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Report

Characterization of tailpipe exhaust emissions from 6 modern diesel passenger cars in demanding conditions

For
The Norwegian Directorate of Public Roads

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Summary
Characterization of tailpipe exhaust emissions from 6 modern diesel passenger cars in demanding conditions

Passenger cars with diesel engines are taking an increasing share of the market in Europe. In other parts of the world diesel has a reputation as a toxic and polluting fuel. This project, which is sponsored by the Norwegian Directorate of Public Roads, has the objective of characterizing tailpipe exhaust emissions from some modern diesel passenger cars in demanding conditions.

Emissions of various Particulate Matter (hereafter PM) and Nitrogen Oxides, NO_x, represent two dominant environmental challenges for diesel engines. On the other hand, diesel engines are at the current state of the art superior to gasoline engines in terms of energy consumption and emission of CO_2.

The cars in this project were tested with the European emission test cycle and with the same test cycle on a simulated 3 % uphill slope. The uphill tests were performed to detect emissions effects at more aggressive driving and emissions in areas with topography similar to that in Norway. The effect of driving the European test cycle on a simulated 3 % uphill slope is illustrated by the fact that this gave an increased fuel consumption of about 40 % for the 6 cars in the project.

The emission tests showed that a modern and environmentally friendly Small car, with only a 1.2 l three-cylinder diesel engine, behaved well and had low values of emissions. The Small car consumed low amounts of fuel and had low levels of all exhaust emissions in all the different driving conditions in these tests. It managed to follow the demanding test on uphill slope even when the accelerator was pushed all the way down.

PM emissions from diesel engines have in the recent years been reduced in weight and, with reference to the tested year 1985 model Mercedes Benz, also in numbers. However, the amounts of PM emitted are enormous even from modern diesel engines. Diesel passenger cars emit PM in the range of 10^{14} particles/km. One car, however, had a factory delivered particle filter with the ability to remove 99.9 % of the PM from the exhaust gas. With this filter the exhaust gas had roughly the same PM concentration as the ambient air.

None of the diesel exhausts contained PM with a diameter exceeding 2 μm. It seems therefore irrelevant to carry on a discussion about whether we should restrict emissions to PM10 or PM2.5. The most significant numbers of diesel PM found had the diameter of about 0.070 μm. Under special conditions extremely high numbers of PM with the diameter of about 0.015 μm were emitted from one car.

The numbers of PM were generally somewhat higher for all cars at uphill driving than in flat conditions. However, formation, desorption and reduction of PM is a complex matter and the 6 cars behaved very differently under different driving conditions.

Emissions of Nitrogen Oxides, NO_x, increased for the 6 modern cars by about 160 % at uphill driving compared with the standard tests on flat road. The amounts of emissions of Total Hydro Carbons, THC, and Carbon Oxide, CO, are generally small from diesel engines, and during uphill driving they were even more reduced.

The emissions of NH_3 (ammonia) was in the range from not detected (0.05 mg/km) to 0.5 mg/km. The emissions of N_2O (laughing gas) were in the range of from 2 to 12 mg/km. The emissions of NH_3 and N_2O increased slightly in 3 uphill slope compared with flat road.

Contents

1. TAILPIPE EMISSIONS FROM MODERN DIESEL PASSENGER CARS

The sale of diesel engine passenger cars and diesel fuel is increasing in Norway as well as the rest of Europe. In 2001 diesel engine passenger cars climbed to 13 % of the total sale in Norway [1]. In Europe and now also in Norway diesel is expected to capture substantial market shares in the future from gasoline as an automotive fuel for passenger cars. Cars with diesel engines are today allowed to have higher harmful exhaust emissions than gasoline engine cars. The gasoline cars equipped with λ-control and three-way catalysts are impressively clean after the "light-off" of the catalyst. On the other hand, diesel engines are more efficient and save energy in comparison with spark ignition gasoline engines. Diesel engines for passenger cars have been developed impressively with respect to their driveability and exhaust emission reduction in the last ten years.

Because of their history as black smoke vehicles, diesel engine passenger cars are not popular in the other continents except for Europe. Exhaust after-treatment equipment with advanced EGR and oxidation catalysts are now common and make the diesel cars less pollutant. The effect of exhaust after-treatment is usually good, but the cleaning effects may vary with the driving pattern. It is important to examine and evaluate diesel exhaust emissions from modern diesel passenger cars in demanding driving conditions with respect to environmental care and to avoid effects on human health.

The health effects of diesel exhaust from the components in diesel exhaust are not fully understood [2]. The two most harmful components to human health are considered to be the various particulate matter (hereafter PM) and NO_x. The effects of NO_x are probably best known and the emissions of NO_x from new passenger cars have gradually decreased. The interest in PM has in the recent years been slightly shifted from gravimetric values (measured as mg/km) to PM numbers and PM size distributions [3]. Medical researchers have reported a high rate of occurrence of asthma and lung cancer in environments with a high PM concentration [2].

The diesel engine for passenger cars has developed from the suction engines of the 1980s to the high pressure well controlled Turbo charged Direct Injection engines of 2000. The positive effect of this development in power, driveability and energy consumption is why new diesel engines are popular for family cars as well as for sports cars.

When tested using the European test cycle, regulated diesel exhaust emissions from new passenger cars are reduced by 90 % compared with the diesel passenger cars of 1980. The challenge is to make sure that this reduction is also valid in real life driving. Legislation must be heedful of the health and environmental effects of all toxic emissions in real life conditions. However, legislation cannot be amended without first conducting research and finding new knowledge. The number and distributions of fine and ultra fine diesel PM emissions is not included in the present legislation and therefore they need to be investigated to find deeper knowledge about them and their medical effects.

The DETR/SMMT/CONCAVE Particulate Research Programme gives insight in PM size and distribution from exhaust tests with heavy engines, light vehicles and different fuels with regulated test cycles [4]. As with PM emissions, it can be expected that the levels of NO_x emissions deviate significantly from normal standard test cycles when the loads and accelerations are high and different from the cycles.

The statutory levels for reduced diesel exhaust emissions in 2005 and 2008 and the environmental demands are likely to call for new and efficient exhaust after-treatment devices. Exhaust after-treatment may have unexpected characteristics in real life driving which are not detected under standard test cycles. De-NO_x catalysts and PM traps are excellent, but sometimes they have unexpected effects in real life driving conditions.

The two most interesting vehicles in this project are an environmentally designed Small 1.2 l car with a unit injection diesel engine and a Large F car with a particle filter.

2. Objectives

The objective of this project was to investigate the pollution levels of modern diesel engine cars under demanding conditions. It is taken for granted that all cars fulfil emission levels that are congruent with the standard test procedures of European legislation. However, when a car is driven under a heavier load and in transient conditions, increased emissions are often found. Heavier loads and higher accelerations than in the European test cycle are relevant in real life conditions in Norway. Uphill as well as downhill slopes of long or short length are common in Norway. Knowledge about emission factors in real life driving is important for calculation of pollution and for environmental actions.

The exhaust emissions of THC (Total Hydro Carbons), NO_x (Nitrogen Oxides) and CO (Carbon Oxide) are regulated and the emission levels in the emission test are well known. In this project all regulated emissions were, in addition to the standard load, also characterized at higher loads. Emissions of PM were of special interest. The NO_x emissions were expected to rise at higher temperatures.

PM concentration and size distribution measurements are new in Norway and this project gave an opportunity to investigate this new field of research with an Electrical Low-Pressure Impactor, ELPI.

New diesel engine oxidation catalysts may at high load and in high temperature contribute to higher generation of NH_3 (ammonia) and N_2O (laughing gas). Ammonia is a toxic polluter and N_2O is a strong green house gas. Another objective for the project was to find out more about these gases in diesel exhaust in demanding conditions.

3. Test arrangements

The tests were conducted at the emission laboratory of the Norwegian Institute of Technology in Oslo in March and April 2002. Expertise on PM size and distribution measurements was hired from VTT, the Technical Research Centre of Finland. Emissions of NH_3 and N_2O were sampled from raw exhaust and analyzed at a chemical laboratory.

3.1 Emission tests

The vehicles were tested with the standard European passenger car (Euro III) test cycle. In addition the vehicles were tested with the same Euro III test cycle on a simulated 3 % uphill slope.

All vehicles were tested at least 3 times in the same conditions to obtain significant and reliable emission data. The emissions were sampled for each of the three phases shown in fig. 3.1. The three phases of the European cycle give information about cold start, warm engine urban driving and highway emissions.

The standard European test cycle is considered to be a somewhat gentle test cycle and vehicles are in real traffic conditions often exposed to more violent accelerations and higher loads. The purpose of running the European test cycle also on 3 % uphill slope was to investigate to what extent higher accelerations and higher loads cause higher emissions. The uphill slope was simulated on the dynamometer simply by adding a load corresponding to a 3 % uphill road during the entire test cycle.

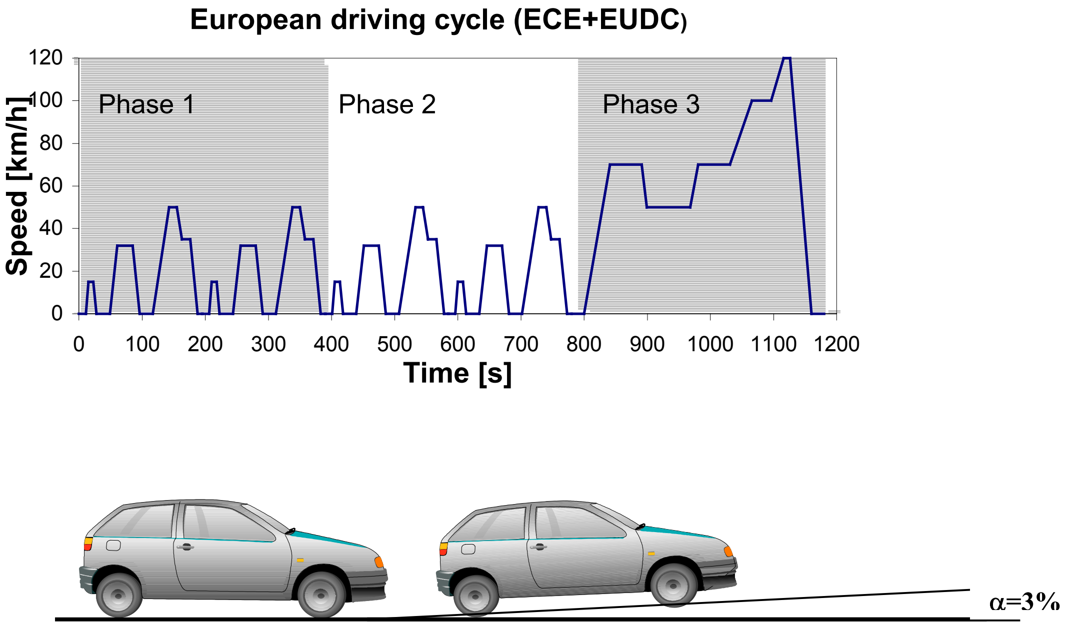


Fig. 3.1: The European test cycle with cold start was run under standard conditions as well as on a simulated 3 % uphill slope

3.2 The emission test laboratory

The emission laboratory has a "Clayton" dynamometer, which was programmed to give the correct driving resistance for each tested vehicle. The exhaust is sampled with a constant volume sampling system. The diluted exhaust gases are collected in sample bags. There are two sets of bags for each of the three phases in the test cycle. The regulated exhaust gases are analyzed with a Horiba Mexa 8420 gas analyzer directly after the test. The PM is collected on filters for gravimetric values for each phase of the driving cycle. In this project the samples for PM (size and distribution), NH_3 and N_2O were taken from raw exhaust directly after the tailpipe. The samples of NH_3 and N_2O were sent to a chemical laboratory for analysis.

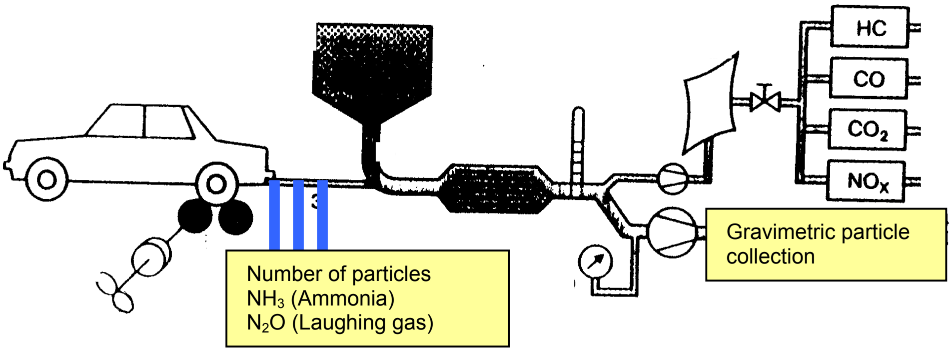


Fig. 3.2: The emission test laboratory set-up with a dilution tunnel and collection of unregulated emissions directly after the tail pipe.

3.3 PM concentration and size distribution

PM size and distribution measurements were found to be a complicated task. Diesel PM from modern cars has a diameter that ranges from 0.01 to 2 µm [3]. Within this study PM mass was found after collected on filters and measured gravimetrically. PM number and size distribution was measured with an Electrical Low-Pressure Impactor, ELPI.

PM smaller than 0.060 µm mainly consists of volatile nucleation mode particles. PM larger than 0.030 µm mainly consists of solid accumulation mode particles with a core of carbon. Research and the characterization of PM with new measurement technology have made it possible to better analyze and understand combustion aerosols [5].

The mentioned DETR/SMMT/Concave report describes the results of PM measurements with Scanning Mobility PM Sizers (SMPS) [4]. In this project an ELPI with 12 size stages from the Finnish firm Dekati was used for continuous measurements of PM concentration and size distribution. The ELPI was rented from VTT in Finland. VTT provided experience and knowledge about the instrument set-up and for the analysis of the emission results.

The ELPI is designed to measure PM by electronic means as shown in fig. 3.3. PM particles are first electrified by plasma corona charging. This implies that the particles will discharge weak currents when trapped on metal plates in the impactor. When measuring these weak currents and applying experimental knowledge, the number of PM for each stage can be calculated by the ELPI.

The impactor is composed of collecting plates, each of which is paired with a nozzle. The size of the nozzles and the distance between a nozzle and a collecting plate are different for each stage in the impactor. This makes every stage in the impactor collect PM of different size. In the first stage large PM particles with large quantity of kinetic energy collide into the first collecting plate and are trapped. Smaller PM particles have less inertia and are swept around the collecting plates to the next stage. In this way PM particles are trapped lower and lower in the impactor according to their size. The lowest stage (stage 1) has the smallest nozzle diameter and the shortest distance between the nozzle and the collecting plate. In this stage the smallest PM particles that are possible to detect with this instrument are trapped.

The working principle of the impactor resembles the human mechanism of inhaling through the nose and the throat into the lungs [3].

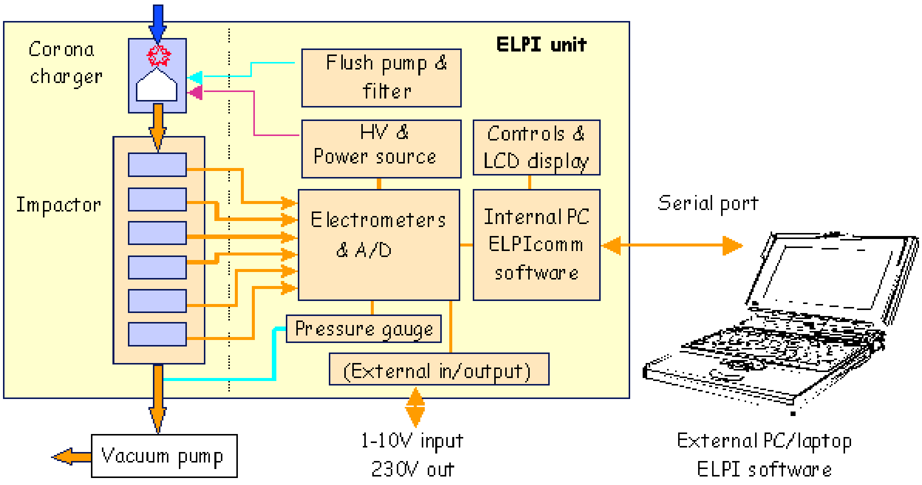


Fig. 3.3: Composition of an ELPI for PM concentration and size distribution

Before entering the ELPI the emission gases were diluted in two steps. A hot dilution step in the temperature of 250 °C was followed by a cold dilution step in room temperature (22-25 °C). The dilution factor of the tailpipe exhaust gases before they entered the ELPI was 85.

The mean diameter of the collected PM particles for each stage in the impactor was calculated by the deliverer of the ELPI, Dekati:

The 12 stages of the ELPI and the calculated mean diameter (in µm)											
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
0.015	0.041	0.074	0.12	0.20	0.32	0.49	0.77	1.25	1.98	3.13	6.36

Fig. 3.4: PM particles with a diameter from 0.015 µm (collecting plate in the upper left-hand corner of the figure) to 6.4 µm (collecting plate in lower right-hand corner) are trapped in each stage of the ELPI impactor

3.4 NH_3 and N_2O measurements

Both NH_3 (ammonia) and N_2O (laughing gas) is actively sampled directly in the tail pipe exhaust from the vehicles.

NH_3 is sampled on silicagel tubes coated with sulfuric acid. Sampling volume is 0,5 litres per minute. The tubes are extracted with water, and the amount of sampled NH_3 is determined by chromatography (657 nm), on the basis of reaction with salicylate/hypochlorite/nitroprusside in alkaline solution.

The limit of detection is 1 µg, and the overall analytical uncertainty is 10 % (RSD). Method references include Sampling: NIOSH 6015 and ISO 7150/2.

N_2O is sampled in Tedlar bags. Sampling volume is 200 ml per minute. The amount of sampled N_2O is determined by gas chromatography with electron capture detection while using a gas loop inlet. The limit of detection is 0.1 ppm, and the overall analytical uncertainty is 10% (RSD). Method references include Draft VDI standard: Messung Gasförmige emissionen – Stickstoffdioxid (manuelles Verfahren)

3.5 Vehicles

The objective of the project was to examine exhaust emissions from modern diesel engine cars. We had the privilege of getting to our disposal demonstration cars from importers in Norway and test vehicles from the Norwegian oil company Statoil. The cars showed registrations certificates from 1998 to 2002. The years of approval for import to Norway were from 1997 to 2002.

In addition to the cars in the project we did a single test with a Mercedes Benz that had a suction engine and registration certificate from 1985.

Table 3.1 shows vehicle identification and essential data for the cars in the project. The small car with 1.9 l engine and the Large F 2.2 l car with a particle filter were of special interest since they can be claimed to have an image of being environmentally friendly.

Vehicle Identification	Year of approval	Engine (dm^3)	Curb weight (kg)	Fuel injection	After-treatment
Large G 2.2 l car	1997	2.15	1335	Turbo, Direct Inj. Common rail	Oxidation catalyst
Mid class 1.9 l car	1999	1.90	1262	Turbo Unit Injector	Oxidation catalyst, EGR
Large 2.9 l car	2000	2.93	1745	Turbo, Direct Inj. Common rail	Oxidation catalyst, EGR
Large J 2.2 l car	2002	2.18	1456	Turbo, Direct Inj. Common rail	Oxidation catalyst, EGR
Small 1.2 l car	2001	1.19	855	Turbo Unit Injector	Oxidation catalyst, EGR
Large F 2.2 l car	2000	2.18	1550	Turbo, Direct Inj. Common rail	Oxidation catalyst, EGR PM trap
Large old 3.0 l car	1985	3.00	1605	Suction Engine	No after-treatment

Table 3.1 Vehicle identification and essential information about the cars in the project

3.6 Preparation of vehicles, fuel and oil

The cars in the project had their tanks drained of old fuel and were all washed twice with the test fuel before the tests. The test fuel was a Statoil winter quality diesel fuel. Fuel filters were changed and the cars were prepared with three EUDC test runs. They were so left soaking for the minimum of 12 hours at 22 ºC to 24 ºC before the start of a new series of tests with cold start. After a test in a row of three, there was no additional preparation driving, just another minimum of 12 hours of soaking. All cars were tested with the same engine oil that they had at delivery – no oil change.

The fuel delivered by Statoil had the following properties:

Cetane Number	Density	Sulphur	Viscosity	Content of C	Content of H
51.8	83.7 kg/m^3	170 ppm	2.38 cm^2/s	86.4 %	13.6 %

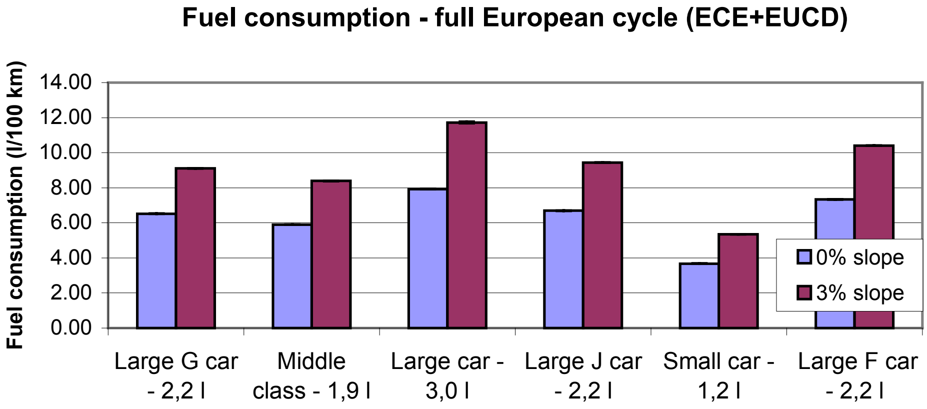
4. Results - regulated emissions

There are many ways to analyze regulated emissions. This project tries to focus on factors that are useful for evaluating to what extent modern diesel cars can be regarded as environmentally friendly in real life driving. However, we believe that several other interesting findings than those we present here can be extracted from the collected data. The test results with regulated emissions from the three phases of the European test cycle on flat road and on 3 % uphill slope are presented in Appendix 1. This Appendix shows average values and standard deviation for THC, CO, NO_x, CO_2 and fuel consumption.

4.1 Fuel consumption and driving on an uphill slope

The increase in fuel consumption when running the European test cycle on a simulated uphill slope of 3 % instead of flat road was around 43 %. The fuel consumption for mixed driving during the total driving cycle for the different cars is shown in fig. 4.1. The consumption increased from 40 % to 48 % for the different vehicles. It was observed that the Small car with a 1.2 l engine managed to follow the driving cycle also on a 3 % uphill slope. However, the engine had to be stressed with the accelerator flat to the floor during the steepest acceleration modes at high speed.

The additional fuel consumption from cold start was found to be about 15 % for modern diesel cars and varied between 10 % and 18 % for the different vehicles. The additional fuel consumption at cold start was calculated by comparing the fuel consumption in phase 1 with that in phase 2 (flat road – 0 % slope).



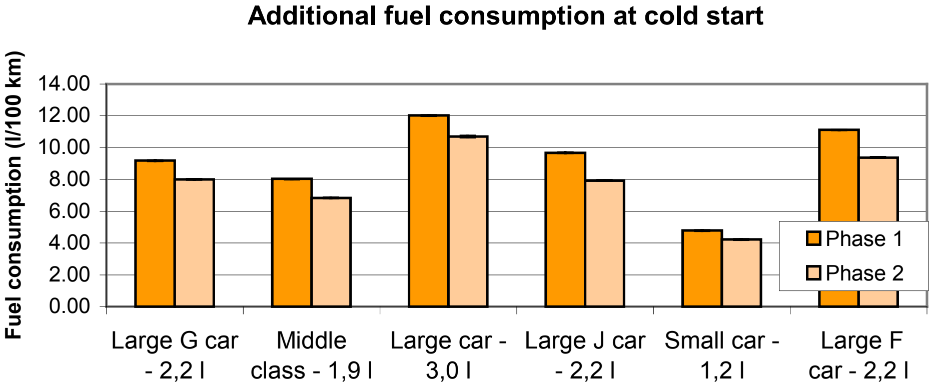


Fig. 4.1: Fuel consumption at 0 % and simulated 3 % uphill slope (above)
Additional fuel consumption at cold start for modern diesel cars (below)

4.2 NO_x emissions

The source of NO_x emissions from combustion engines is in Nitrogen reacting with Oxygen under the combustion process. The reaction between Nitrogen and Oxygen and the generation of NO_x increase as an exponential function of temperature. The introduction of advanced EGR (Exhaust Gas Regeneration) in the latest modern diesel engine cars has the aim of reducing the harmful NO_x emissions.

The emissions of NO_x were found to be about 160 % higher when driving on a 3 % uphill slope in relation to driving on 0 %. The Large car with a 3.0l engine and the Small car with a 1.2l engine had the highest increase of NO_x, i.e. 190 %. Appendix 1 shows that during phase 3 and 3% uphill driving all the cars emitted more than 1g/km of NO_x. The NO_x emissions levels were during this phase at least twice the legal limits for emission of NO_x from new cars. The old 1985 Mercedes Benz was found to have only slightly higher NO_x emissions than modern cars.

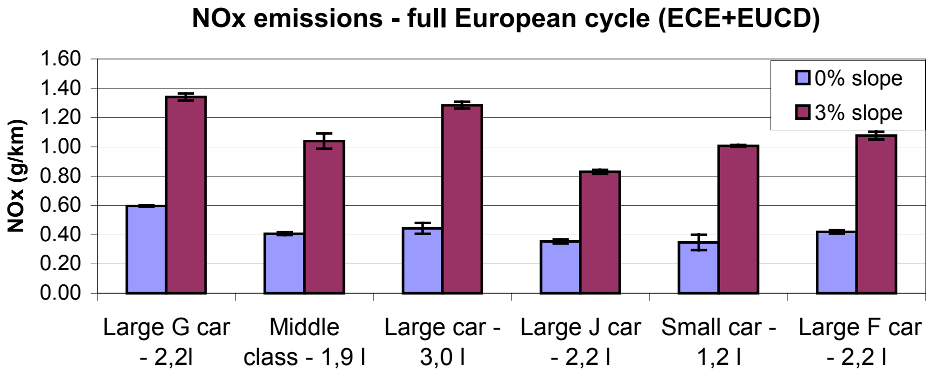


Fig. 4.2: The emissions of NO_x was in general found to be around 160% higher when driving on 3 % uphill slope than when driving on 0%

4.3 THC and CO emissions

The great advantage with modern diesel engines is that they very effectively combust the fuel inside the combustion chambers. High pressure, sophisticated fuel injection and refined electronic control are continuously making diesel engines more and more effective. The result is a better and more complete combustion. The emissions of unburned THC (Total amount of Hydro Carbons) from the exhaust valves are low. The excess of Oxygen during combustion also makes the CO emissions low, since CO is a result of incomplete combustion.

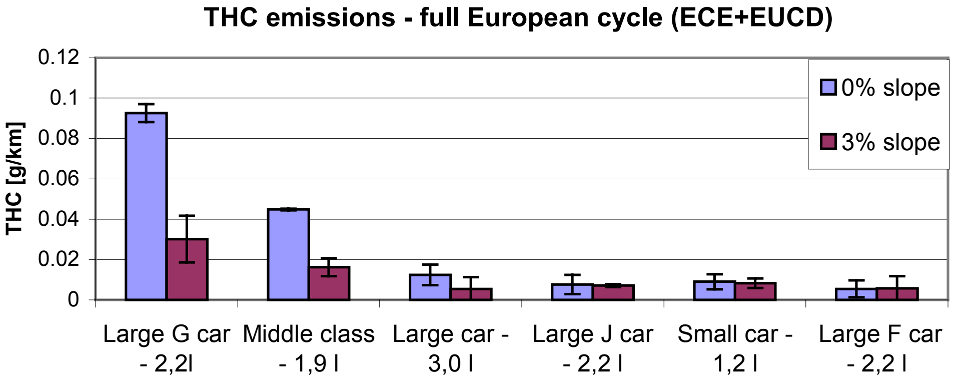


Fig. 4.3: The emissions of THC are low with diesel engines and driving on 3 % uphill slope made them even lower

The tests of this project demonstrated that uphill driving made the combustion, or the effects of the oxidation catalyst, even more effective. The result was lower THC and CO emissions during the total test cycle. The reduction was most evident in phase 1, where the THC and CO values were less than half of the values on flat road for all the other cars except the Small 1.2l car.

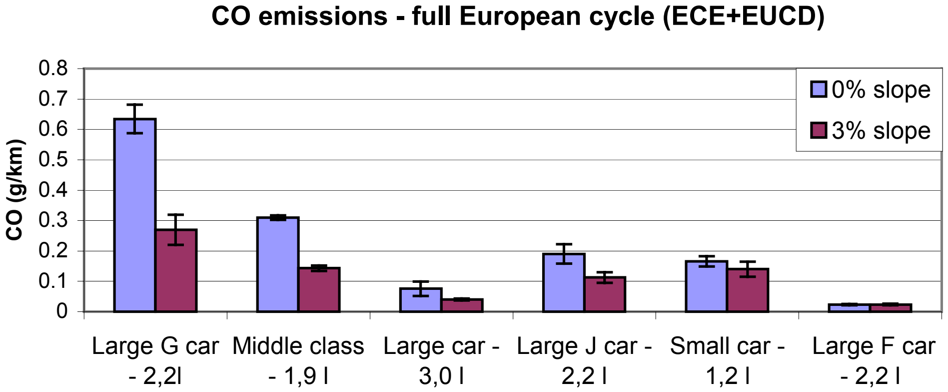


Fig. 4.4: The emissions of CO are low for diesel engines and driving on 3% uphill slope made them even lower

4.4 Gravimetric PM emissions

The gravimetric PM measurements are presented in this section. Formation of solid PM, which mainly consists of carbon, is a problem with diesel engines. Even if the combustion process has been improved over the years and the gravimetric PM is lower, there is still a great deal of PM left. In this project all the cars had legally acceptable values of gravimetric PM in the standard test on flat road.

On the 3% uphill slope the emissions varied a great deal between the cars. The two 3-year-old cars emitted highest values of PM in the first, and lowest values in the last, in the row of three tests. Possible explanations for this effect are deposits of soot and the effect of an exceptionally high engine temperature. The Small 1.2 l car and the Large F 2.2 car with a particle filter had low and nice values on their gravimetric PM emissions also on the 3% uphill slope. There are correlations between the gravimetric PM and the number of emitted particles. The correlations are discussed in section 5, where the results of the concentration and distribution measurements are presented.

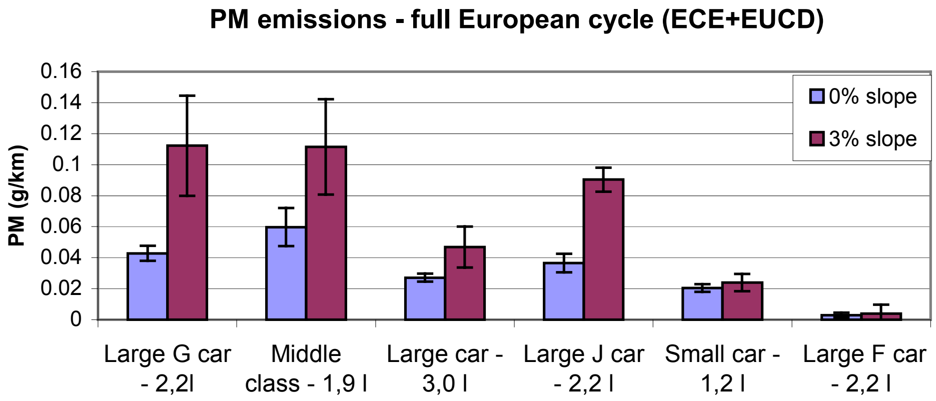


Fig.4.5: The emissions of gravimetric PM

5. Results - unregulated emissions

The unregulated emissions measured in this project were PM particle concentration and distribution, N_2O (Laughing gas) and NH_3 (Ammonia). Most of the efforts were focused on measuring, understanding and analyzing PM particle concentrations and distributions. The N_2O and NH_3 measurements were accomplished with the aim to find out if new diesel catalysts in modern diesel cars generate unexpectedly and harmful high levels of these gases.

5.1 PM distribution and concentrations

The ELPI provides PM particle concentration and distribution for its 12 stages for every second of the measurement record. The concentration of PM in the exhaust gases varies a great deal during the test cycle. Acceleration, deceleration, transient loads and idle give different concentrations. ELPI software makes it possible to study emissions in real time or replay the tests. Real time studies give an enlightening understanding about how the engine and the exhaust after-treatment work in different driving conditions. Analysis of real time engine and exhaust after-treatment behavior of the different cars is however beyond the scope of this project.

By calculating the mean values of the time record we got mean concentration values for the whole European test cycle and for the three phases of the cycle. As an example we show the mean concentration of PM in the exhaust for the Large J 2.2 l car in fig. 5.1. The mean PM concentrations with the European cycle for the cars in the project are shown in Appendix 2.

Fig. 5.1 shows the PM concentration for the 7 stages with PM particle size below 0,8 µm. Visible signs of particles were only found on the first 8 collecting plates (which collected the smallest particles) for the modern cars in the project. That is why we only show the distribution of PM for the first 7 impactor stages because larger-size PM does not contribute significantly to the total number of particle emissions. However the larger the PM particles are the more they contribute to the gravimetric value. The relation between size and weight is the square value of the diameter.

Figure 5.1 shows clearly that the Large J car emits significantly higher numbers of PM (larger than 0.05 µm) when it is driven on a simulated 3 % uphill slope than when driven on 0 %. On the other hand, the number of the smallest PM was somewhat lower in 3 % uphill tests. The corresponding gravimetric values for the Large J 2.2l car were 0.04 g/km on 0 % slope and 0.09 g/km on 3 % uphill slope.

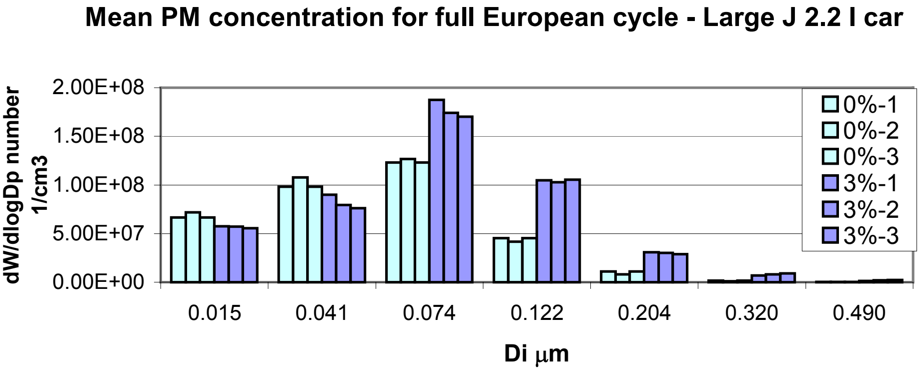
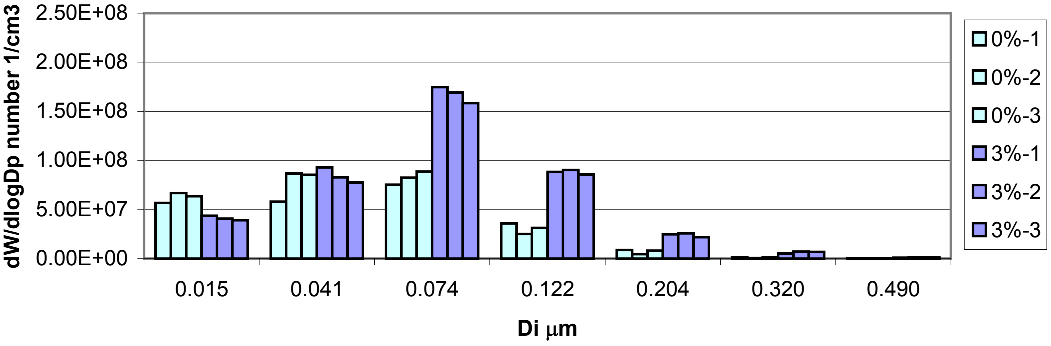


Fig. 5.1: Concentration and distribution of PM in the exhaust of the Large J 2.2 l car through the full European test cycle

At first the Large J car looked rather promising in real time mode with respect to getting low PM emissions during the tests with 3% uphill slope. However, contrary to the other test cars, this car emitted more "large particles" (large is in this context 0.1-1.0 µm) during phase 3 than during the earlier phases. Some other cars had considerably lower emissions of "large particles" during phase 3. The emissions from the large J car were about the same level for phase 1 and 2 but, as illustrated in fig 5.2, the emissions increased during phase 3.

PHASE 2: Large J 2.2 l car



PHASE 3: Large J 2.2 l car

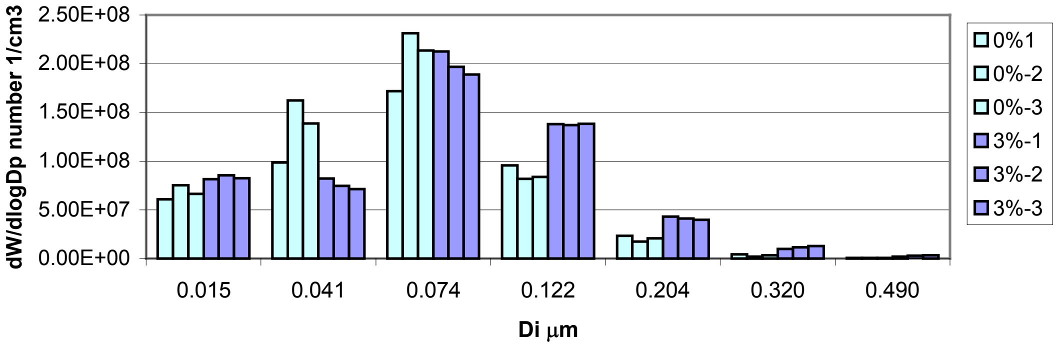


Fig. 5.2: Concentration and distribution of PM in the exhaust of the Large J 2.2 l car during phase 2 and 3 of the ECE+EUDC cycle

5.2 The Small 1.2 l car with a high energy efficiency and low PM emissions

The Small 1.2 l car behaved very differently from the Large J car and had the lowest particle concentrations in phase 3 of the uphill driving cycle. In this phase the PM emissions were lower than in phase 1 and 2 and also lower than on flat road. Fig. 5.3 shows that the PM concentrations for phase 3 during simulated uphill driving have low values and that they are significantly lower than on flat road.

The Small 1.2 l car had the lowest concentration of PM of all the modern cars except for the Large F car with a particle filter. As the amount of exhaust gas was also half of that from the other cars, it became evident that this car had a good particle emission profile. The measured gravimetric values of 0.2 g/km on 0 % as well as on 3 % slope and the relatively low numbers of emitted PM were convincing. This car behaved well in all driving conditions. The gray color of its gravimetric filters is shown in fig. 5.4. In fig. 5.4 we can also observe the black color of a set of filters from a test with really high PM emissions and the totally white filters from a test with the Large F 2.2 l car.

Fig. 5.3 shows that there is a rather large variation in the concentrations of the smallest PM between the first and the second test at 0%. A cleaning service that was made to the ELPI every 12th - 18th test is likely to have had a degrading effect on the repeatability of measurements of the smallest PM. In this case the cleaning service was done between the first and the second test. For all the tests we performed we chose to use the average value of the three tests to calculate the emissions per kilometer.

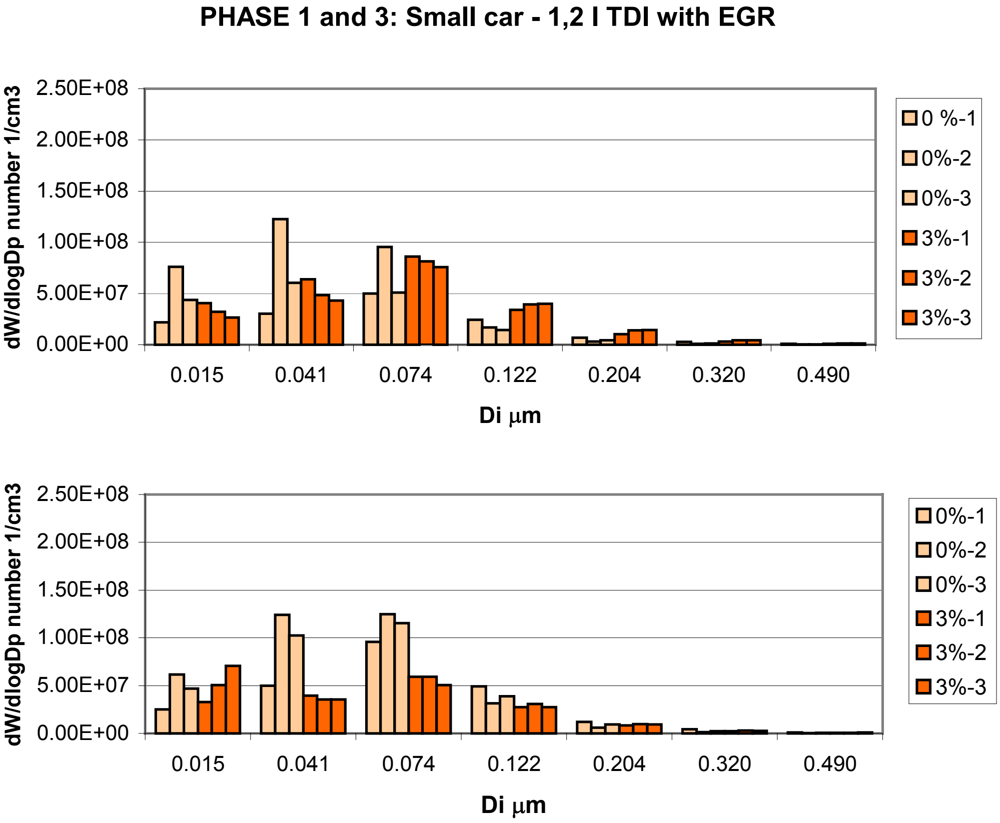

PHASE 1 and 3: Small car - 1,2 l TDI with EGR

Fig. 5.3: Concentrations and distributions of PM in the exhaust of the Small 1.2 l car at phase 1 (above) and at phase 3 (below)

Fig. 5.4: To the left we see the gravimetric PM filter sheets from the three phases of the three tests. In the row above are the sheets from the 1985 Mercedes Benz; In the middle are the sheets from the Small 1.2l car; Below are the sheets from the Large F car with a PM filter

To the right we can see the ELPI metal plates with the enormous numbers of PM. The ELPI traps the PM particles in these 12 different stages of the impactor

5.3 PM particle emissions per kilometer

The mean emission concentrations from Appendix 2 were used to calculate the total number of emitted particles per kilometer for all the cars. The emission of total number of particles per kilometer was calculated by help of information about the total exhaust gas volume (from the CVS system for regulated emissions) and knowledge about the driven distance.

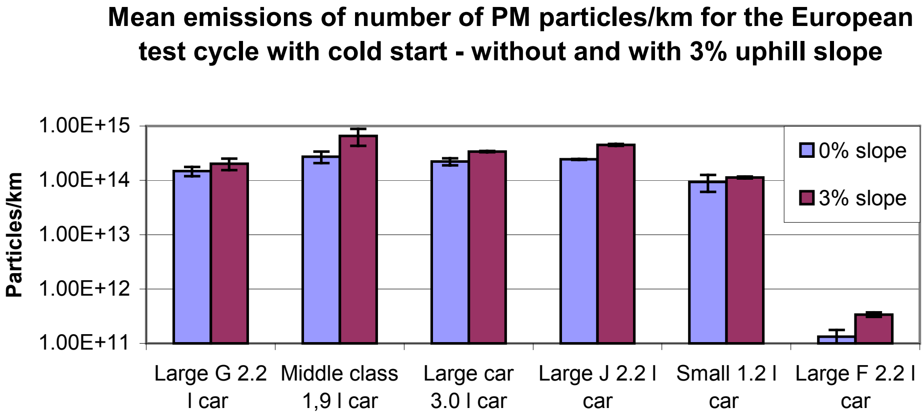


Fig. 5.5: Emission of total number of PM/km for the modern cars in the project

5.4 Observations on the PM particle concentration measurements

We did not always find as good repeatability for the PM concentration measurements and for correlation with gravimetric values as with the Large J 2.2 l car. During the tests we found the largest variations in the concentration of particles in the segments of 0.015-0.040 µm. The measurement of high numbers of those particles does not contribute much to the gravimetric values but they may still be important because of health effects. There are many explanations for the variations in the measurements of those small PM particles [4]. Since we in this project did a large number of measurements in a short period of time, we accidentally noticed that the first measurements after a cleaning service (of the ELPI) seemed to give a higher number of the smallest particles than an average test later after the cleaning.

5.5 Desorption and emission of PM smaller than 0.070 µm

The large G 2.2 l car and the Middle class 1.9 l car were 3 years old and had a mileage of 60 000 - 90 000 km. They were both prepared to avoid confusing emissions from desorption of deposits. However, the Middle class 1.9l car showed extraordinarily high emissions of the smallest PM during phase 3 of the test cycle on 3 % uphill slope. During the tests it was observed that the high emissions of PM 0.015-0.040 µm came in the short period at the end of the test cycle with 120 km/h. High concentrations of PM 0.015-0.040 µm remained in the exhaust even after the car had decelerated down to stand still and was idling at the end of the cycle.

The mean distribution and concentration of PM for the Middle class 1.9l car in phase 3 is shown in fig 5.6. This was the only car and driving phase among the 6 modern cars where the numbers of PM 0.015-0.040 µm were high and dominated the total emissions of PM. The high numbers of the very small PM at 120 km/h made the Middle class 1.9l car the modern car with the highest number of PM emissions.

The extraordinarily high numbers of emitted PM from the Middle class 1.9l car decreased for every test run, as can be seen in fig. 5.6. A possible explanation for this is that the deposits became more and more burned out in the engine or in the exhaust system.

As mentioned in section 4 and seen in fig. 4.5, we had a poor repeatability with the gravimetric measurements on 3% slope with the 3-year-old cars. However, the Large G 2,2l car did not have this peak of PM 0.015-0.040 µm at 120 km/h.

For the year 1985 Mercedes Benz the PM 0.015-0.040 µm dominated the size distribution and made the total number of PM high. This gives us an indication that modern diesel cars not are worse than older cars in numbers of emitted PM.

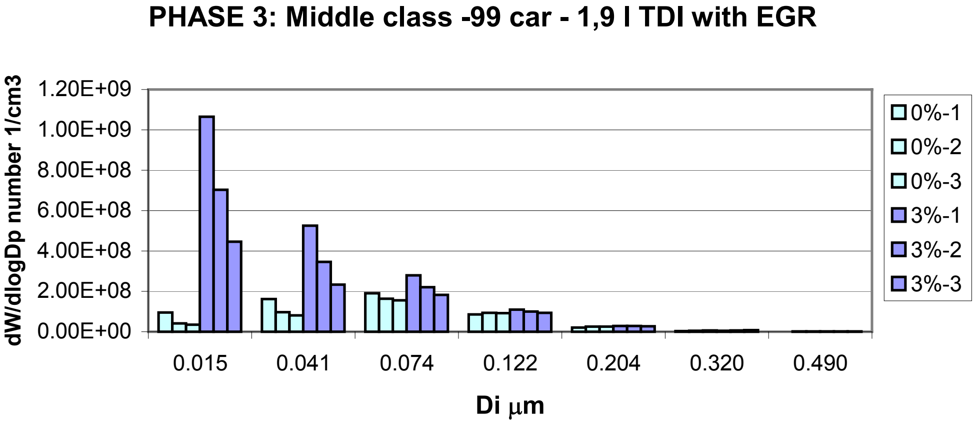


Fig. 5.6: Mean concentration and distribution of PM in the exhaust of the Middle class 1.9 l car at phase 3

5.6 Large F 2.2l car with a particle filter

The time records for particle emissions are interesting to study since they so well reveal what happens with the combustion and the cleaning processes. In the case of the Large F 2.2 l car with a particle filter only the time record of phase 1 was interesting. The time record for phase 2 and 3 showed a constant low concentration of PM that was equal to the ambient air.

As was seen in fig 5.5, the PM emissions from the Large F 2,2 l car were in the range of 10^3 - 10^4 lower than for the other cars in the project. This Large F car has a filter that traps and burns the PM. The burning is accomplished by the help of an additive liquid that contains the material cerium. The filter has a service interval of 80 000 km and it normally renews itself regularly without service actions.

Between the first and second test on 0% slope we did a controlled burn out of the particle filter with the service instrument. The burn out or renewal of the filter did not cause undesirably high PM emissions. We only observed that the temperature of the exhaust system increased and that the ELPI recorded a higher level of PM 0.015-0.040 µm.

Fig 5.7 shows the PM concentration for the PM emissions of phase 1 and 2. We can see that the Large F car has some PM emissions in phase 1. These emissions have very low values and were recorded before the light off of the filter. In fig 5.7 we have also added the recorded PM concentration and distribution of the ambient air in the emission laboratory.

As seen in fig 5.7, the PM concentration and distribution of filtered clean laboratory air was on the same level as PM emissions from a warm Large F car with a particle filter. It is an intriguing question whether cars like this would actually filter and improve the PM air quality in most cities!

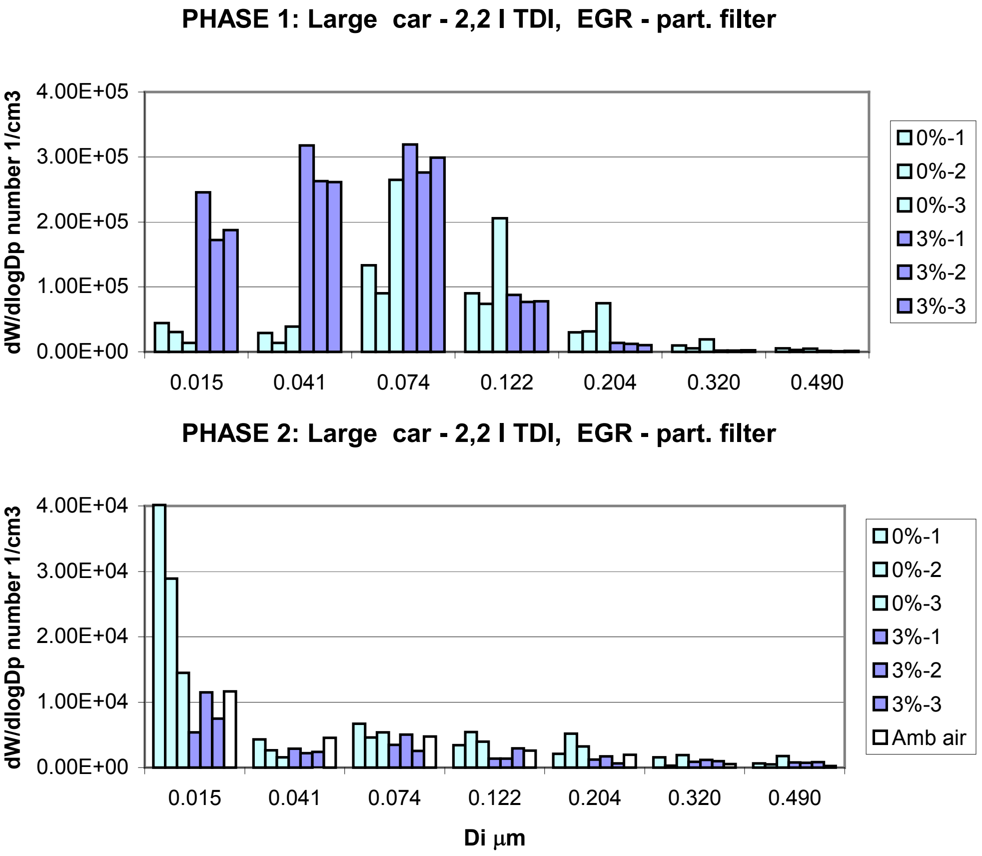


Fig.5.7: Mean concentration and distribution of PM in the exhaust of the Large F 2.2l car with a PM filter during phase 1 and 2.

5.7 Other PM emission observations

We have discussed the modern diesel cars with the highest and lowest mean PM concentrations. It seems that diesel engine technology and the normally used after-treatment systems can be tuned in to somewhat different behavior. Some cars emit more PM than others when they are exposed to exceptional conditions.

The 1985 Mercedes Benz had gravimetric PM emissions of 0.26 g/km. It was observed that the PM particles from this car had a size distribution that included somewhat larger particles than the 6 modern cars.

We made the observation that the PM emissions tend to be high at the transient start of accelerations. This applied to all the tested cars.

The two cars that have not been discussed much are the Large G 2.2 l car and the Large 3.0 l car. The measurements with these cars did not show any effects that made them special from any point of view. Examples of the PM distribution for those cars that did show special emissions effects have been discussed in this section. For information on the PM distributions for the Large G 2.2 l car and the Large 3.0 l car see Appendix 3.

5.8 NH_3 and N_2O emissions

NH_3 emissions

Due to the measurement technique using absorbents for sampling of NH_3 (ammonia) the concentration of NH_3 measured directly in the tail pipe exhaust is a mean concentration over the sampling period. The emission of NH_3 per kilometre is calculated with information about the total exhaust gas volume (from the CV system for regulated emissions) and information with regards to the distance driven during the test cycle. The emission of NH_3 per kilometre for the different vehicles without and with 3 % uphill slope is demonstrated fig. 5.8.

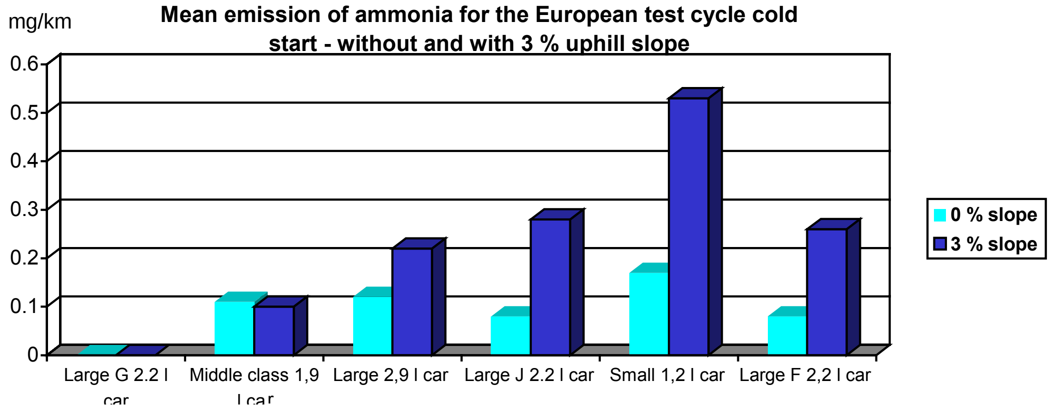


Fig 5.8 Emissions of NH_3

N_2O emissions

Due to the measurement technique using Tedlar bags for sampling of N_2O (laughing gas), the concentration of N_2O measured directly in the tail pipe exhaust is a mean concentration over the sampling period. The emission of N_2O per kilometre is calculated with information about the total exhaust gas volume (from the CV system for regulated emissions) and information with regards to the distance driven during the test cycle. The emission of N_2O per kilometre for the different vehicles without and with 3 % uphill slope is demonstrated in figure 5.9.

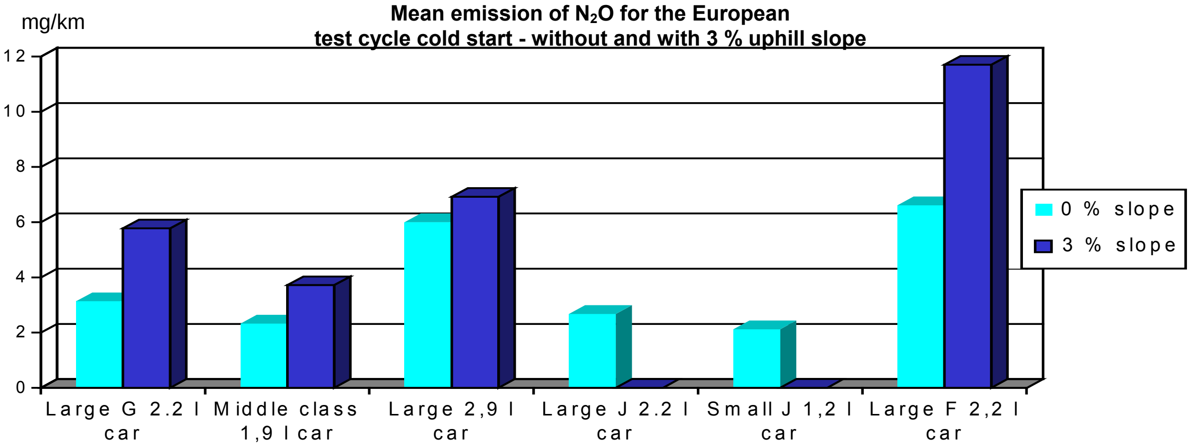


Fig 5.9 Emissions of N_2O

6. Discussion and conclusions

Emissions of regulated exhaust components as well as emissions of unregulated toxic components have been reduced significantly in modern diesel passenger cars in comparison with cars from the 1980s. The amounts of reduction are proved for Volkswagen/Audi vehicles in a comprehensive SAE report from 1999 [7].

Improved diesel fuels, such as the Swedish city class diesel, reduce emissions for regulated emissions as well as for almost all other toxic components. The emissions of toxic components, such as Benzene, 1.3 Butadien and ammonia, are with modern cars and with reference diesel down in the order of 1 mg/km or less. With the Swedish city class diesel the reductions are another 30-60 %.

The emissions of aldehydes are in modern diesel cars in the order of 5-10 mg/km, depending on the fuel formulation. The emissions of polyaromatic hydrocarbons PAH are in the order of 1 µg/km and also here the reductions with the Swedish city class diesel are another 30-60%.

The values above are derived from tests with the US FTP 75 legislation test cycles. The US FTP 75 cycle has more transient loads than the European cycle.

Fuel quality influences and reduces exhaust emissions [7]. However, with engine and exhaust after-treatment technology it is possible to get radically higher reductions. Technology has reduced almost all kinds of exhaust components with a factor 10 since the 1980s. Reduction of PM and NO_x to really low values seems to be the remaining challenge for diesel engine technology. In almost all other aspects diesel engines are excellent. Unfortunately high temperatures, which basically favor PM reduction, at the same time increase NO_x. Low temperatures on the other hand are unfavorable for the combustion process but decrease NO_x.

This project demonstrated that demanding driving conditions with high loads and high accelerations create high levels of NO_x. All modern diesel cars emitted about three times more NO_x when driven on uphill slope than when driven on flat road. The emissions of NO_x were during these conditions about 1 gram/km. However, a small car with an engine of 1.2 l did not emit higher values of NO_x than the larger cars.

High injection pressure and new diesel injection systems have reduced the gravimetric values of PM emissions from modern cars. The total numbers of PM and the size distributions for small size PM of solid fractions were, however, found to be similar to a 1985 Mercedes Benz.

The average PM emissions in different driving conditions are 10^{14} to 10^{15} particles/km, but the variation was significant between the different cars. Some cars can be good during extreme load conditions and less good in other conditions. Other cars have the opposite characteristics. There are possibilities for future optimization and reductions in numbers of PM emissions. Diesel passenger cars should in the future be expected to exhibit contemporary low values in all driving conditions.

A radical way to really reduce PM emissions was shown to be a factory equipped PM filter. Similarly, a radical way to really reduce NO_x is to install effective De-NO_x catalysts. Additional exhaust after-treatment equipment, however, needs to be tested and evaluated from all possible points of views. Additional exhaust after-treatment equipment makes the vehicles more expensive and more complicated. Costs and reliability have to be judged against the harmful effects of the emission components. Ammonia and laughing gas are emitted in so low values that there should be no need for special actions.

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5. Moisio, Tampere University of Technology: Real Time Measurement of Combustion Aerosols
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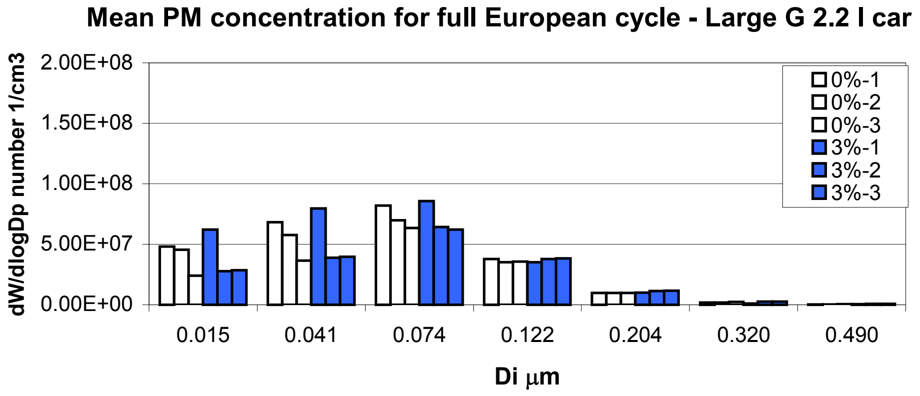
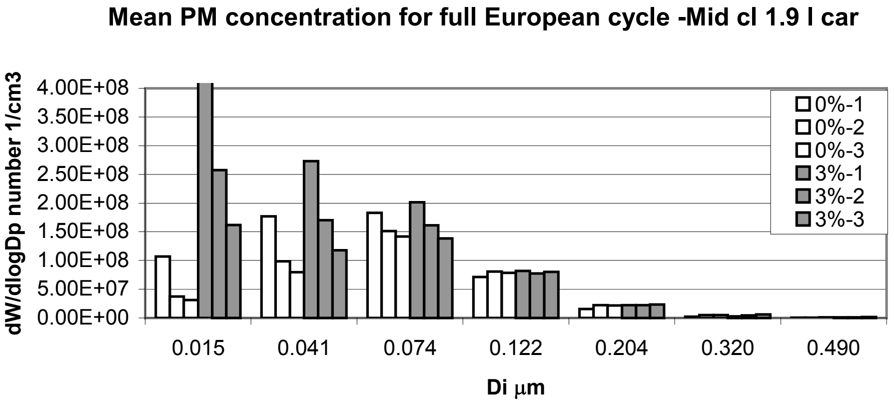
7. Neumann et al. Wolkswagen AG: Unregulated Exhaust Gas Components of Modern Diesel Passenger Cars, SAE Technical Paper 1999-01-0514

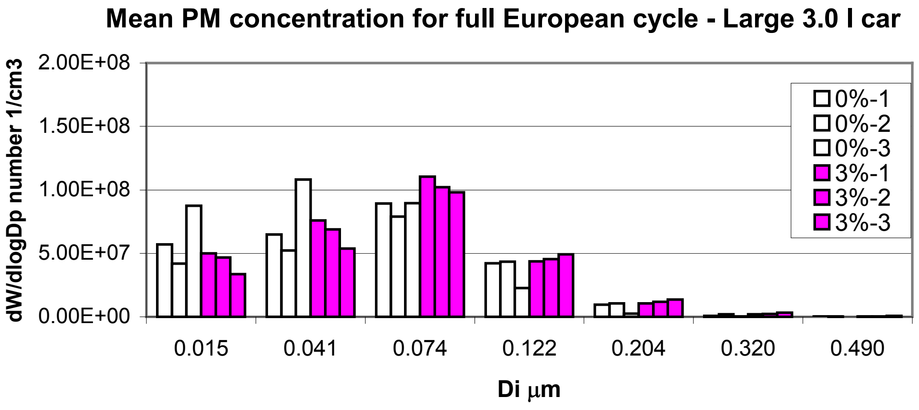
Regulated emissions																										**APPENDIX 1**		
	ECE (Phase 1)							**ECE (Phase 2)**							**EUDC (Phase 3)**							**ECE+EUDC (Phase 1-3)**						
	THC	CO	NOx	PM	CO2	FC	FC	THC	CO	NOx	PM	CO2	FC	FC	THC	CO	NOx	PM	CO2	FC	FC	THC	CO	NOx	PM	CO2	FC	FC
	[g /km]	[g /km]	[g /km]	[g /km]	[g /km]	[g /km]	[l/km]	[g /km]	[g /km]	[g /km]	[g /km]	[g /km]	[g /km]	[l/km]	[g /km]	[g /km]	[g /km]	[g /km]	[g /km]	[g /km]	[l/km]	[g /km]	[g /km]	[g /km]	[g /km]	[g /km]	[g /km]	[l/km]
Large G 2.2 l car 0%																												
Mean value	0,28	2,52	0,55	0,06	238	76,9	0,092	0,16	0,85	0,48	0,04	211	67,0	0,080	0,02	0,02	0,64	0,04	142	44,9	0,054	0,09	0,63	0,60	0,04	172	54,6	0,065
Std deviation	0,01	0,12	0,03	0,01	5	1,5	0,002	0,02	0,13	0,03	0,02	5	1,4	0,002	0,00	0,00	0,02	0,01	2	0,6	0,001	0,00	0,05	0,01	0,00	2	0,6	0,001
Large G 2.2 l car 3%																												
Mean value	0,11	1,23	1,08	0,06	308	98,0	0,117	0,02	0,13	1,01	0,05	277	87,6	0,105	0,01	0,03	1,51	0,14	211	66,6	0,080	0,03	0,27	1,34	0,11	241	76,3	0,091
Std deviation	0,02	0,19	0,02	0,01	5	1,5	0,002	0,01	0,07	0,04	0,01	3	0,8	0,001	0,01	0,00	0,02	0,05	0	0,1	0,000	0,01	0,05	0,02	0,03	2	0,5	0,001
Middle 1.9 l car 0%																												
Mean value	0,13	1,28	0,38	0,07	211	67,3	0,080	0,07	0,35	0,34	0,08	181	57,3	0,068	0,01	0,01	0,44	0,05	132	41,7	0,050	0,04	0,31	0,41	0,06	156	49,4	0,059
Std deviation	0,01	0,02	0,02	0,02	2	0,7	0,001	0,00	0,02	0,01	0,05	1	0,3	0,000	0,00	0,00	0,01	0,01	1	0,3	0,000	0,00	0,01	0,01	0,01	1	0,3	0,000
Middle 1.9 l car 3%																												
Mean value	0,07	0,72	0,74	0,07	282	89,5	0,107	0,01	0,02	0,62	0,09	252	79,7	0,095	0,00	0,01	1,25	0,13	196	61,8	0,074	0,02	0,14	1,04	0,11	222	70,3	0,084
Std deviation	0,00	0,04	0,04	0,01	1	0,2	0,000	0,01	0,00	0,04	0,00	1	0,2	0,000	0,00	0,00	0,06	0,05	1	0,4	0,000	0,00	0,01	0,05	0,03	1	0,2	0,000
Large 3.0 l car 0%																												
Mean value	0,03	0,39	0,51	0,04	318	100,7	0,120	0,01	0,01	0,51	0,04	284	89,6	0,107	0,00	0,00	0,40	0,02	157	49,5	0,059	0,01	0,08	0,44	0,03	210	66,4	0,079
Std deviation	0,01	0,13	0,02	0,02	7	2,3	0,003	0,00	0,00	0,01	0,00	4	1,3	0,002	0,00	0,00	0,06	0,01	2	0,6	0,001	0,01	0,02	0,04	0,00	3	0,9	0,001
Large 3.0 l car 3%																												
Mean value	0,03	0,17	0,81	0,08	443	139,9	0,167	0,01	0,01	0,83	0,06	392	123,7	0,148	0,00	0,01	1,56	0,03	248	78,5	0,094	0,01	0,04	1,28	0,05	311	98,2	0,117
Std deviation	0,01	0,01	0,02	0,01	21	6,7	0,008	0,00	0,00	0,05	0,01	25	7,9	0,009	0,01	0,00	0,02	0,02	8	2,7	0,003	0,00	0,00	0,02	0,01	11	3,6	0,004
Large J 2.2 l car 0%																												
Mean value	0,05	0,92	0,41	0,03	256	81,1	0,097	0,01	0,10	0,33	0,03	211	66,4	0,079	0,00	0,00	0,34	0,04	145	45,7	0,055	0,01	0,19	0,35	0,04	178	56,1	0,067
Std deviation	0,00	0,19	0,02	0,03	4	1,4	0,002	0,01	0,02	0,01	0,01	5	1,6	0,002	0,00	0,00	0,02	0,00	4	1,3	0,002	0,00	0,03	0,01	0,01	1	0,4	0,000
Large J 2.2 l car 3%																												
Mean value	0,03	0,54	0,51	0,08	335	105,9	0,126	0,01	0,04	0,45	0,11	287	90,5	0,108	0,01	0,01	1,03	0,09	215	67,7	0,081	0,01	0,11	0,83	0,09	251	79,0	0,094
Std deviation	0,01	0,05	0,01	0,04	2	0,6	0,001	0,00	0,05	0,01	0,04	0	0,1	0,000	0,00	0,00	0,02	0,01	2	0,5	0,001	0,00	0,02	0,01	0,01	1	0,4	0,000
Small 1.2 l car 0%																												
Mean value	0,03	0,64	0,28	0,04	126	40,0	0,048	0,01	0,13	0,26	0,03	112	35,3	0,042	0,00	0,04	0,39	0,01	85	26,6	0,032	0,01	0,17	0,35	0,02	97	30,8	0,037
Std deviation	0,00	0,03	0,01	0,01	8	2,6	0,003	0,00	0,03	0,02	0,01	9	2,8	0,003	0,00	0,03	0,08	0,01	2	0,7	0,001	0,00	0,02	0,05	0,00	2	0,6	0,001
Small 1.2 l car 3%																												
Mean value	0,03	0,65	0,60	0,02	166	52,7	0,063	0,01	0,09	0,54	0,02	151	47,6	0,057	0,00	0,00	1,27	0,03	132	41,7	0,050	0,01	0,14	1,01	0,02	142	44,8	0,054
Std deviation	0,00	0,12	0,01	0,01	1	0,4	0,000	0,00	0,02	0,02	0,01	1	0,2	0,000	0,00	0,00	0,01	0,01	1	0,3	0,000	0,00	0,02	0,01	0,01	1	0,2	0,000
Large F 2.2 l car 0%																												
Mean value	0,02	0,10	0,63	0,01	295	93,1	0,111	0,01	0,01	0,33	0,00	249	78,5	0,094	0,00	0,01	0,38	0,00	149	46,9	0,056	0,01	0,02	0,42	0,00	195	61,5	0,073
Std deviation	0,00	0,01	0,01	0,01	3	1,1	0,001	0,01	0,00	0,01	0,00	2	0,6	0,001	0,01	0,00	0,02	0,00	1	0,3	0,000	0,00	0,00	0,01	0,00	1	0,3	0,000
Large F 2.2 l car 3%																												
Mean value	0,01	0,05	1,21	0,01	382	120,4	0,144	0,01	0,01	0,71	0,01	330	104,0	0,124	0,01	0,02	1,15	0,00	230	72,3	0,086	0,01	0,02	1,08	0,00	277	87,1	0,104
Std deviation	0,00	0,01	0,03	0,01	5	1,5	0,002	0,01	0,00	0,02	0,01	2	0,5	0,001	0,00	0,00	0,04	0,00	1	0,4	0,000	0,01	0,00	0,03	0,01	1	0,4	0,000
Large 1985 3.0 l suction engine car 0%																												
	0,51	1,77	0,76	0,27	332	105,7	0,126	0,31	1,29	0,76	0,17	284	90,4	0,108	0,11	0,56	0,58	0,28	193	61,2	0,073	0,24	0,91	0,65	0,26	235	74,7	0,089

APPENDIX 2

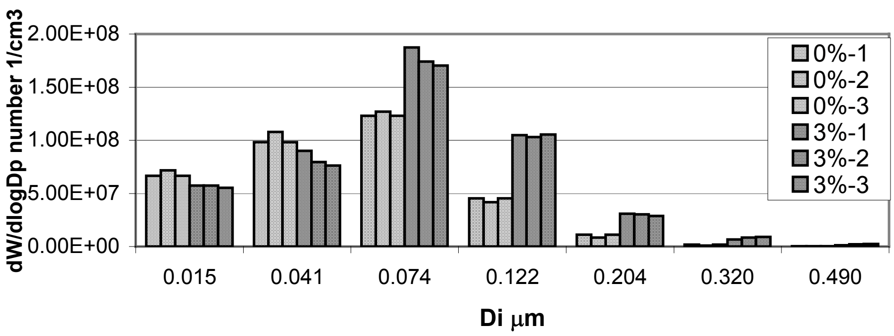
Mean PM concentration in the exhaust for the full European cycle

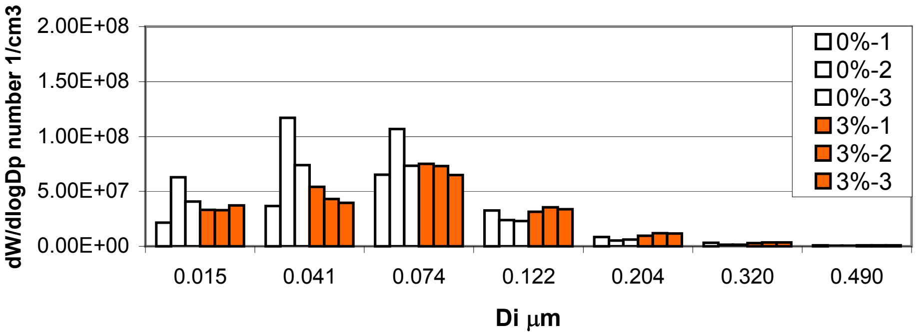

Mean PM concentration for full European cycle - Large G 2.2 l car

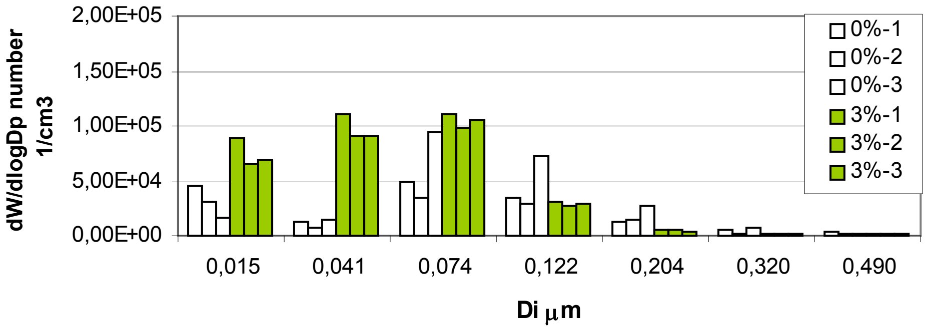

Mean PM concentration for full European cycle -Mid cl 1.9 l car

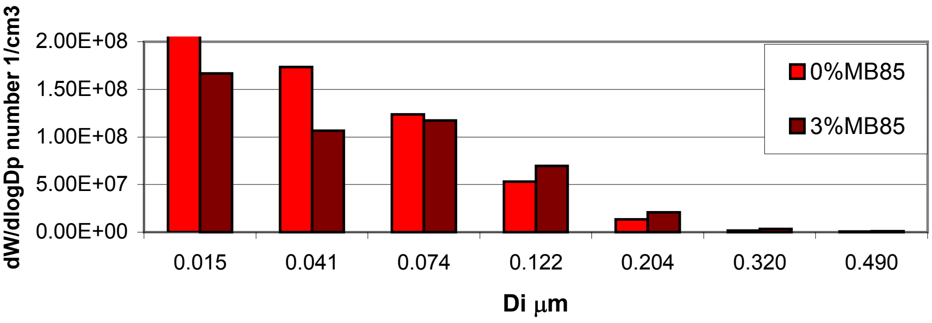

Mean PM concentration for full European cycle - Large 3.0 l car

APPENDIX 2


Mean PM concentration for full European cycle - Large J 2.2 l car

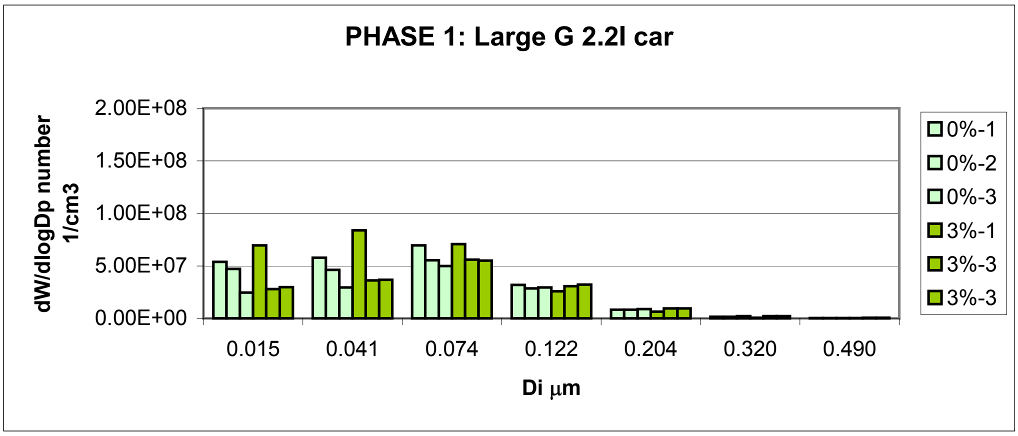

Mean PM concentration for full European cycle - Small 1.2 l car

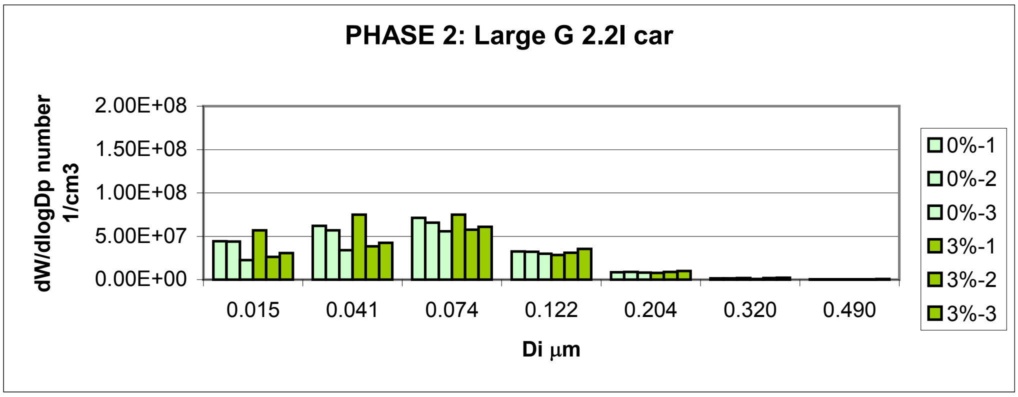

Mean PM concentration for full European cycle - Large F 2.2 l car

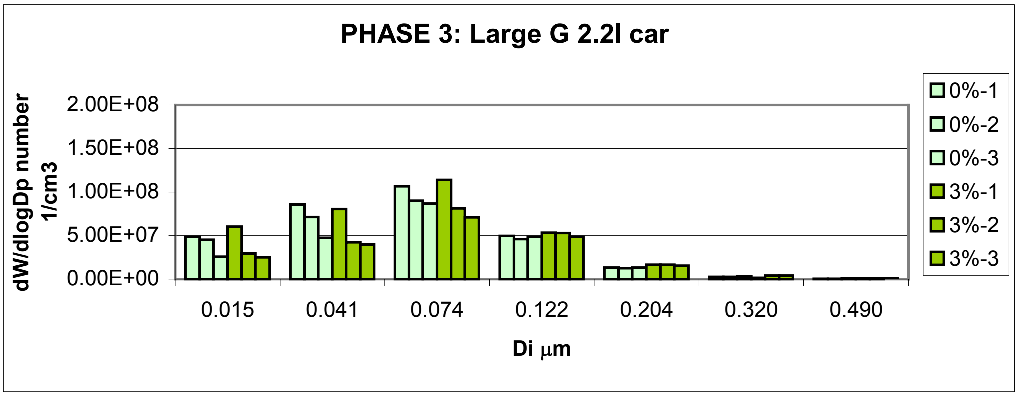

Mean PM concentration for full European cycle - MB 85 3,0 l

APPENDIX 3

Mean PM concentration in the exhaust for the three phases of the European test cycle







APPENDIX 3

Mean PM concentration in the exhaust for the three phases of the European test cycle