a scale by recording the mass consumed during the test. This data was converted into consumption as litres per one hundred kilometres (l/100 km).

Compared to the diesel fuel, RME reduced particulate emissions significantly and increased nitrogen oxide emissions. The result is highly typical. In other tests with the same fuels, the NO_x emission increased somewhat and the particulate emission decreased significantly. The change percentages vary slightly with different engines. In this test, the particulate emission of pure RME reduced by 65–75 % compared to the particulate emission measured from diesel fuel, and the NO_x emission increased by 12–20 %. The changes in the nitrogen oxide and particulate emissions were fairly linear, even though there are no measurements from the range RME 50–100 %.

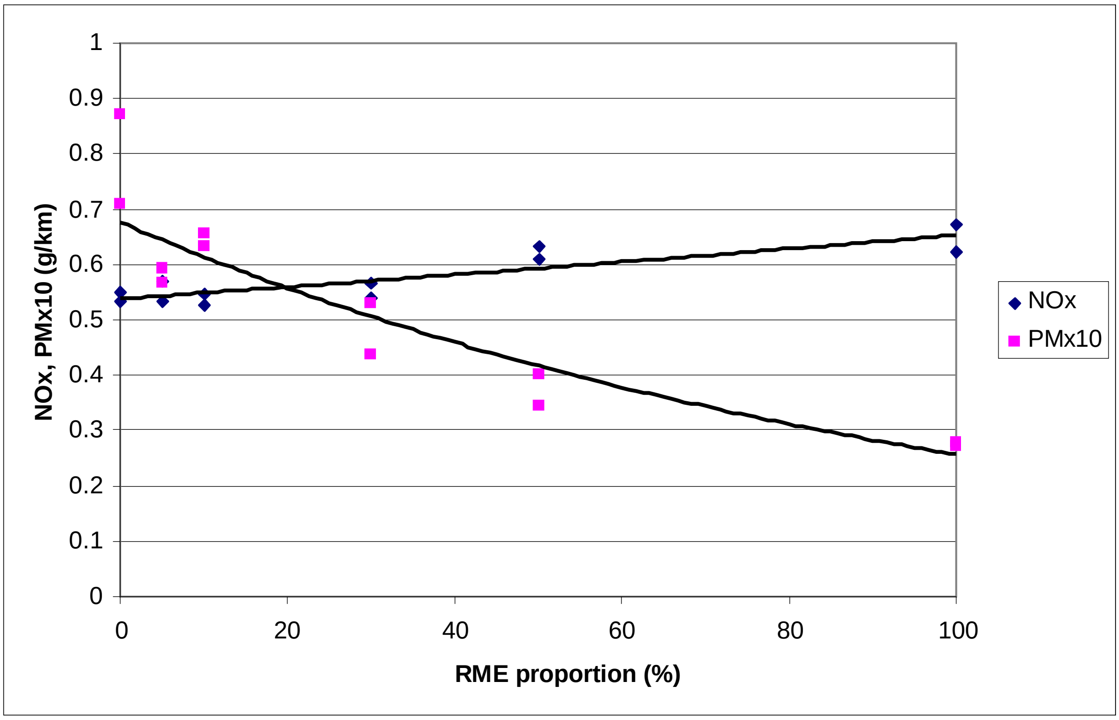


Figure 3.1. NO_x and particulate emission (particulate emission x 10) for different fuel mixtures in postal delivery cycle.

With pure RME, the volumetric fuel consumption increased by 8–11 % compared to the corresponding values measured from diesel fuel. The increase is greater than could be expected based on the difference in fuel temperature values (diesel fuel typically 36 MJ/l, RME 34 MJ/l; in other words, the difference is approximately 6 %).

3.2.2 Heavy-duty delivery vehicle tests

The heavy-duty vehicle measurements were carried out using a 2004 MAN Euro III truck equipped with medium-duty EGR technology. The truck type is used by the Finnish Postal Service for short distance delivery. The test cycle used was a delivery cycle developed by VTT, describing a typical short-distance delivery in suburban areas.

The test fuels were a summer-grade diesel fuel, NExBTL bio fuel, RME and mixtures of RME and diesel fuel containing 5 %, 30 % and 50 % of RME. The tests were performed on the VTT heavy-duty fleet chassis dynamometer. The diesel fuel and RME results for trucks were largely similar to those obtained for a van. Compared to the diesel fuel, RME reduced particulate emissions significantly but increased nitrogen oxide emissions. The particulate emission of pure RME decreased by 65 % compared to the particulate emission measured from diesel fuel, and the NO_x emission increased by 21 %. The changes were still quite linear as the RME content increased. The scattering of results was very small.

In terms of particulate emissions, NExBTL was similar to the 50/50 mixture of diesel fuel and RME (-30 %). Its NO_x emissions, however, were nearly 10 % lower compared to the emissions of conventional diesel fuel, and approximately 25 % lower compared to the NO_x emissions of pure RME.

The volumetric fuel consumption of pure RME increased by approximately 9 % from the consumption of conventional diesel fuel. With NExBTL, the corresponding increase was about 4 %. The density of NExBTL is smaller than that of conventional diesel fuel, which is the cause of the increase in volumetric consumption.

3.2.3 Tests on buses (NExBTL) and trucks (MK1)

In 2006, comparison tests were carried out using conventional diesel fuel, NExBTL bio fuel, and Swedish MK1 fuel. The NExBTL measurements were carried out on two Euro IV-level buses only. At the request of the Swedish Vägverket, the Swedish MK1 diesel fuel (Miljöklass 1, a low-emission diesel fuel) was tested in two heavy-duty vehicles.

The 100 % NExBTL bio fuel measurements were carried out on a Euro IV-certified, 9-litre Scania EGR vehicle and on a 7-litre Volvo SCR vehicle. The comparison fuel was a summer-grade commercial diesel fuel. In both vehicles, the NExBTL fuel reduced the NO_x emission by almost 10 %. The impact on particulate emission was more significant. In the SCR Volvo, the quantity of particulates decreased by 30 %, and in the EGR Scania, as much as by 46 %. Fuel consumption in litres grew in the range of 5 %, which is due to the density of NExBTL that is lower than that of conventional diesel fuel.

The comparison of the Swedish MK1 fuel and the Finnish diesel fuel was carried out using two 60 ton combination trucks: a MAN and a Mercedes-Benz. In both vehicles, the MK1 fuel decreased particulate emissions: in the Mercedes-Benz by 15–20 % and in the MAN by as much as 40 %. On the other hand, in the MAN truck equipped with EGR technology, the MK1 fuel increased NO_x emissions. In the Mercedes-Benz equipped with an SCR system, however, the MK1 fuel reduced the NO_x emissions by 25 %. The impact of MK1 on fuel consumption was as expected, in other words, there was no change in the mass based fuel consumption and a slight increase in the fuel consumption measured in litres due to the smaller density of MK1 compared to conventional diesel fuel.

3.3 LUBRICANT TESTING

Research into the effect of engine lubricant quality on the fuel consumption of the Cummins ISBe4 160B (Euro IV) engine continued with aged lubricants in 2008. The

2006 RASTU annual report contained the results of tests carried out using 14 new lubricant oils, including the reference oil. The largest measured difference between two lubricants was approximately 1.2 %. In an individual load point, the maximum difference was approximately 1.5 %. The test series for 2008 measured fuel consumption in three lubricants that were aged on buses. The vehicles used in the aging were used in regular operations. Each lubricant was aged on two buses operated by Oy Pohjolan Henkilöliikenne Ab, one of which was used in city traffic and the other in regular coach traffic. The vehicle pairs were selected so that the aging of each lubricant was as equal as possible. In city traffic, the lubricants were aged for approximately 32,000 kilometres and in regular coach traffic, on average, nearly 50,000 kilometres. Engine tests were carried out with combined lubricant samples: in other words, the same lubricant brand samples taken from a city bus and coach were combined into one sample. The basic data for lubricants used in engine tests is presented in Table 3.1. The viscosity of one lubricant had decreased to slightly under the lower limit of the grade in question.

Table 3.1. Lubricants used in the tests

Lubricant	Viscosity grade	viscosity of an **aged** sample at 100 °C, cSt	average distance travelled, km
Neste Turbo LXE	10W-40	12.19	39770
Castrol Elixion LowSAPS	5W-30	10.76	43900
Shell Rimula Ultra (E7)	10W-40	13.45	37960

The engine used in the testing is a 4.5-litre Cummins Euro IV-level engine equipped with SCR technology with a maximum power of 118 kW. The technical specifications of the engine are presented in Figure 3.2.

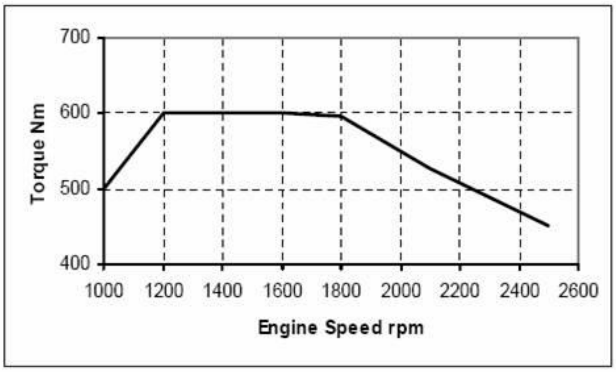
Engine Model: ISBe4 160B
Advertised Power: 118kW @ 2500rpm
158BHP @ 2500rpm

CPL: 8781
Peak Torque: 600Nm @ 1500rpm
443lbft @ 1500rpm

Displacement: 4.5 Litre
Configuration: 4 cylinder in-line

Bore: **mm
Stroke: **mm

Aspiration: Turbochargered & Aftercooled
Fuel System: Bosch HPCR



	Torque	
rpm	**Nm**	**lb-ft**
1000	**500**	**369**
1200	**600**	**443**
1400	**600**	**443**
1600	**600**	**443**
1700	**599**	**442**
1800	**597**	**441**
2100	**528**	**390**
2500	**451**	**333**

Figure 3.2 Cummins ISBe4 160B engine technical specifications.

The measurements were carried out by running six different load points of the ESC cycle on a fully warmed-up engine, with the emphasis on partial loads. The consumption was measured gravimetrically in load points A25, B25, C25, B50, B75 and C75 (Figure 3.3). In Figure 3.3, the load point weighting used in the calculation of the emission result is given next to each load point. Each load point was run for 38 minutes, during which time eight consumption measurements, each lasting approximately three minutes, were carried out.

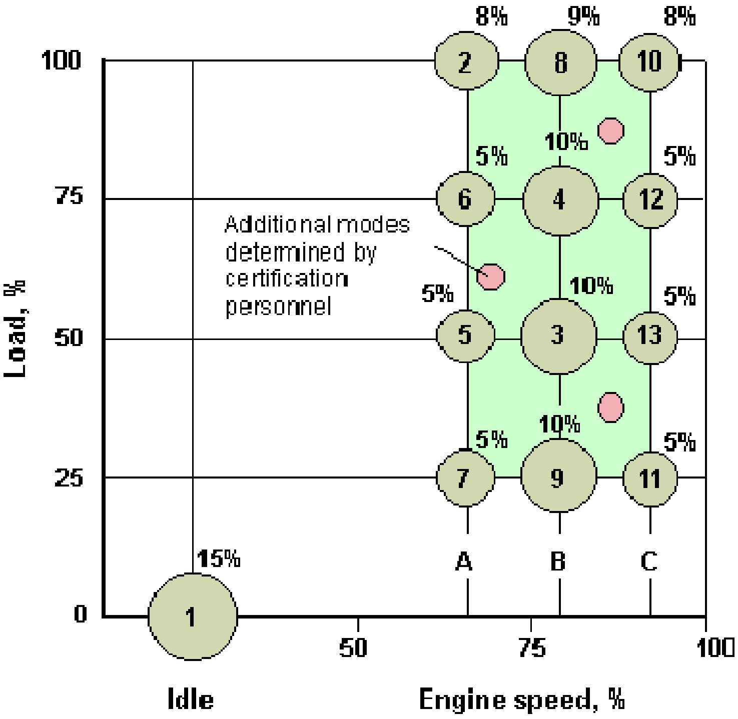


Figure 3.3. Load points of the ESC cycle. The circles in the points display the weighting of each point in the emission measurement.

Figure 3.4 shows the average of the characteristic consumption value of the load points for different lubricants. The result for the reference oil (Neste LXE 10W-40) is the zero level. The maximum difference between two oils, even with the aged lubricants, was approximately 1 %, in other words, at the same level as with new oils. The relative differences in fuel consumption grow on lighter loads just as earlier measurements had shown. The relative share of friction increases as the load decreases, leading to an increase in potential differences between lubricants.

In earlier HDEnergy and RASTU project engine tests, the fuel consumption results correlated reasonably well with the kinematic viscosity (@ 100 ºC) of lubricants. Of the three engines, the correlation was the weakest in the Cummins engine used in this test. In these tests as well, fuel consumption was the highest with the highest-viscosity oil in all load points. However, based on viscosity alone, the difference between the thinnest lubricant and the reference oil should have been bigger, and, correspondingly, the difference between the most viscose lubricant and the reference oil should have been smaller. During the measurements, the oil temperature was between 92ºC–101ºC.

Based on the results, the effect of lubricants on fuel consumption does not change significantly during the oil change interval.

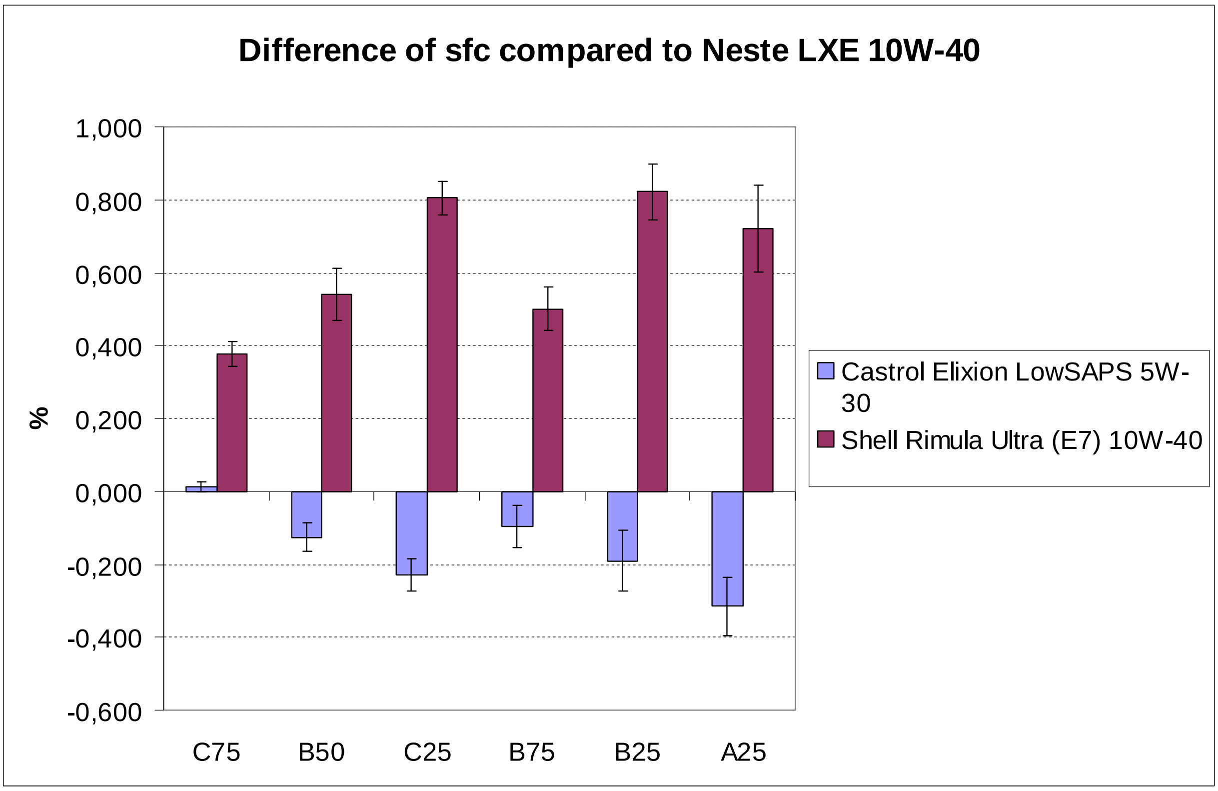


Figure 3.4 The effect of engine lubricant on the fuel consumption of a diesel engine (Cummins ISBe4 160B) at different load points. Fuel consumption with Neste LXE 10W-40 oil is the reference consumption to which the other two oils were compared.

In 2007, a limited test series was performed on a complete vehicle (Kabus ML city bus) using a chassis dynamometer. The vehicle had a similar 4.5-litre Cummins engine as in the engine tests. Vehicle measurements were performed on three engine oils: 10W40 grade prototype lubricant (development formulation 333) and commercial 10W40 and 15W40 grade lubricants. The tests were performed using a Braunschweig cycle simulating city driving.

The development formulation of viscosity grade 10W40 provided the lowest fuel consumption, the 15W40 grade provided a 1.1 % higher consumption, and the third oil (10W40) rendered a 1.8 % higher result than the development formulation. The margin of error was wider in the vehicle tests than in the engine tests due to a larger number of factors affecting the result, of which the most important were the driver and the tyres. In the cycle simulating city driving, the engine load rate is on average small, increasing the relative significance of friction losses. In other words, the potential effect of oil on fuel consumption increases. The difference between the two 10W40 grade oils was 1.8 %, which is significant.

The same bus and test arrangements as in the engine oil test were used to test the vehicle's original automatic transmission oil and the Neste AFT-X oil. With the ATF-X oil, fuel consumption decreased by 2.9 %, calculated from the averages of two tests. Scattering in the results of tests performed using the original oil is regrettably substantial but the difference between the different oils is still clear and proves that the correct choice of transmission oil is an important factor in decreasing fuel consumption in vehicles with an automatic transmission. The limitations set for the oil by the manufacturer must be taken into consideration with automatic transmission oil as well as other oils.

3.4 FUEL ALTERNATIVES OF TRANSPORT - PROGRESS REPORT

In 2002, VTT carried out a survey within the MOBILE^2 research integrate on the emission and usability characteristics of various fuel alternatives. This report was mainly available in table form. In 2007, the Ministry of Transport and Communication commissioned an update to the report. The report and its summary can be downloaded from the RASTU website at
http://www.motiva.fi/fi/raskaskalusto/rastu/rasturaportit/polttojavoiteluaineet/

Development has progressed rapidly, in particular in the field of bio fuels since 2002. In 2003, the EU issued a directive on bio fuels in transportation that set the bio fuel usage objective calculated as energy for 2005 to 2 % and for 2010 to 5.75 %. Due to this, the production of bio fuels increased five-fold in Europe between 2002 and 2006.

In addition to emission and usability characteristics, the report covers the environmental challenges of road transport on a general level, the global production and use of transport fuels as well as measures to promote alternative forms of fuel. The total share of alternative fuels on a global level was approximately 3.5 % and that of bio fuels approximately 1.5 % in 2007.

4 DEVELOPMENT OF VEHICLE ENGINEERING

Responsible parties: HUT and VTT

Text: Henri Ritola, Mikko Lehessaari and Osku Kaijalainen (HUT), Tommi Hangasmaa and Petri Laine (VTT)

4.1 GENERAL

A majority of the subtasks concentrating on the development of vehicle engineering have focused on one year only, with 2006 and 2007 as the central years. This document only reports the most central results of aerodynamics, trailer safety technology, heavy-duty vehicle weight studies, lightweight structure engineering, tyre measurements, stability of a modular combination and the energy-efficiency benchmarking of the 42/60 ton combinations, for which reports have been provided earlier. The subtask of axle alignment carried out in 2008 is reported in greater detail.

4.2 LIGHTWEIGHT STRUCTURE ENGINEERING (HUT)

The Master's Thesis by Ritola in 2007 studied the construction, materials and bodies of trailers with the objective of providing an overview of the components of the trailers' tare weight and to find solutions for decreasing the tare weight. The study concentrated on trailers for general cargo transportation.

A trailer's tare weight consists of a number of components, of which the frame, body, axles, tyres, breaking system and various machines are the most significant factors. Table 4.1 shows an example of the shares of the different components of a semi trailer and full trailer. The chassis weight is composed of the frame, axles/suspension, tyres, accessories and other parts.

Table 4.1. The shares of the different components in the tare weights of semi trailers and full trailers.

Component	Semi trailer (42 ton)	Full trailer with 5 axles (42 ton)
Tare weight (kg)	9000 (10000)	10600
Chassis (kg)	5250	8400
Frame (kg)	2900	4300
Axles/suspension (kg)	1500	2500
tyres (kg)	700	1150
Accessories (kg)	50	300
Other (kg)	100	150
Body (kg)	3750	2200
Refrigerator (kg)	(1000)	-

The most common method of reducing the weight of trailers is to replace traditional steel and iron with aluminum, high strength steel, various metal alloys or composites. This method significantly reduces the weight of the frame and body. To reduce the weight of the body panels, glass or carbon fibre can be used. The majority of a trailer's weight, however, consists of the axles, breaks, suspension and tyres. The greater part of the weight is on the bodies and frames. Manufacturers do offer various lightweight versions of the aforementioned components, but they are not yet widely used, compared to the lightweight options for bodies. The trailer's tare weight can be reduced by hundreds of kilograms by, for example, switching to smaller diameter tyres or to so-called super single tyres. According to HUT simulations, a 1,000 kg reduction in the total weight results in fuel consumption decrease of over one percent.

4.3 THE STABILITY OF MODULAR VEHICLE COMBINATIONS AND THE EFFECT OF TYRES (HUT)

The Stability of the modular vehicle combination section is based on Lehessaari's Master's Thesis completed at HUT in 2007.

A modular combination is a vehicle combination with a length of over 22 metres and a total weight of 60 tons. The maximum length is 25.25 metres. There are four types of modular combinations: a towing vehicle and a full trailer; a towing vehicle, a dolly and a semi trailer; a towing vehicle, a semi trailer and a central axle trailer; and a towing vehicle, a semi-trailer, and a second semi-trailer or a so-called "B" train. Modular combinations and especially a combination of a truck and a full trailer or one of a towing vehicle, a dolly and a semi trailer, are problematic in terms of stability. These kinds of combinations are nevertheless becoming more common in Europe.

Tyres have a significant effect on the behaviour of vehicles and vehicle combinations. The recommendation for passenger cars is to place better tyres in the rear wheels. Based on the results of the same Master's Thesis, this same recommendation seems to apply to vehicle combinations as well: good tyres should be placed on the rear axle of each vehicle unit.

The second and fifth axles of a full trailer should have tyres as good as possible at all times. Overall, the tyres should be replaced at the latest when the tread depth is 3 mm. In the winter, the recommended safety minimum is 5 mm, and the second and fifth axles of a trailer should have tyres that are better than that.

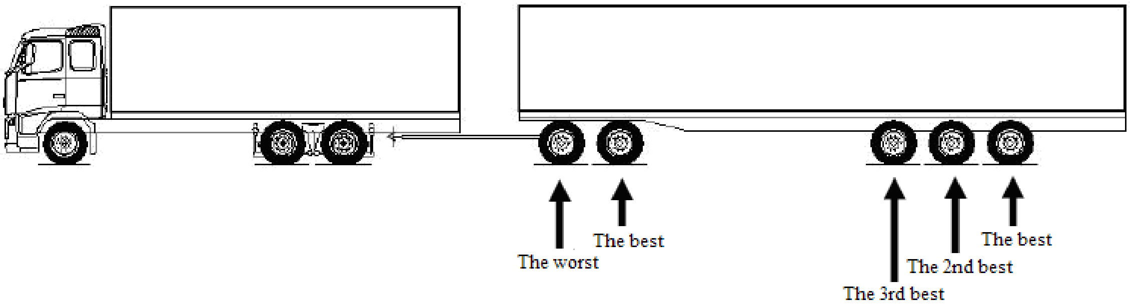


Figure 4.1. Trailer tyre recommendation.

4.4 FUEL EFFICIENCY COMPARISON OF 42/60 TON VEHICLE COMBINATIONS (VTT)

The goal of the comparison was to determine the differences in fuel efficiency between a 42 ton and a 60 ton vehicle combinations and to find out which combination is more fuel efficient. This task, in which two vehicle combinations were compared, did not aim to determine the overall efficiency or profitability of the combinations. Profitability depends on a number of factors (wages, number of vehicles required etc.), and the selection of the combinations is affected by other requirements and legislation as well. Full trailer combinations with a maximum weight of 60 tons are mainly permitted in Finland and Sweden; for example, in Central Europe they are not allowed. The French energy agency ADEME and the Swedish Road Administration Vägverket were also interested in the results of this test.

4.4.1 Vehicle selection

Regular cargo combinations were selected as the vehicles since they are common, easily available and their dimensions provided comparable measurements. The objective was to use a cargo space 4.2 metres high since this is the height of the towing vehicles of the most common 60 ton combinations. The vehicles needed to be modern and equipped with cabin air deflectors. For the 60 ton combination, a modular combination was selected. As a result, the same trailer could be used with both combinations and avoid differences in results caused by different trailers. The vehicles needed to have a manual or robotic transmission without hub reduction. Automatic transmission and/or hub reduction are both less common and increase resistance forces, leading to increased fuel consumption. As for engine power, a decision was made to have a slightly more powerful 60 ton towing vehicle than the 42 ton towing vehicle, and hence the vehicles selected for comparison were Volvo FH 440 as the towing vehicle of the 42 ton combination and Volvo FH 480 as the towing vehicle of the 60 ton combination. In practical applications, compromises were needed; these are discussed in more detail in the vehicles section.

<u>42 ton combination</u>

The towing vehicle used in the 42 ton combination was a 2006 Volvo FH 440 equipped with a middle bogie and with approximately 30,000 kilometres. The middle bogie causes some extra weight but the vehicle was still deemed suitable for the tests. The trailer used in the tests was a nearly new curtainside trailer owned by PNO Trailer. The target height of the trailer was 4.2 metres, or the same as the cargo space of the towing vehicle of the 60 ton combination, but we had to do with a 4 metres high trailer. Four metres is a very common height for semi trailers in Finland and it is the maximum height in nearly all European countries.

Figure 4.2 A 42 ton combination, Volvo FH 440 and a semi trailer

<u>60 ton combination</u>

The towing vehicle in the 60 ton combination was a new 2007 Volvo FH 480 with a fixed 4.2 metres high cargo space manufactured by Närko. The trailer was the same semi trailer and it was attached to the truck with a dolly manufactured by Närko.

Figure 4.3. A 60 ton combination, Volvo FH 480 and a semi trailer connected by means of a dolly

4.4.2 Carrying out the tests

To determine the total resistance of the vehicles, both vehicles were rolled on a highway both empty and loaded to the highest allowed weight. The roll tests were carried out on Highway 3 in a straight section with a known elevation profile near Nurmijärvi. Data obtained from the roll tests were used to calculate the vehicles' total resistance values. These in turn were used to calculate resistance values for fuel consumption difference measurements to be carried out on a chassis dynamometer. After this, the vehicles were tested on the dynamometer in order to find out the precise differences in fuel consumption.

The combination weights used in the roll tests were:

- 42 ton combination, empty 15,150 kg
- 42 ton combination under full load 41,515 kg
- 60 ton combination, empty 21,400 kg
- 60 ton combination under full load 61,630 kg

The actual weights of the combinations were determined by weighing them at the Paperinkeräys Oy Hakuninmaa recycling station and at the A-Katsastus Oy Hakuninmaa vehicle inspection office. The trailer was loaded using concrete weights borrowed from Volvo Kaivoksela, and the towing vehicle of the 60 ton combination was loaded using concrete weights borrowed from the Rajamäki branch of the TTS Work Efficiency Institute.

Figure 4.4. Loading the Volvo FH 480

Figure 4.5 shows the total resistance determined on the basis of the highway roll tests. These values were used for calculating the resistance values for the dynamometer. The values indicate that due to its lighter weight, the 42 ton combination rolls more easily. After determining the total resistance, the actual differences in fuel consumption were measured using the VTT heavy-duty vehicle chassis dynamometer.

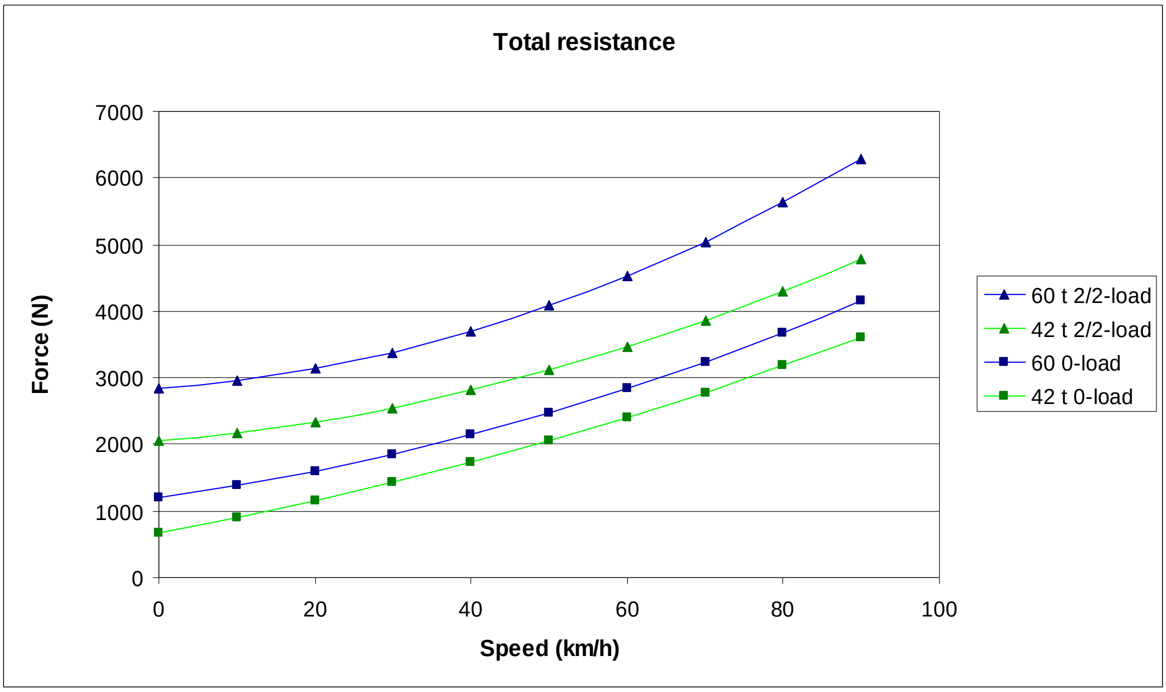


Figure 4.5. Total resistance based on highway roll tests

4.4.3 Chassis dynamometer measurements

Different vehicles were used in the dynamometer tests than in the highway roll tests. Both vehicles were new trucks borrowed from Volvo. The 42 ton combination towing vehicle in the test was a Volvo FH 440 with an emission class ranking of Euro IV, and the 60 ton combination towing vehicle was a Volvo FH 480 with an emission class ranking of Euro V. Both vehicle types were equipped with an SCR catalyst, and based on earlier tests on equivalent vehicles, we knew that there were no significant differences in their specific fuel consumption.

Consumption readings were determined for the vehicles using the dynamometer. In order to determine fuel efficiency, consumption was calculated in relation to the payload in the format of litres per ton kilometre. The results were calculated as an average of two consecutive measurements.

Figure 4.6 shows the results of the fuel consumption measurements of both vehicles. The highway consumption of the 42 ton combination with an empty vehicle was 25.5 litres/100 km and with a full load 35.6 litres/100 km. The respective values on a freeway were 24.7 litres/100 km and 32.0 litres/100 km. The highway values of the 60 ton combination were 28.7 litres/100 km with an empty vehicle and 45.4 litres/100 km with a full load. The respective values on a freeway were 27.4 litres/100 km and 40.0 litres/100 km. Figures 4.7 and 4.8 show the fuel consumption as litres per ton kilometre. The precise highway cycle value for the 42 ton combination with a full load was 0.013 litres/ton kilometre and the freeway cycle value was 0.012 litres/ton kilometre. The highway cycle value for the 60 ton combination was 0.011 litres/ton kilometre and the freeway cycle value was 0.010 litres/ton kilometre.

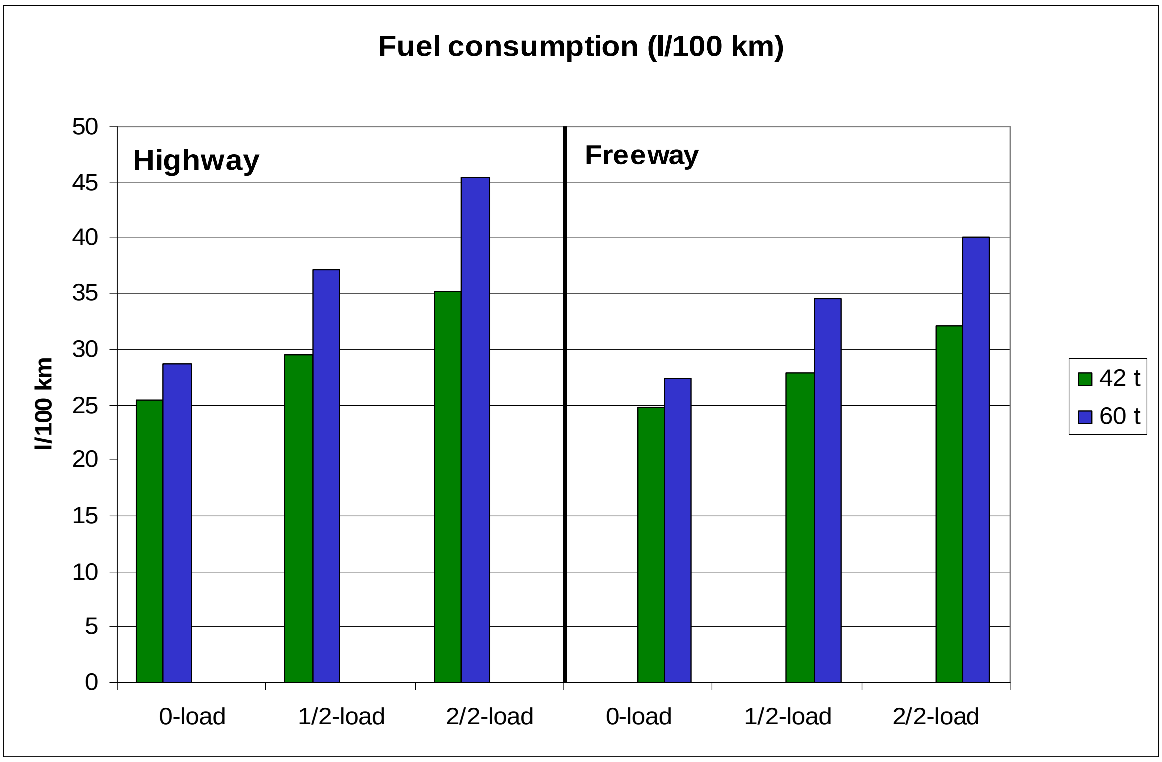


Figure 4.6 Fuel consumption with load in the highway and freeway cycles

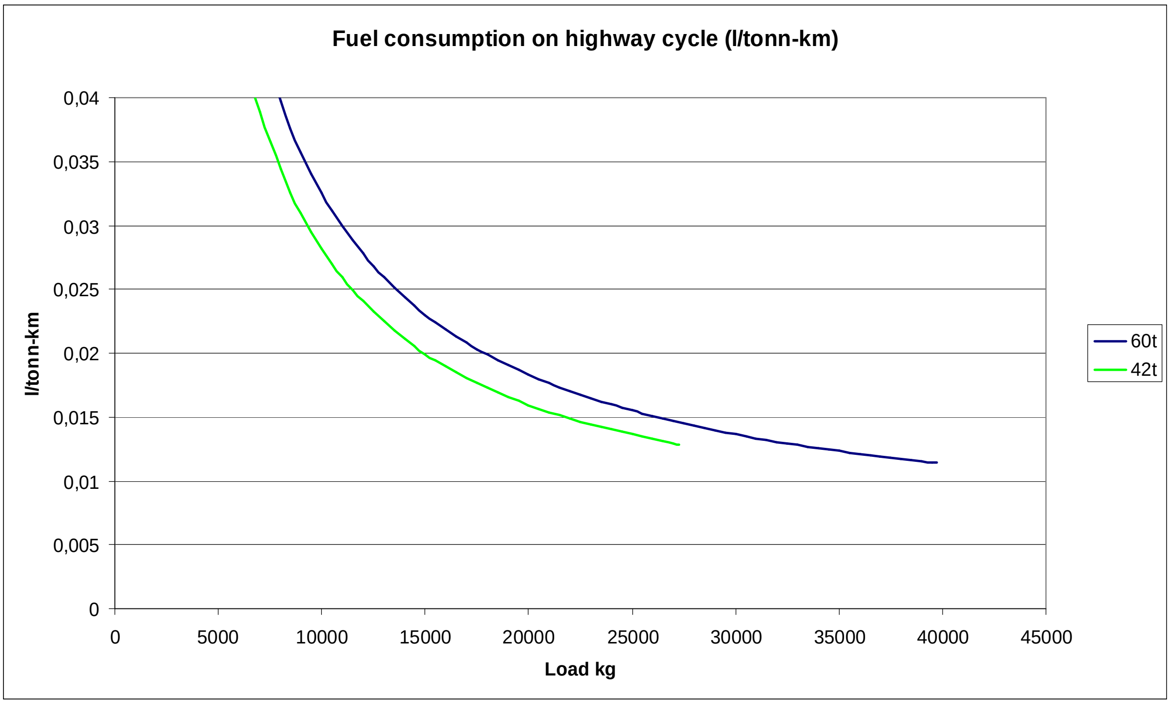


Figure 4.7 Highway cycle consumption litres/ton kilometre

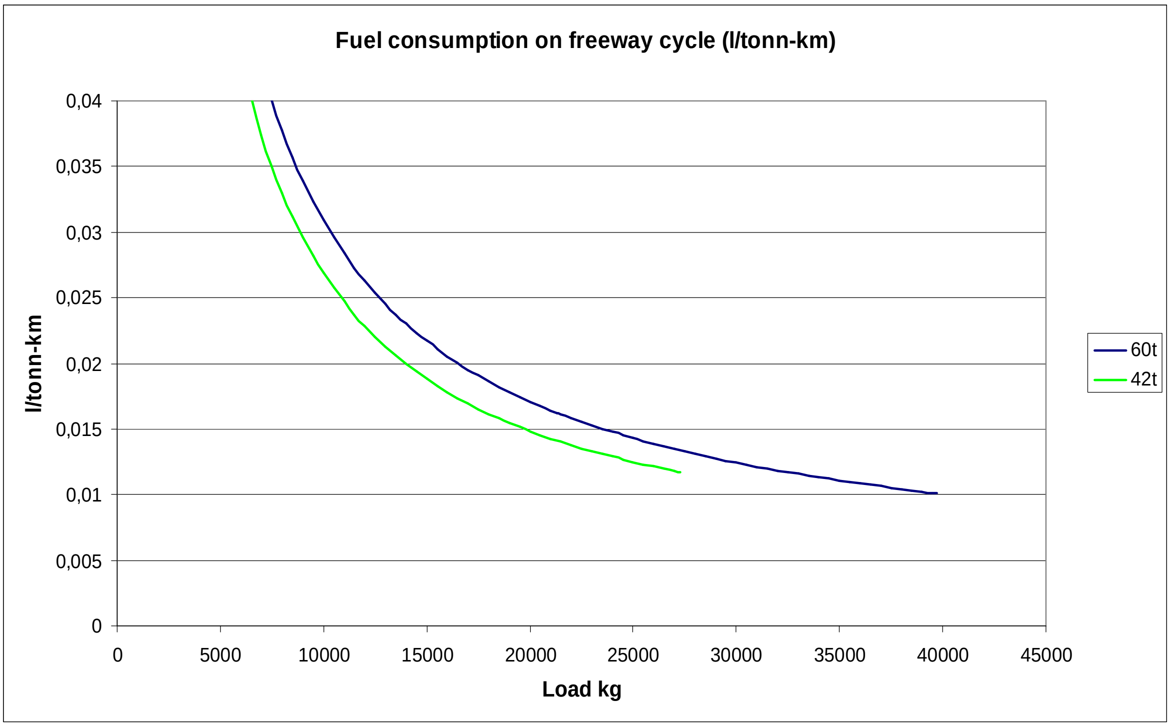


Figure 4.8. Freeway cycle consumption litres/ton kilometre

The results show that the 42 ton combination is more energy-efficient than the 60 ton combination up to the full 42 ton load. The 60 ton combination with a full load provides better energy-efficiency than the 42 ton combination at its best.

As for aerodynamics, both compared vehicles were modern. The entire cabin is aerodynamically designed, and there is an air deflector on the roof to direct the flow of air over the trailer, as well as deflectors on the sides of the cabin to deflect the flow of air past the trailer.

The comparison results apply to vehicle combinations that are equivalent. The selection of vehicle types for comparison has a significant impact on the results. A different pair may produce a different result. This test is also not an indication of how economical the vehicle combinations are overall, since this aspect is impacted by, among other things, the drivers' wages, quantity of fleet needed and the volume of the cargo space. The total volume of the cargo space in the 60 ton combination is significantly larger, which is beneficial for overall efficiency even when the loads are partial in terms of weight but still fill the entire cargo space. Regardless of the combination type and the load to be transported, carrying unnecessary weight in the construction of the combination always increases fuel consumption and decreases profit, no matter whether the combination carries a full load or not. This is why transportation companies should look at the big picture of their fleet, and, for example, determine if the benefit gained from a swap body is worth the additional tare weight, smaller payload and the resulting weaker energy-efficiency, in other words, increased fuel consumption.

4.4.4 Comparison with the results of the HDEnergy project

The results obtained in the roll tests carried out in the HDEnergy project were compared with the results of these tests. The conclusion was that with the 42 ton combination, there were no notable differences in measuring accuracy whereas differences were detected with the 60 ton combination. This outcome was expected, based on the comparison of the combination used in the HDEnergy project and the one used in this test.

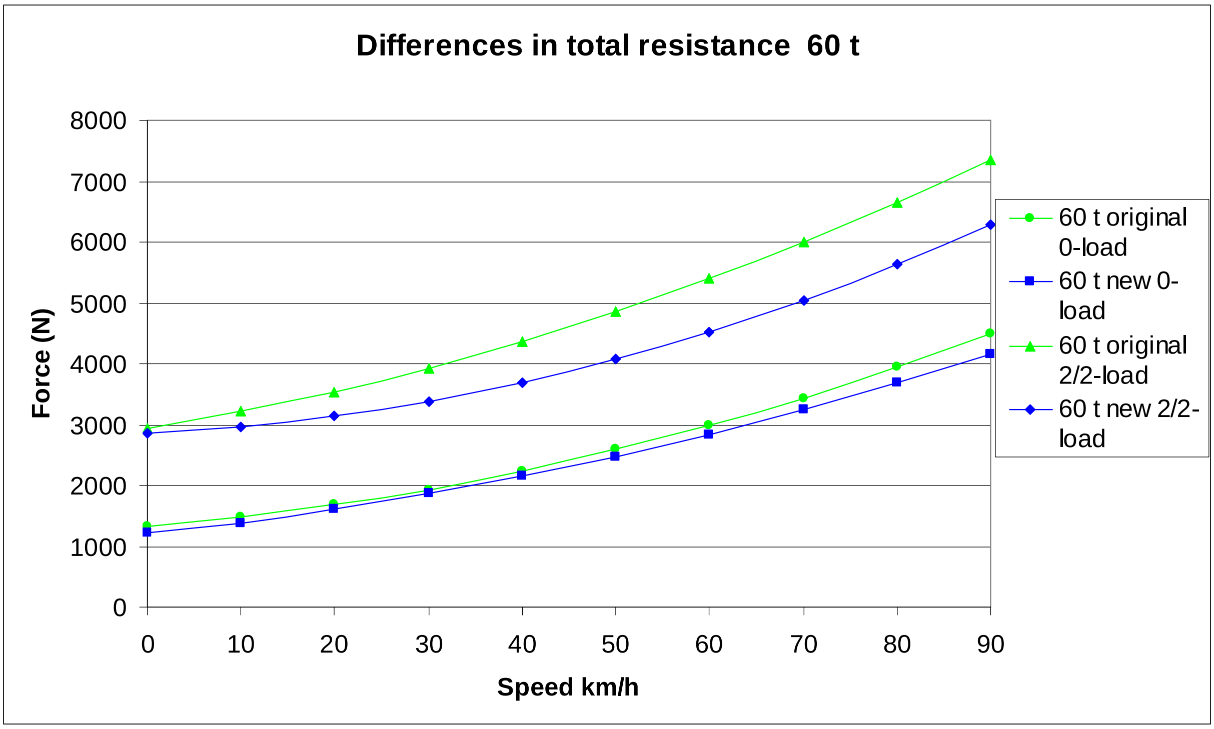


Figure 4.9. total resistance of the previous and the current 60 ton combinations

Figure 4.9 shows that the current 60 ton combination tested rolled much better than the combination tested earlier. The difference is significant in the full load results in particular.

The most significant difference in favour of the current combination is the clearly better aerodynamics and lighter tare weight. The current combination was 5,300 kg lighter in total weight compared to the earlier combination. This kind of difference can be directly used for the payload. It also signifies lower fuel consumption when the combination is driven without a load. The differences in weight are attributable to, among other things, the fixed cargo space of the towing vehicle, which is clearly lighter than a swap body container, and a curtainside trailer that is lighter than a fixed body. Differences in aerodynamics are due to the earlier combination having a low cabin without separate air deflectors and a tall swap body, which caused unfavourable wind resistance.

Fuel consumption is affected favourably in the trailer due to low tare weight as well as the fact that the 60 ton combination has five axles: three in the trailer and two in the dolly. This kind of trailer rolls more easily than a four-axle trailer, especially under load.

4.5 TYRE TESTS (VTT)

An extensive set of tests was completed in 2006 and 2007 on the impact of tyres on the fuel consumption of heavy-duty vehicles. The drive resistance test method created by VTT for the chassis dynamometer allows for measuring the effect of freely rolling wheels and tractive wheels as well as of transmission. The accuracy of the method has been evaluated by comparing it to the official roll resistance method and to results obtained from highway tests. Detailed results have been reported in previous annual reports.

The correct tyre selection in the truck trailer, drive shaft and front axle can provide fuel consumption savings of up to more than 10 %. However, safety should not be neglected. Even if a tyre is beneficial for fuel consumption, it is not necessarily optimal in terms of traction. The opposite is true as well. Overall it can be said that a tyre designed for winter driving conditions is not competitive with a summer tyre in terms of fuel consumption. A winter tyre increases fuel consumption, which is why using winter tyres in the summer makes no sense. In the comparison, a worn winter tyre was slightly better in terms of fuel economy than a summer tyre but its traction properties are no longer as new. The tyre construction, however, is sensible: when the tyre wears enough, the segments wear off and the tyre slip decreases.

The impact of the drive shaft tyres on fuel consumption was studied in 2007. For a coach, the fuel consumption between transversely grooved tyres was 3.3 % at a maximum. Correspondingly, the difference in roll resistance was about 25 %. The fuel consumption difference with longitudinally grooved tyres was 1.8 %. The measurements showed that there was not necessarily a correlation between the tyre roll resistance and fuel consumption on the tractive tyres.

Fuel consumption results for city buses in the Braunschweig cycle were very close to those of the highway cycle. The effect of tyres on fuel consumption was nearly of the same magnitude in urban driving as in highway driving (when studying the extremes). The measured difference in fuel consumption for transversely grooved tyres was 2.5 % at a maximum in the urban cycle. For longitudinally grooved tyres, the difference was 2.6 %. In tests on a truck, the fuel consumption difference between tyres was 3.7 % at a maximum.

4.6 AERODYNAMICS

4.6.1 General

The section on aerodynamics is primarily based on two Master's Theses completed at HUT.

The detailed geometry of a heavy-duty vehicle is extremely complex. The flow around the vehicle is completely three-dimensional. The flow is highly asymmetric and turbulent. The fluctuations in the pressure gradient are sharp, and continuous detachment and reattachment of flow takes place. The vehicle's operating environment varies a lot as a function of time and space, and the various speed components of the vehicle and its surroundings hardly ever meet. The revolving tyres, the discontinuation points of the chassis and the ground effect support the complexity of the flow. The vehicle leaves a large, turbulent wake behind.

Heavy-duty vehicles have not been designed for a certain aerodynamic effect. On the contrary, the shape is determined by functionality, the form by economics and aesthetics. The evolution of trucks reveals how the development of aerodynamics has in recent decades concentrated on the front end of the combination: the cabin and the leading edge of the cargo space. Hence the cabins of trucks used today are aerodynamically alike. The aerodynamic enhancements of the actual cargo spaces have received less attention; they are box-like, with sharp edges. Maximising volume within the limits allowed by law has inevitably lead to the current solutions.

Resistance cannot be completely removed from any object that interacts with flow. In order to minimise aerodynamic resistance, one needs to know the nature of flow. Once the local conditions are known, flow is directed downstream with energy losses that are as minimal as possible. The flow should remain attached to the object as a laminar flow for maximum efficiency. Keeping flow laminar on the surfaces of a truck is, however, an impossible task. Keeping flow comprehensively attached, even if turbulent, to the truck is in itself impossible unless extreme compromises are made on the practical limitations.

4.6.2 Trucks

Traditionally, the need to maximise the size of the cargo area and to make loading and unloading as easy as possible have governed the design of trucks. For aerodynamic design, the situation is challenging since the development has been going in the wrong direction for nearly a hundred years. Killström's Master's Thesis sought to find ways to cut the wind resistance factor of the 60 ton combination in half.

A truck's resistance can be reduced, most of all, by modifying the shape of the nose and the rear. The goal is to reduce the average pressure of the front part of the nose and to increase the average pressure in the rear. In other words, the aim is to minimise the pressure difference between the vehicle's front and rear. When seeking the minimum resistance, one should also bear in mind simple things, such as the straightness, quality and cleanliness of the cargo space.

In reducing a truck's resistance, it is the whole that counts. Enhancing the aerodynamics of an individual part may reduce resistance in the area being viewed, but in the worst case, the resistance of a part downstream may increase. There are theories on the relations of resistance with one another, but these theories are not yet applicable as such to the aerodynamics of trucks.

Wind tunnel models

For the purpose of resistance measurements, two wind tunnel models were constructed: a reference model and a modular, modified model aiming at a low resistance factor. The scale of the models was 1:10. The reference simulated, for the most part, the actual full trailer combinations currently used. The initial plan was not to account for the practical limitations in the case of the modified model. However, the design attempted, to a certain extent, to keep in mind the applicability of the model to a full-size aerodynamic combination. Since the objective of the thesis, cutting the resistance factor in half, is extremely challenging, some of the aerodynamic shapes were deliberately taken to extremes.

The cabin contours were influenced by the nose of a high velocity train. The cabin was extended forward by about 1.5 metres from the current length and the driver was placed in the centre of the cabin. The back wall of the cabin was moved all the way to the cargo space which eliminated the gap between the parts. The arrow shape of the cabin was increased to 15 degrees. The rounding of the edges were sized according to the Reynolds number so that the flow would detach as little as possible at highway speeds. Trailing edge flaps and a fence were installed between the cargo spaces. Alternatively, the gap can be closed completely. Three different shapes were designed for the rear of the combination: 10 degree trailing edge flaps, rear edge arcs and an actual boat-tail. The first two can also be used with trailing edge blowing.

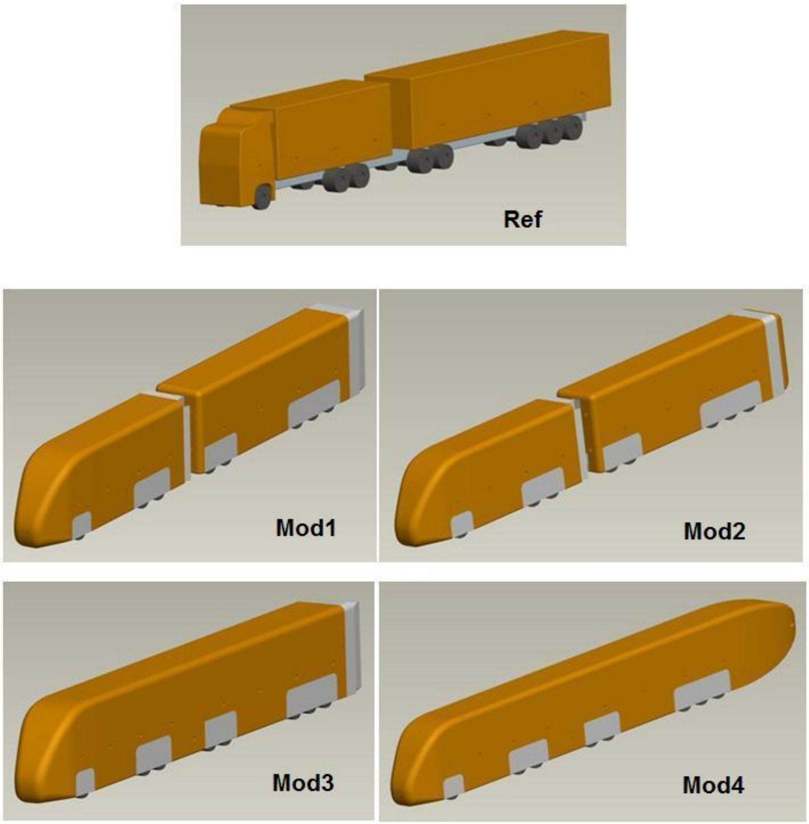


Figure 4.9. Wind tunnel models

One shared 150x100x4 mm steel frame was constructed for the wind tunnel models. The body and wheels were attached to it by means of bolts. The wheels made of plywood were fixed, with the bottom section levelled. The bottom of the model was simplified, rear-view mirrors and the engine coolant air flow channel were not included. The external surfaces were carefully primed and painted with a dark matte paint. Figure 4.9 shows the models and titles used in the tests.

Wind tunnel tests

With the truck's maximum allowed speed of 80 km/h and direction angle of 15º, the side wind component is approximately 6 m/s, equalling the maximum annual average of the prevailing wind speed in Finland. Based on this, the resistance values were measured at five degree direction angle intervals of -15º, -10º, -5º, 0º, 5º, 10º, and 15º. All models were measured at a minimum of two speeds, 40 m/s and 45 m/s. The higher speed caused strong vibration on some combinations, which led to the suspension of these tests. The value of each measuring point at a specific speed and direction angle is the average of three measurement records.

In addition to data obtained from scales, the flow behaviour was observed using dye tests. The dye test of the reference model shows heavy detachment and turbulence of flow, Figure 4.10.

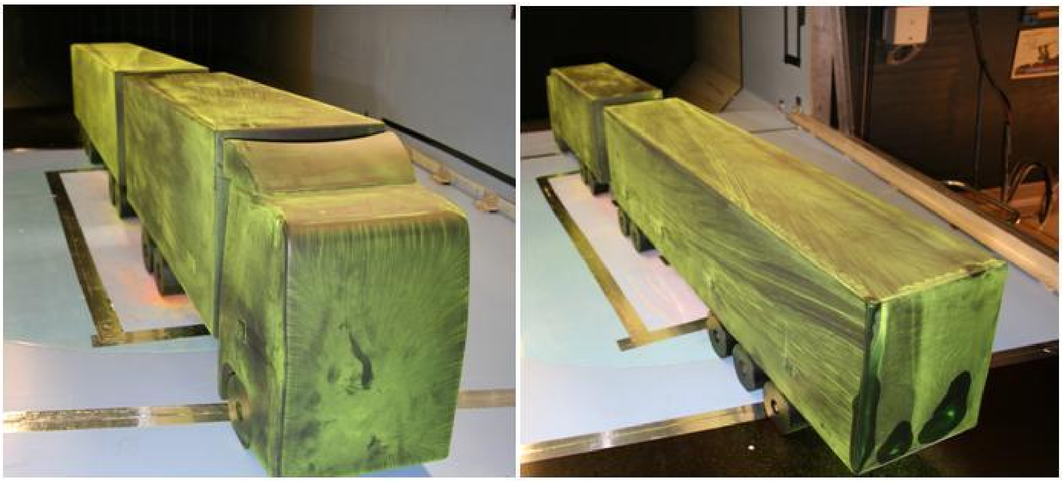


Figure 4.10. Reference model dye test using a 10^o direction angle.

All in all, power measurements were performed on seven different model combinations. Resistance factor, wind tunnel correction and a corrected resistance factor were calculated from the results. The resistance factors of the wind tunnel models are shown in Figure 4.11. The resistance factors of the aerodynamic combinations were significantly lower than those of the reference model, as expected. The best result was provided by the Mod4 model equipped with an actual boat-rail rear. Its resistance factor was more than 76 % lower than that of the reference model with a direction angle of zero. The least resistance reduction was provided by Mod2, with a resistance factor of about 64 % lower than that of the reference model when the flow is directly from the front. It was interesting to note that all modified models reduce the resistance factor at direction angle five more than at angle zero. When the angle is ten degrees, the resistance reduction is roughly the same as at zero degrees.

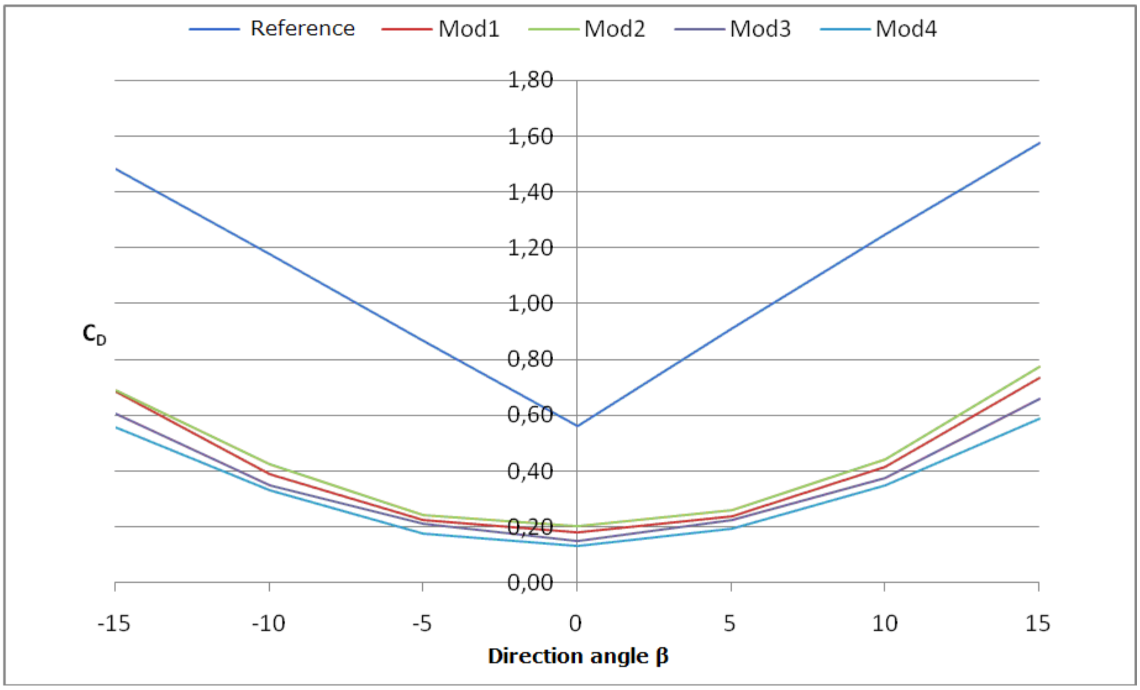


Figure 4.11. Wind tunnel resistance factors at 45 m/s.

The impact of trailing edge blowing on the resistance factor was tested using models Mod1 and Mod3. The speed of blowing in both cases was approximately 105 m/s or slightly more than 2.3 times the driving speed. The flow brought inside the model using a pressure hose was blown from all four sides of the trailer trailing edge. The blow forms a sort of virtual boat-tail rear. Figure 4.12 shows a comparison of resistance factors with the blow and without it. In the case of model Mod1, the blow reduced the resistance factor by 19 % at best, whereas the corresponding value for Mod3 was about 9 %.

Comparing the lowest resistance combinations of the model with and without trailing edge blowing shows that the factors are very close to one another, see Figure 4.13. For practical purposes and feasibility, trailing edge blowing is a clear choice. By increasing the blowing speed, the resistance can be reduced even further.

There is thus room for development in the aerodynamic efficiency of trucks. A majority of the methods to reduce wind resistance has been known for decades. They have not become popular in the market due to greater difficultly in operating trucks, poor economic efficiency and compatibility problems. The increase in prices of crude oil, however, makes the unutilised aerodynamic technology economically crucial. In that situation, reducing wind resistance by as little as a few percent creates significant savings.

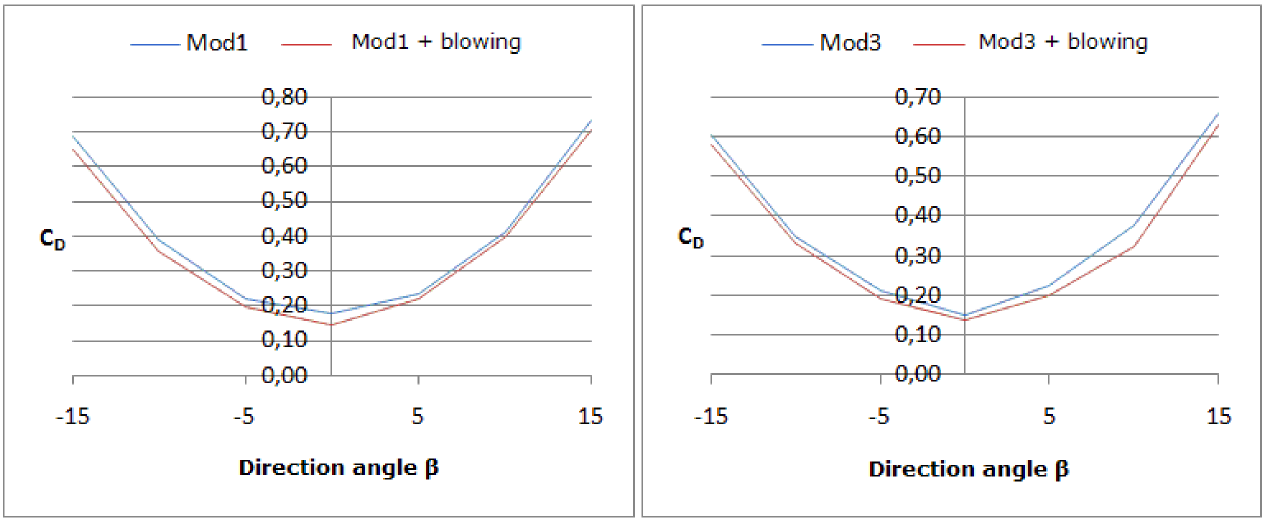


Figure 4.12. The impact of trailing edge blowing on resistance at a speed of 45 m/s.

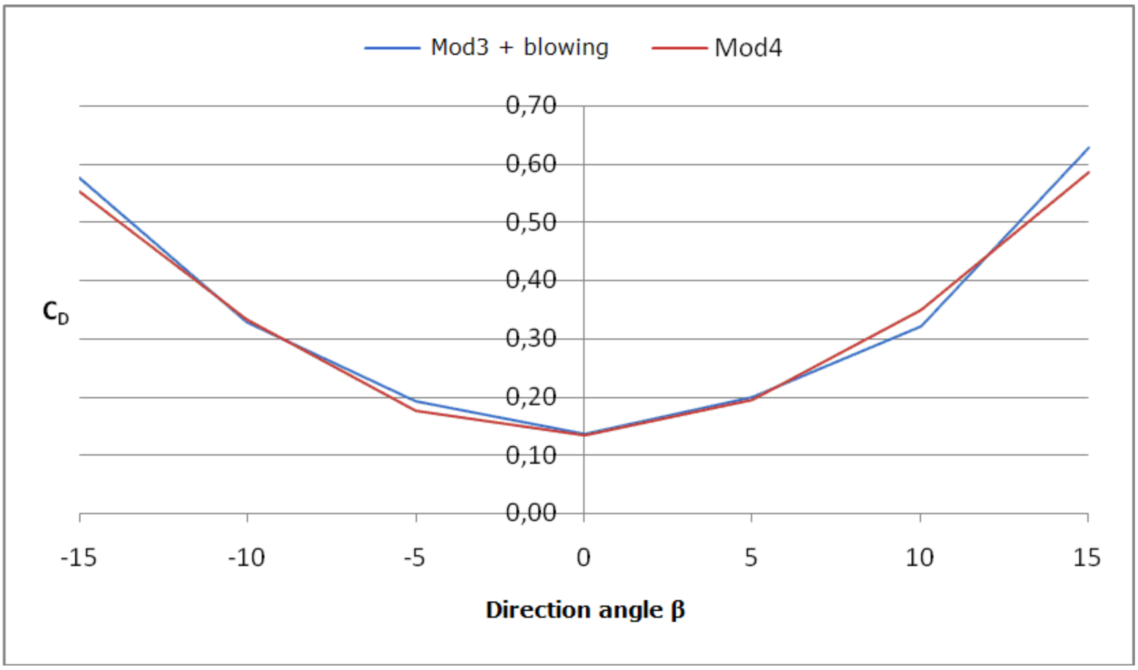


Figure 4.13. Comparison of trailing edge blowing and an actual boat-tail rear resistance factors at a speed of 45 m/s.

4.6.3 Buses

Compared to trucks, the designers of buses have a lot more freedom. Furthermore, compared to trucks, buses have contours that are more aerodynamic since, in principle, the vehicle is just a prism with straight angles. Just as always in reaching for good aerodynamic properties, all external surfaces of buses should be smooth. Modern express coaches often have fairly refined details.

The easiest way to reduce resistance is to round the front edges and the leading edge of the roof. The aerodynamics of the nose can be enhanced by chamfering the nose on the sides or by tilting the nose backward at the top edge. Both alternatives are more challenging to implement in the structure than a simple rounding of the edges. In terms of resistance, the best result is reached when all methods are used: making a nose that is chamfered at the sides and tilted at the top, with all edges clearly rounded. For the total resistance of the vehicle, the design of the bottom part of the nose is also important: the further down the nose reaches, the less air is directed underneath the vehicle.

The design of the rear is perhaps even more challenging than that of the nose since several areas important for the vehicle's operation are located in the rear. As with the nose, the simplest way to reduce resistance is to round the edges and the back edge of the roof. The best results would be provided by the boat-tail shape in which the roof and the sides are chamfered over a long distance. In the modern buses with a long rear overhang, the bottom is already steeply chamfered for other reasons. The sides of the chamfer should be properly rounded so that the chamfer could suck air from the chassis and the sides of the vehicle. The angle between the bottom and the rear should also be properly rounded.

An important design component in buses is the behaviour of the vehicle in side wind. The simplest way to reduce the impact of side wind is to round the side edges of the roof. Rounding the edges of the nose and the rear also makes a big difference.

4.7 MASS OF HEAVY-DUTY VEHICLES (TURKU UNIVERSITY OF APPLIED SCIENCES)

The objective was to investigate what are the tare weights and the distribution and range of tare weights in towing vehicles and trailers used in heavy-duty vehicle combinations operating in Finland. Bearing capacity would increase if the tare weight could be reduced without affecting strength. This would increase the payload and reduce fuel consumption and CO_2 emissions proportionate to the payload.

The review was limited to semi- and full trailer combinations registered in or after 1995 with the Finnish Vehicle Administration. The study included only van trailers for piece goods, and, in the case of full trailer combinations, also platforms for piece goods with a removable cover.

There were clear differences in tare weights between mutually comparable vehicles. There have not been radical changes in tare weights over the past ten years or so; over the reviewed period, only the weight of full trailer combination trucks has increased.

Based on the achievable reduction in weight, example calculations were made for a situation in which the total weight remains constant, providing additional bearing capacity; and for a situation in which the payload remains constant, providing reduced total weight.

In the first case, reductions of fuel consumption and CO_2 emissions were calculated per ton kilometre. In the second case, reductions of fuel consumption and CO_2 emissions were calculated per kilometre travelled. In addition, based on the recorded performance, the impact on the annual fuel requirement and CO_2 emission volumes were calculated for the whole of Finland (Table 4.2).

Table 4.2. Summarised key figures calculated from the differences in tare weight between the average and lightest combinations.

FULL TRAILER COMBINATIONS		On average	Lightest	Difference
Tare weight (kg) of current combinations		23 600	20 350	3 250
Reductions per transportation performance (total weight is constant)	fuel consumption (l/ton km)	0.0012		
	CO2 (g/ton km)	3		
Reduction per distance travelled (load is constant)	fuel consumption (l/100 km)	2.3		
	CO2 (g/km)	60		
Nationwide annual reduction in consumption (million litres)		25		
Nationwide annual reduction in CO2 (tons)		62 000		

SEMI TRAILER COMBINATIONS		On average	Lightest	Difference
Tare weight (kg) of current combinations		13 850	12 050	1 800
Reductions per transportation performance (total weight is constant)	fuel consumption (l/ton km)	0.0008		
	CO2 (g/ton km)	2		
Reduction per distance travelled (load is constant)	fuel consumption (l/100 km)	1.1		
	CO2 (g/km)	30		
Nationwide annual reduction in consumption (million litres)		3		
Nationwide annual reduction in CO2 (tons)		7 500		

4.8 AXLE ALIGNMENT

4.8.1 General

Axle misalignment means the deviation in the angle of the vehicle/trailer axle in relation to the centreline of the vehicle. It is a known fact that there are alignment deviations in the trailer axles of heavy-duty vehicles. However, it is not known how common these deviations are or how they affect fuel consumption.

A working group was set up to solve the problem. Members of the group included VTT, representatives of alignment device manufacturers and service shops for heavy-duty vehicles. The study subjects were vehicles in Transpoint's fleet. Based on study materials collected before the project, proper alignment would provide significant improvements in fuel economy.

The first step in the study was to find out how common axle misalignments were in Transpoint's fleet and in what magnitude. The parties cooperated in order to carry out the alignment measurements in connection with regular maintenance. A database was compiled from the results that allowed for the determination of the current state of the fleet and the selection the test subjects for the next stage.

The second stage consisted of determining tractive resistance using the VTT method for misalignment situations selected from the database representing typical deviations. Based on the results of the second stage, the total resistance difference between misalignment and a normal situation could be determined.

4.8.2 Database

The database consisted of a slightly smaller than planned but still representative number (30) of five-step trailer measurements that were used for determining typical deviations. Table 4.3 shows the deviation order of magnitude and ways to determine an average deviation. Determining an average deviation is difficult based on the values alone since the quality of misalignment is also important. In the Table, misalignments are presented in the format mm/m. One degree corresponds to approximately 17.5 mm/m.

Table 4.3 Average misalignments in Transpoint's trailer fleet. The column on the right displays average differences between different axles and is not directly connected to the left column.

mm/m	1	2	3	4	5		1-2	3-4	3-5
avg	0.0	0.4	-0.3	-0.2	0.1	**avg**	1.0	0.7	1.2
median	0.1	0.0	-0.2	-0.3	0.1	**median**	0.7	0.4	0.7
mode	0.1	0.3	0.0	-0.3	0.7	**mode**	1.2	2.0	0.3
max +	3.7	3.7	2.4	1.9	5.3	**max**	5.3	2	6
max -	-2.6	-2.0	-2.9	-3.4	-4.7	**min**	0.0	0.0	0.0

4.8.3 Determining tractive resistance

Based on the axle alignment database, two interesting cases emerged. For the measurement, a five-axle trailer was prepared by creating in it the misalignment to be studied. After the highway cycle measurement, the axles on the trailer were aligned and a new highway measurement was carried out. The first case represents an average deviation and is qualitatively in line with the selected actual measurement:

mm/m	1	2	3	4	5
1 missal.	-2.0	1.2	0.9	-0.6	-0.5
1 aligned	0.3	0.1	0.0	0.3	0.0

The second case depicts a deviation that is large for the measured series, and that, according to a representative of the axle alignment device manufacturer, is qualitatively the worst case scenario in which the axles "wiggle" in relation to each other.

mm/m	1	2	3	4	5
2 missal.	5.6	1.4	5.3	0.3	4.6
2 aligned	0.0	0.0	0.0	0.0	0.0

Figure 4.14 shows the roll resistance for both trailers with misaligned and aligned axles. The figure shows that no differences in the measuring accuracy is detectable between the misaligned and aligned axles. On the other hand, the figure shows how consistent the results are for the aligned axles. This is an indication that the measuring method is repeatable and that factors in the surroundings did not affect the results of the test.

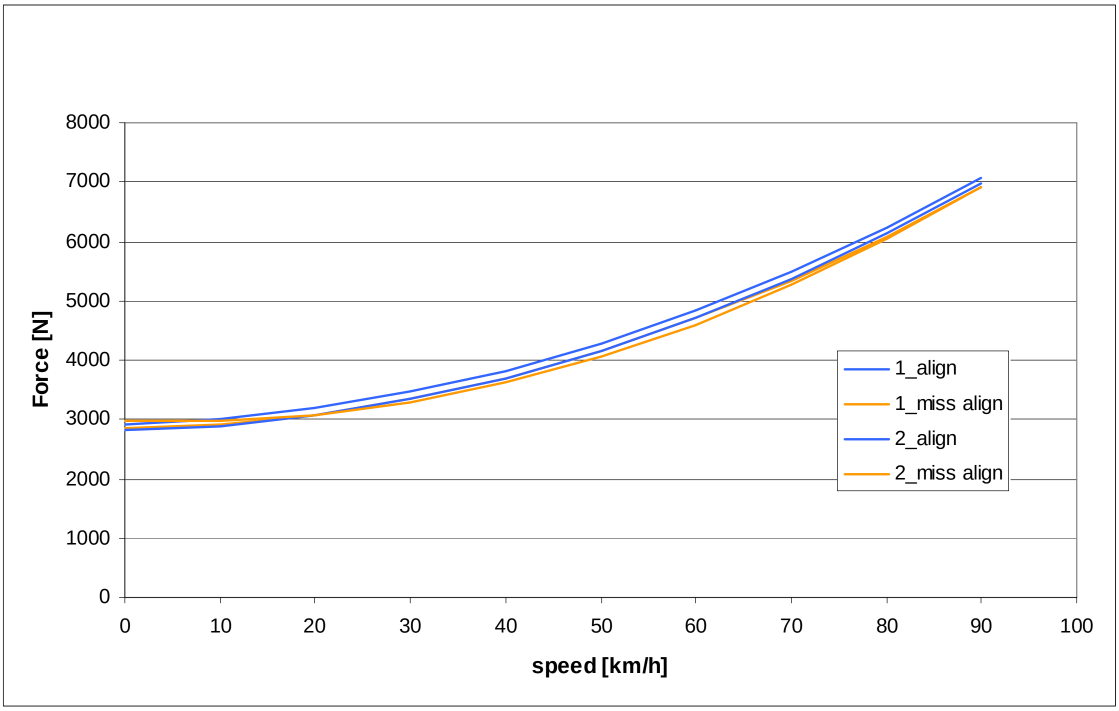


Figure 4.14 Total resistance graphs

The results show that the average axle misalignment present in Transpoint's fleet does not have a significant effect on the total resistance of the vehicle. The result is very different from what was expected. The study was continued in the VTT heavy-duty vehicle laboratory in order to determine the actual effects of the limited measuring accuracy of the highway cycle and axle misalignment.

The study carried out by Nokian Tyres investigated the impact of misalignment on tyre wear. The result showed that misalignment in the vehicles cannot be considered to cause significant wear in tyres.

4.8.4 Impact of axle misalignment

The laboratory tests were carried out on a heavy-duty chassis dynamometer. Axle misalignment was created by adjusting the total toe-in on the front axle of the truck. The vehicle used was a natural gas powered Sisu truck. The tyres were Nokian NTR-

843 295/80 R22.5 @ 8.0 bar. Axle load at the time of measurement was 4,920 kg. Several misalignment values were used on the axle to determine the impact of the deviation (Figure 4.15)

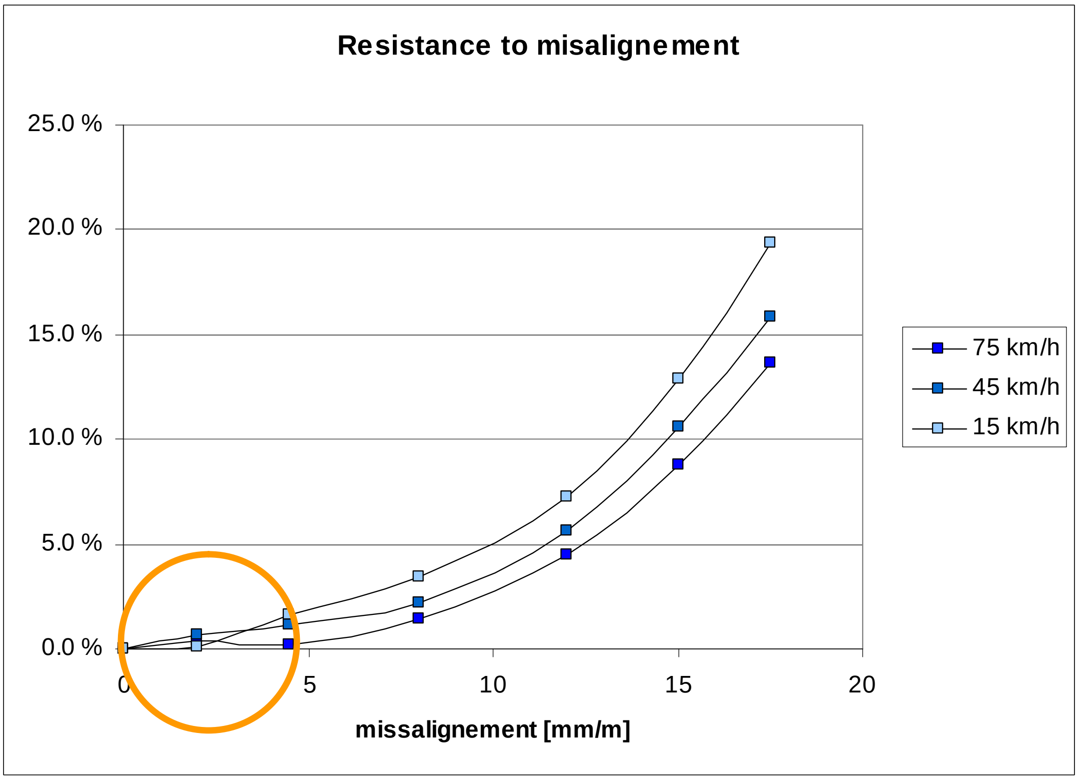


Figure 4.15. The impact of axle misalignment

The results show that the resistance does not increase significantly in the misalignment range that typically occurs in Transpoint's fleet. Highway measurements verify an approximately 4 % change in the total resistance. Converted to axle misalignment, this would mean a deviation of about 12 mm/m (approximately 0.7 degrees). In addition, the deviation should appear in order of magnitude on all axles for it to have an effect of approximately 2 % on the total resistance and hence on fuel consumption. The increase in roll resistance does not have a direct impact on total resistance since, at higher speeds, wind resistance grows to significant values.

In the case of Transpoint, even the greatest of the average misalignments were so minor that the axle alignment has a very small effect on the fleet's fuel consumption.

5 DEVELOPMENT OF METHODOLOGY

Responsible party: VTT Technical Research Centre of Finland

Text: Kimmo Erkkilä, Juhani Laurikko and Nils-Olof Nylund

5.1 GENERAL

The 2006 annual report covered, for example, the implementation of measurement tyres, compiling comparable measurement results and highway measurements. In 2007, tyre tests were modified to ensure that highway and chassis dynamometer measurements provide consistent roll resistance results.

At the beginning of 2008, exhaust emission tests on buses were performed using the PEMS (Portable Emissions Measurement System) equipment in cold conditions at Rissala airport. Measurements on the chassis dynamometer in the VTT laboratory are only possible at regular room temperature.

The portable PEMS equipment was a key device in the measurements carried out in cold conditions in the field. PEMS is a device that can be installed in the vehicle, allowing for the study of emissions during vehicle operation. These measurements used measuring instruments borrowed from Volvo Buses in Sweden.

5.2 PEMS MEASUREMENTS

5.2.1 Measuring arrangements

The PEMS device was obtained from Volvo Powertrains in Sweden. The device was preinstalled in two city buses being studied prior to the actual measurements. The test cycle was the SORT 2 cycle that simulates the general driving situation of a city bus. The SORT cycle that is originally based on distance was modified into a time-based cycle so a separate marked test range was not needed.

The test location was Rissala airport in Kuopio. The base station between the tests was the Kuopion Liikenne depot. Due to air traffic and to ensure that the weather was cold, the tests were carried out at night.

The test vehicle was left outside for a day so that it was properly cold. After the start-up, the vehicle was allowed to run for five minutes before the measurement was started. During the actual measurement, the SORT 2 cycle was repeated until the coolant temperature did not change significantly. At that point the vehicle was considered stabilised.

5.2.2 Fleet

Two buses with different levels of after-treatment technology were selected for the tests. These were Volvo Euro III, a typical city bus operating in Helsinki metropolitan area traffic, and Volvo EEV, a city bus equipped with SCR after-treatment equipment and the latest engine and cleaning technology.

5.2.3 Results

5.2.3.1 Method comparison

The results of the PEMS test were compared to the laboratory test performed with the same vehicle (Table 9.1). The test methods differ so result differences were to be expected.

In the PEMS results, the NOx emissions were about 7 % lower compared to the laboratory test, whereas the CO2 and CO results were somewhat higher. In HC emissions, the percentage differences were big but absolute differences very small. Considering the inaccuracies that are characteristic to analysers, the PEMS results correlate very well with those obtained with the laboratory equipment.

Table 9.1. The top portion lists the Volvo EEV tests with averages. The bottom portion contains the average of the last five Volvo EEV PEMS results and correction based on consumption.

EEV

Results AMA

	CO(g/km)	HC(g/km)	NOx(g/km)	CO2(g/km)	PM(g/km)	
	1.8	**0.007**	**8.6**	**1115**	**0.035**	
	2.1	**0.035**	**8.8**	**1116**	**0.034**	
	1.9	**0.021**	**8.7**	**1116**	**0.034**	**0.44** l/km

EEV

Average last 5

	CO(g/km)	HC(g/km)	NOx(g/km)	CO2(g/km)	PM(g/km)	
	1.9	**0.061**	**8.0**	**1108**		**0.43** l/km
HCk	**2.0**	**0.062**	**8.1**	**1132**		**0.43** l/km
	-0.1 %	191.7 %	-8.6 %	-0.7 %		-0.9 %
	2.2 %	198.1 %	-6.6 %	1.5 %		-0.9 %

5.2.3.2 Field tests

The weather conditions differed somewhat between the tests, and although the targeted freezing temperatures were not reached, the test still represents typical weather conditions of Finland.

Ambient temperature

Euro 3	-2
EEV	0

End of test

Exhaust

Euro 3	213
EEV	207

Coolant temperature

Euro 3	56
EEV	72

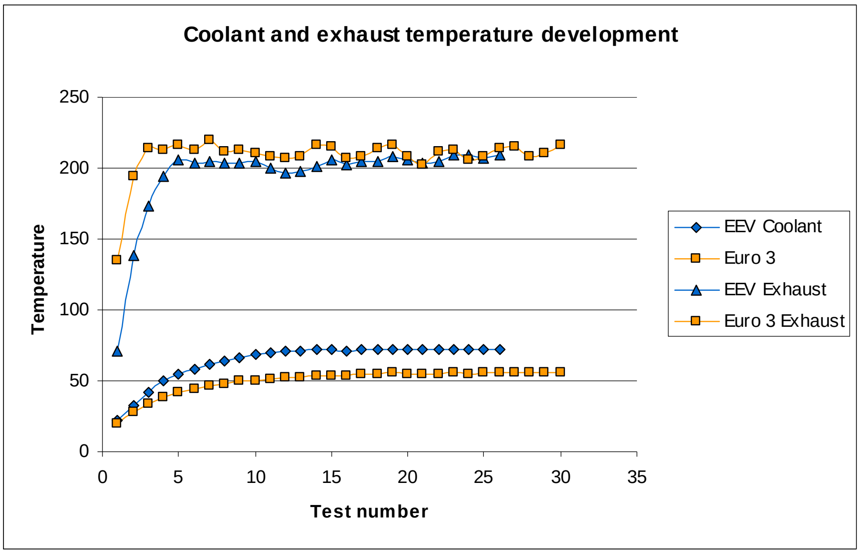


Figure 9.1. Test conditions and vehicle status at the end of the test.

Figure 9.1 shows how the temperature in both test vehicles rose during the measurement cycles. The coolant temperature in the Euro III vehicle was significantly low even after having evened out, but still stabilised. The low level was probably due to a thermostat with a low opening temperature.

Fuel consumption decreased steadily as the vehicles warmed up. The fuel consumption of the Euro III vehicle decreased by about 30 % and that of the EEV vehicle as much as 40 %. In this respect, the level of technology does not seem to have an effect on how the vehicles behave in cold weather.

An example of nitrogen oxide emissions shows the known sensitivity of EEV SCR technology to the heat radiating from the exhaust. It it noteworthy that there is a difference in the measured emissions also at low coolant temperatures (e.g. a cold vehicle). In the emissions graph, the presentation method in relation to engine temperature should be noted. As Figure 9.1 shows, the exhaust temperature rose to its final level by about the fourth test, during five minutes. By test number 4, the NOx emission of the EEV vehicle decreased to a normal level (Figure 9.3). In normal daytime traffic, a vehicle does not cool down significantly once it has warmed up.

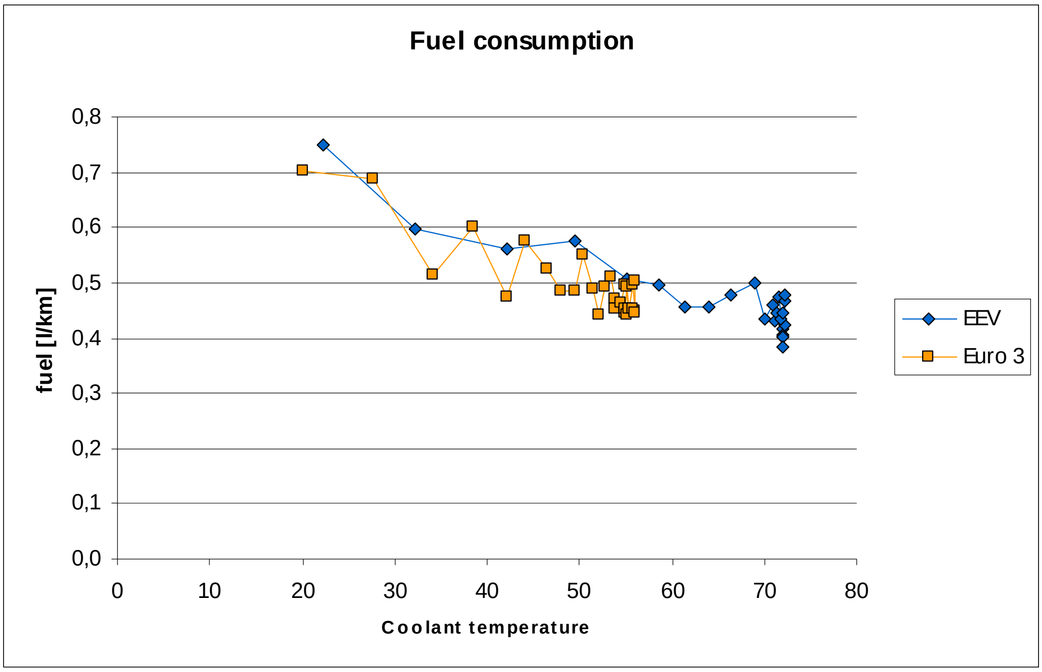


Figure 9.2 Fuel consumption

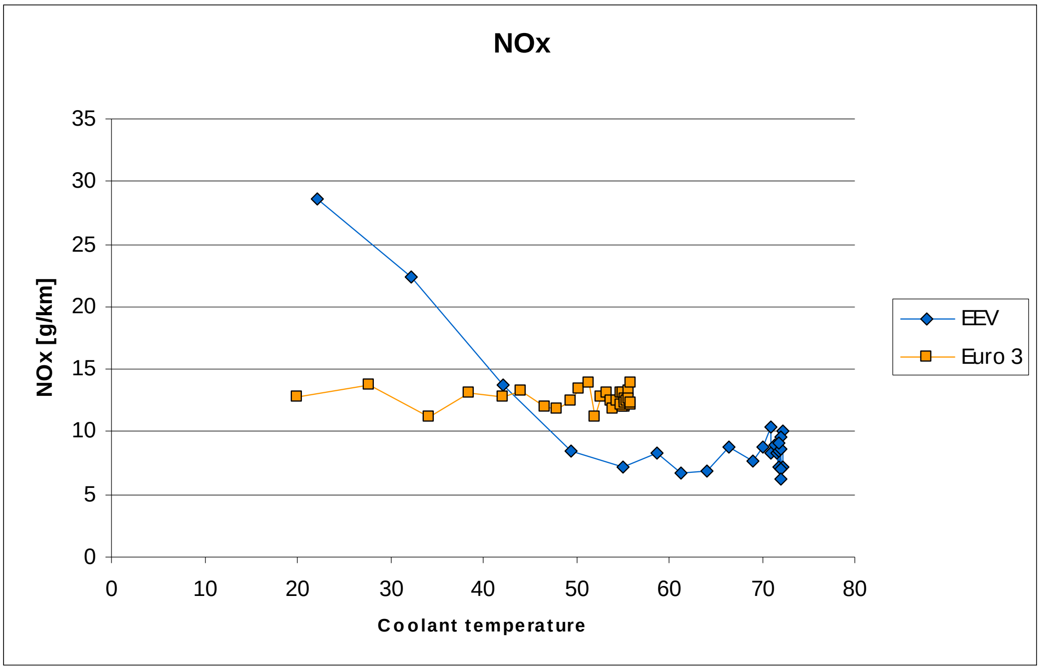


Figure 9.3 Nitrogen oxides

5.2.4 Conclusions

The PEMS equipment is very suitable for field tests and studying difficult conditions. The equipment provides an interesting new study area that provides data that surely can be used. PEMS cannot, however, replace full laboratory equipment and it is not suitable for high-accuracy fuel consumption or emission comparison between vehicles. The equipment should be tested more and the results analysed before further conclusions can be made. Testing in cold conditions will also continue.

6 EMISSION MEASUREMENTS

Responsible party: VTT Technical Research Centre of Finland

Text: Maija Lappi, Anu Solla, Kimmo Erkkilä and Nils-Olof Nylund

6.1 INTRODUCTION

When comparing vehicles with differing technology and emission levels, so-called unregulated emissions should also be analysed. Regulated emissions are components that are restricted by exhaust legislation in terms of their maximum allowable quantities. Currently these include CO, THC (total hydrocarbon content), NOx and total particulate mass. These emissions, however, do not always provide a sufficient picture of the exhaust properties, their environmental impact or potential exposure on people. The measurement methods were originally developed for vehicle comparisons and type approvals. When comparing different vehicle technologies, the content of, for example hydrocarbons and particulates should be studied in greater detail and carbonyl compounds should be analysed.

Within the RASTU project, certain measurements of unregulated emissions were carried out on vehicles with both old and new technology. The portion on the NO_2 emissions was carried out in a separate project called ”Connection between new vehicles and NO_x compounds and particulate content in urban air (Uusipäästö)”, sponsored by VTT, the Ministry of the Environment, the Helsinki Metropolitan Area Council, the Vehicle Importers' Association, Gasmet Technologies Ltd, Helsinki City Environmental Centre and the Finnish Meteorological Institute. As agreed, the Uusipäästö project reported on the exhaust NO/NO_2 ratio in particular to the RASTU project as well. An underlying fact is that the NO_2 content of urban air has not decreased although the NOx emissions of vehicles have been restricted significantly.

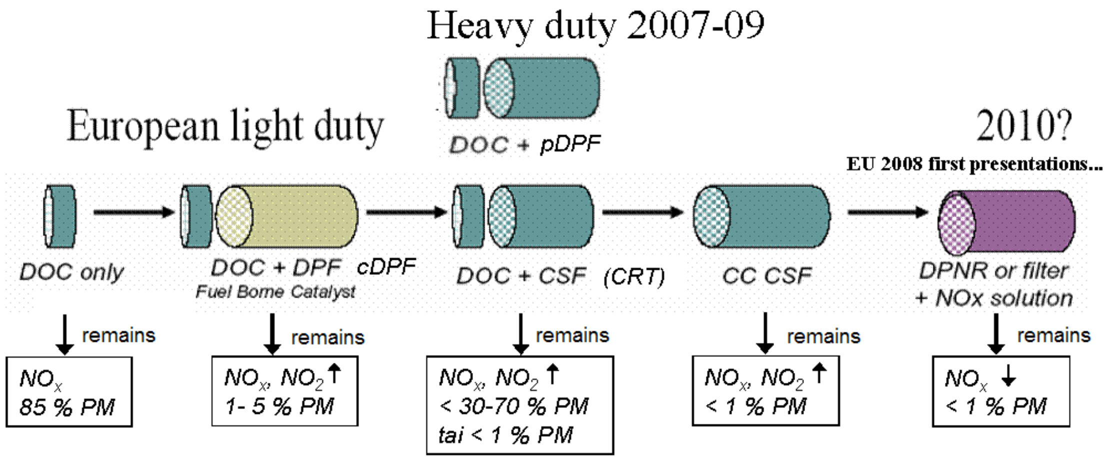
6.2 NO/NO_2 RATIO AND ITS EFFECT ON URBAN AIR

Both NO and NO_2 quantities and their ratios are very strong functions of engine technology, fuel technology, exhaust after-treatment technology and driving style. The NO_2 amount is dependent on not only the temperature of the engine combustion chamber but also the temperatures after engine operation. NO_2 formation is a strong function of both the exhaust temperature and the temperature of the after-treatment device, in particular in diesel vehicles.

The Uusipäästö project studied the impact of an urban vehicle pool that keeps changing as a result of exhaust legislation, exhaust after-treatment technology as well as taxation and incentive practices on the NO_x compound quantities and, secondarily, on primary particulate levels in street routes with high traffic volumes. The test produced actual urban driving NO and NO_2 emission factors for light-duty (LD) and heavy-duty (HD) vehicles in different vehicle classes, and was a basis for models simulating urban air quality and pollutant dispersion in street canyons and open routes.

In the heavy-duty vehicle group, emission tests were performed on a total of 24 Euro II – Euro V & EEV emission level buses (model year 1999–2008) and on 8 Euro IV-level trucks. All vehicles represented the vehicle base currently in use in urban traffic. The new buses and trucks that were studied contained solutions that had been optimised for the reduction of either NO_x level or particulate emissions, or for both. Depending on the orientation, the after-treatment technology varied highly. Figure 10.1 shows the technical changes implemented in generations of after-treatment devices as the exhaust legislation changes.

The oldest vehicles represent the bus pool in use in the city during rush hours and they either do not have exhaust after-treatment devices or they have been retrofitted with the devices. The Euro IV and Euro V vehicles generate NO_x compound and particulate emissions that differ from earlier emission levels since the vehicles are equipped with effective after-treatment devices. High emission levels were also detected in this pool, in particular for NO_2 since some of the HD after-treatment concepts are targeted for the Euro V emission period and are still in the development stage. No attention needs to be paid to NO_2 as a separate emission component. Naturally, well maintained natural gas, or CNG, vehicles with a carburettor engine and a three-way catalyst (TWC) are particularly clean.



DOC = oxidation catalyst (Pt)
DPF = particulate filter (potential catalyst in fuel)
cDPF = catalysed DPF
CSF = (oxidation) catalysed particulate filter
pDPF = partial diesel particulate filter (NO_2 oxidiser for regeneration)
CRT = HD particulate filter (NO_2 oxidiser for regeneration)
CC CSF = a CSF placed near the engine
DPNR = a combined PM and NO_x removal solution (currently SCRT and SCR+CRT; reducing the use of noble metals)

Figure 10.1. Development trends of exhaust after-treatment devices.

The vehicle emission measurements were carried out on the VTT chassis dynamometer using driving profiles typical for the vehicles. For buses, the "Braunschweig city bus cycle", the oldest and most commonly used city driving simulation in Europe, was used. The NO_2/NO ratios and specific emissions of the RASTU project vehicles, the Euro II - EEV buses, depict city driving primarily by means of this driving style.

In different cycles, the emission of both NO and NO_2 within the unit of time (/s) was somewhat independent of the speed of city driving. However, the slower the city driving, the more NO and NO_2 was generated per distance travelled.

The delivery, highway and freeway cycles recorded by VTT in real-life road conditions were used for trucks. Since the goal was to have the emission results simulate driving in densely populated areas, the emission results for trucks were mainly from the delivery cycle with an average speed of approximately 37 km/h. In the highway and freeway cycles, the average speeds were 80 and 83 km/h, respectively.

Figure 10.2 shows the NO/NO_2 emission results for vehicle technologies that represent all buses used in public transportation, some the newest vehicle technologies that in 2007 were not yet on the Finnish market, and the Euro IV truck group tested. All CNG buses were new, from model years 2005-2007. The comparison group of the Euro IV - EEV vehicles consisted of the Euro II - Euro III emission level buses without catalysts, a newer Euro III emission level equipped with an oxidation catalyst as well as a Euro II-level bus equipped with a retrofitted pDPF. In bus operation in densely populated areas, vehicles equipped with pDPFs, both with first time installation or retrofitted technologies as well as new and effective oxidation catalysts (& EGR) are problematic after-treatment techniques at the moment in terms of direct NO_2. Their exhausts may have a notably high NO_2 level and the share of NO_2 in NO_x may range from 25 % to more than 60 %. The highest NO_2 emission and portion of NO_x was obtained in an EEV-level SCRT vehicle when driving in a slow Paris city centre cycle (Ademe, travel speed 10.8 km/h). SCRT is a combination technology in which an after-treatment device incorporates the purging of NO_x with an SCR device and removal of particulates with a DPF filter. Fairly high NO_x emissions were measured in some Euro IV- and EEV-level vehicles as well.

The Euro emission restrictions have been defined as the emissions produced by an HD engine per power, i.e. g/kWh. The estimated Euro III limit calculated per driving performance for a bus fleet with typical power consumption is approximately 9 g/km and the Euro IV limit is about 7 g/km.

The NO/NO_2 ratio of a bus is not necessarily permanent during the lifecycle of the bus. As shown in Figure 10.2, NO and NO_2 for a Euro IV-level bus with an EGR+oxidation catalyst were determined after 30,000 km, 130,000 km and 244,000 km. The share of NO_2 in NO_x decreased from 50 % to less than 5 % after driving a bit more than 200,000 km. This was probably caused by the weakening of the oxidation catalyst. The NO_x emission level of stoichiometric or nearly stoichiometric natural gas buses equipped with a carburettor engine is usually lower than that of diesel buses, as is also the NO_2/NO_x ratio of the CNG buses (less than 5 %, Figure 10.2). Depending on the fuel/air ratio of the combustion mix, either three-way or oxidation catalysts are used in natural gas powered buses.

The observations made on buses also apply to trucks (orange bars, Figure 10.2). Problematic after-treatment technologies exist in terms of, at least, direct NO_2 at the Euro IV emission level. High NO_2/NO ratios and absolute emission levels of NO_2 were generated in the pDPFs, oxidation catalyst and some SCR applications. The levels were not quite as high as those in buses, which may be due to higher driving speeds and thus higher temperatures.

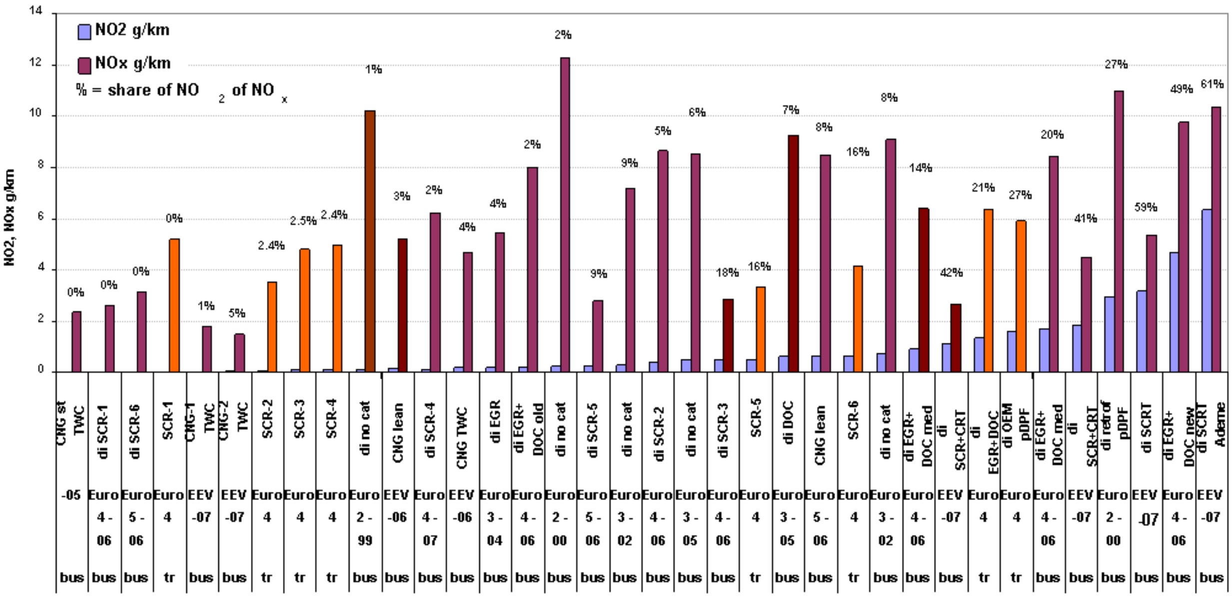


Figure 10.2. The NO and NO_2 emissions of Euro II – Euro V/EEV emission level buses and trucks in city driving. A Braunschweig cycle is usually used for buses and the delivery/highway cycle for trucks.

The comparisons of specific emissions (Figure 10.2) for different vehicle types were calculated from different driving performances and proportioned to driving speed. It should be kept in mind that the average speed in the Braunschweig cycle is 22.5 km/h and that of the delivery cycle of trucks approximately 65 % higher.

Since the vehicle tests in the Uusipäästö project on buses, trucks and passenger cars were extensive and were a good representation of the current vehicle pool in city traffic and of city driving styles, they were used as a basis for estimates on the impact of heavy-duty and light-duty traffic on NO_x and NO_2 local emissions.

Due to the higher engine power of buses and trucks, their role in producing nitrogen oxides is naturally at a whole different level than passenger cars. On streets used by public transportation, the proportion of buses can easily be almost 20 %, which makes heavy-duty vehicles an incomparable source of both NO_x and NO_2 emissions in urban air. According to this study, approximately 90 % of NO_x and over 80 % of NO_2 may be generated by heavy-duty city vehicles. Along streets were light-duty (LD) traffic dominates (e.g. 96-98 %), light-duty vehicles are an equal or even greater source of direct NO_2 emissions than buses and trucks. NO_x emission levels are also very close to each other in different vehicle groups. The average NO_2/NO_x ratio of the passenger car pool in actual city driving is, however, significantly higher than that of HD vehicles. This is mainly due to the recent increase of the newest vehicles that generate more NO_2 emissions among diesel powered passenger cars. The direct NO_2 emission of a medium-sized passenger car with new technology and equipped with a particulate filter was as high as that of a 2005 Euro III emission level bus that did not have exhaust after-treatment devices.

SCR technology has become more common in Europe with the goal of restricting the nitrogen oxide emissions of heavy-duty vehicle engines. In some cases, SCR technology did not work as expected in vehicles tested in this study (Figure 10.2): However, when the technology does work properly, it effectively reduces the amount of both NO and NO_2 in exhausts, and this will naturally impact the production ratio of the nitrogen oxides between light-duty (LD) and heavy-duty (HD) vehicles. The HD development in the Euro 6 stage may have an opposite impact, when DPFs, and the potential high NO2 emissions they generate, become more common. Restricting the NO_2 emission in HD engines will be considered in the Euro 6 stage.

Conclusions

The increased NO_2 local emissions in the heavy-duty vehicle pool is most affected by new vehicles equipped with an effective oxidation after-treatment device (DOC). Many particulate filter solutions are also oxidation catalysts, in particular those that use NO_2 in the filter regeneration of soot. NO_2 is formed from NO catalytically in the pre-oxidiser, or it is formed on the surface of a (Pt) catalysed filter. The benefit of NO_2 as an oxidising agent is the low regeneration temperature of the soot filter.

The new SCR + DPF combinations in buses were also problematic in terms of direct NO_2 emission amounts. This is a partial indication of how the exhaust legislation does not, thus far, contain any restrictions on direct NO_2, only on the total amount of nitrogen oxides. In part, it indicates how ready these after-treatment technologies "of the future" are. A provision has, however, been included in the newest exhaust regulations (Euro VI) for the restriction of either NO_2/NOx ratio or NO2 emission. If implemented, this would improve the situation in the long-run.

Based on the results, it seems that lower combustion temperatures due to EGR or a leaner combustion mix increase the formation of NO_2 in exhaust.

Currently, 10 % of the NO_x generated by heavy-duty city traffic and 19 % of that generated by light-duty traffic is estimated to be direct NO_2, considering the driving performances.

The specific NO_x emissions of heavy-duty diesel engines are very high compared to those of diesel powered passenger cars. Compared to differences in fuel consumption, they are about 3-5 times as high. Currently, new HD engines have also in many cases been optimised for PM reduction and after-treatment is used to remove high NO_x.

It would seem that after-treatment solutions that are mature and optimal for the reduction of NO_2 and NO_x emissions already exist among the exhaust cleaning technologies used in heavy-duty vehicles: there are well-functioning SCR catalysts (at least when new) and established three-way catalyst solutions for stoichiometric natural gas powered buses. In both, the total emission of nitrogen oxides and the share of direct NO_2 emissions are small.

6.3 UNREGULATED EMISSIONS OF BUSES

6.3.1 General

Unregulated emissions were tested on the following six city buses:

- Scania Euro III emission level vehicle (model year 2002)
- Scania Euro IV emission level vehicle (model year 2006)
- Scania EEV emission level vehicle (model year 2008)
- Volvo EEV emission level vehicle (model year 2008)
- CNG - Lean Mix. MAN. EEV emission level three-axle vehicle (model year 2006)
- CNG - stoichiometric. MAN EEV emission level vehicle (model year 2007)

The following exhaust components were measured in the special tests:

Gas phase:

- hydrocarbon analysis for C_1 - C_8 compounds (toluene) (GC)
- aldehydes (DNPH sampling, HPLC)
- ammonia NH_3 (FTIR)

Particulate phase:

- particulate quantity distribution and total quantity (ELPI)
- PAH analysis of the particulate matter (polyaromatic hydrocarbon compounds)
- Ames test for the particulate matter (particulate mutagenicity)

6.3.2 Hydrocarbon emissions

In the hydrocarbon analysis, ten different hydrocarbon compounds were determined using a gas chromatograph: methane, ethene, acetylene, ethane, propene, propane, isobutene, 1,3-butadiene, benzene, and toluene. Figure 10.3 shows the results of the hydrocarbon analysis in mg/km for different vehicles.

Based on the results, the hydrocarbon emissions of natural gas powered vehicles consist of solely methane.

Natural gas / methane engines are available with both lean mixture and stoichiometric mixture adjustment. With lean mixture technology, the methane emission is many times higher than that of a stoichiometric engine. This can be seen in Figure 10.4 which shows the hydrocarbon emissions of EEV-level vehicles only in the Braunschweig cycle. The result of the hydrocarbon analysis on Euro III and Euro IV-level basic diesel vehicles is very similar in terms of the components and content levels observed. The exhaust of both vehicles contains methane, ethene, propene, 1,3-butadiene, benzene, and toluene. The methane emission of Scania's EEV vehicle is threefold compared to the Euro III- and Euro IV-level vehicles and fivefold compared to Volvo's EEV vehicle. Volvo's EEV vehicle has the lowest methane emission among the diesel powered vehicles and it is at a level characteristic of diesel technology (less than 20 mg/km). Volvo's EEV vehicle emission also had a detectable benzene content.

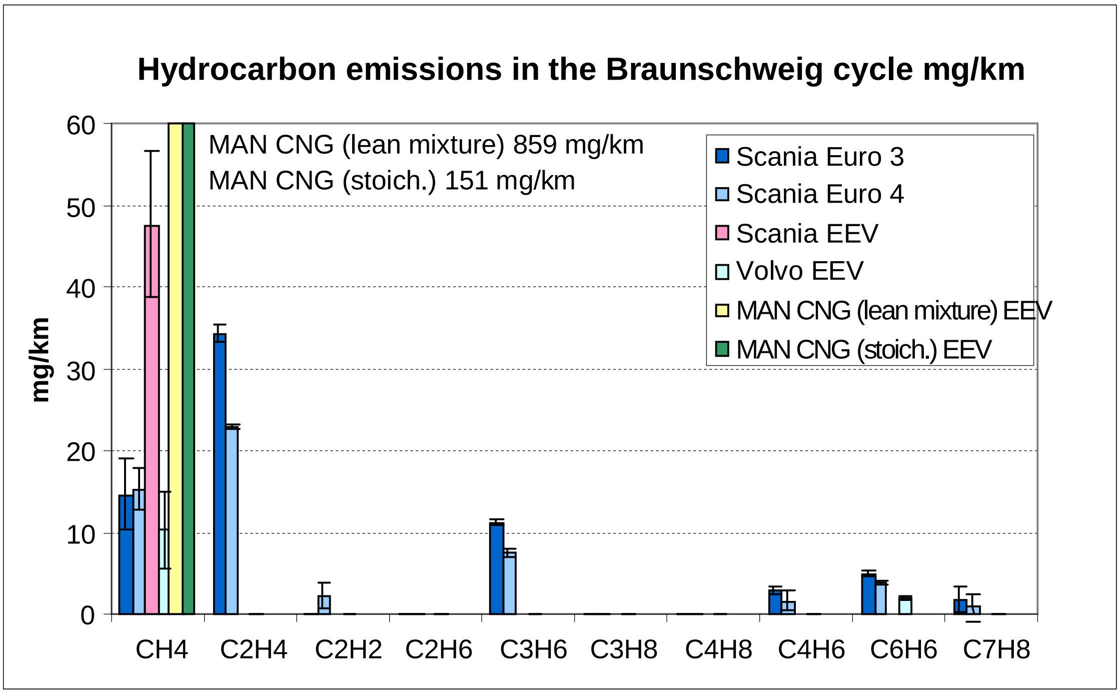


Figure 10.3. Hydrocarbon emissions (g/km) in different vehicles in the Braunschweig cycle.

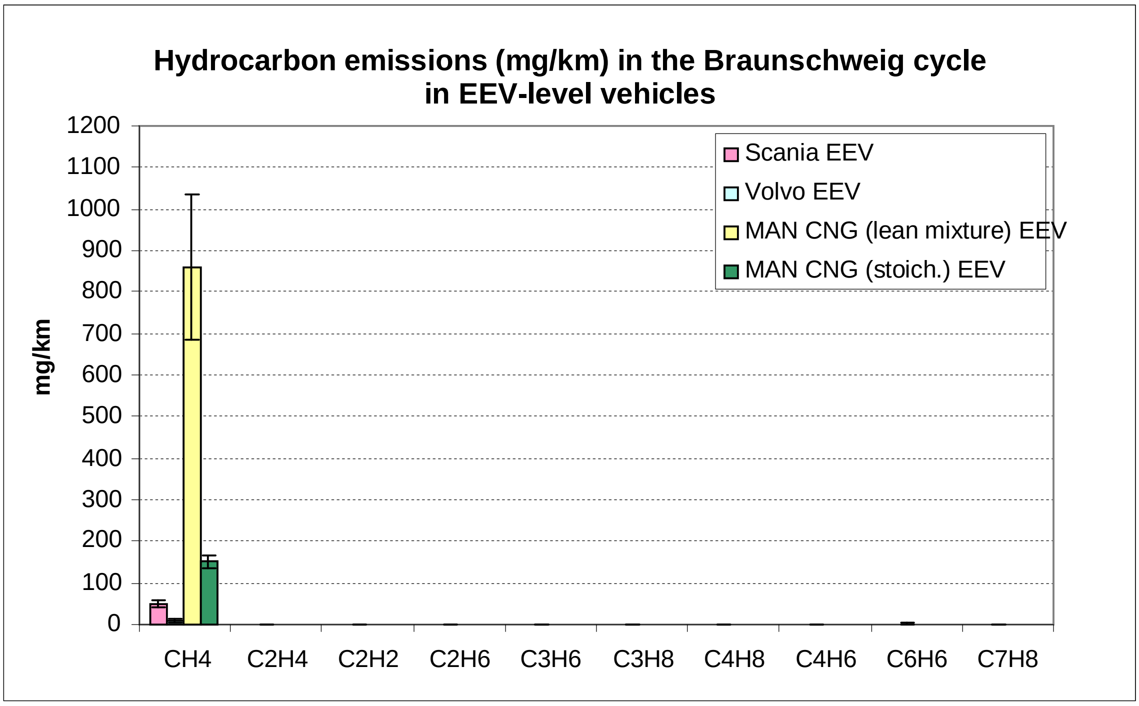
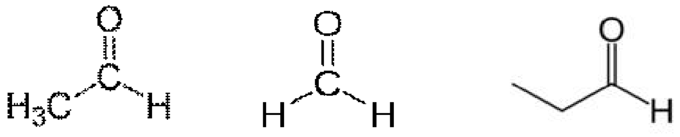


Figure 10.4. Hydrocarbon emissions (g/km) in EEV vehicles in the Braunschweig cycle.

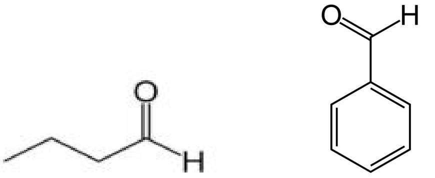
6.3.3 Carbonyl compounds

Samples were taken from diluted exhaust by means of the exhaust reacting with DNPH cartridges at a suitable sample flow. After the test, the cartridges were extracted with acetone nitrile. Before analysis, the extract was diluted in water in a 1:1 ratio. The content of a total of 10 carbonyl compounds was analysed with liquid chromatography (HPLC). The compounds analysed were: formaldehyde, acetaldehyde, acrolein, propionaldehyde, crotonaldehyde, butylaldehyde, benzaldehyde, valerylaldehyde, m-tolualdehyde, and hexanal. The health effects caused by carbonyl compounds consist most commonly of eye and respiratory irritation. Of the aldehydes studied, the content of formaldehyde and acetaldehyde was usually the highest. Diesel exhaust may also contain propionaldehydes, butylaldehydes and benzaldehydes but the content of these is usually less than 0.3 ppm. Formaldehyde content smaller than that of acetaldehyde (2-4 ppm) causes a burning sensation in the eyes and irritation of respiratory mucous membranes (Finnish Institute for Occupational Health/OVA guidelines). In addition, IARC (IARC 1989) and NIOSH (NIOSH 1995) have found formaldehyde strongly carcinogenic. According to NIOSH, the STEL limit (Short Term Exposure Limit) of an exposure as short as 15 minutes is only 2 ppm. Formaldehyde in the air dissolves as a result of exposure to light and has a half-life on 2-6 hours.

Figure 10.5 shows the chemical formulas of some of the most common carbonyl compounds.



acetaldehyde formaldehyde



butylaldehyde benzaldehyde

Figure 10.5. Formulas of carbonyl compounds (Source: Wikipedia).

Figure 10.6 shows the total content of carbonyl compounds (sum of ten carbonyl compounds) and the formaldehyde and acetaldehyde emissions of the vehicles studied. Carbonyl compounds could not be determined for the EEV-level Scania since the DNPH reagent had run out during the test. This is due to the fact that Scania has an effective oxidation catalyst generating high levels of NO_2 which consumed the reagent in the sample cartridge.

Earlier studies by VTT (Erkkilä et al., 2007) have shown that the formaldehyde and acetaldehyde emissions of a Euro III diesel powered bus equipped with an oxidation catalyst are approximately 50 % of the emissions of a bus without a catalyst. There are no significant differences in the carbonyl compound contents of Scania's Euro IV and Euro III vehicles. The total content and aldehyde contents of carbonyl compounds decrease systematically when moving from the Euro III-level to the EEV-level. The total sum of carbonyl compounds in an EEV-level vehicle is nearly 100 % of formaldehyde and acetaldehyde.

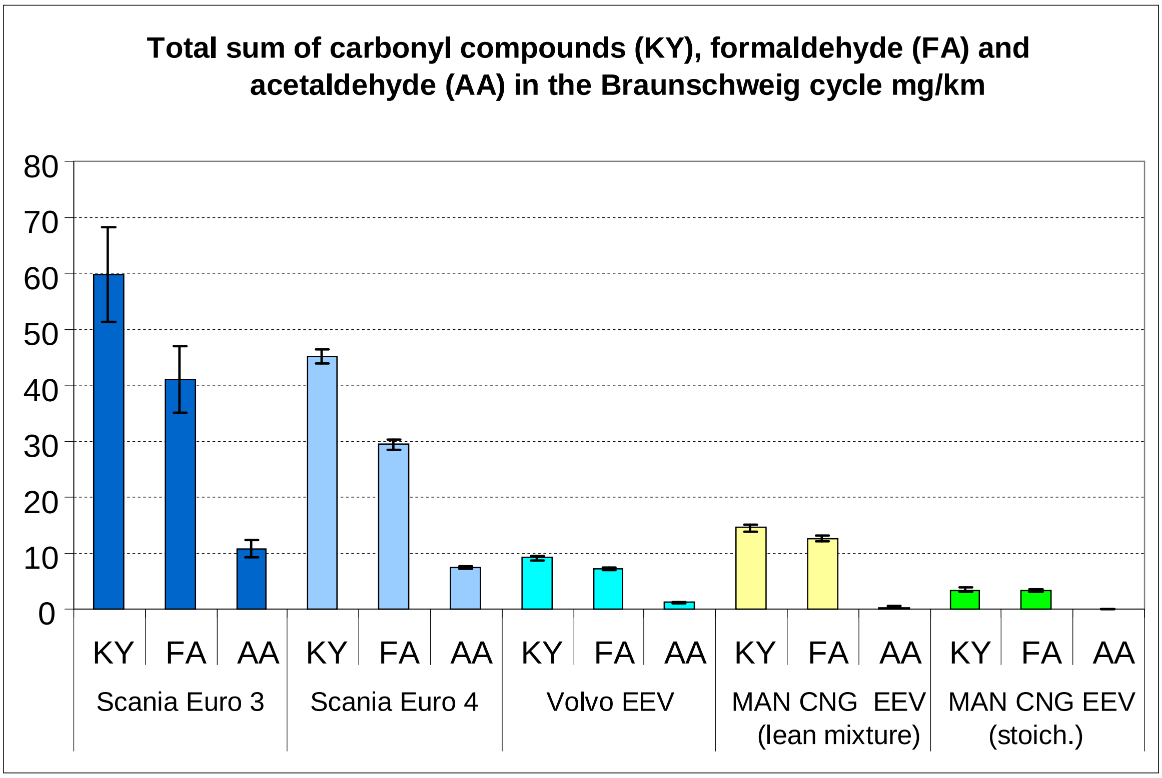


Figure 10.6. The total sum of carbonyl compounds and the formaldehyde and acetaldehyde emissions in the Braunschweig cycle

The total content of carbonyl compounds and formaldehyde emission are many times higher in a lean mixture natural gas powered vehicle than in a stoichiometric natural gas powered vehicle. In the stoichiometric natural gas vehicle, the total sum of carbonyl compounds is almost completely formaldehyde. Although the differences between the two vehicles are great, the formaldehyde emission of the lean mixture natural gas vehicle is fairly small, equalling 1.2 ppm in exhaust. Although the carbonyl compound content detected is low in both of the natural gas powered vehicles, the detected level is higher than that in tests performed in the IANGV project in 2004 (previously, FA and AA were at zero level). The emissions of the lean mixture natural gas vehicle have exceeded the level of the diesel EEV vehicle. It should be noted that the accumulated travelled kilometres of the lean mixture and stoichiometric natural gas powered vehicles of the different makes studied in the IANGV project in 2004 were less than 50,000. At the time of the current tests, the accumulated kilometres of the stoichiometric vehicle were approximately 206,000 and those of the lean mixture vehicle, 307,000.

6.3.4 Ammonia emission

Ammonia emissions were measured continuously using a Gasmet FTIR device in the Braunschweig cycle.

The EU has defined an indicative occupational exposure limit (IOELV) for short-term exposure to ammonia, which is 50 ppm/15 minutes. This is the same as the so-called HTP value (the known hazardous content in workplace air). In the USA, different types of exposure are also described with the IDLH value (Immediately Dangerous to Life and Health, USA) where the limit of acute toxicity of ammonia is 30 ppm/30 minutes.

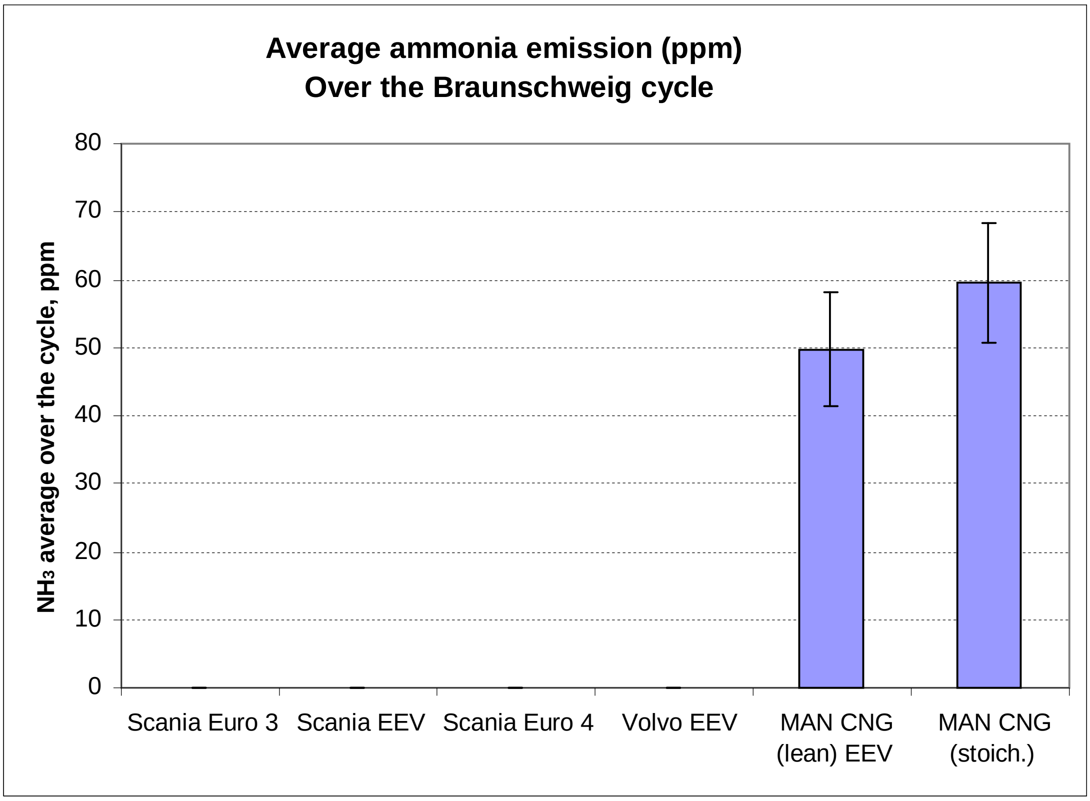


Figure 10.7. Average ammonia content (ppm) in different vehicles in the Braunschweig cycle.

Figure 10.7 shows the average ammonia content in the raw exhaust of different vehicles in the Braunschweig cycle. The average ammonia emission of a natural gas powered bus equipped with stoichiometric technology was 60 ppm, and that of a bus equipped with lean mixture technology was 50 ppm in the Braunschweig cycle. No ammonia contents exceeding the detectable limit (3 ppm) were observed in diesel powered vehicles.

Figure 10.8 shows the ammonia emission of EEV-level vehicles in a continuous FTIR measurement in the Braunschweig cycle. Based on this figure, the ammonia emission of natural gas powered vehicles follows a certain pattern due to the cycle load. The stoichiometric natural gas vehicle has more ammonia spikes than the lean mixture vehicle. As a result, the average ammonia emission of the stoichiometric natural gas powered vehicle is higher. This has also been observed in earlier studies by VTT and it has been assumed that the phenomenon is related to the catalyst technology used in the vehicles. No ammonia is detected in the Scania EEV-level diesel powered vehicle during the cycle.

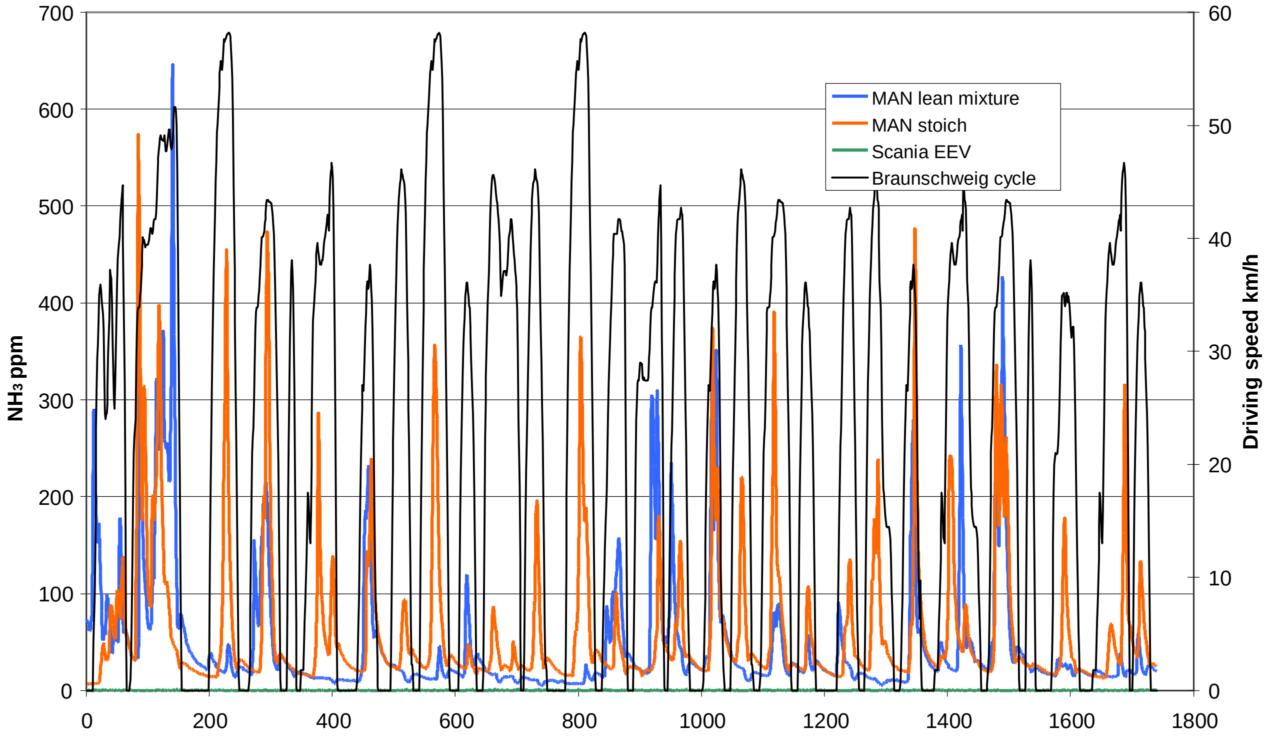


Figure 10.8 Ammonia emissions in different vehicles in the Braunschweig cycle.

6.3.5 Particulate size and quantity

The particulate size distribution and total quantity were measured using the ELPI instrument. The instrument categorises the particulates to different size classes based on their aerodynamic diameter in a vacuum impactor. A sample obtained from the tailpipe was diluted in two stages by using a porous tube diluter as the primary diluter and an ejector diluter as the secondary diluter. The actual dilution ratio was determined by measuring the CO_2 content of undiluted exhaust and the diluted sample. Figure 10.9 shows the particulate size distribution of all six vehicles.

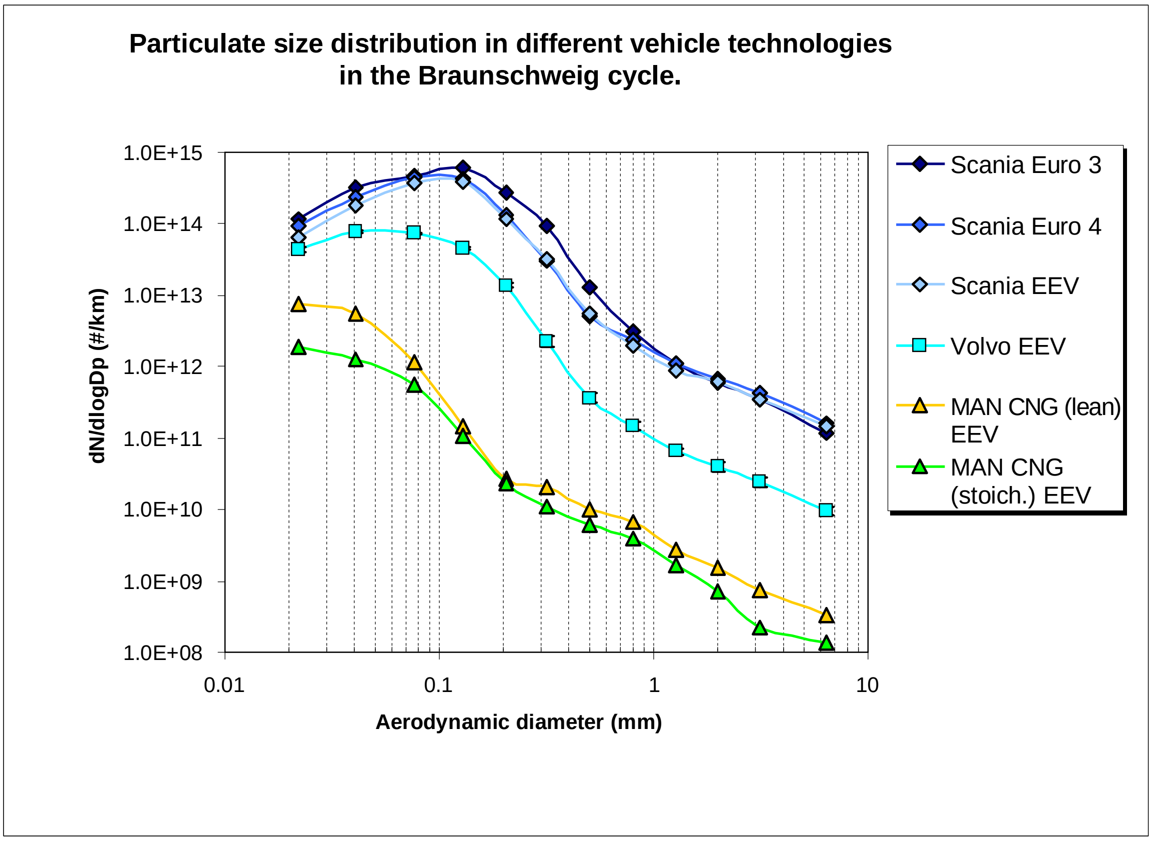


Figure 10.9 Particulate size distribution in different city buses in the Braunschweig cycle. The Y axle scale is logarithmic.

The figure illustrates the differences between different vehicle technologies in particulate quantities. The differences also correlate directly with the mass emission and total quantity of particulates (Figure 10.10). The quantities in the different size categories for natural gas powered vehicles are roughly 1-3 times smaller in the order of magnitude compared to the Euro III emission level vehicle. The particulate emissions of the Euro IV and EEV vehicles are mutually the same size and slightly lower than those of the Euro III vehicle. The particulate emissions of the EEV 2 vehicle are, on average, one order of magnitude smaller than those of the Euro III vehicle. In the Euro III vehicle, the peak of size distribution is at 129 mm, and when moving to cleaner technologies, the peak moves to smaller particulate sizes.

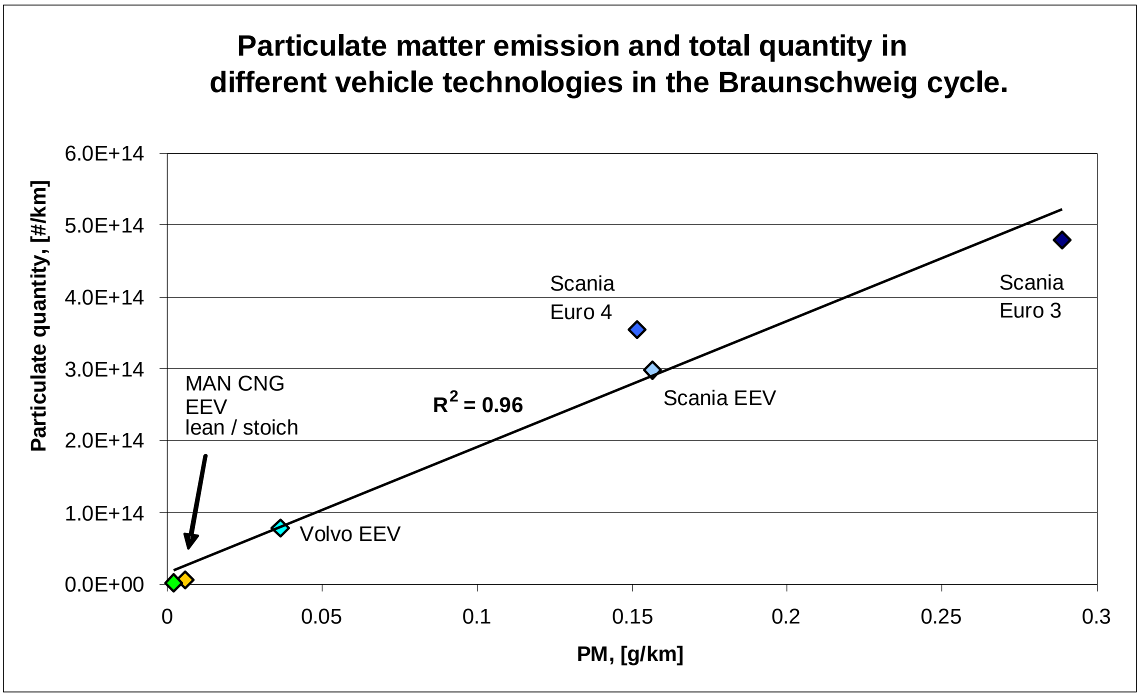


Figure 10.10. Particulate total quantity in relation to the particulate matter emission in different vehicle technologies.

Figure 10.10 shows how the total quantity of particulates changes during the Braunschweig cycle. For clarity's sake, the second EEV and CNG vehicles have been left out of the Figure. Spikes in particulate quantities occur in all vehicles during acceleration. The particulate quantities are clearly the highest in the Euro III and Euro IV vehicles. The particulate levels of the natural gas powered vehicles are extremely low in all driving situations.

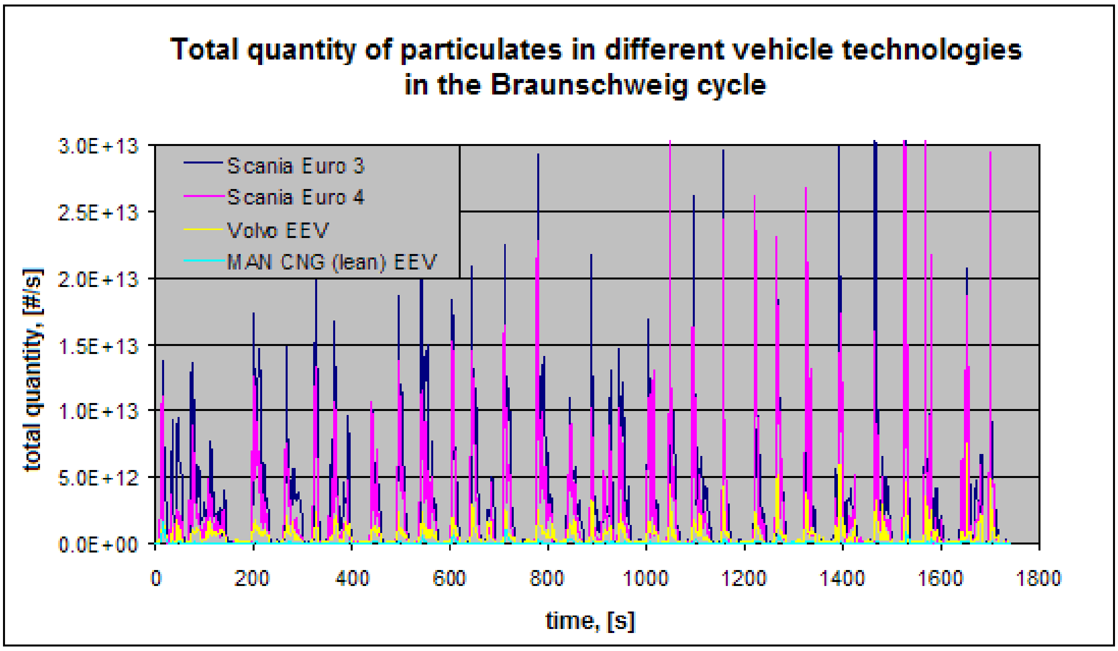


Figure 10.11. Total quantity of particulates in different vehicle technologies in the Braunschweig cycle.

6.3.6 PAH emissions

Figure 10.12 shows a composite of the emission quantities of various PAH compounds. Of the compounds, those with 2-3 aromatic rings are less harmful and those with more than 4 rings are known carcinogenic compounds. In addition, the Figure shows the total of all PAH compounds analysed. The EPA/IARC category is currently based on eight PAH compounds that the International Agency for Research on Cancer (IARC) and the US Environmental Protection Agency (EPA) have listed as known or suspected carcinogens (priority PAH compounds):

- benzo(a)antrasene
- benzo(b)fluorantene
- benzo(k)fluorantene
- benzo(a)pyrene
- dibenzo(a,h)antrasene
- indeno(1,2,3-cd)pyrene
- crysene
- 7,12 -dimethylbenzo(a)antrasene (added in 2006)

VTT has been analysing the last compound since 2006, and it is included in the Mobile Source Air Toxics list (MSAT, EPA 2000).

Figure 10.12 shows the totals of the PAH compounds in PM emission. The results show that both the total quantities and consistency of the PAH compounds change radically as the vehicle technology changes: a Euro III diesel powered vehicle has the highest total PAH content and a vehicle equipped with EEV technology has the lowest. Moving from Euro III-level to Euro IV-level causes a clear reduction in the 4-ring PAH emissions in the same manufacturer's vehicle although the change in the total PAH content is not as radical. Although an EEV-level diesel powered vehicle produced very low content of PAH, both EEV-level natural gas powered vehicles achieved even lower PAH levels.

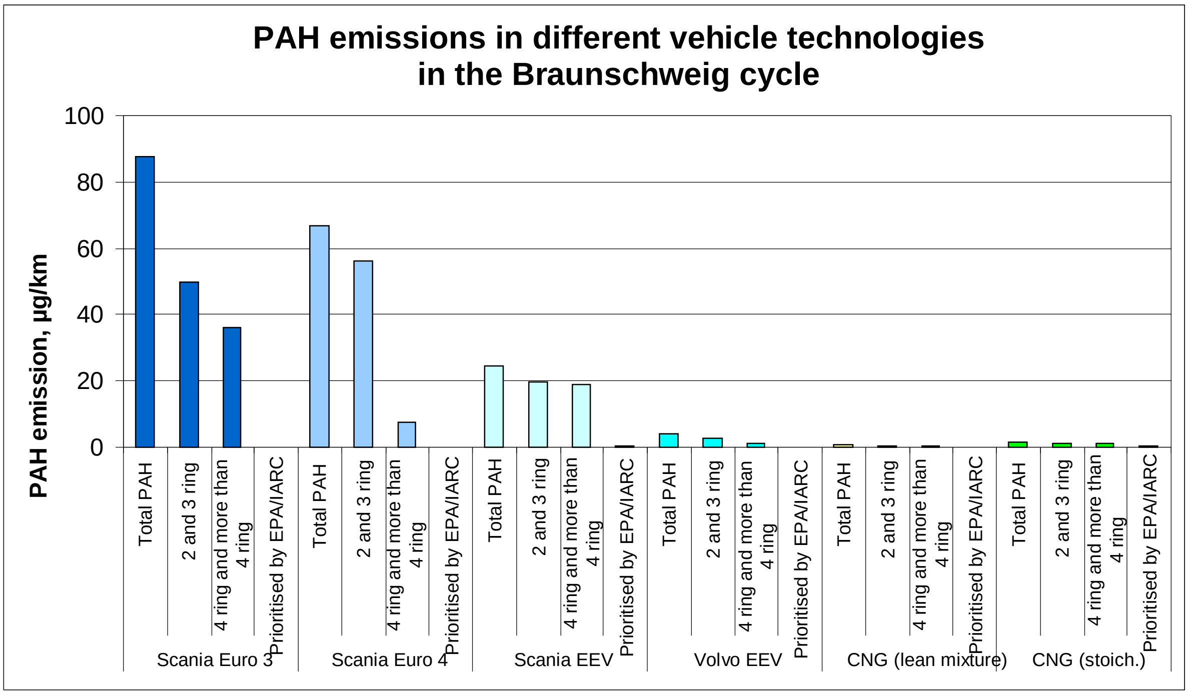


Figure 10.12. PAH emission in vehicles representing different vehicle technologies (Braunschweig cycle)

6.3.7 Particulate mutagenicity

The Ames test was used to study the mutagenicity of particulates. Tests measuring mutagenicity can be performed on solid exhaust particulates and, with certain reservations, on semi volatile compounds as well. The simplest of these tests is the *Ames* bacterium test. The nitro-PAH compounds are mutagens with a direct effect and they react in *Salmonella typhimurium* test cells without metabolic activation *(TA98-S9*). With metabolic activation *(+S9*), additional response is typically obtained from indirectly affecting non-substituted PAH compounds (Maron & Ames 1983).

The importance of the Ames test has significantly decreased in recent years and it is being replaced by more demanding but also more illustrative animal or human cell tests. The Ames test matrix is presented below. The particulate emissions of natural gas powered vehicles were so low that not enough particulate matter could be collected for all strains of bacteria.

strain of bacteria	Euro3	Euro4	EEV	EEV	CNG (lean mixture)	CNG (stoich.)
TA98 -S9	x	x	x	x	x	x
TA98 +S9	x	x	x	x	-	x
TA98NR -S9	x	x	x	x	-	-

The Euro III vehicle, both of the EEV and the stoichiometric natural gas powered vehicles indicated marginally direct mutagenicity with strain TA98-S9. The same vehicles did not indicate mutagenicity with strain TA98NR-S9, so it can be concluded that direct mutagenicity is caused by nitro-PAH compounds. With the aforementioned vehicles, minor indirect mutagenicity was also observed (strain TA98+S9). The mutagenicity responses of all the aforementioned vehicles were, however, so small that no conclusions can be drawn between different vehicle technologies.

6.4 UNREGULATED EMISSIONS OF TRUCKS

6.4.1 General

The measurements of unregulated emissions in trucks focused on the measurement of the particulate size and quantity distribution. In addition, only ammonia emissions were measured. These can occasionally be high in vehicles equipped with SCR technology.

6.4.2 Particulate size and quantity

The particulate size and total quantity were measured with the ELPI instrument. The test is described above in 10.3.5.

Figures 10.13 to 10.18 show the particulate size distribution of vehicles equipped with SCR technology with solid lines and that of vehicles equipped with EGR technology with dotted lines. In the highway cycle, the share of the 30-100 nm particles is larger in the EGR vehicles than in the SCR vehicles. The share of the less than 30 nm particles, however, is clearly larger in the SCR vehicles (with the exception of MB Actros) than in the EGR vehicles (Figure 10.13).

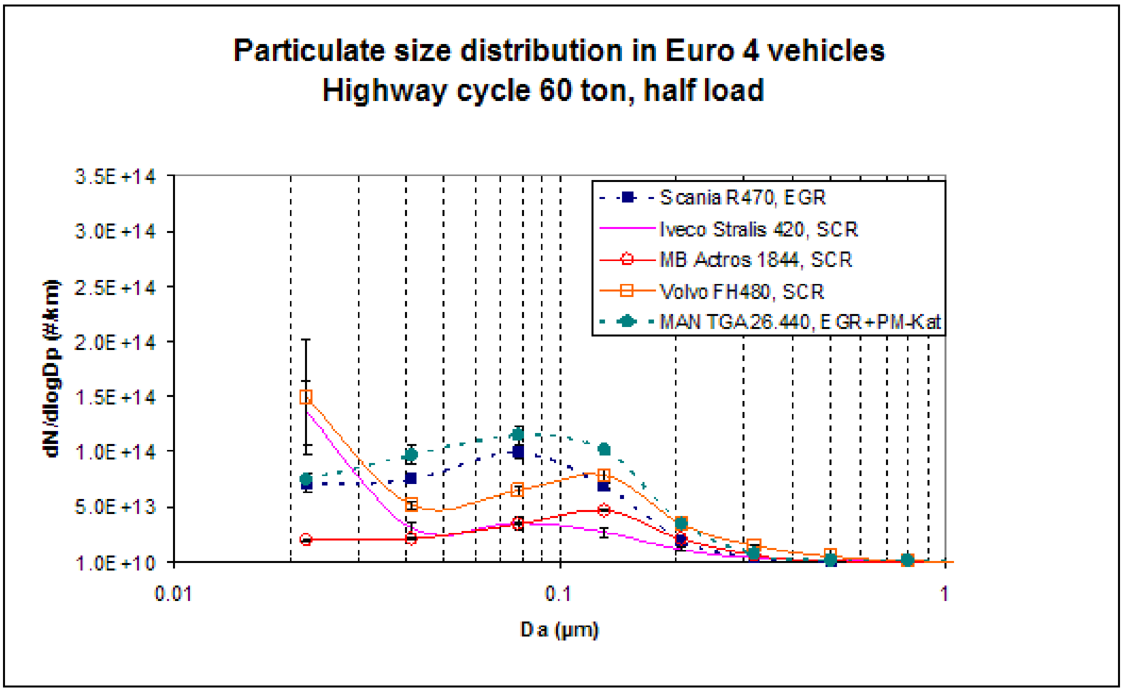


Figure 10.13. Particulate size distribution in different vehicles in the highway cycle.

The peak of the size distribution accumulation mode in the EGR vehicles (Scania and MAN) and the SCR vehicle (Iveco) is approximately at 78 nm, whereas in two other SCR vehicles (Volvo and MB) it is approximately 130 nm. The share of nanoparticles is higher in Iveco and Volvo than in the other vehicles.

Figure 10.14 shows the particulate size distribution of all five vehicles in the freeway cycle. In principle, the distributions are similar to those in the highway cycle but the difference between vehicles equipped with different technologies are larger. The particulate size distribution of the SCR vehicles are very congruent, with the exception of the quantity of the < 30 nm particulates. The share of nanoparticles is higher in Iveco and Volvo than in the other vehicles. In these vehicles, the quantity of the accumulation particles in relation to the nanoparticles is clearly smaller than in the highway cycle. In the freeway cycle, the peak of the accumulation mode of the particulate size distribution in Scania is approximately at 75 nm whereas in the other vehicles it is approximately at 130 nm.

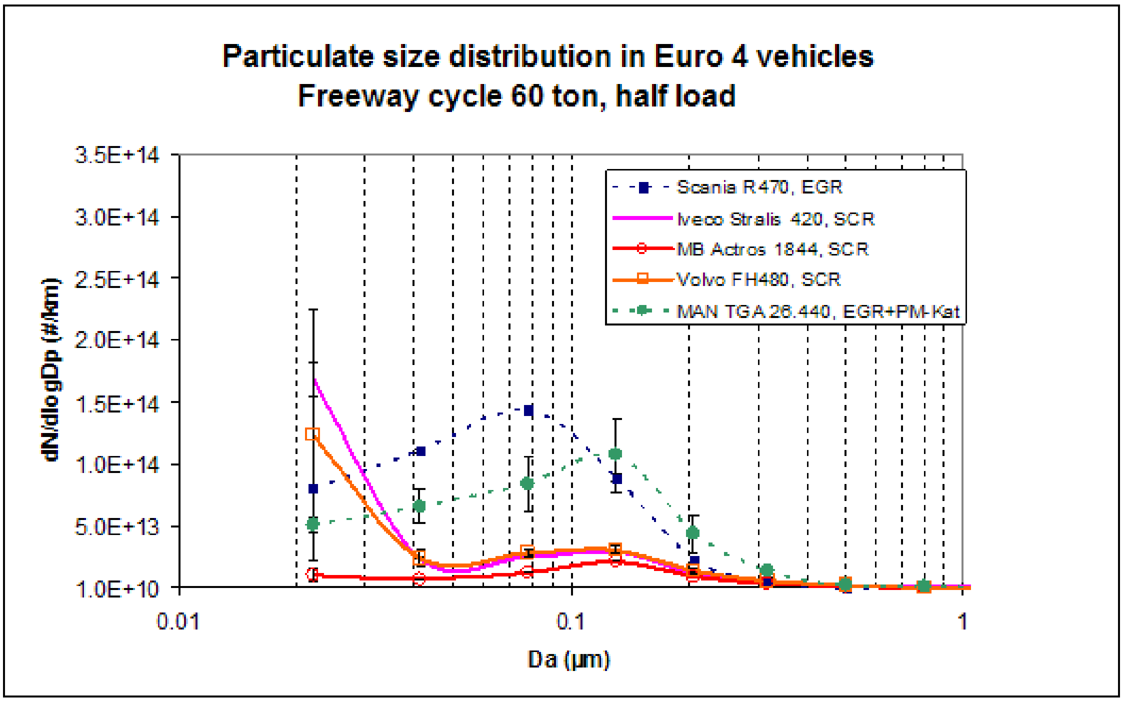


Figure 10.14. Particulate size distribution in different vehicles in the freeway cycle.

In the freeway cycle, the effect of load was also studied with Scania EGR technology vehicles and Iveco SCR technology vehicles. Two supplementing measurements were carried out on both vehicles with a full load and without a load (empty). The basic matrix measurements were carried out with a half-load. The results are shown in Figure 10.15. The position of the size distribution peak moves in both vehicles to a higher size category when comparing a full load to an empty load. Although the size of the accumulation mode decreases when moving from an empty load to a full load, the shift in the accumulation mode position towards a larger particulate size causes the measured total particulate matter to grow in both vehicles as well. With Scania's half load, the share of the under 100 nm particles is halfway between the empty load and a full load, and the position of the distribution accumulation mode shifts to a slightly larger particulate size than in an empty load. With Iveco's half load, the shape of the particulate size distribution follows that of the full load but the share of the under 100 nm particles is the lowest.

Figure 10.16 shows the particulate size distribution of all five vehicles in the delivery cycle. The particulate size distribution of the delivery cycle in all vehicles differs from that of the highway and freeway cycles. Nanoparticles dominate in Scania's size distribution and there is no clear accumulation mode. In Volvo's size distribution, nucleation mode is no longer detectable. What is also important is the fact that the particulate quantities in MAN and Scania in size category 80-200 nm are very close to those of the SCR vehicles; in Scania, the particulate quantity is the lowest in the over 100 nm particles.

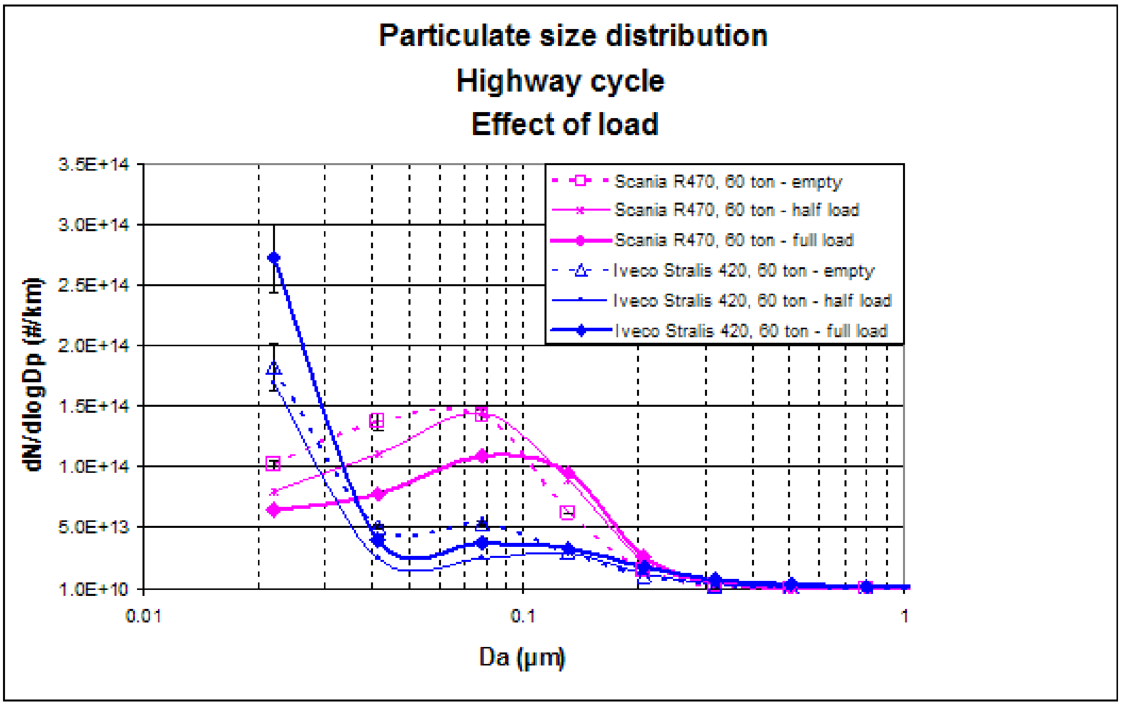


Figure 10.15. The effect of load on particulate size distribution in vehicles equipped with two different technologies in the freeway cycle.

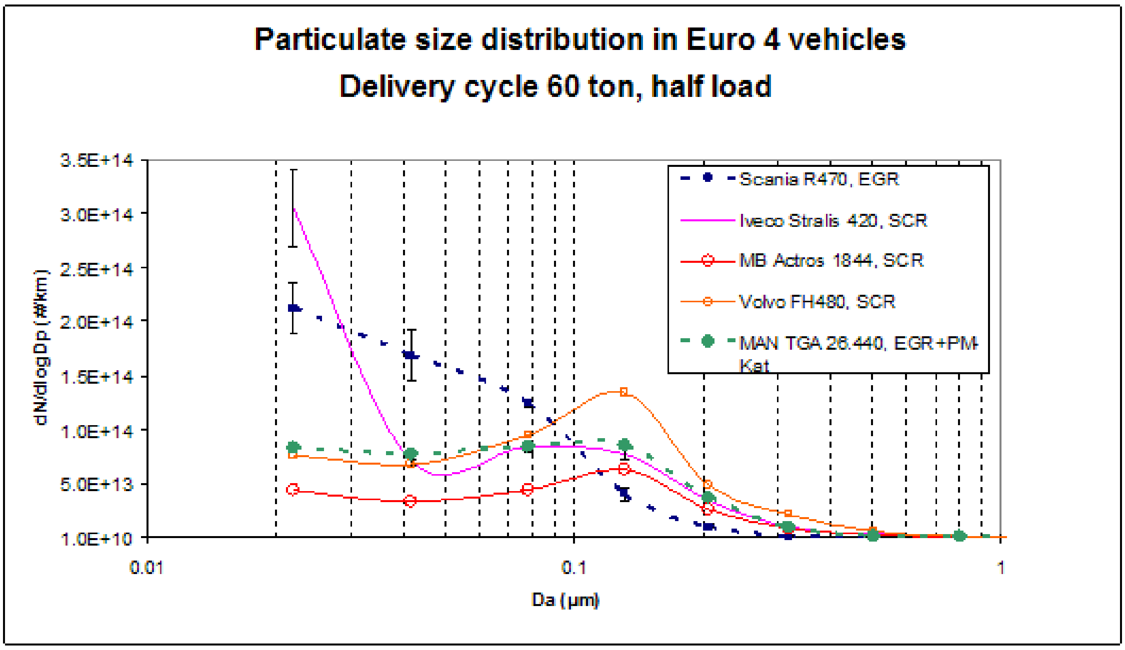
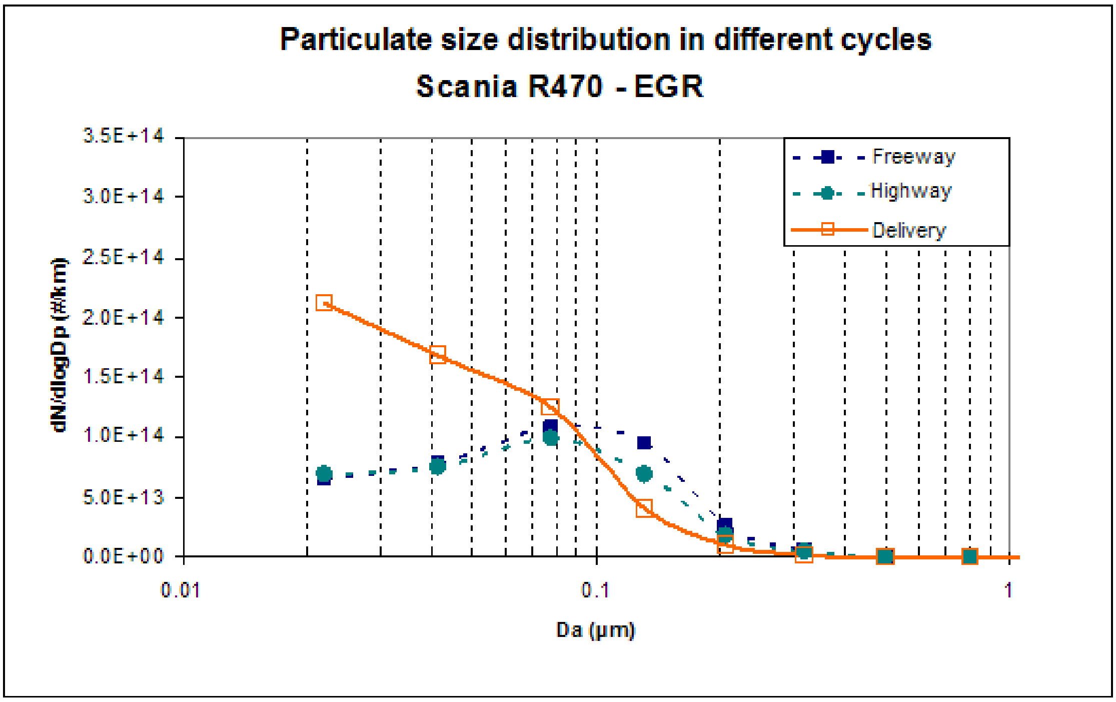


Figure 10.16. Particulate size distribution in different vehicles in the delivery cycle.

The effect of the cycle on the distribution is easiest to view by selecting two vehicles, representing different technologies in which the changes in the shape of the distribution are most radical, and by reviewing the changes between these vehicles. Figure 10.17 shows the particulate size distribution of Scania and Iveco in different cycles. The figure illustrates that the distributions in the highway and freeway cycles are very close to each other but the distribution in the delivery cycle differs from the other cycles in both vehicles. This may be due to the different load rate of the delivery cycle. In the cycle, vehicles are idle more than in the other cycles, leading to an increase in the number of volatile particulates in particular. In the Iveco, the size of the accumulation mode and the quantity of the nanoparticles increases, which may be caused by SCR insufficiently removing hydrocarbons and particles generated during idling, and this shows in the particulate emission. In the Scania, the soot mode disappears and the share of volatile particulates grows due to EGR.

Figure 10.18 shows the total quantities of particulates and particulate matter emissions in different vehicles in different cycles. The MB Actros has the lowest total particulate quantities in all cycles. Scania and Iveco clearly produced the most particulates in the delivery cycle, compared to the other vehicles due to the large quantity of nanoparticles (Figure 10.17).

The measures indicated that the total particulate emission of the MAN TGA 26.430 EGR vehicle in the highway cycle was 0.124 g/km whereas the average for the SCR vehicles was 0.035 g/km. The results indicated that the vehicle was defective and it was replaced with a MAN TGA 26.440. The total particulate emission of the new MAN vehicle was 0.050 g/km, or nearly 60 % lower. The particulate size distribution measurements indicated an approximately ten-fold difference in the total quantities of these two vehicles.   Figure 10.19 shows the particulate size distribution of these two MAN trucks in the highway cycle. The results proves the natural point that well-functioning after-treatment devices are extremely important for the achievement of a low emission level.



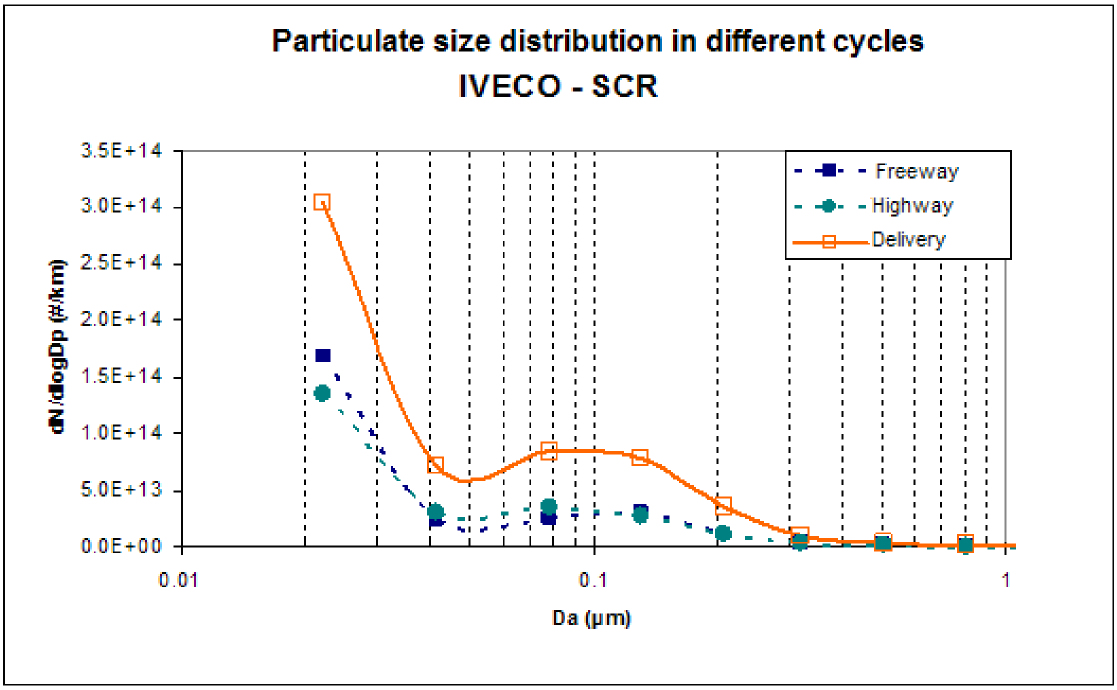
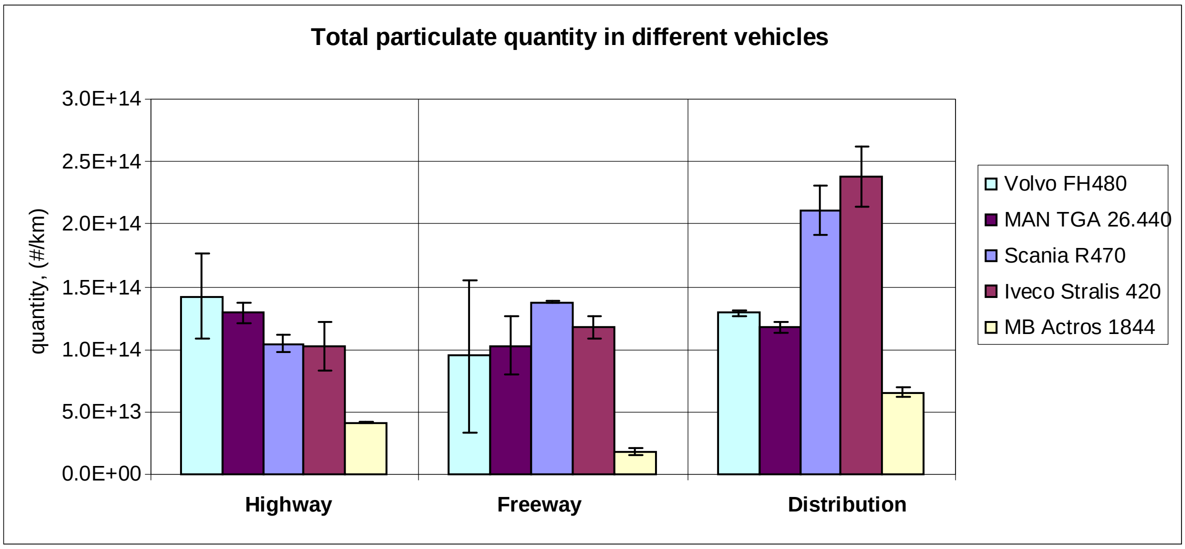


Figure 10.17. Particulate size distribution in the Scania and Iveco in different cycles.



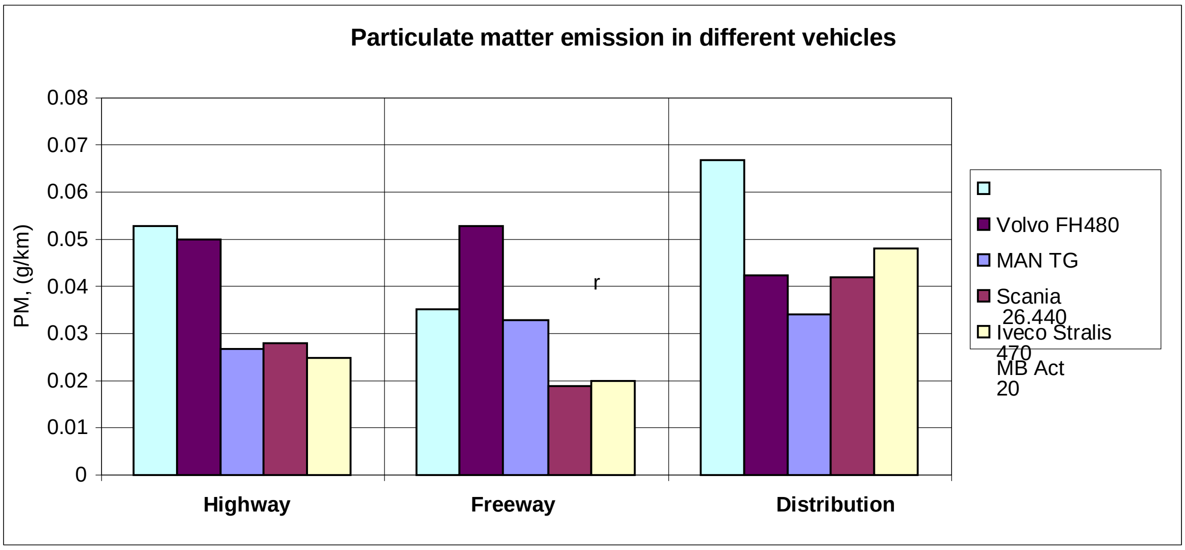


Figure 10.18. Total particulate quantity and particulate matter emission in different vehicles in different cycles.

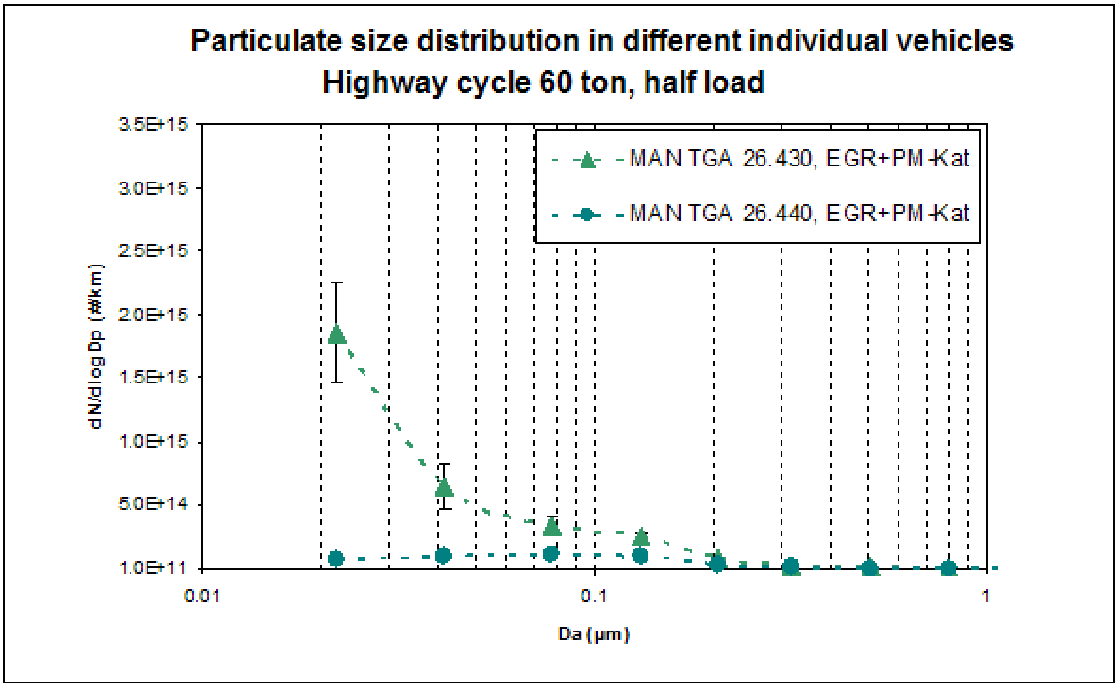


Figure 10.19. Total particulate quantity distribution of two different MAN trucks in the highway cycle.

6.4.3 Ammonia emission

Ammonia emissions were measured continuously using a Gasmet FTIR device. The ammonia emissions were measured only on the SCR vehicles. The average ammonia content in the measured cycles did not exceed the detectable limit (3 ppm) in any vehicle.

6.5 SUMMARY

Research by VTT has concentrated on the measurements of unregulated emissions in both new and old vehicles representing a wide range of different engine and after-treatment technologies. The studies cover hydrocarbon and carbonyl emissions testing, particulate size and quantity distribution measurements as well as the particulate consistency primarily in buses. The measurements of unregulated emissions in trucks focused on particulate size and quantity. Taking the special characteristics of vehicle technology into account, the share of ammonia emissions, among other things, was also measured during the test cycle. Passenger cars were also included in tests on the importance of the structure of vehicle fleet in the elevated NO_2 content of urban air.

The studies showed that NO_2 local emissions of heavy-duty and light-duty vehicles were most impacted by vehicles that were equipped with a powerful oxidation after-treatment device, pDPF or catalysing filter. CSCR+DPF combinations simultaneously reducing both nitrogen oxide and particulate emissions that have become more common in buses were also shown to be problematic in terms of direct NO_2 emissions. With these technologies, the NO_2/NO_x ratio is not necessarily constant during the vehicle's lifecycle but decreases as the catalyst system ages and the filtering efficiency weakens. For heavy-duty vehicles, the best technologies among those currently in use for reducing NO_2 and NO_x emissions were well-functioning new SCR systems and TWC catalysts in stoichiometric natural gas powered buses.

Hydrocarbon emissions and particulate size distribution in exhaust from diesel powered buses at different emission levels (Euro III and Euro IV) were very similar. The total content, aldehyde content, particulate size distribution and particulate PAH compounds of the carbonyl compounds decreased systematically when moving from the Euro III-level to the EEV-level. The particulate size distributions correlated with the particulate matter emission according to standard. The quantitative and qualitative change in the PAH content of the particulates was more radical than with the other emissions and was dependent on the vehicle technology. In different bus technologies, as the regulated emissions decreased, so did the unregulated emissions as well. Methane, formaldehyde and ammonia dominate in the unregulated emissions of natural gas powered buses. Characteristic to the lean mixture technology, the methane emission and total content of carbonyl compounds were many times higher than in a stoichiometric engine.

As for truck technologies, the shape of the particulate size distribution and the position of the accumulation mode may vary depending on the load of the driving cycle and the vehicle technology. No clear conclusions between different vehicle technologies can be made.

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7 SUMMARY

The RASTU project continued the HDEnergy project that had focused on the enhancement of fuel efficiency in heavy-duty vehicles during 2003-2005. In addition to the fuel efficiency perspective, the RASTU project themes included environmental impact and safety.

The main objective of RASTU was still the reduction of fuel consumption by means of vehicle engineering. Ways to reduce and impact fuel consumption were sought from, for example, tyres, vehicle selection, lubricants, aerodynamics, driver incentives and automated driver aid systems. Safety-related research focused on the impact of automatic slip detection and heavy-duty vehicle tyre selection on stability.

Approximately 60 bus tests were carried out during the project. The pool of measured vehicles included 10 EEV-level diesel powered vehicles, all of which turned out to have fairly low emissions. The stoichiometric natural gas powered buses continue to be better than the best diesel powered buses in terms of emissions. The measurements included 16 EEV-level natural gas powered buses. At best, the normal structure (non-lightweight structure) buses generated a CO_2 emission of about 1,100 g/km in the Braunschweig cycle. This applies to both diesel powered and natural gas powered buses. In three-axle buses, the CO_2 emission level was 1,400 g/km.

Follow-up tests were carried out on a total of five vehicles. Two of them (Volvo Euro II and Scania Euro III) had a retrofitted pDPF particulate catalyst. A new particulate catalyst reduced the particulate emission in both vehicle types by about 45 % and the emission level did not increase during the 120,000 km follow-up period. The emission level increased in a vehicle equipped with an oxidation catalyst over the course of a long follow-up period; the catalyst should have been replaced between 200,000 and 300,000 kilometres. The CO and THC emissions of the Euro IV-level Scania with EGR increased clearly during the 380,000 km follow-up period, the NOx emission decreased slightly and the PM emission increased slightly. The emissions of a stoichiometric natural gas powered MAN vehicle increased extensively after 350,000 km, possibly due to a malfunction.

In trucks, the new vehicles with Euro IV and Euro V technologies turned out to be more economical in terms of fuel consumption (including urea used for NOx reduction) than Euro III-level vehicles on average. This was most evident at freeway speeds. The vehicles' emissions were also quite low, although fairly high emission levels were measured in delivery cycles with an average load.

The overall conclusion is that the newest heavy-duty vehicles complying with the strictest emission categories are also cleaner in real-life driving. There continues to be room for improvement, in particular in the emissions generated by city bus driving in which engine load levels change rapidly. It is also noteworthy that the newest engine types of both city buses and trucks are also more fuel efficient than before, although emission restrictions tightened significantly over the course of the project. This is partly due to the implementation of SCR systems that have made it possible to optimise engine adjustments based on fuel consumption. On the other hand, the new emission regulations require accelerated development of combustion in engines, which may also have expedited the improvement of fuel efficiency.

Fuel studies were conducted on a van (Volkswagen) and a medium duty truck (MAN Euro III) powered by a mixture of diesel fuel and traditional biodiesel (RME). Included in tests were also 100 % RME, and for trucks, also 100 % NExBTL. The results were as expected. RME reduced particulates effectively but increased the NO_x emission. In the van, particulate emission decreased by 65–75 % and the NO_x emission increased by 12–20 % with the 100 % RME fuel. In the truck, the 100 % NExBTL had the same particulate reducing effect as did the 50 % RME mixture. However, NExBTL did not increase the NO_x emission but, instead, decreased the NO_x emission by about 10 % compared to regular diesel fuel.

Lubricant tests were carried out on a bus in a chassis dynamometer and on a bus engine in an engine test bench. In vehicle tests, the difference in fuel consumption between two 10W40 grade lubricants was at a maximum 1.8 %. Changing the oil in automatic transmission brought fuel savings of up to 3 %. In engine tests on both new and aged lubricants, the differences between lubricants were a little over one percent at a maximum, calculated as the average of certain standard load points. The largest differences were measured with small loads.

Several vehicle engineering development subtasks were completed as academic theses. Potential development areas included aerodynamics, tyres, reducing the weight of heavy-duty vehicles by means of light-weight structure technology, axle alignment, stability of the modular combination as well as energy efficiency benchmarking of 40 and 60 ton combinations.

The most common method of reducing the weight of trailers is to replace traditional steel and iron with aluminum, high strength steel, various metal alloys or composites. According to HUT simulations, a 1,000 kg reduction in the total weight results in fuel consumption decrease of over one percent.

The second and fifth axles of a full trailer should have tyres as good as possible at all times to ensure stability. Overall, the tyres should be replaced at the latest when the tread depth is 3 mm. In the winter, the recommended safety minimum is 5 mm, and the second and fifth axles of a trailer should always have tyres that are better than that.

The correct tyre selection in the truck trailer, drive shaft and front axle can provide fuel consumption savings of up to more than 10 %. However, safety should not be neglected. Even if a tyre is beneficial for fuel consumption, it is not necessarily optimal in terms of traction. In buses, the difference in fuel consumption between transversely grooved tyres in the city cycle was 2.5 % at a maximum. For longitudinally grooved tyres, the difference was 2.6 %. In tests on a truck, the fuel consumption difference between tyres was 3.7 % at a maximum.

In comparison measurements of two vehicles equipped with typical technology, the 42 ton combination proved more fuel efficient than the 60 ton combination up to a full 42 ton load. The 60 ton combination with a full load provides better energy-efficiency than the 42 ton combination at its best.

The wind resistance of a truck can be decreased most of all by modifying the contours of the nose and the rear. By reducing the average pressure on the nose and increasing the average pressure in the rear, the resistance decreases. When seeking a minimum resistance, one should bear in mind factors that are important for usability, such as the straightness, quality and cleanliness of the cargo space surfaces.

Compared to trucks, the designers of buses have a lot more freedom. Furthermore, compared to trucks, buses have contours that are more aerodynamic since, in principle, the vehicle is just a prism with straight angles. Minimising unevenness of external surfaces improves the aerodynamics of buses as well. Modern express coaches often have fairly refined details.

The tests showed that axle alignment has minimal significance in the fuel consumption of heavy-duty vehicles with the misalignments typically present in the vehicles. The conclusion is based on documenting misalignments and fuel consumption measurements on a variety of misalignments.

The project developed the following IT applications for vehicles: driver aid system, automatic slip detection and load detection. The driver aid system focused on city buses. Characteristic to city buses are routes that are fixed and repeated as well as large variations of speed. Service level and, in particular, staying on schedule are important in passenger traffic. The purpose of a driver aid system in city bus traffic is to

- guide the driver to drive in a fuel-efficient manner and
- stay on schedule.

A driver aid system prototype was implemented in a total of 15 buses in the Helsinki metropolitan area and in Jyväskylä. Experiences of the functioning of the aid system are positive but still only preliminary due to the small number and short duration of use.

The basic principle of the slip algorithm developed is to observe the speed difference between the tractive wheels and front wheels in relation to the thrust provided by the engine. This provides a slip index that is reverse to the friction coefficient. Experience has shown that the system is able to detect slip before the driver notices it but the operations are not sufficiently unambiguous yet. A central unsolved issue in the functioning of the method is how to take the differences between vehicles (construction, tyres, loads) and between different roads into consideration.

The method of estimating the weight of a vehicle combination is based on observing the changes in the cause and effect relationships in the vehicle's dynamic state by means of the energy principle.

For the optimisation of bus operations, data was collected by means of driver aid systems installed in the buses. The goal of the optimisation of operations was to increase the economics and efficiency, enhance the quality of the operations and to speed up traffic. Tools developed in the project have been used, for example, to optimise the scheduling of the green phases in traffic lights. The driver aid system on a bus could adjust the speed to eliminate unnecessary accelerations and starts, which makes it easier to hit the green phases of traffic lights.

The economical driving incentive system for drivers can improve and prolong the effects of training provided on an economical driving style, creating savings for transportation companies. The system developed for Tampere City Transport (TKL) has proved feasible in city bus operations. Drivers have received the system positively and with interest. The system also provides reports of vehicle-specific fuel consumption, which has already helped identify buses that are malfunctioning or adjusted incorrectly. The fuel consumption data by bus line helps the transportation company price the lines to better match the expense level.

In the subtask for evaluating the efficiency of energy-saving measures, calculations to evaluate the measures were developed. The measures include, for example, switching to newer Euro categories, using fuel-saving tyres and lubricants, etc. The energy service directive requires that energy savings be calculated in a manner that does not depend on the amount of the actual consumed energy. The main idea is that the calculations can be used to show how much more energy would be spent now. had the measures not been taken. Thus the actual energy consumption may have increased or decreased. An Excel model was created for the calculation in which fleet quantities and their properties at different times can be entered. The impact of changes in the fleet on fuel consumption is calculated by using coefficients that describe the consumption differences of different measures. Once all measures have been described in the model, the total impact of the change between review points is obtained.

NO_2 levels occasionally grow too high in the air of densely populated areas, which is a problem that the RASTU exhaust test tackled. NO_2 formation is a strong function of both the exhaust temperature and the temperature of the after-treatment device, in particular in diesel vehicles. According to this study, approximately 90 % of NO_x and over 80 % of NO_2 may be generated by heavy-duty city vehicles. The highest NO_2 share measured, approximately 60 %, was measured in a bus equipped with an EEV-level SCR catalyst and a CRT particulate filter. With an SCR catalyst alone, the direct NO_2 emission is low, as it is in natural gas powered buses as well.

Exhaust measurements also studied so-called unregulated emissions of new low-emission vehicles, such as aldehydes, ammonia, gaseous single hydrocarbons, particulate PAH compounds and mutagenicity. In addition, both particulate quantity and size distribution was measured. Overall, EEV-level diesel vehicles were "cleaner" than Euro III and Euro IV vehicles in terms of the emissions mentioned above. The particulate emissions of natural gas powered vehicles were naturally very low. The high methane content of exhaust was also a known fact, but the high ammonia content was new information. This is assumed to be due to the partial oxidation that takes place in the catalyst.

The directive (2009/33/EC) that was passed in April 2009 aims to promote clean and energy-efficient road transport vehicles. The directive aims to include the lifetime costs for energy consumption, carbon dioxide emissions and pollutant emissions as award criteria in the procurement of vehicles and services. The directive calls for the measurement of heavy-duty vehicles in the way it was performed in the RASTU project.

RASTU has increased knowledge on factors impacting fuel consumption, which may be useful in operating vehicles, designing them and in decision-making in society. In addition, information gained on using IT systems in the vehicle applications developed in the project make it possible to develop and use new IT applications.

Appendix 1.

RASTU SPONSORS

Tekes the Finnish Funding Agency for Technology and Innovation

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