Emissions of Ultrafine Particles from Different Types of Light Duty Vehicles

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1 INTRODUCTION

There is growing concern in Europe and elsewhere over the impact on human health of ultrafine particles emitted from diesel vehicles. It is less well recognised that petrol fuelled vehicles also emit relatively high concentrations of fine particles. This is particularly evident with the direct injection petrol engine, which shares some important design features with the diesel engine. This engine is expected to become a major element of the automotive industry's effort to fulfil its commitment to the European Union to reduce the average specific fuel consumption of new passenger vehicles below 140 g/km by 2008-09.

The mass of particles emitted from diesel vehicles is regulated by EU legislation. Particles emitted from petrol vehicles are not regulated because the mass emitted is low. The number of particles emitted is not regulated for any type of vehicle, but may be an important indicator of the health impacts. Ultrafine particles are believed to penetrate deeper into the lungs and to stay there longer than larger particles. The mass of one particle with a diameter of 3 µm is equal to the mass of 1 million particles with a diameter of 0.03 µm. Most particles from gasoline engines fall below 0.1 µm. This is why they contribute little to the mass of particles collected during a conventional emissions test.

This report evaluates the emissions from 45 different light duty vehicles (or cars, vans and pickups) including direct injected turbocharged diesel engines and three types of gasoline engines; spark ignited and naturally aspirated (SI NA), spark ignited and turbocharged (SI turbo) and spark ignited and direct injected (SI DI). The number of particles emitted has been measured at 18 different engine-operating points. The objective of the report is to analyse the results and to discuss the need for additional regulation of particle emissions.

2 SOURCES AND TYPES OF PM

2.1 Sources of PM

Most pollutants are a single chemical substance. Airborne particles however vary widely in composition and physical characteristics, and have many natural and man-made sources. Particles can be emitted directly into the air (known as primary particles) or formed from other pollutants in the air (secondary particles). Primary particles come from man-made sources such as traffic, coal fired power stations, cement factories, and open cast mines. They also occur naturally as airborne spores, pollen grains and windblown soil. The concentration of primary particles varies considerably depending on the proximity to local sources and their magnitude. Secondary particles comprise mainly ammonium sulphate, ammonium nitrate and secondary organic compounds, which are formed slowly as air masses travel over long distances. These particles show no appreciable gradient between urban and rural areas.

The likelihood of a particle affecting human health depends largely on its size. Particles most likely to be inhaled into the lung are usually below about 10 µm in diameter. These particles, known as PM10, can be in one of three size categories:

- Ultrafine particles are those below 0.1µm in diameter. These are formed by condensation of hot vapour from combustion processes and from the chemical conversion of gases to particles. Particles of this size have a high chance of deposition in the deepest parts of the lung, the alveolar, and therefore have the greatest potential to cause harm. There are a very large number of these particles in the air, but due to their extremely small size they contribute little to the mass of PM10 measured.

- Particles between 0.1 and about 1 µm in diameter are typically formed from the ultra fine particles by coagulation and adsorption of gaseous material from the atmosphere onto pre-existing particles. These particles can remain suspended in the air for several weeks.

- Coarse particles are those greater than about 2.5 µm in diameter. These are generally formed by the break-up of larger matter, and include windblown dust and soil, particles from construction and sea spray. Their size means that they remain in the air for relatively short periods. They make (in relation to their numbers) a disproportionate contribution to PM10 mass, especially when measured close to a source of coarse particles. Coarse particles generally account for about 20-50% of the urban background PM10 mass in the UK.

The first two categories above are also known as fine particles or PM2.5, that is particles with an aerodynamic diameter of less than 2.5 µm. Combustion processes produce ultrafine particles based on carbon with a variety of metals and organic chemicals derived from the fuel burnt. Secondary particles, in northern Europe, mainly consist of ammonium sulphate and ammonium nitrate, derived in part from gases produced by combustion sources and in part from ammonia derived from farming. Distinct differences in the proportions of these components occur in different seasons. The coarser fraction may contain a wide variety of chemical substances including sea salt, silicates and biological particles, depending on local sources.

Work undertaken for the European Commission suggests that road traffic contributes 10-15% of the total man-made primary emissions of PM10 in the European Union as a whole (SENCO, 1999). However, in many cities with little heavy industry, such as London, traffic can contribute as much as three quarters of the total man-made emission (Airborne Particles Expert Group, 1999). Traffic makes an even greater contribution to the total emissions of ultrafine particles. In another study of particle emissions in Europe, traffic was estimated to contribute 17% of PM10, 20% of PM2.5 but over 40% of the ultrafine particles (TNO, 1997). In some Scandinavian cities, where wood burning accounts for a few percent of domestic heating, it can be an important source of PM. For example, small scale wood burning accounts for 62% of emissions in Greater Stockholm, while road transport accounts for only 6 % (SLB-Analys, 2000).

Information on emissions alone does not provide insight into the contribution of traffic to airborne concentrations of particles, because it fails to take account of secondary particles. Receptor modelling techniques have shown that in the UK traffic contributes typically 30-40% of the annual average concentration of PM10 at city centre sites. This is generally much higher during local pollution episodes (Airborne Particles Expert Group, 1999).

2.2 Health Effects

It has been known for a long time that airborne particles have an adverse effect on human health. However, since the late 1980s many studies have shown adverse health effects at concentrations previously considered safe. These studies have been made possible due to the development of new statistical techniques, and the availability of sophisticated software and electronic databases of pollution, weather, health effects and treatment.

Even low levels of PM10, in the range 0-100 µg/m3, can increase mortality, as well as increase the number of hospital admissions for respiratory disease and, to a lesser degree, cardiovascular disease. Particles are associated with exacerbation of asthma and coughing and small reductions in lung function (Pope and Dockery, 1999).

There is no evidence that a threshold exists below which effects do not occur. However, insufficient epidemiological evidence of health impacts below a concentration of 5 to 10 µg/m3 exists to be certain that there is no threshold (World Health Organization, 2000). The results from a number of studies suggest that a 10 µg/m3 increase in PM10 concentration, averaged over 24-hours, increases the daily deaths by about 1%, although there is some variation between different studies undertaken around the world. Typically the increase in mortality occurs concurrently or within one to five days of an increase in air pollution.

Limited evidence from studies on dust storms suggests that the coarser PM10 particles are less toxic than those associated with combustion sources, and that the observed effects are associated with PM2.5 (World Health Organization, 2000). Sulphates have also been associated with health effects. These compounds are a constituent of PM2.5. However, sulphates do not account for all the observed effects of PM2.5 (Expert Panel on Air Quality Standards, 1999).

Evidence is also emerging that long-term repeated exposure to fine particles increases the risk of chronic respiratory disease and the risk of cardio respiratory mortality. These studies suggest that increasing chronic exposure to PM2.5 by 5 µg/m3 increases mortality by 2-4% (Pope and Dockery, 1999).

The consistency of the results across different studies suggests that the precise chemical composition of the inhaled particles is not important. Studies of rats exposed to particles of the same chemical composition but of different sizes have shown that the toxicity of ultrafine particles results from their small size rather than their chemical composition. It has been suggested that the particles form free radicals in the lungs causing inflammation (MacNee and Donaldson, 1999).

Experimental animal and limited human studies indicate that the smallest particles, that is those less than 0.1µg, cause more inflammation in the periphery of the lung than do larger particles (Expert Panel on Air Quality Standards, 1999). In this size range particle mass is unlikely to be important, as they are so small. It is not known whether particle number or the size of their surface area is the most crucial indicator of the harmful effects of these particles.

The inflammatory reaction caused by inhalation of particles may lead to worsening of pre-existing lung disease and enhance the sensitivity to allergens of people with hay fever and asthma. It may also have the capacity to alter blood coagulability and circulating red cells and platelets, a mechanism that could explain the adverse influence of inhaled particles on cardiovascular morbidity and mortality.

3 THE TESTS

3.1 Vehicles and fuels

This study reports the number and size distribution of particles emitted from 45 new light duty vehicles (cars, pickups and vans) tested on a chassis dynamometer (ROTOTEST VPA) at steady loads. The vehicles had been driven for 3,000-10,000 km before the tests were undertaken. All the vehicles were borrowed from dealers and serviced before being tested. The lubricant oil used differs from car to car depending on the brand used by the manufacturer or dealer.

The vehicles tested are listed in Annex 1. They range in engine size from 1.0 to 5.3 litres. Seven direct injection turbocharged diesel engines, including the new Peugeot 607 with particle filter, and 38 vehicles with spark ignition engines (i.e.

petrol engines) were tested. Of the petrol vehicles 28 had naturally aspirated (NA) engines, six had turbocharged engines, one a supercharged engine and three had direct injection engines.

The test fuels used meet the requirements of Swedish environmental class 1 diesel and Swedish environmental class 1 petrol. The former is a low sulphur blend (< 10 ppm S) with properties quite different from European standard diesel (i.e. EN590), the latter is equal to the EC specification that enters into force in 2005. Using Swedish class 1 diesel lowers the emission of particulate mass (PM10) by 10-30% (Arthur D Little, 1998). Its effect on particle numbers and size distribution is less well known. The full specification of Swedish environmental class 1 diesel is provided in Annex 4.

3.2 The test equipment

The chassis dynamometer used in this study was a ROTOTEST VPA (Figure 1), which is characterised by direct coupling to the wheel-hubs and a very high measuring accuracy of the torque and speed.

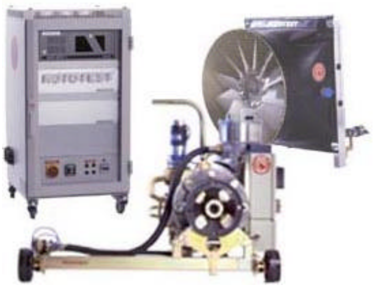

Figure 1 - ROTOTEST VPA

Particle number and size distribution were measured using an Electrical Low Pressure Impactor (ELPI) supplied by Dekati. This instrument can measure the aerodynamic diameter of particles from 10 µm down to 10 nanometers.

The sampling system is made from metal. The sampling point is underneath the car, and is located after the catalyst. The raw exhaust is diluted in two stages, firstly with heated air and secondly with cold air (Annex 4). Both diluters are of the ejector-type from Dekati and the dilution ratio is ~1:8 in both stages, giving a total dilution ratio of 1:64. One drawback of the sampling point is that the exhaust pressure changes with the engine load, and the first dilution ratio has to be corrected for the actual pressure ratio over the venturi. However, this drawback is small and easily corrected.

There is a significant advantage in taking the sample "early" in the exhaust system. Maricq et al (1999), and others, have showed problems with constant volume dilution tunnels. The hot exhaust gases cause desorption and/or pyrolysis of organic material from the walls of the car's exhaust system as well as from the dilution tunnel. Desorption also occurs when the exhaust temperature rises as a result of load changes and the problem is worse if there is a large "emitting surface area", such as silencers, upstream of the sampling point. In this case longer times for stabilising the sampling equipment are required. The sampling system itself is held at a constant temperature.

Desorption is a problem if it produces a large proportion of the total number of particles measured. To minimise the problem the vehicles were firstly operated at full-load to burn off most of the surface deposits, and make the starting conditions of each test more similar. Particle measurements were undertaken at steady conditions and at 18 different engine loads covering the lowest load at 50 km/h to the highest load at the maximum power output.

All the tests began with a stabilising phase before the measurements were taken to reduce the effect of desorption. The length of this stabilising phase depends on the load. At low loads the sampling system was stabilised for about one minute, while at higher loads the length of the stabilisation phase was dependent on the power output. However, a PM burn-off phase was seen at the beginning of the stabilising phase, and measurement occurred after this. When the measurement was finished and the load reduced, the temperature remained high and therefore desorption continued. However, the particle concentration at this stage is dramatically reduced, suggesting that the contribution from desorption of surface particles is small.

4 RESULTS

4.1 Introduction

All the results are taken fom Rototest's ordinary benchmarking database, see Annex 3. The database also includes measurements of fuel consumption and exhaust emissions (CO2, CO, NOx, O2, and THC) which are used to calculate lambda and the total amount of particles.

The results of the tests have been primarily analysed to detect the differences between the engine types. The engines have been split into five categories:

Spark ignited and naturally aspirated	(SI NA)
Spark ignited and turbo charged or supercharged	(SI turbo)
Spark ignited and direct injected	(SI DI)
Compression ignited	(Diesel)
Compression ignited with particle filter	(Diesel + filter)

The last category, diesel + filter, includes only one car, the Peugeot 607 HDi. It is of special interest since it is the first car on the market to be fitted with a particle filter as standard. The filter is regenerated when the particle loading is above a certain level. This is detected by the pressure loss over the filter. However, the actual start of regeneration does not occur at any specific loading, instead the engine management system determines the best time to do it, depending on how the vehicle is being driven. Regeneration can be started with extra fuel injected to raise the exhaust temperature to the level required to burn off the particles. It is better, however, to regenerate the filter when the car is driven on the highway, as less extra fuel is needed. This is because the exhaust temperature is closer to that required. If the car is under heavier load the exhaust will reach the required temperature without extra fuel, and start the regeneration process. This means that the results presented in the figures can have some regeneration included and must therefore be evaluated with some care.

The results for the vehicle with the supercharged SI-engine have not been reported separately from the turbocharged vehicles because the results are similar.

Identifying the causes of high particle emissions is not easy, as a number of factors can have an influence. In this report the effect of the amount of fuel injected into the engine, the air fuel ratio, engine load, and specific power output on the number of particles emitted have been investigated.

4.2 The effect of the amount of fuel injected

The first question of interest is whether there is a relationship between the number of particles produced and the amount of fuel injected. In Figure 2 the total number of particles (0.01-1µm) are plotted against the amount of fuel used. The emission of particles from the diesel vehicles (except the one fitted with a particle filter) is relatively constant, that is, the emission is independent of the amount of fuel injected. The particle emission from the vehicles with the NA and turbo SI-engines, however, tends to increase with the amount of fuel injected, such that when the amount of fuel injected increases by a factor of two the number of particles emitted increases by a factor of about 10.

The vehicles with NA and turbo SI-engines exhibit a larger range of PM emissions than the other vehicle types. The number of particles emitted varies by a factor of several thousands for the same amount of fuel injected. Some of these vehicles, in particular those with turbo SI-engines, can emit a similar number of particles as the diesel vehicles, when large amounts of fuel are being used.

The vehicles with SI DI engines emit a greater number of particles than those with NA and turbo SI-engines, and often emit a similar number of particles for a given mass of fuel injected into the engine as the diesel vehicles.

The diesel + filter vehicle also shows an increase in the number of particles emitted with increasing fuel use, although it is highly variable. This is likely to be due to the regeneration of the particle filter. The emissions from this vehicle are in many cases lower than, or at least similar to, the best SI engines when the filter is not regenerating. When the filter is regenerating the emissions are still similar to good SI engines.

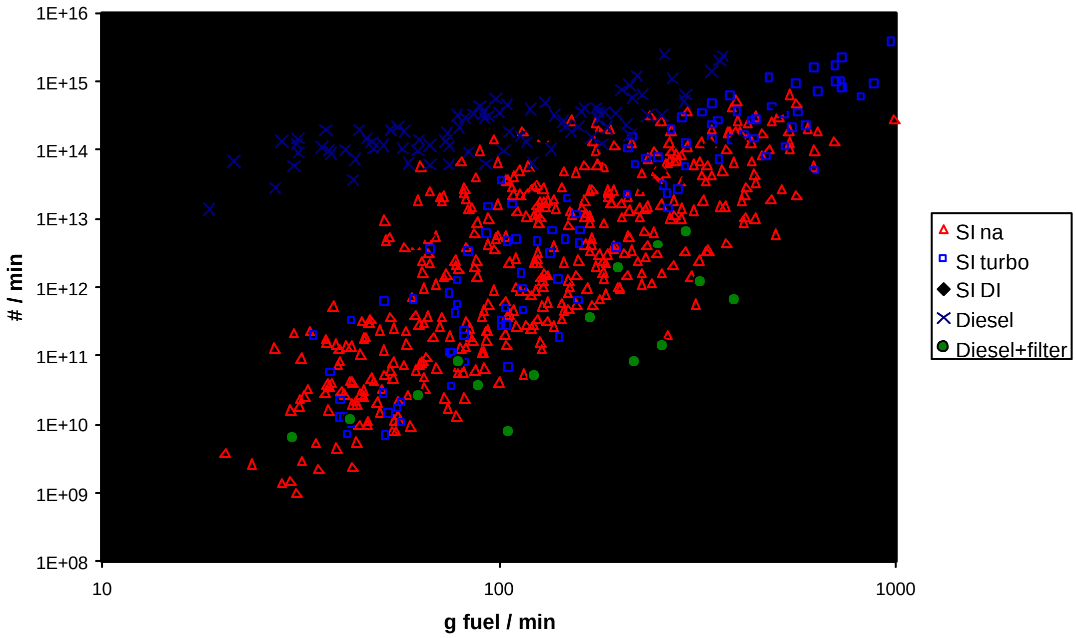

Figure 2 - Total particle number per minute related to fuel mass flow

4.3 The effect of the air fuel ratio

Normally the air fuel ratio (A/F-ratio) has a large influence on the gaseous emissions from petrol engines and the PM emissions from diesel engines. It is therefore interesting to see if there is any correlation between the A/F-ratio and the emission of ultrafine particles.

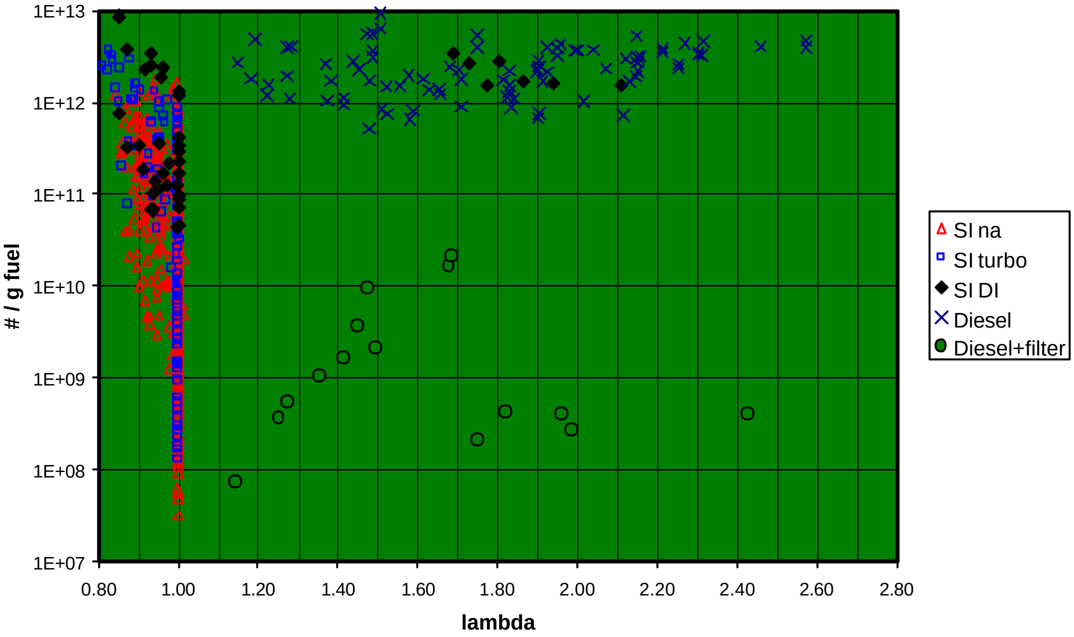

Figure 3 - Total particle number per fuel mass related to lambda

In Figure 3 the number of particles emitted per minute per gram of fuel are plotted against the relative stoichiometric A/F-ratio (lambda). Diesel engines seem to have a low sensitivity to lambda. Enlarging the area of the graph where lambda is less than 1, Figure 4, shows the tendency for petrol engines to emit more particles when running rich. It is also evident that when lambda = 1, emissions of particles are not low from all petrol vehicles.

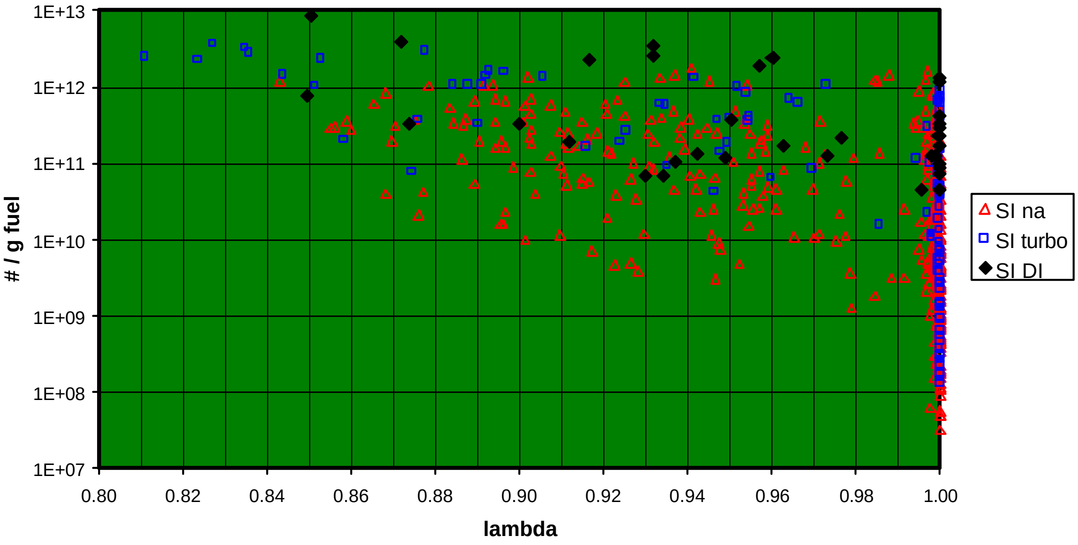

Figure 4 - Total particle number per fuel mass related to lambda = 1

The SI DI engines exhibit two distinct types of behaviour. When these engines run lean they produce a similar number of particles as the diesel engines. On the other hand, when running rich they behave more like the conventional SI-engines. However their emissions are never as low as the best NA and turbo SI-engines.

The diesel + filter vehicle emits between 100 and 10,000 times less ultrafine particles per gram of fuel used than the diesel engines without filters, and emits considerably fewer particles than most of the SI engines.

4.4 Effect of engine load

In Figure 5 the particle concentration (i.e. number of particles per cubic centimetre) is plotted against the specific torque (i.e. torque per litre engine capacity). The later is a way of describing the engine load taking account of the different engine sizes.

Particle emissions from diesel engines seem to be insensitive to engine load whereas those from NA and turbo SI-engines tend to increase with load. There is no clear relationship between particle emissions and engine load for the vehicles with SI DI engines.

At low specific torque the NA and turbo SI-engines have low particle emissions, similar to those measured for the diesel + filter vehicle. As the load increases the particle concentration in the exhaust of these vehicles also increases. This has also been reported in other investigations (e.g. Mohr et al, 2000). Some vehicles with SI-engines have similar particle concentrations at relatively moderate specific torque levels as those with diesel engines. At very high specific torque, i.e. greater than 100 Nm/dm3, the particle concentration is at the same level for vehicles with both SI turbo and diesel engines.

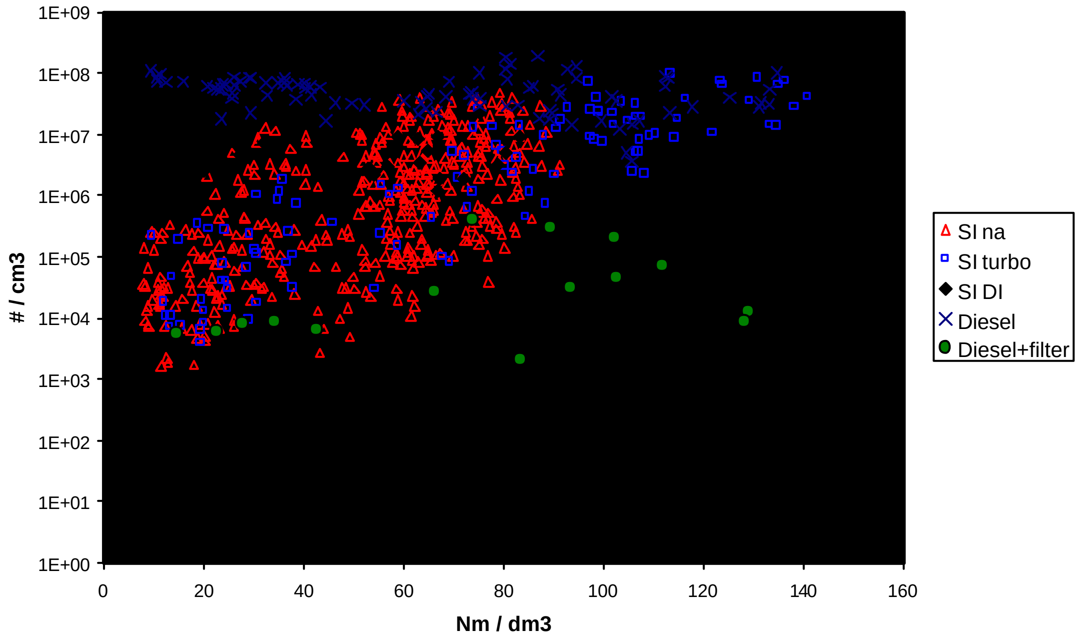

Figure 5 - Particle concentration related to specific torque

Diesel engines have high particle emissions, with concentrations typically in the range 10 million to 100 million particles per cubic centimetre. The lowest particle concentrations are in the exhaust of the diesel + filter vehicle. These are typically in the range 1,000 to 100,000 particles per cubic centimetre, over a large range of specific torque.

In general, the particle emissions from SI DI engines tend to fall between the diesel and the NA and turbo SI-engines. To put these figures into context the particle concentration in "clean" air in buildings may be around 5,000 particles per cubic centimetre (Clair Intl, 2000). At the roadside typical hourly average concentrations are of the order of 100,000 particles per cubic centimetre, but there are short term fluctuations ranging from about 1,000 to 10 million particles per cubic centimetre (Airborne Particles Expert Group, 1999).

4.5 Effect of specific power output

An alternate way of comparing different sized engines is by using the power density, expressed as specific power output (that is, power per litre engine capacity). This has been plotted against brake specific particle number (number of particles per kilowatt-hour) in Figure 6. From this figure it is clear that at low specific power outputs the vehicles with NA and turbo-SI engines generally emit much fewer particles than those with SI DI and diesel engines. However, at a specific output of just 10 kW/dm3, a few vehicles with SI-engines produce a similar number of particles as vehicles with diesel engines. This shows that using a car with a NA or turbo SI-engine is no guarantee of low particle emissions. With increasing specific power output the brake specific particle number emitted from the vehicles with NA and turbo SI-engines increases.

The vehicles with SI DI and diesel engines show a similar trend as seen before, that is, they have smaller variations in the brake specific particle emissions with changing specific power. The diesel + filter vehicle has, in general, very low specific emissions; lower than most of the SI-engines.

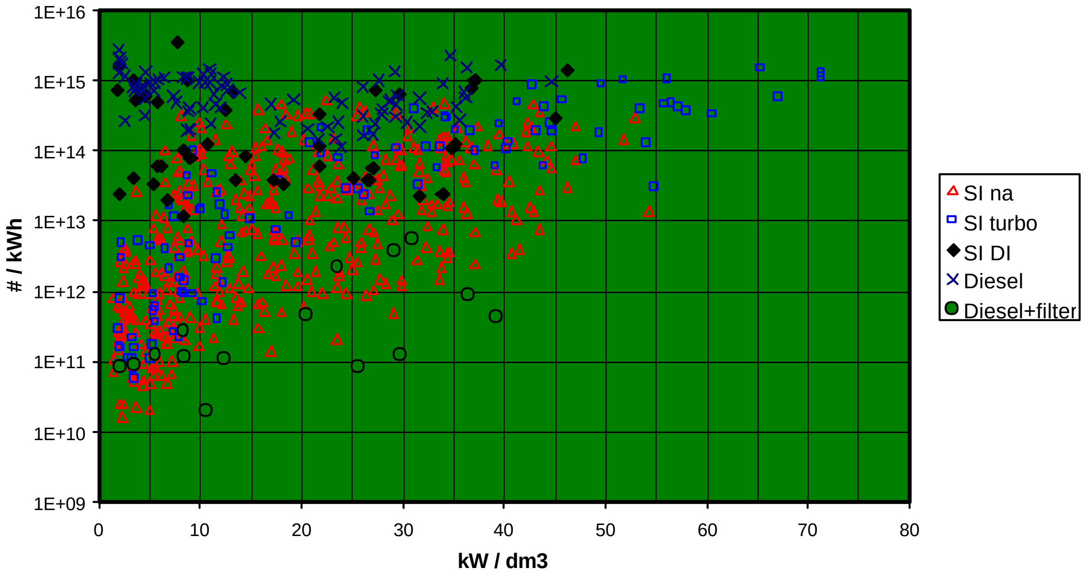

Figure 6 - Brake specific particle number related to specific power output

4.6 Particle size distribution

To further understand the PM emission characteristics for vehicles with different engine types the particle size distributions have been investigated. Since the vehicles tested range from small cars to vans and pickups, the comparisons need to be made on a comparable basis.

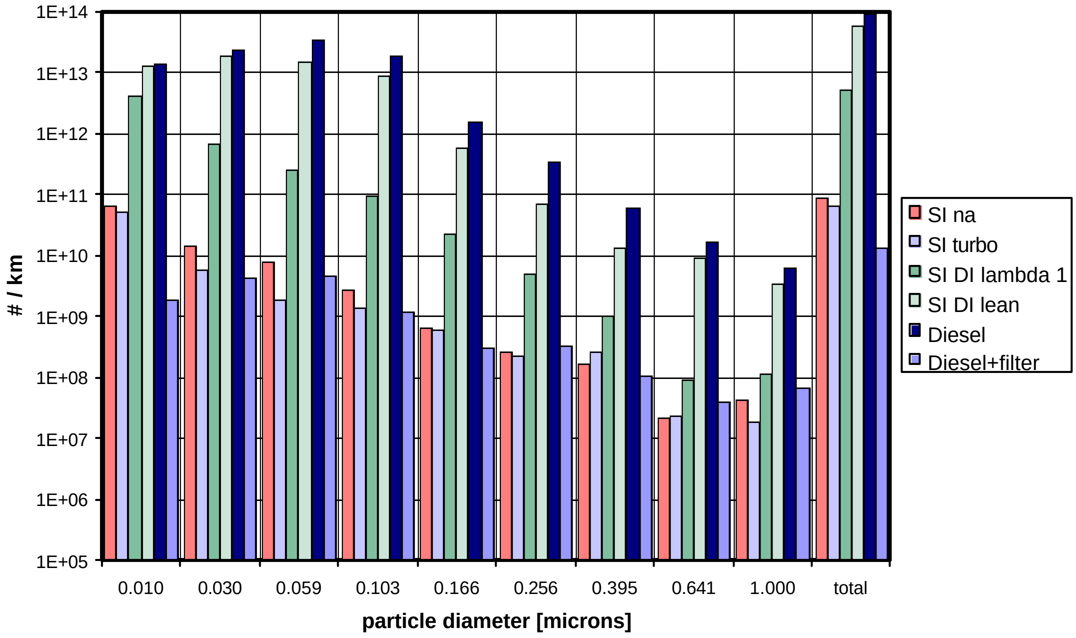

Figure 7 - Particle size distribution at 90 km/h

In Figure 7 the size distribution is shown at a constant speed of 90 km/h. Results are presented for the number of particles per km, and have been normalised to a power demand on the wheels of 10 kW to drive the car.

Vehicles with petrol engines tend to produce more smaller particles compared to those produced from vehicles with diesel engines. The size category with the largest number of particles is the smallest size category i.e. 10 nanometers (nm) (there may be more particles of smaller sizes, but the ELPI cannot measure below 10 nm). For the diesel vehicles the number of particles peak at around 60 nm.

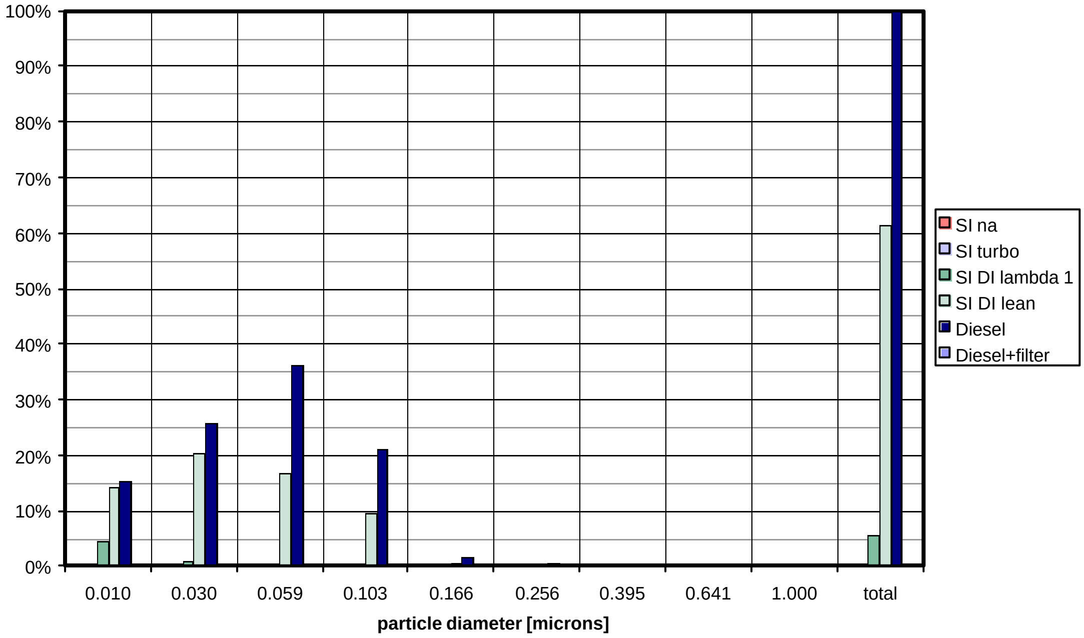

Figure 8 - Particle size distribution at 90 km/h relative to Diesel

Figures 8 and 9 show the relative emissions compared to the total emissions from the diesel vehicles. The results for the vehicles with NA and turbo SI-engines are too low compared to the diesel emissions to be observed in Figure 8. Figure 9 shows the same data, but with an expanded scale for the range 0-1% of the total diesel emission. The most interesting results are for the SI DI engines. At 90 km/h some of these engines run lean while others run stoichiometric (i.e. lambda 1). When the SI DI engines run lean the size distribution is similar to that of diesel engines, but with about half the emissions. When running stoichiometrically the size distribution is more similar to that of the NA and turbo SI-engines but with the emissions about a hundred times higher. The lowest number of particles are emitted from the diesel + filter vehicle, and are about one tenth of those emitted from the vehicles with the NA SI-engines. The filter was not regenerating during this test and it shows a removal efficiency of 99.99%.

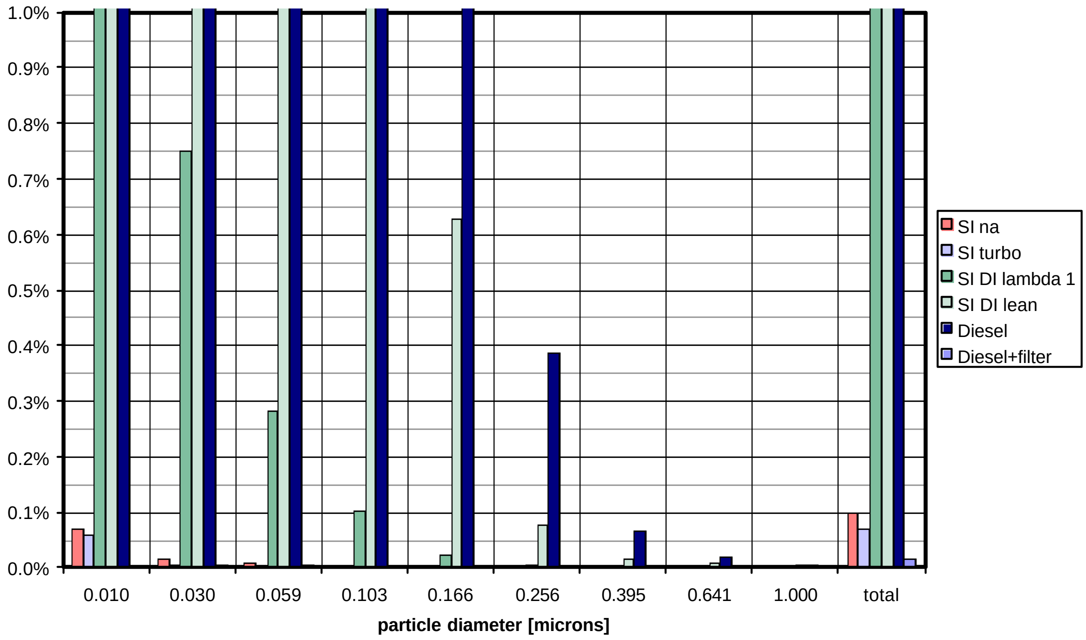

Figure 9 - Expanded scale 0-1%

The acceleration in normal traffic is, in many cases, higher than those represented in the regulation driving cycle. At maximum torque the engine is producing the greatest motive force for the car. NA and SI DI engines often have a maximum load of 80 Nm/dm3 whereas the vehicles with turbo SI-engines and diesel engines normally have a maximum load of around 120 Nm/dm3.

The earlier figures have shown that the total number of particles emitted from vehicles with SI turbo and diesel engines can, under high load, be similar. Figure 10 shows that at maximum torque vehicles with SI turbo engines can emit more particles than diesel engines. One reason is that the maximum torque is produced at higher engine speeds for the SI-engines in general, another is that these engines have lower efficiencies. Both result in higher mass flows.

An interesting comparison is that driving 0.16 seconds at maximum torque with a SI NA engine can produce the same total number of particles as one minute of driving at 90 km/h.

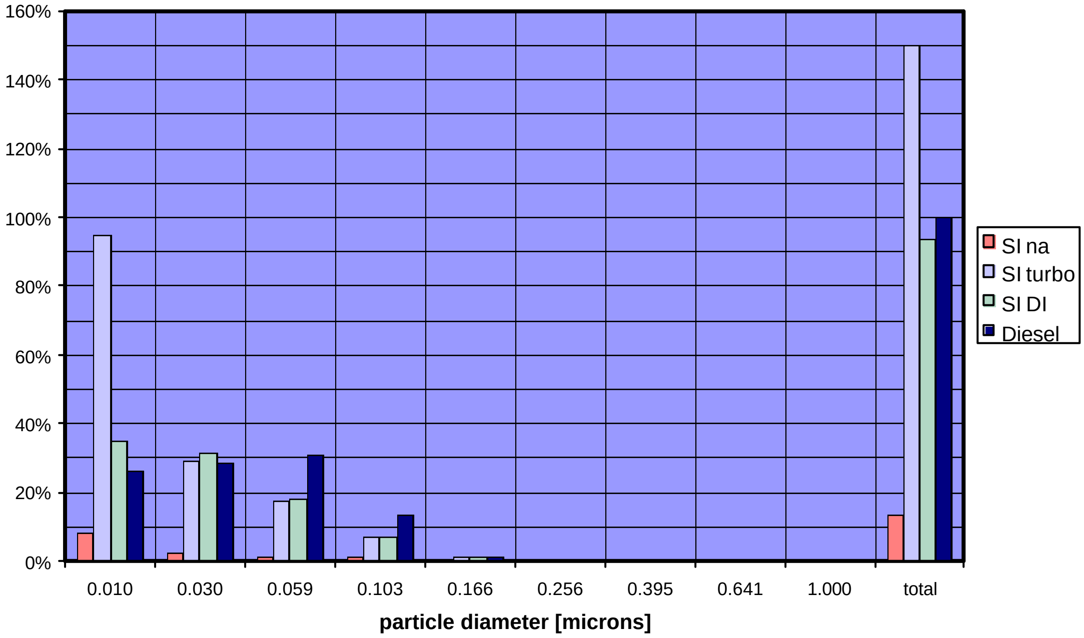

Figure 10 - Particle size distribution at maximum torque relative to diesel

The total number of particles emitted during normal driving is very dependent on the driving style. Rototest has estimated the emissions for two simulated driving conditions: one representing moderate and the other representing gentle driving. The size distributions from these mixed driving conditions are presented in Figures 11 and 12.

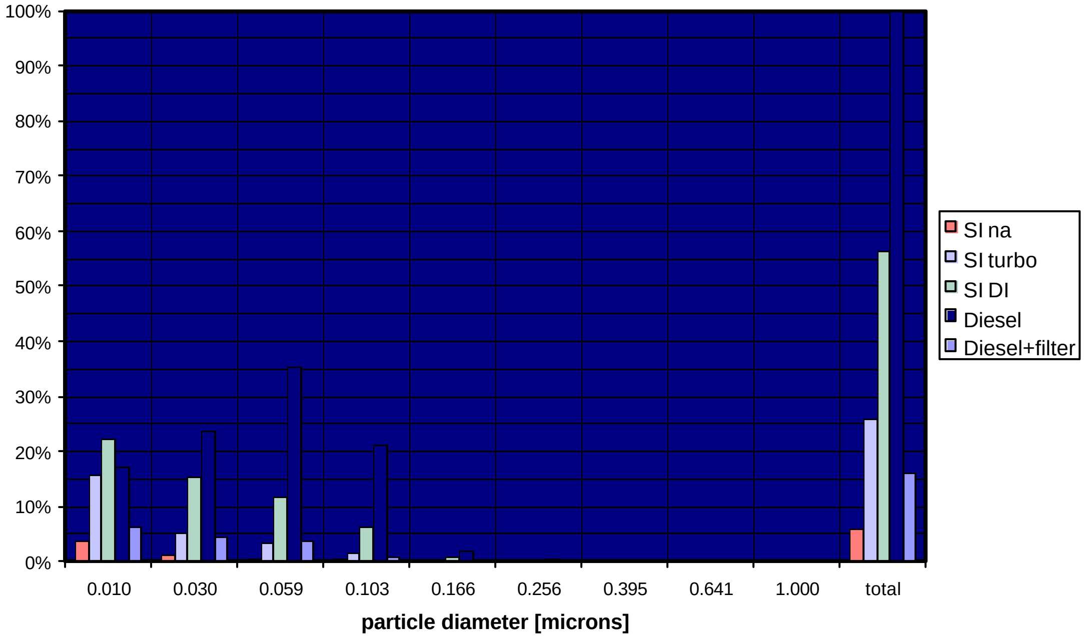

Figure 11 - Moderate mixed driving relative to diesel

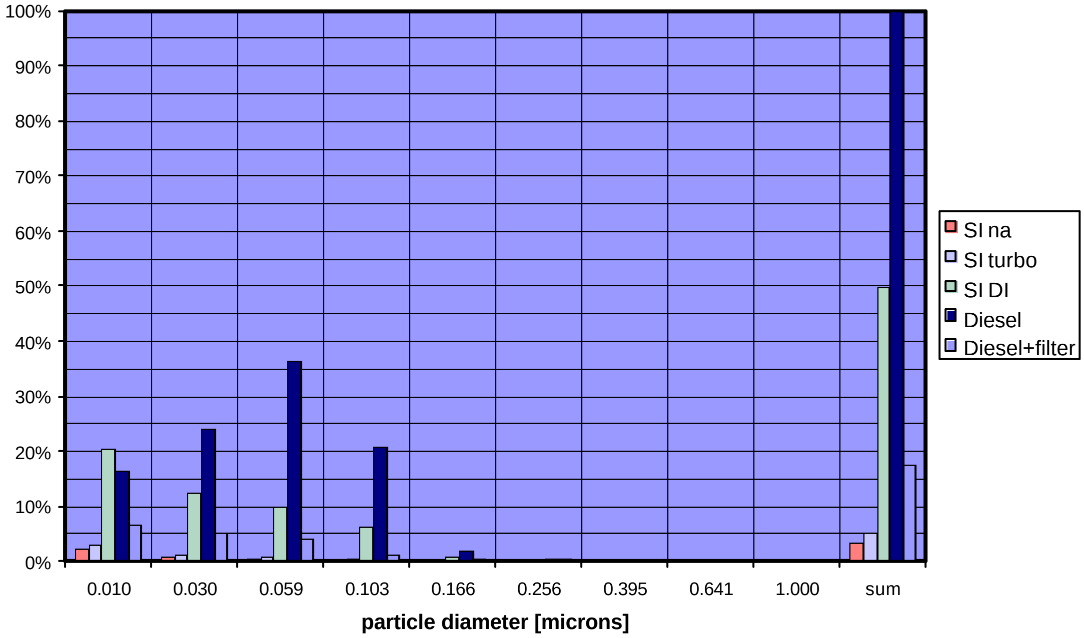

Figure 12 - Gentle mixed driving relative to diesel

There are surprisingly small differences in the number of particles emitted with these two driving styles. The main difference is with emissions from the SI turbo engines. When these engines are under high load the number of particles emitted increases significantly. The size distribution of the particles emitted from the diesel engines are similar as in Figure 8, whereas the SI DI engines is a mixture of the lean mode, with diesel engine resemblance, and the lambda 1 and rich mode which resembles the normal SI-engines.

The emissions from the diesel + filter car under both driving conditions are less than 20% of those from the diesel vehicles. The result includes the contribution from regenerating the filter.

4.7 Variations among models with the same type of engine

There is a considerable variation between vehicles with the same type of engine as shown in Figures 13 and 14. Under gentle mixed driving (Figure 14), the worst SI NA engine emits 1,000 times more particles than the best engine of the same type. Under moderate mixed driving conditions, the spread still exceeds a factor 100.

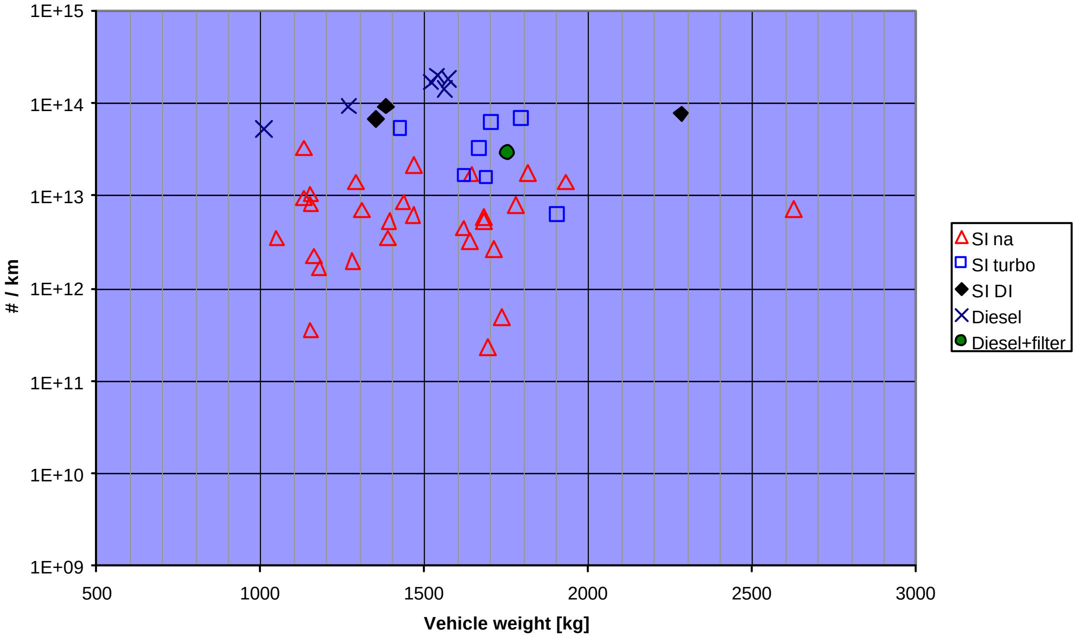

Figure 13 - Moderate mixed driving; Total numbers related to vehicle weight

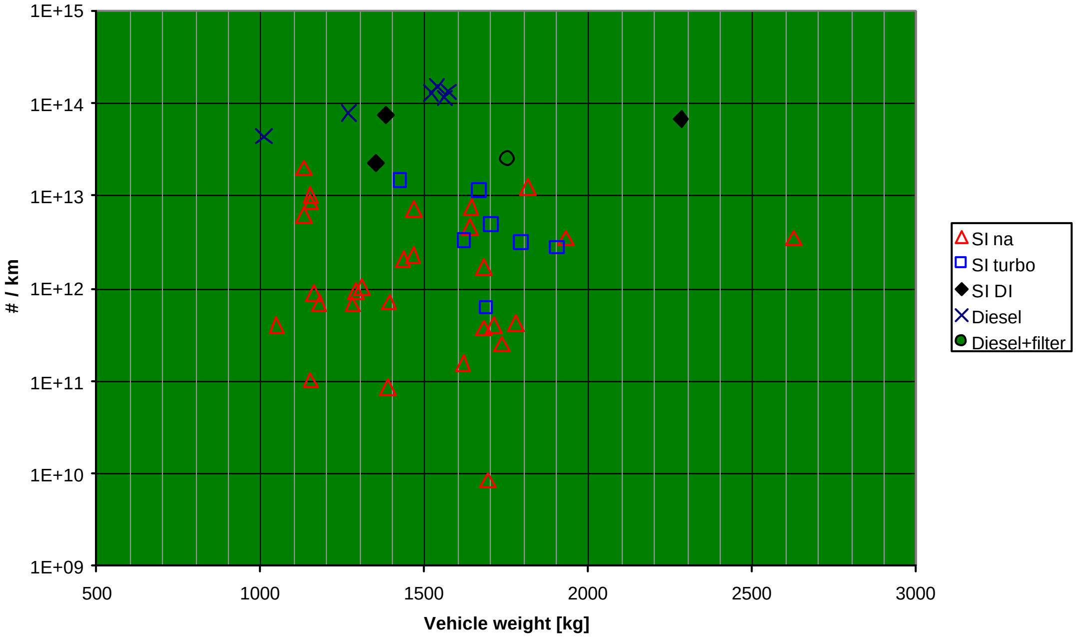

Figure 14 - Gentle mixed driving; Total numbers related to vehicle weight

Among the SI turbo vehicles the spread is smaller. Under moderate mixed driving the worst emits around ten times more than the best.

The variation is much smaller among cars with diesel or SI DI engines. Under both gentle and moderate mixed driving conditions the best diesel car, being considerably smaller than the others, emits around 70% fewer particles per km than the worst. The worst SI DI emits around three times as many particles under mixed gentle driving as the best SI DI. This difference shrinks to a factor less than 2 under moderate mixed driving conditions.

An important notice is that all the variations are discussed in relative terms. In absolute numbers, the spread is largest for the diesel engines.

5 SUMMARY AND CONCLUSIONS

This report evaluates the emissions from 45 different light duty vehicles including direct injected turbo-charged diesel engines and three types of gasoline engines; spark ignited and naturally aspirated (SI NA), spark ignited and turbocharged (SI turbo) and spark ignited and direct injected (SI DI). The number of particles emitted has been measured at 18 different engine-operating points.

The objective of the report is primarily to detect differences between the various engine types and to discuss the need for additional regulation of particle emissions.

5.1 Diesel engines

For diesel engines the tests show that both the number of particles emitted and the size distribution appear to be relatively unaffected by load, excess air and driving style. The number of particles rises modestly with increasing fuel injection. For diesel vehicles the number of particles peak at around 60 nanometers (nm).

However, the number of particles varies considerably between the different diesel vehicles. The worst emit more than three times as many particles as the best. Consequently there is in many cases room for improvement even without having to resort to particle filters.

The results show that the French particle filter very efficiently removes ultrafine particles from the exhaust. The number of ultrafine particles emitted is less than 20% of those from diesel vehicles without particulate filters. In many conditions the number of particles emitted from the Peugeot 607 HDi is lower than the numbers emitted from the cars with turbo SI engines.

5.2 NA and turbo SI-engines

At low specific power outputs vehicles with NA and turbo engines emit much fewer particles than vehicles with SI DI and diesel engines. The emissions are less than 1% of those from diesel engines. However, unlike diesel engines, the particle emissions from these engines show a large variation with load, air/fuel ratio and in some cases approach diesel levels of emission. There is a linear relationship between the amount of fuel injected and the number of particles produced per minute. Increasing the fuel injected by a factor of two produces a tenfold increase in the number of particles. Increasing the specific power output affects the number of particles in a similar way. At maximum torque the total number of ultrafine particles emitted from vehicles with SI turbo engines can be greater than those from diesel engines, while those from SI NA engines are very low, less than 15% of those from diesel engines.

For NA and turbo SI vehicles the results show increasing numbers of particles emitted with decreasing lambda values. There is a large variation between car models depending on the extent to which they operate stoichiometrically. Where manufacturers have not taken responsibility for ensuring that Lambda=1 under high loads, these vehicles can be high emitters during fast accelerations. Some vehicles with SI engines approach diesel emission levels at relatively moderate specific torque.

The NA and turbo SI engines tend to produce smaller particles compared to those produced by vehicles with diesel engines. The smallest size category (i.e. 10 nm) represents the largest number of particles of all size categories. There may be even more particles of sizes below 10 nm though the equipment is unable to measure them.

As shown above, vehicles with NA and turbo SI-engines exhibit a large range of particle emissions. The number of particles emitted varies by a factor of 100 to 10,000 depending on load, torque, A/F ratio and other factors. Unlike diesel engines, particle emissions from NA and turbo SI vehicles are sensitive to driving behaviour.

There are also considerable differences between different NA and turbo SI engines. Under mixed driving conditions the worst vehicle may emit more than 100 times more particles than the best.

5.3 Direct injection SI

Only three models in the test represented the SI DI vehicles. The results should thus be interpreted with some caution.

The particle emission from the SI DI engines appear to be relatively independent of the amount of fuel injected per minute as well as of torque and engine load. In most circumstances the number of ultrafine particles emitted approach those of the diesel vehicles. Unlike NA and turbo SI engines the SI DI engines produce relatively high numbers of particles at low specific torque. At low loads the numbers fall slightly below those of the diesel vehicles and at moderate and high loads they are close to those from vehicles with SI NA engines.

The vehicles with SI DI engines seem to behave like those with diesel engines when running lean and like those with conventional SI engines when running stoichiometric or rich. At 90 km/h one of the three engines runs lean while the others operates stoichiometrically (i.e. lambda = 1).

The size distributions are different from both those of conventional SI and diesel engines. When the SI DI engines run lean, the size distribution is similar to that of diesel engines, but at about half the numbers. When running stoichiometrically the size distribution is more similar to those of the NA and turbo engines but at numbers that are about one hundred times higher.

5.4 Impact on future air quality

The total number of ultrafine particles (0.01-1µm) emitted from road traffic is not known. The results from the “moderate mixed driving” simulation indicates that in a situation where a fleet consists of 50% diesel and 50% petrol vehicles (mostly SI NA) the former would account for more than 90% of the total number of particles. The proportion of the total number of particles emitted from petrol fuelled vehicles would be even lower in situations where “gentle mixed driving” is applicable.

However, if the manufacturing industry undertakes a general shift from SI NA engines to SI DI engines for reducing specific fuel consumption, one can envisage a future situation where direct injected petrol vehicles make up more than half the car fleet of a city (most of the rest being diesels). If the current difference between diesel and SI DI engines in terms of particle numbers still prevails at that time, the latter would then account for something close to 40% of the total emission by numbers. Interestingly, the particle number penalty that goes with reducing CO_2 emissions by shifting from traditional petrol vehicles to diesel or SI DI vehicles appears on average to be approximately proportional to the reduction of CO_2. One should, however, recall the large variations in particle numbers between individual models of both engine types.

5.5 Regulating ultrafine particles?

Both the Environment Protection Agency of the United States and the European Commission are currently addressing the issue of how to regulate PM emissions from vehicles in the future. The EC is about to start a large study looking at the regulation of emissions from Heavy Duty Vehicles, which will address the issue of the measurement of particle mass. A problem of the current regulation, for both light and heavy duty vehicles is that as PM mass declines the existing measurement methods are insufficiently sensitive, and therefore a new method is needed. As the medical evidence is increasingly pointing to the ultrafine particles being the main cause of the adverse health effects observed, it is important that any new test method includes, directly or indirectly, this metric.

However, currently, there is insufficient agreement and knowledge over the best method for measuring ultrafine particles from vehicles. Any new measuring procedure should attempt to reproduce, as closely as possible, the dilution and other conditions that effect the transformation of particles as they leave the vehicle exhaust and are diluted with air. This is to ensure that future legislation controls emissions of those particles that, directly or indirectly, cause the health effects.

In December 2000 German, French, Dutch, Swedish and British government experts jointly proposed to co-ordinate their work on the development of a test method that can measure size distribution of particle emissions from a broad range of vehicle technologies including both spark and compression ignition engines. The new method could then be used in addition to, or in place of, mass measurement. The aim is to develop the new test method within two years.

Given that it will take several years after the experts have eventually developed and agreed a new test procedure before it will be introduced into EU legislation, it is vital that information on particle emissions from different cars becomes available to the public. This would give added market value to low-emitting cars while waiting for new legislation.

5.6 Regulating PM emissions from petrol cars?

It may at first glance seem unnecessary to regulate particle emissions from petrol cars, as the number of particles emitted is typically less than those emitted from diesel vehicles. However, the results from this study, and others, show that some petrol fuelled vehicles can have similar emissions of ultrafine particles as some diesel vehicles. If these vehicles – particularly SI DI, but also to a lesser extent turbo-SI - obtain a significant market share they could become major contributors to the number of ultrafine particles emitted from road transport if they continue to be unregulated.

For example, the best diesel car (without a filter) included in the study emits fewer particles than all three of the SI DI vehicles, and the same or fewer than three of the seven turbo SI vehicles tested under the moderate driving conditions. However, this car is considerably smaller and 200-500 kilograms lighter than most of the SI DI and SI turbo vehicles.

The emissions from the diesel vehicle fitted with a particle filter were lower than all the SI DI, most of the turbo SI and some SI NA vehicles under moderate driving conditions. If fitting particle filters to diesel vehicles becomes widespread practice, petrol vehicles could become the major source of ultrafine particles.

Three circumstances may argue in favour of regulating particle emissions from SI DI vehicles:

1. During moderate mixed driving the best diesel (without filter) in Rototest's sample emits fewer particles than the all three SI DI vehicles. The second best diesel is equal to the worst SI DI.

2. The current difference in numbers and mass between vehicles with SI DI engines and most diesel vehicles may disappear, as the diesel engines become cleaner to meet the 2005 standards. If diesel manufacturers choose to equip their models with particle filters, the diesel cars will definitely emit fewer ultrafine particles than cars with SI DI engines.

3. The relatively large differences in particle numbers between different models with SI DI engines (a factor of 3 according to "gentle mixed driving") indicate that an emission limit value by mass may trigger improvement provided that there is a relatively good correlation between mass and numbers.

Regulating particle emissions from NA and turbo SI vehicles is also an option. During "moderate mixed driving" the worst SI turbo engines emit ultrafine particles in numbers close to those of the best diesel engines. However, during "gentle mixed driving" there is a considerable difference to the advantage of the SI turbo.

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Annex I

Vehicles tested

SI na (28)

Car model	Engine size litres	Gearbox type	Test weight kg
BMW 330 CI	3.3	manual	1618
Chevrolet Tahoe	5.3	auto	2625
Citroen Evasion	2.0	manual	1681
Citroen Xsara Picasso	1.8	manual	1464
Ford Mondeo	2.0	manual	1466
Honda HR-V	1.6	manual	1391
Hyundai Elantra	2.0	manual	1434
Hyundai Trajet	2.0	manual	1930
Mazda MPV	2.0	manual	1778
Mercedes C320	3.2	auto	1694
Nissan Almera	1.8	manual	1389
Opel Agila	1.2	manual	1152
Peugeot 607	2.2	manual	1642
Renault Clio	1.4	manual	1163
Renault Megane	1.6	manual	1280
Renault Scenic RX4	2.0	manual	1680
Seat Ibiza	1.4	manual	1131
Skoda Fabia	1.4	manual	1131
Suzuki WagonR+	1.3	manual	1152
Suzuki WagonR+	1.3	manual	1152
Toyota Celica	1.8	manual	1290
Toyota Previa	2.4	auto	1816
Toyota Yaris	1.0	manual	1049
Volvo V70 103 kW	2.4	manual	1735
Volvo V70 125 kW	2.4	manual	1711
Volvo V70 GLT	2.4	manual	1638
VW Golf	1.6	manual	1309
VW Polo	1.4	manual	1178
average	2.0		1489

SI turbo (7)

Car model	Engine size litres	Gearbox type	Test weight kg
Audi TT 1,8T	1.8	manual	1426
Mercedes C200 Kompressor	2	manual	1623
Saab 9-5 2.3T	2.3	manual	1690
Saab 9-5 Aero	2.3	manual	1706
Volvo S60 T5	2.3	manual	1668
Volvo V70 T5	2.3	manual	1796
VW Sharan 1.8T	1.8	manual	1906
average	2.1		1688

SI DI (3)

Car model	Engine size litres	Gearbox type	Test weight kg
Mitsubishi Carisma GDI 1,8	1.8	manual	1382
Mitsubishi Pajero Wagon V6	3.5	auto	2283
Renault Mégane Cab 2.0 idE -00	2.0	manual	1350
average	2.4		1672

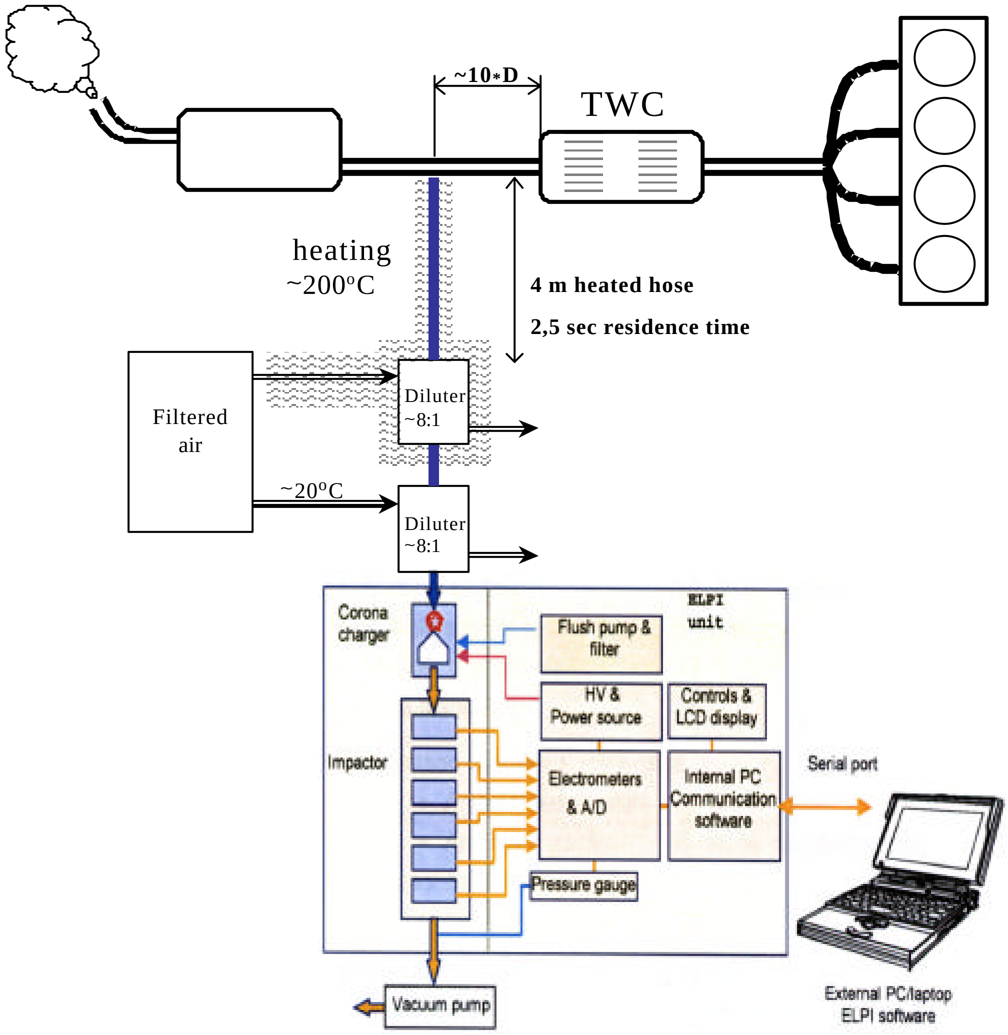
Diesel DI turbo (7)

Car model	Engine size litres	Gearbox type	Test weight kg	
Audi A2 TDI	1.4	manual	1268	
BMW 320d	2.0	manual	1561	
Mercedes Benz C 220 CDI	2.2	manual	1574	
Peugeot 607 HDi	2.2	manual	1753	+part.filter
Renault Laguna 1,9 dTi	1.9	manual	1538	
Saab 9-3 TID	2.2	manual	1520	
VW Lupo 3L TDI	1.2	auto	1009	
average	1.9		1460	

Total (45)

Annex II

Particle measurements, sampling from raw exhaust



Annex III (1/2)

Database specification, Rototest BD

Benchmark Database

Value presentation

- **All test values are presented with standard error (at 95% confidence) and systematic error (at 95% confidence).**
- Source of information is presented as:

RTV = Rototest test values
EI = External information
ELV = External lab values
ESV = Estimated values

Vehicle Specification

- Vehicle (Make, Model, Model year, ...)
- Engine (Type, Displ., Rated power, ...)
- Transmission (Type, Gear ratios, ...)
- Wheel (Type, Dimension, ...)
- Chassis dimension (Wheel-base, Track width, ...)
- Accessories (AC, Power steering, ...)
- Weights (Curb, Axle, Distribution, ...)
- Centre of gravity (Distance from front axle, ...)
- Vehicle dynamics (Drag, Frontal area, ...)

Test conditions

- Test weight
- Test fuel (Composition, Density ...)
- Atmospheric pressure
- Ambient temperature
- Relative humidity
- Engine oil temperature
- Engine inlet air temperature
- Test engineer

Test points and measurement values

- All test points have measurement values of emission components CO, CO_2, NO, and THC and fuel consumption, drive wheel power, engine speed, etc.

Measurement of particle emission

- Rototest has implemented regularly particle emission measurements since March 2000, for all test cars, petrol, alcohol, natural gas and diesel cars.
- For every test car, Rototest measure particle emission with an **E**lectrical **L**ow **P**ressure **I**mpactor from DEKATI Finland. Results are presented in numbers and in size distribution 0.01µm to 1.00µm in 9 steps.
- The exhaust samples are taken directly from the exhaust pipe (exhaust temperature and pressure are measured at the sample point) and diluted in 2-stages before measurement.

Vehicle speeds

- Speeds measured at steady state.

01	50 km/h
02	70 km/h
03	80 km/h
04	90 km/h
05	110 km/h
06	120 km/h
07	130 km/h
08	Theoretical max speed

Engine speeds

- Full load

09	Low engine speed
10	Medium engine speed
11	Medium high engine speed
12	High torque engine speed
13	High power engine speed

- 80% load

14	Low engine speed
15	Medium engine speed
16	Medium high engine speed
17	High torque engine speed
18	High power engine speed

Graphs and tables

All test points have measurement values of fuel consumption, drive wheel power, engine speed, transmission ratio, etc.

Full load performance

Engine speed vs. power, torque and specific fuel consumption Approximately 14 test points from 1000 1/min to maximum engine speed in 500 1/min steps. Presented in test figures and graphs.

Max performance within closed-loop control

Engine speed vs. power, torque Presented in test figures and graphs.

Environmental Pollution Index EPI-01

According to Rototest internal standard RS-00120101

Mixed Fuel Consumption MFC-01

According to Rototest internal standard RS-00120102

Miscellaneous

On request

- Ammonia (NH_3)
- ..., etc.

Rototest the leading provider of accurate automotive drive train Benchmarking information

(2/2) *Total number of vehicles in the database*

ALFA ROMEO

1996	146 2.0ti
1997	145, 2.0
1998	156 2.0TS
1999	166 3.0
1999	166 3.0V6 aut

AUDI

1996	A4 1.8
1996	A6 Avant 30v
1996	A3 1.8
1997	A4 1.9, TDI
1997	A6 2.4 V6
1997	A3 1.8 Turbo
1998	A6 1.8Turbo
1998	A6 V6 TDI
1998	A6 Avant 30v
1998 P	A4 2.5 TDI aut
1998 P	TT 1.8T
1999	A6 2.4 V6
1999	A4 1.8T
1999	A6 2.7T aut
1999	TT 1.8TQ
2000	A6 2.4 100kW
2000	A6 2.8 Multitr
2000 P	A2 1.4
2000 P	A2 1.4 TDI
2001 P	A4 2.0 Multitr

BMW

1996	523i
1996	M3
1996	540i aut
1996	318ti
1996	318i Touring
1997	520i
1997	Alpina B10
1998	320i
1998	323ti Compact
1998	528i aut
1998	318i
1998	328i
1999 P	320d
1998	Z3 2.8
1999	328 C
1999	523i Touring
2000 P	330 CI
2001 P	M3 Coupé

CADILLAC

1998	Seville STS

CHEVROLET

1998	Camaro Z28V8
2000 P	Tahoe V8

CHRYSLER

1998	300M
2000(P)	PT Cruiser 2.0

CITROEN

1998	Xsara 1.6
1998	Berlingo 1.8
2000 P	Xsara Picasso
2000 P	Evasion 2.0

DAEWOO

1998	Nubira 2.0 Estate
1999	Matiz 0.8

DAIHATSU

1999	Sirion 1.0

FIAT

1996	Brava 1.6
1997	Barchetta 1.8
1999	Multipla 1.6 ELX
2000	Punto 1.2 16v

FORD

1996	Mondeo 2.0
1996	Scorpio 2.0
1996	Fiesta 1.25
1996	Galaxy 2.8 CDV6
1997	Mondeo 2.0
1997	Escort 1.8RS
1997	Galaxy 2.3
1997	KA 1.3
1998	Focus 1.6
1998 P	Mondeo 2.0
1999	Cougar V6
1999	Windstar V6
2000	Fiesta 1.25

HONDA

1996	Civic 1.4
1997	1.8 VETEC
1999	Accord 2.0
1999	Logo 1.34
1999	Accord type R
2000	S2000
2000 P	HR-V 1.6

HYUNDAI

1997	Elantra 1.8
1998	Sonata 2.0
1998	Atos 1.0
1999	Sonata 2.4 GLS
2000 P	Trajet 2.0
2000 P	Elantra 2.0

JAGUAR

1996	XJ6 Sovereign
1997	XK8 V8 4.0
1999	S-type 4.0

JÖSSE CAR

1996	Indigo 3000

KIA

1997	Clarus 2.0
1997	Clarus 1.8
1999	Pride 1.3

LEXUS

1998	GS 300
1999	IS 200

MAZDA

1995	323 1.5
1997	Miata MX-5
1998	626 2.0
1998	626 1.8
1998	MX-5 1.8
1998	323F 1.8
1999	Premacy 1.8
2000 P	MPV 2.0

MERCEDES-BENZ

1996	C 180
1996	E 290
1996	C 250
1997	SLK 230
1998	V230
1998	CLK 230
1997	C 200
1998	A 160
1998	A140
1998 P	C220 CDI
1999	240E V6, 2.4
2000 P	C200 Kompr
2000 P	C320 aut

MG

1997	MGF 1.8i
1998	MGF 1.8 VVC

MITSUBISHI

1996	Colt 1.6
1997	Carisma 1.6
1997	Galant 2.0
1998 P	Carisma GDI
1999	Spacestar 1.3
1999	Space Wagon
1999	Space StarGDI
2000 P	PajeroV6 GDI

NISSAN

1996	Micra 1.3
1996	Almera 1.6
1997	Primera 2.0i
1997	Micra 1.3
1998	Primera SLX 2.0
1999	Primera 1.6
2000	Primera 2.0
2000	Primera CVT
2000 P	Almera 1.8

OPEL

1996	Vectra 2.0
1997	Tigra 1.6
1997	Vectra 2.0 Estate
1997	Sintra 2.2
1998	Astra 1.6 16v
1999	Vectra 1.6 16v
1999	Zafira 1.6 16v
2000	Omega 2.2
2000 P	Agila 1.2
2000(P)	Astra 2.2Coupe
2000 P	Corsa 1.2

PEUGEOT

1996	406 SV
1997	406T
1997	306 GTI
1997	106 1.4
1997	406 V6
1997	406 2.0
1998	406 V6 Coupe
1998	306 1.6 XR
1999	206 1.4
1999	406 ST 2.0
2000 P	607 2.2
2000 P	206 1.4
2000 P	607 HDI

PORSCHE

1996	911 Tiptronic
1997	Boxster
1998	911 Carrera
1999	911 GT3
1999	Boxter
2000 P	911 Carrera 4
2000(P)	911 Turbo

RENAULT

1996	Laguna 2.0
1995	Clio 1.4
1996	Mégane 1.6
1997	Megane 2.0
1998	Sport Spider
1998	Laguna 1.6 16v
1998	Clio 1.4 RTE
1998 P	Laguna 1.9 dTi
1999	Twingo 2, 1.2
1999	Megane1.6 Est
1999	Scenic 1.6 16v
2000 P	Clio 1.4
2000 P	Megane 1.6
2000 P	Scenic RX4 2.0
2000 P	Megane 2.0 idE

ROVER

1997	620 Si 2.0
1997	Mini Cooper 1.3
1999	75 V6

SAAB

1996	900 S 20
1996	9000 CS 2.0
1998	9-5 2.0Turbo
1998	9-5 2.3 Turboaut
1998	900 Talladega
1998	9-3 2.0
1998	9-3 2.0T, 200hp
1999	9-5 V6 Griffin
1999 P	9-3 TID
1999	9-5 2.3T
1999	9-3 Viggen
1999	9-5 2.0T
1999	9-3 2.0T
1999	9-5 2.3T Estate
2000	9-5 Aero aut
2000 P	9-5 2.3T Aero
2000 P	9-5 2.3T

SEAT

1997	Ibiza 1.6
1998	Arosa 1.4
1999	Toledo 1.6
2000 P	Ibiza 1.4 MPI

SKODA

1996	Felicia 1.6
1997	Octavia 1.6
1998	Octavia GLX 1.6
1999	Octavia 1.8T
2000 P	Fabia 1.4 MPI

SUZUKI

1997	Baleno 1.6
2000 P	Wagon R+
2000 P	Wagon R+

TOYOTA

1997	Camry 2.2
1998	Corolla 1.6
1998	Starlet 1.3
1998	Avensis 2.0
1998	Corolla1.3 Xli
1998	Avensis 1.8 LB
1999 P	Yaris 1.0
2000	Yaris Versio
2000 P	Celica 1.8
2000 P	Corolla 1.6
2000 P	MR2
2000 P	Previa 2.4 aut

VOLVO

1996	940 SE 2.3
1996	850 GLT
1996	850 R
1996	S40 2.0
1996	V40 1.8
1997	S70 2.5 SE
1997	S70 GLT
1998	S40 T4
1998	C70
1998	V40 2.0T
1998	V40 1.6
1997	V70 2.5T
1998	V40 1.8i (GDI)
1998	S80 2.9 aut
1999 P	V70 GLT
1998	S80 T6aut
1999	S80 2.4
1999	C70 2.5T
1999	S40 1.8RN
1999	S80 2.4, 170hp
2000	V70 2.4T 200hp
2000 P	V70 T5
2000 P	V70 140 hp
2000 P	V70 170 hp
2000 P	S60 T5

VOLKSWAGEN

1996	Polo 1.4
1996	Golf 1.4
1996	Sharan 2.0
1996	Golf VR6
1996	Golf Variant 2.0
1997	Golf GTI 2.0
1997	Passat 1.8T
1997	Polo 1.4
1997	Golf GL 2.0
1997	Polo 1.416v
1997	Polo 1.6
1997	Golf GL 1.8
1997	Golf 1.6
1997	Passat 1.6
1997	Passat 1.9 TDI
1998	Golf V5
1998	Polo 1.6
1998	Golf GTI1.8T
1998 P	Golf 1.6
1998	Golf 1.8
1998 P	Golf TDI
1998(P)	Passat 1.9 TDI
1999	Lupo 1.4
1999	Beetle 2.0
1999	Sharan 1.8T
1999	Lupo 1.0
1999	Bora 1.6
1999	Golf 1.6 Estate
2000 P	Polo 1.4 16v
2000 P	Lupo 3L TDI
2000 P	Sharan 1.8T

Annex IV

Diesel reference fuel

Specification	**Swedish environmental class 1**	
Sulphur	ppm maximum	**10**
Aromatics	volume % maximum	**5**
PAH	volume % maximum (3 or more aromatic rings)	**0.02**
Cetane index	minimum	**50**
T95 °C	maximum	**285**