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In-use compliance programme passenger cars
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Summary

This report presents a general overview of the results of the Dutch In-Use Compliance programme for passenger cars over the year 2003. The work in this year was executed under a contract with the Dutch Ministry of Housing, Spatial Planning and the Environment for the period 2000-2003. The passenger car in-use compliance programme basically assesses the emission performance of passenger cars in use, against the corresponding emissions legislation. The data gathered are additionally used for the calculation of emission factors and for supporting the Dutch Government on national and international policy issues.

In 2000 the Euro 3 emission legislation and limits entered into force. In the years 2001 and 2002 the in-use compliance programme therefore focused on gathering information on the emission performance of this generation of vehicles. In both years a large number of Euro 3 and Euro 4[1] vehicles was tested. Anticipating the 2005 introduction of the Euro 4 limits, the regular programme of 2003 focused on expanding the emission database.

Additional to checking under type approval test conditions, further testing was done to establish real-world emission factors of passenger cars in order to understand the mechanisms that lead to differences between Type Approval (TA) and real-world testing. These insights are also important for emission factors modelling purposes. For this purpose additional tests were executed using two sets of special test cycles:

- Motorway traffic situations, using the categorisation from the Dutch Emissions & Congestion project, in order to extend the existing emission database with Euro 3 data (initially only Euro 1 and 2 were included).
- General real-world emissions, using the Common Artemis Driving Cycle (CADC), in order to establish emission data under dynamic circumstances for the purpose of advanced emission modelling closely linked to other European research work.

In 2002 it was agreed with the Ministry of Housing, Spatial Planning and the Environment to set up the programme differently in order to be able to fulfil the actual research needs of the Ministry. As a consequence additional research topics were addressed in 2003 in several different sub-programmes. These sub-programmes which were identified in co-operation with the Ministry were the following:

- Emissions of cars with different kinds of **automatic transmissions**
- Emissions of older cars, the so-called **'old-timers'**
- The emission performance of a car fitted with a **Diesel Particulate Filter** (DPF)
- The emission performance of cars with **Petrol Direct Injection**

Another sub-programme that was executed in 2003 was the in-use emission performance of LPG vehicles. The results of this programme were already described in the 2003 report entitled *"In-use compliance programme – Overview of Automotive LPG vehicles 1999-2003"*, report no. 03.OR.VM.037.1/HVDB. Therefore no further attention will be paid to these tests in this report.

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[1]) The Euro 4 limits are valid from 2005 onwards, but Euro 4 compliant cars (petrol) were already available from 2001.

The next table gives an overview of the vehicles tested in 2003:

Table 1 Number of vehicle types tested in 2003 per sub-programme

	Petrol	Diesel	LPG
Regular programme	7	2	4[a]
Automatic transmissions	4	-	-
Old-timers	4	2	2
Diesel Particulate Filter	-	1[b]	-
Petrol Direct Injection	3[b]	-	-

a) LPG vehicles were reported separately
b) also included in the regular programme

Besides the information of in-use emission performance, valuable information is gathered for supporting policy makers. This is made available through direct communication with the Ministry as well as by means of the output of the Dutch vehicle emission model VERSIT and some additions to the model. For instance the Dutch annual traffic emissions are calculated by input based on this model given to RIVM through the channels of the Dutch "Taakgroep Verkeer".

Further dissemination is achieved by TNO-Automotive actively taking part in ARTEMIS workshops and the DACH+NL group. Furthermore, publications have been made which were presented at the annual Transport and Air Pollution conference.

The main findings and conclusions for the year 2003 were the following.

For the **petrol vehicles** tested in the **regular programme** of 2003 it can be concluded that they had very low emissions levels, just like in previous years. Most of the vehicles tested (both Euro 3 and 4) complied with the Euro 4 limits. The Euro 4 vehicles did not show a significantly different emissions characteristic compared with the Euro 3 vehicles. A considerable proportion of the emissions was produced during the cold start.
Direct injection (DI) petrol vehicles appeared to have a higher HC and CO emission level compared to indirect injected vehicles, although this is not true for all vehicles. The NO_x emissions on a cold start can be lower for these vehicles than for a warm start.
The emissions of the Euro 3 **diesel vehicles** proved to be within the limits. NO_x emissions were close to the allowable level, while other emission components achieved the required levels comfortably. There were, however, insufficient vehicles tested to draw general conclusions, although the trends seen in recent years seem to continue. One vehicle tested was fitted with a particle filter; obviously this vehicle had significantly lower PM emissions than the vehicle without a filter.
The results from additional tests on the **real-world testcycles** ('Emissions and congestion' cycles and Common Artemis Driving Cycles) were added to the results that had been gathered in previous years to improve the statistical foundation of the emission characteristics.
The DI petrol vehicles were tested for the first time on these real-world cycles. They showed higher NO_x emissions on the urban hot and CADC urban cycles (due to lean operation at low engine speeds) compared to indirect injected vehicles, but a reduction on the CADC highway cycle. For the CADC urban, the HC emissions of the DI petrol vehicles were higher, along with the CO on the CADC highway. This type of vehicle

has measurable PM emissions that showed a similar trend to that for diesel vehicles (with the exception of the CADC highway), although the absolute levels (on a mass basis) were a factor 2 to 5 lower.

For the petrol vehicles equipped with an **automatic transmission** the HC, CO and NO_x emission levels did not show a clear correlation with the application of an automatic transmission. The automatic vehicles can show better, worse or even equivalent emissions behaviour compared to manual variants. On a per vehicle basis, handshifting the automatic vehicles actually resulted in a slight improvement in the emissions behaviour of the vehicles tested. The largest effect was found on CO_2 emissions. All automatic vehicles, except for one, showed improvements in CO_2 emissions on the NEDC cycle compared to the manual variant. That one vehicle, however, was classified in a higher inertia class than its manual counterpart, in addition to being a conventional 4-speed transmission, which explains some of the result. If correctly designed, the automatic variant can provide a net reduction of CO_2 emissions, not only on the homologation cycles but also on real-world cycles. In fact, the improvement appeared larger on the CADC Road cycle than on the EUDC cycle.
On real-world cycles, the automatic vehicles showed worse emission results on the highway and road CADC cycles. On other cycles, the results were mixed. In general, the results on the real-world cycles were not representative for the emission levels on the UDC and EUDC cycles.

The emission results of the **'Old-Timers' and Pre- Euro 1 vehicles** showed a very large variation. For the petrol vehicles generally the emissions were typically more than a factor 20 higher than new (Euro 3) vehicles. It was observed that in general the state of maintenance for cars of this age becomes the dominant parameter over the legislative category that determines the emission level.

The tests performed with the **Diesel Particulate Filter (DPF) equipped vehicle** showed the following results.
Due to the high sulphur content of the fuel that was used during the loading phase of the DPF, a high amount of sulphur was accumulated in the DPF. This was released during regeneration. As a result the PM measured values were much higher than what was expected from the Type Approval value for this vehicle. The results obtained are therefore regarded as a worst case scenario. Nevertheless, when calculating the weighted emission results according to Regulation 83, the vehicle still complies with the Euro 3, with PM being only 10% of the limit value.
The test procedure as prescribed by Regulation 83 was regarded as very time-consuming and costly. Three emission tests needed to be performed instead of one, and the loading phase of the DPF took up a lot of time, due to the required consecutive driving of operating cycles. For future vehicles it is foreseen that the number of operating cycles to load the DPF will increase because of the larger regeneration interval. Without the possibility for disabling regeneration, and without the co-operation of the vehicle manufacturer it is a very difficult procedure to execute. Cost and time consequences are huge in case of setback during the measurements.

The tests on three **direct injected petrol vehicles** to determine **their particle emission characteristics** showed the following results.
A wide variety in direct injected gasoline engine strategies exists. Basically there is heterogeneous, stratified (lean) combustion, and homogeneous lean or stoichiometric combustion. Heterogeneous combustion is often only applied at lower and moderate power demands. At higher power demands, the engine switches to homogeneous

combustion. Generally, during heterogeneous combustion, more particles were observed than during homogeneous combustion under moderate load conditions.

During high load situations, all technologies operate in the homogeneous mode, either stoichiometric or rich. In this case high particle counts were seen. This may be caused by the release of sulphur deposits on the catalyst surface, being released at high temperature.

The direct injected petrol engines emitted higher particle numbers than indirect injected petrol engines, but not as high as direct injected diesel engines. It was measured that on the NEDC, direct injected petrol engines emit approximately 10% of the particle number per km of direct injected diesel vehicles. Indirect injected petrol engines again emit approximately 10% of the particle number per km of direct injected petrol vehicles.

Contents

Appendices

1 Introduction

This report presents a general overview of the results of the Dutch In-Use Compliance programme for passenger cars over the year 2003. The work in this year was executed under a contract with the Dutch Ministry of Housing, Spatial Planning and the Environment for the period 2000-2003. The passenger car in-use compliance programme basically assesses car emission performance in use, against the corresponding emissions legislation.

The passenger car in-use compliance programme was started in 1986 in order to obtain objective relevant data on the environmental performance of the then sold first generation of "clean" vehicles. These vehicles received a tax incentive based on the expected environmental benefits, but these benefits still had to be proven in real-world use. This basic concept of vehicles proving their actual environmental performance in real-world use, is still utilised in the ongoing programme for the years 2000-2003, but with evolving vehicle technology and legislation over the years, the set-up of the in-use compliance programme has changed also. A major point that has gained importance over the years is real-world driving conditions during testing. In this respect the European Type Approval Procedure proves to be insufficiently representative for real-world driving. Therefore next to testing vehicles on the type approval procedure, additional tests are conducted to gain insight into the real-world emission behaviour of passenger cars. The data gained from testing have proved to be very useful for emission modelling purposes. Therefore gathering information on the real-world emission behaviour of passenger cars has become one of the basic targets of the Dutch in-use compliance programme.

The basic programme generally consists of testing about 50 different types of vehicles per year (tested basically in threefold per type). The selection of the vehicles to be tested is based on the actual sales (in the year before) of certain engine families. Generally relatively young cars are tested (usually below 35,000 kilometres in the so-called initial test) in order to check whether the cars that have actually been sold during the last years meet their emission limits "in use" also. Executing the in-use compliance programme in this set-up for many executive years now supplies a valuable database on the emission performance of the Dutch passenger car fleet. In addition to the "initial vehicles", vehicles with a higher age and mileage are tested to check whether the durability of exhaust aftertreatment systems meets the durability requirements.

In 2000 the Euro 3 emission legislation and limits entered into force. In the years 2001 and 2002 the in-use compliance programme therefore focused on gathering information on the emission performance of this generation of vehicles. In both years a large number of Euro 3 and Euro 4[2] vehicles was tested. Anticipating the 2005 introduction of the Euro 4 limits, the regular programme of 2003 focused on expanding the emission database.
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In the next chapters an overview is given of the results of each of the above-mentioned subject.

2 Petrol Passenger Vehicles

2.1 Initial tests

The vehicles tested in 2003 were predominantly Euro 3 vehicles. During 2001 and 2002, the Dutch government provided incentives for vehicles already conforming to the Euro 4 specifications. As these incentives have since been dropped, there is little stimulus to obtain this certification for the vehicles prior to the introduction of Euro 4. Therefore there appears to be a drop in the availability of this type of vehicle on the market.

The emission limit values in force for the petrol vehicles tested in the 2003 programme are shown in Table 2:

Table 2 Emission limits for type approval of petrol passenger vehicles

Emission component	Euro 3 limit value [g/km]	Euro 4 limit value [g/km]
CO	2,3	1,0
HC	0,20	0,10
NO_x	0,15	0,08

The exhaust emissions are measured using the standard Euro 3 test procedure with a cold start at 20°C. Since the –7°C test was not yet applicable to any of the vehicles tested, the tests executed represent the full type approval test set-up for exhaust emissions, with the exception of the use of market fuel rather than reference fuel.

Due to the increasing number of petrol direct injection (DI) vehicles on the market, 3 vehicles with this new technology were selected to investigate their emission behaviour. Further discussion on this subject is presented in Section 9. Of these three vehicles, however, only one remains on the market today; the other two were available in limited production runs only. Since petrol DI vehicles are expected to produce particulate emissions, these were also included in the test programme and are reported on in Section 9.

Table 3 shows the 7 vehicle types that were tested in 2003.

Table 3 Vehicle types tested in 2003 (petrol)

Vehicle make	Vehicle type	Euro 3	Euro 4	DI
Alfa Romeo	156 2.0 JTS		✓	✓
Chrysler	Neon 2.0l 16V	✓		
Citroën	C5 2.0 HPi	✓		✓
Ford	Ka 1.3l 44kW	✓		
Renault	Laguna 1.8 16V 89kW	✓		
Renault	Laguna 2.0 16V IDE	✓		✓
Skoda	Octavia 75kW		✓	

In Figure 1, the average emissions test results (for 3 vehicles tested per vehicle type) of each vehicle type are plotted in comparison with the Euro 3 and Euro 4 limits.

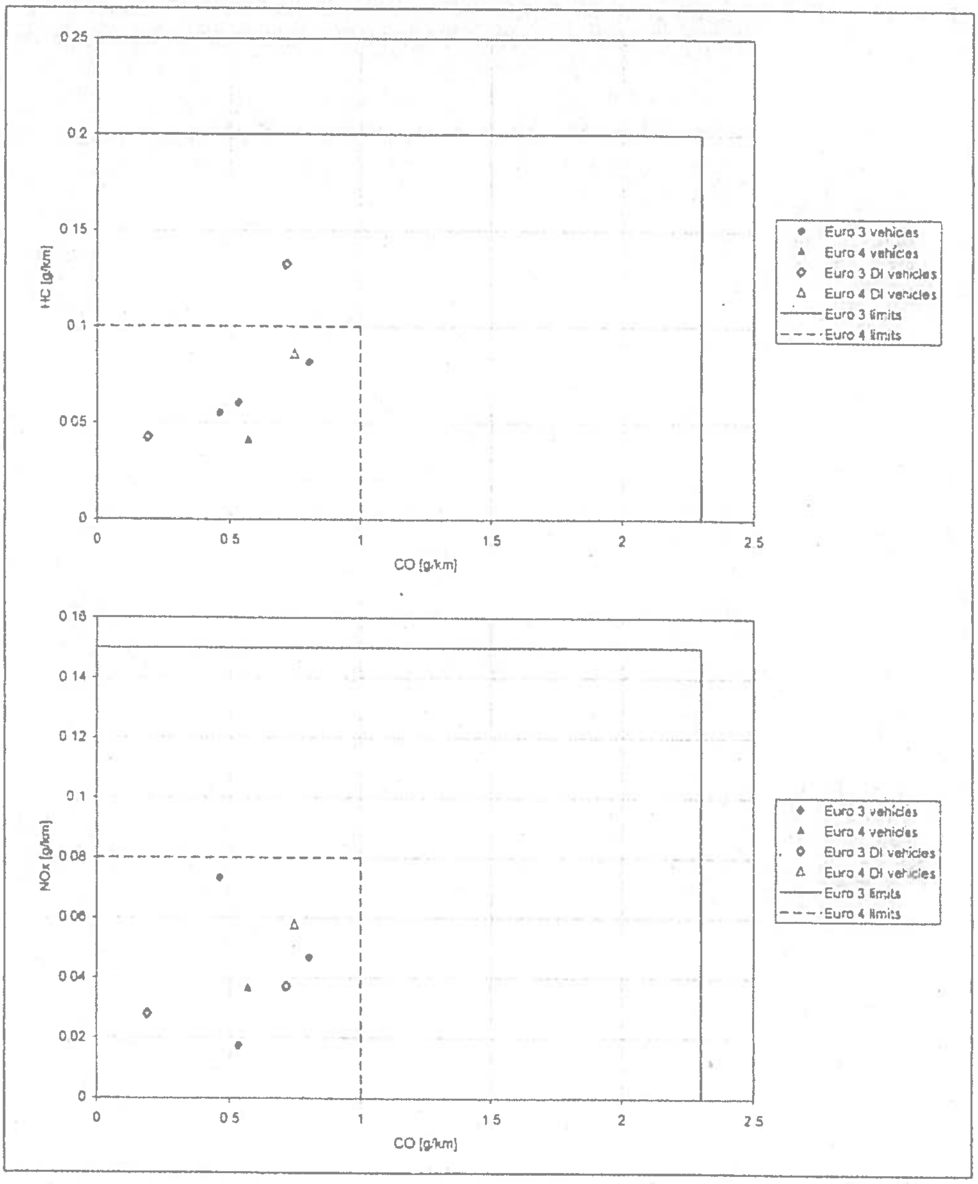

Figure 1 - Results of in-use petrol passenger vehicle types during the standard type approval test procedure (average per vehicle type).

As shown in Figure 1, all vehicle types conform to the Euro 3 limits for all emission components. Further, all vehicle types tested conformed to the Euro 4 limits with the exception of one Euro 3 DI vehicle for HC emissions. The Euro 4 DI vehicle is very close to the limits, especially given the typically large variance of emissions expected of petrol vehicles. Of note is the difference between the two Euro 3 DI vehicle types; one comfortably achieves Euro 4, the other exceeds Euro 4 due to HC emissions. The Euro 4 DI vehicle also shows high CO and HC emission levels. This is likely to be due to the fundamentally different approaches to emission control possible with DI. The main differences between the various petrol DI configurations are given in Section 9.

Several Euro 3 vehicle types produce emission levels equivalent to or better than other Euro 4 vehicle types. This may be due to either an excessively large variance in emission levels expected per vehicle type or may indicate that the vehicle type is Euro 4 capable but only Euro 3 certified. As Euro 4 is due to be enforced in 2005, this approach would reduce the engineering changes required due to the introduction of the stricter legislation. Individual vehicle results, shown in Figure 2, suggest both situations are present.

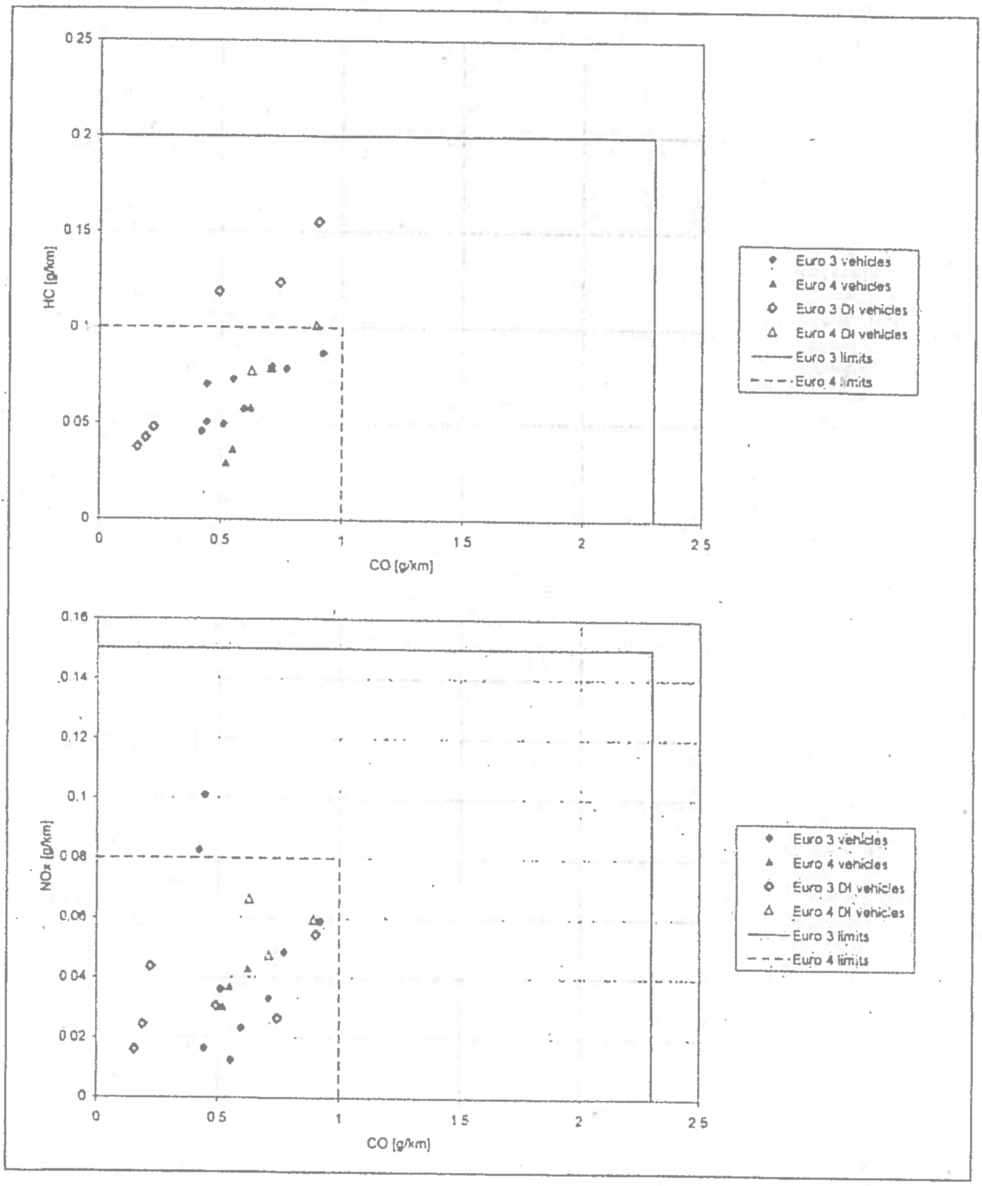

Figure 2 - Results of in-use petrol passenger vehicle types during the standard type approval test procedure (individual results).

When observing the individual vehicle results (Figure 2), the large level of scatter typical for petrol vehicles is apparent. The three Euro 3 vehicles of one type (with direct injection) was not able to achieve Euro 4 results due to high HC emission levels, while one Euro 3 type (with indirect injection) showed large scatter with NO$_x$ and therefore exceeded the Euro 4 limits. All other vehicles tested conformed to the Euro 4 limits. Noticeable is one Euro 4 DI vehicle that sits on the limit for Euro 4 HC emission. Per vehicle type, the spread in emission results per type is shown in Figures 3-5.

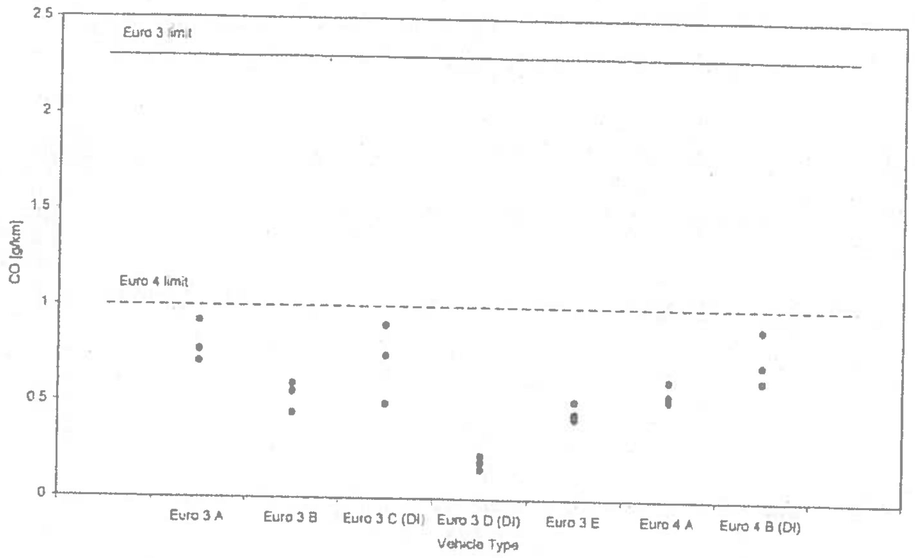

Figure 3 - CO-emission of individual petrol vehicles.

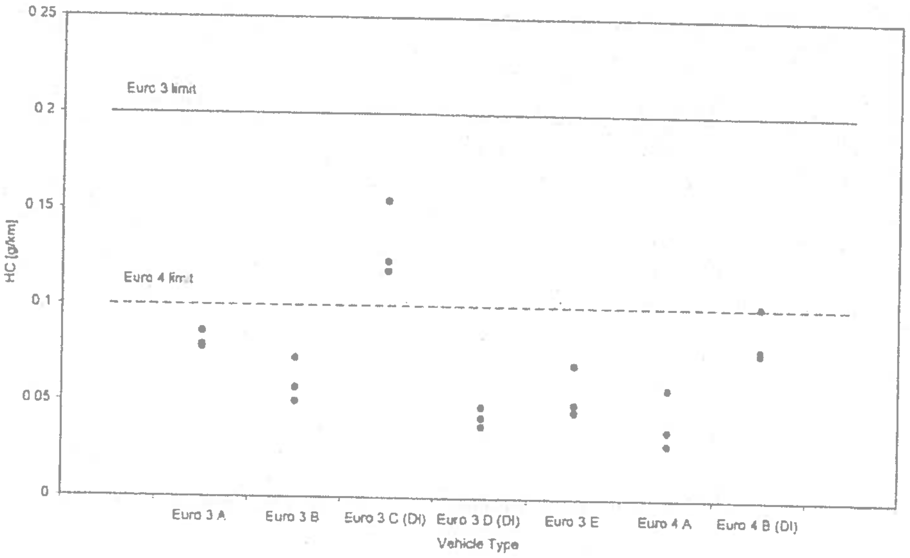

Figure 4 - HC-emission of individual petrol vehicles.

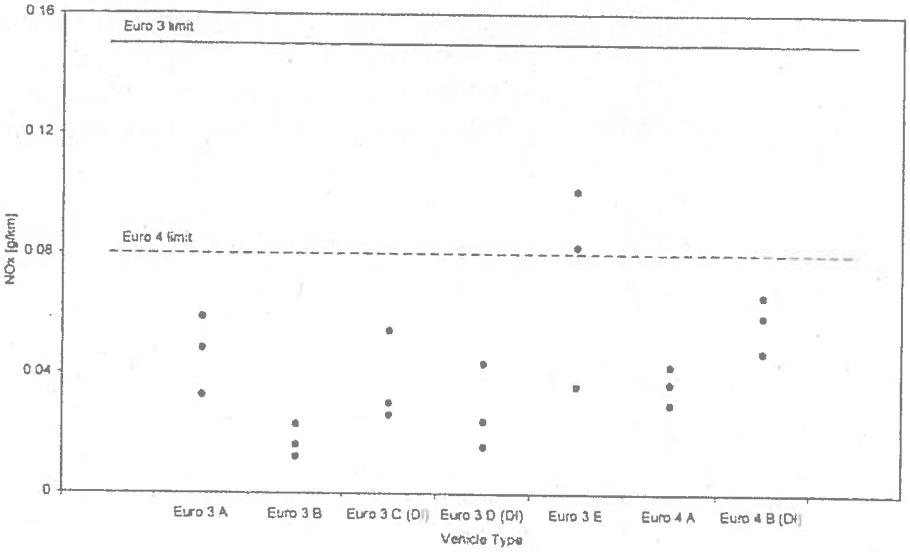

Figure 5 - NOx-emission of individual petrol vehicles.

It appears that, as observed in previous years, the CO and HC emissions show a relatively small spread for vehicles of the same type. The NO_x emissions show a much higher variation. The Euro 4 vehicles though seem to show less variation than Euro 3 vehicles, more in line with the CO and HC variation (when considered relative to the emissions limit). However, on such a small sample it is not possible to draw any conclusions on this point.

One Euro 4 vehicle (Euro 4 B) appears to have difficulty in achieving the Euro 4 requirement on an individual vehicle basis, which was not observable in previous years where most vehicles appeared to have a large safety margin.

The DI vehicles, with the exception of the vehicle type with very low emissions mentioned previously, show a higher level of HC emissions than for the multi-point vehicles. The CO emissions show this to a lesser extent. For the DI vehicles, the NO_x emissions are in line with that of the multi-point vehicles.

2.2 Cold start emissions

Apart from executing the standard Euro 3 test cycle with a 20°C cold start, one vehicle per vehicle type underwent an additional test to collect data on the effects of a cold start on emissions. For this purpose, the urban part of the Eurotest (the UDC) was driven twice:

1. With a cold start from 20°C, and
2. With a hot start (conditioned on a full UDC + EUDC).

The difference between the two values is the "cold start emission factor" in g/cold start or g/km after cold start. This value is important for emission modelling purposes. The differences in emissions between cold and hot start are mainly caused by the time it takes for the catalyst to reach light-off temperature from cold start. Cold start enrichment (and therefore non λ=1 operation) will most probably play no role of any importance, since at or above 20°C this fuelling method is not often utilised anymore in modern multi-point injected engines. For DI engines, however, various techniques are possible to speed catalyst warm-up, e.g. by using stratified charge with ignition retard. In Figures 6-9, the results for petrol engines are presented per emission component.

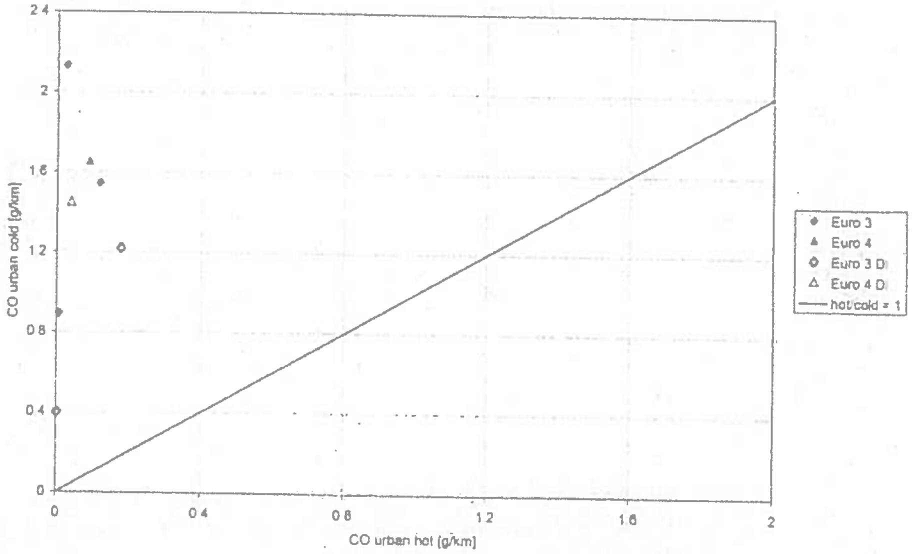

Figure 6 - UDC cold start emissions versus UDC hot start emissions for petrol vehicles: CO

As can be concluded from Figure 6, the CO emissions after hot start are mostly close to zero, whereas the cold start emissions are higher and vary considerably from 0.4 g/km to 2.1 g/km. Apparently the 'hot' and 'cold' emissions have no direct relation to each other and differ considerably from car type to car type. Euro 3 and Euro 4 vehicle types are intermixed, with the Euro 4 vehicles actually performing worse than many Euro 3 vehicles by a cold start. Compared with previous years, a clear separation of Euro 3 and 4 vehicles is not evident. For modelling purposes the average "extra cold start emission" is calculated as one single figure per vehicle class.

Although Euro 4 approval also involves meeting the –7°C test, it appears that this has not influenced the difference between vehicle emissions from a 20°C cold start and that of a warm start. A possible reason for this is that any reduction of catalyst light-off time through application of catalysts with lower heat capacity can be traded off by reducing exhaust gas temperature, leading to increased engine thermal efficiency. As most Euro 3 vehicles complied with Euro 4 limits, further reduction of light-off times is not necessary and the existing air-fuel ratio control seems sufficient for 20°C cold starts. The extra –7°C requirement has therefore likely lead to extension of the light-off control to cover the temperature range of –7°C to 20°C, with the main concern being HC emissions during cold start (Figure 7). The basic structure of the aftertreatment system is not significantly different for stoichiometric engines for Euro 3 and Euro 4.

In general, the DI vehicles have lower CO on a cold start.

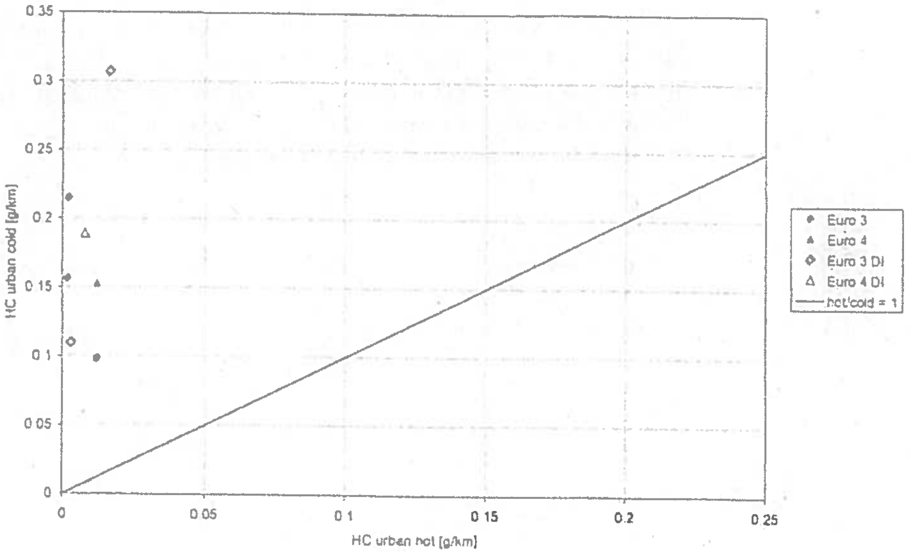

Figure 7 - UDC cold start emissions versus UDC hot start emissions for petrol vehicles: HC

The HC emissions present a similar result. The warm start emissions are very low, while the cold start emissions are considerably higher and widely spread, ranging from 0.1 to 0.31 g/km. As for CO, the Euro 3 and 4 vehicles are intermixed.

The DI vehicles are similar to multi-point vehicles for cold start HC, although one DI vehicle has a higher emission level.

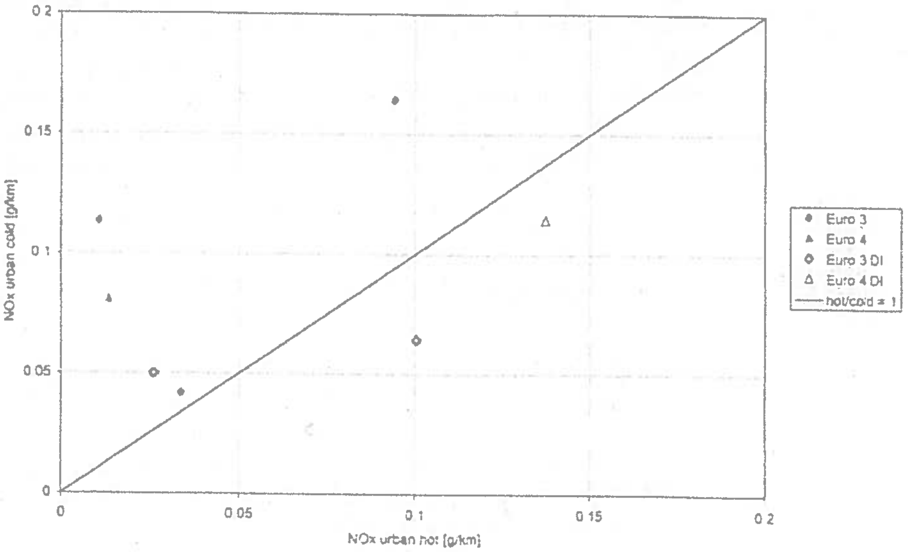

Figure 8 - UDC cold start emissions versus UDC hot start emissions for petrol vehicles: NO_x

The NO_x behaviour shows less dependency of this emissions component on the cold start. Note that the values are relatively low, due to the low loads and engine temperatures on the UDC. For two vehicles, the cold start resulted in lower NO_x emissions than the warm start. These are both DI vehicles. It is evident that catalyst light-off has a lower effect on the NO_x emissions than for HC and CO. Once again, the Euro 3 and 4 vehicles are not clearly distinguishable. DI vehicles can have a better NO_x behaviour on a cold start than on a warm start.

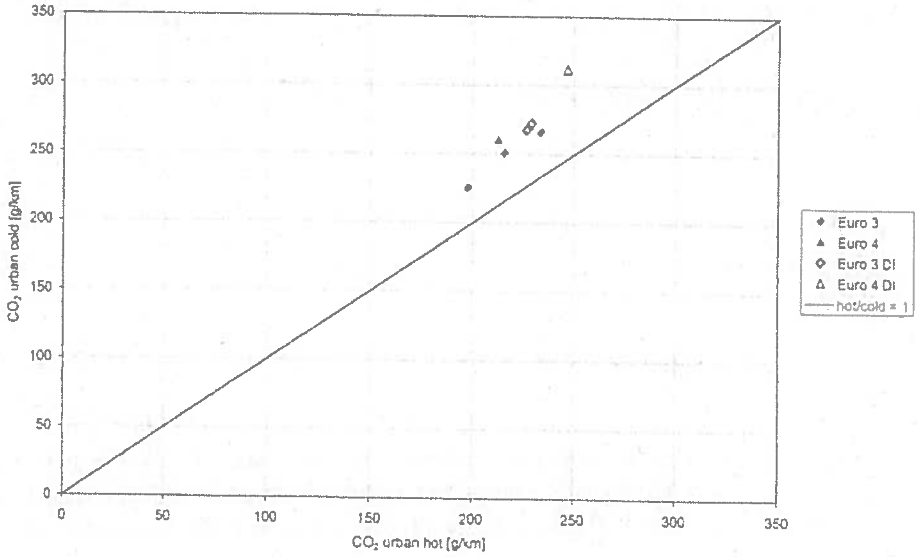

Figure 9 - UDC cold start emissions versus UDC hot start emissions for petrol vehicles: CO_2

The CO_2 emissions increase due to cold start shows a stable pattern. There appears to be a small difference in the cold start penalty for Euro 3 and Euro 4 vehicles, 16% for Euro 3 and 25% for the Euro 4 vehicles, although this is based on a small sample size and may not be statistically significant. The average across all vehicles is 19%. This effect points at increased friction at a 20°C start, increased thermal losses and probably some minor cold start enrichment effects. The DI vehicles performed similar to multi-point vehicles.

2.3 Summary of results for petrol vehicles

From the previous section it can be concluded that new petrol vehicles have very low emissions levels. Most of the vehicles tested (both Euro 3 and 4) complied with the Euro 4 limits. The Euro 4 vehicles did not show a significantly different emissions characteristic compared with the Euro 3 vehicles. It appears that a significant proportion of the emissions is produced during the cold start. The initial impression is that the −7°C test has had little effect on emissions from a 20°C cold start.

DI vehicles appear to have a higher HC and CO emission level, although this is not true for all vehicles. The NO_x emissions on a cold start can be lower for these vehicles than for a warm start. The vehicle with the lowest emissions was a DI vehicle, while those with the highest level were also DI (with the exception of one multi-point vehicle for CO).

3 Diesel Passenger Vehicles

3.1 Initial tests

Only Euro 3 diesel vehicles were tested in 2003. The selection consisted of 2 types. In some foreign markets grants are given to vehicle types that already meet the 2005 Euro 4 limits. However, since diesel technology has proven more difficult to adapt to Euro 3 requirements, there were no suitable vehicles available in this category and hence this category was not tested in 2003.

The emission limit values in force for diesel Euro 3 vehicles are shown in Table 4.

Table 4 Emission limits for type approval of diesel passenger vehicles

Emission	Euro 3 limit value [g/km]
CO	0,64
NO_x	0,50
$HC + NO_x$	0,56
PM	0,05

The exhaust emissions are measured using the standard Euro 3 test procedure. The vehicle selection 2003 was based on the best selling vehicles which had not been tested in the years 2001 / 2002. The 2 vehicle types tested in 2003 are shown in Table 5.

Table 5 Vehicle types tested in 2003 (diesel)

Vehicle make	Vehicle type	Features
Ford	Mondeo 2.0D 85kW	Common rail fuelling
Peugeot	307 SW 2.0 HDi 80kW	Common rail fuelling, particulate filter

In Figures 10-11, the average results for each vehicle type (taken over 3 vehicles) are plotted in relation to the Euro 3 limits.

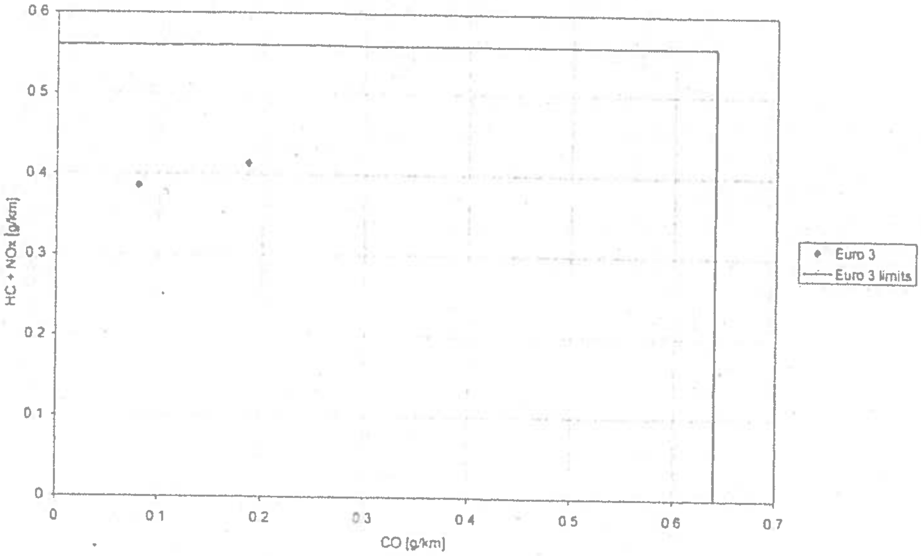

Figure 10 - Results of in-use diesel passenger car types during the standard type approval test procedure, CO and HC+NOx (average per vehicle type).

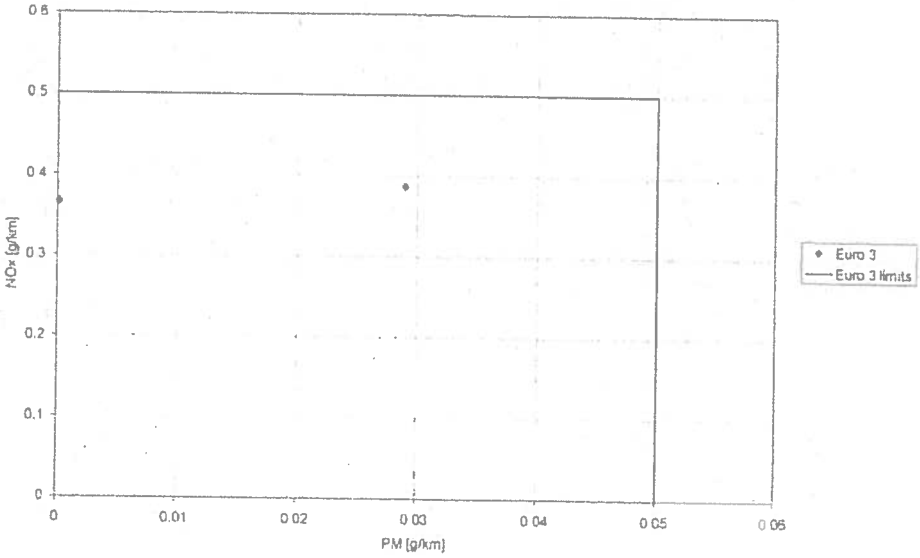

Figure 11 - Results of in-use diesel passenger car types during the standard type approval test procedure, PM and NOx (average per vehicle type).

The NO_x and $HC+NO_x$ emissions are relatively close to the limit value, but they do not exceed in any case. The CO and PM limits are met comfortably. Noteworthy is the very low PM value for one vehicle type; this vehicle was fitted with a particle filter. The measurements were made prior to filter regeneration. During regeneration the PM emissions are expected to be higher. For this reason, a vehicle was also tested during regeneration. An account of these tests is given in Section 8.

The test results for individual vehicles are shown in Figures 12 and 13.

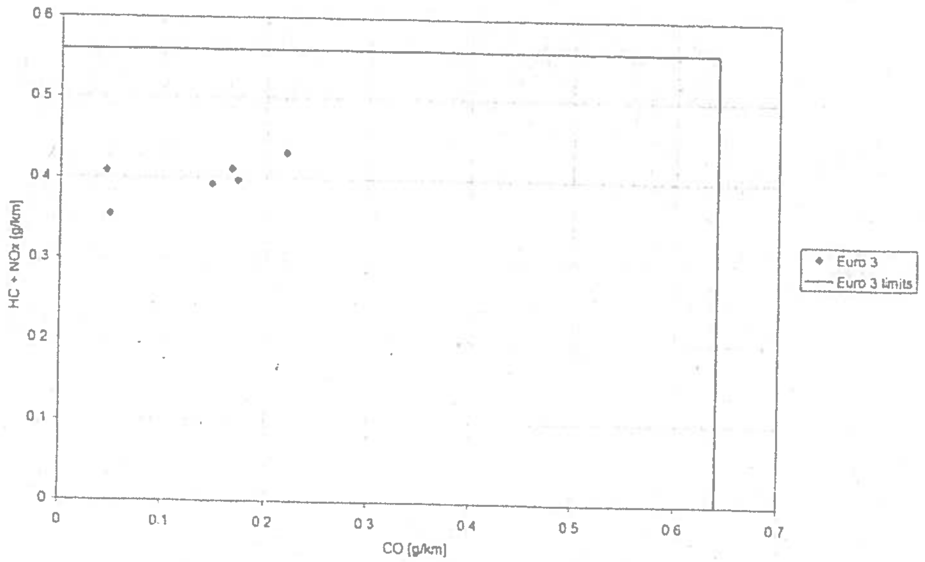

Figure 12 - Results of in-use diesel passenger car types during the standard type approval test procedure, CO and HC+NOx (individual results)

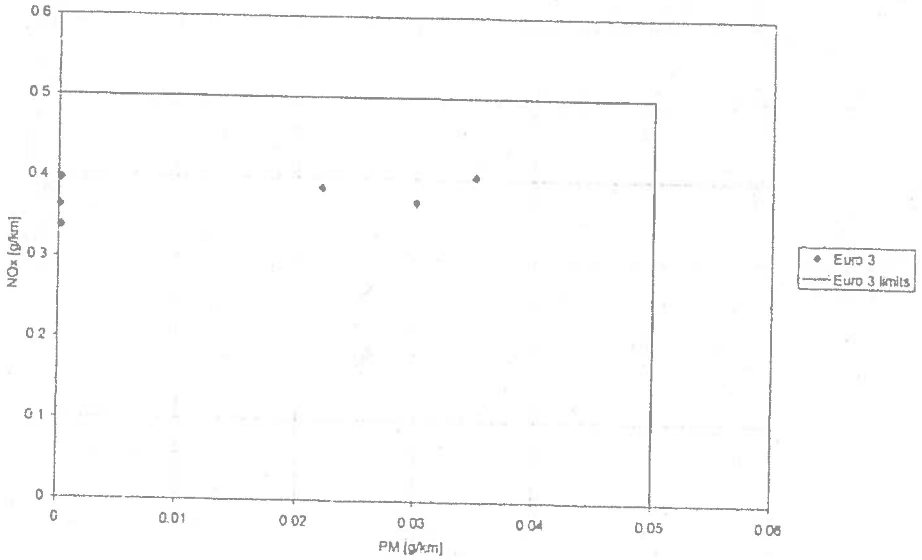

Figure 13 - Results of in-use diesel passenger car types during the standard type approval test procedure, PM and NOx (individual results)

The individual vehicle results confirm the impression of the average per vehicle type results, with all vehicles conforming to the Euro 3 limits.

The detailed analyses of the emission performance of vehicles from the same type (Figures 14,15,16 and 17) show that the variation between vehicles appears lower than for petrol vehicles, with NO_x being the closest to the limit value. PM shows the most scatter per vehicle type when a PM filter is not applied. The vehicle fitted with a PM filter shows significantly lower absolute variance in the PM emissions between vehicles compared with that of a vehicle without.

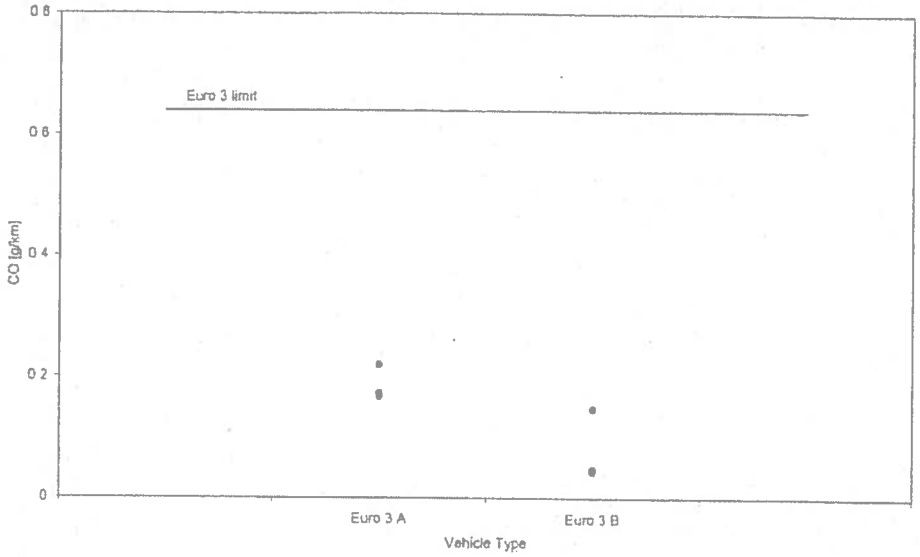

Figure 14 - CO-emission of individual diesel vehicles

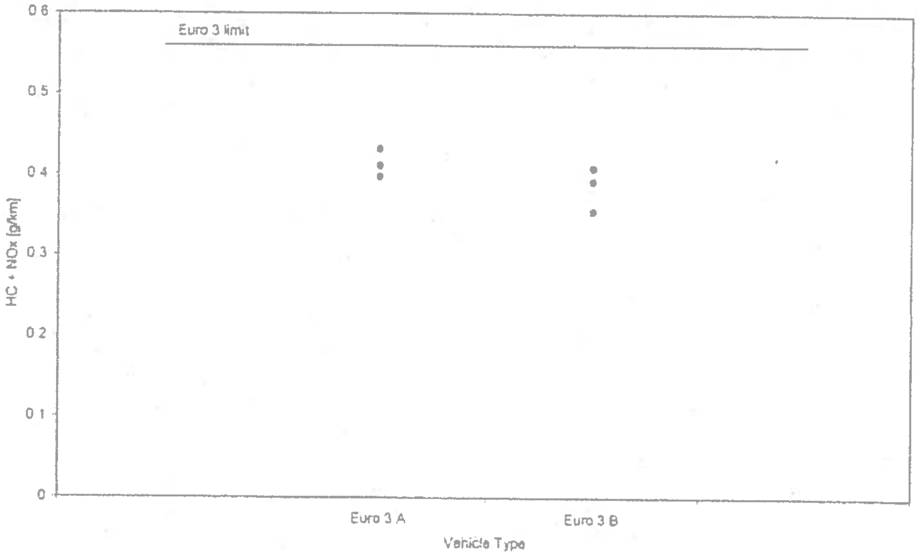

Figure 15 - HC-emission of individual diesel vehicles

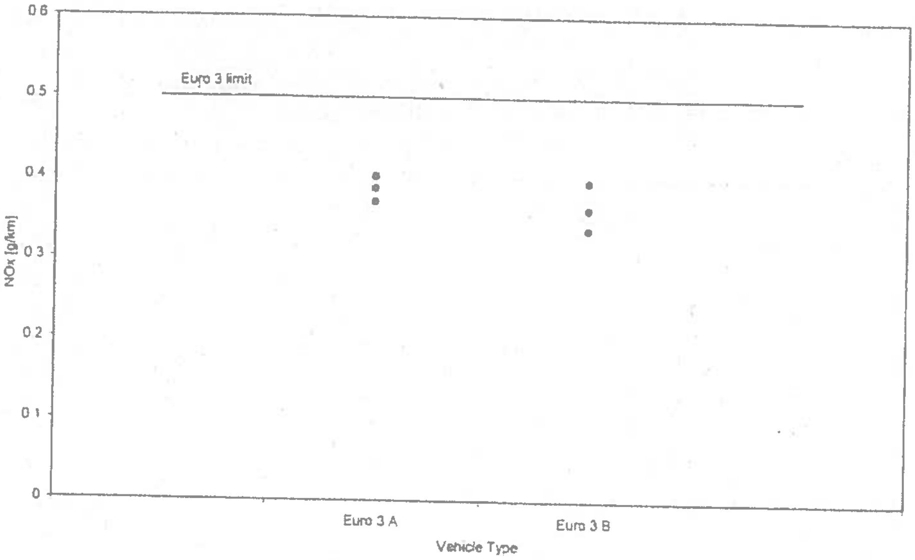

Figure 16 - NO_x-emission of individual diesel vehicles

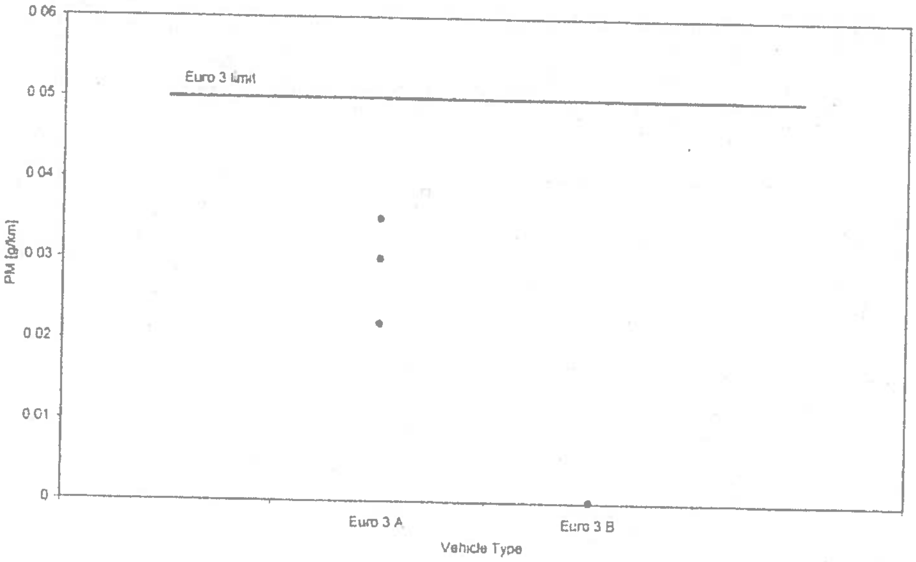

Figure 17 - PM-emission of individual diesel vehicles

3.2 Cold start emissions

For the same reason as for petrol cars, the additional emissions due to a 20°C cold start were measured. The results are shown in Figures 18, 19, 20, 21 and 22.

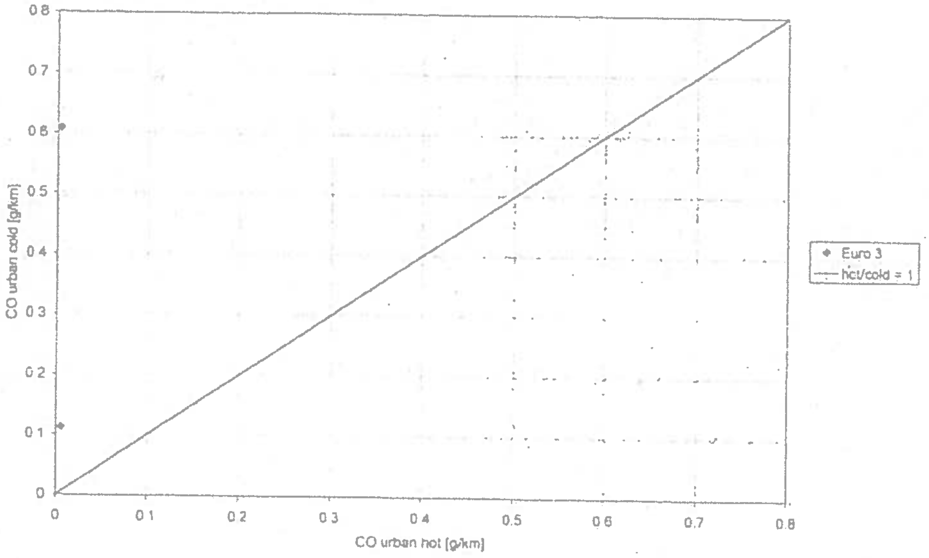

Figure 18 - UDC cold start emissions versus UDC hot start emissions for diesel vehicles: CO.

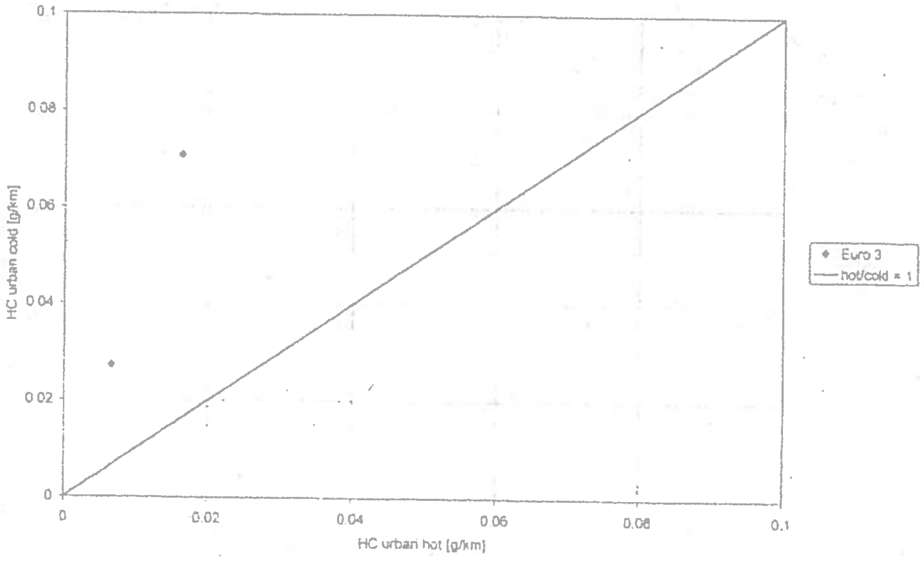

Figure 19 - UDC cold start emissions versus UDC hot start emissions for diesel vehicles: HC.

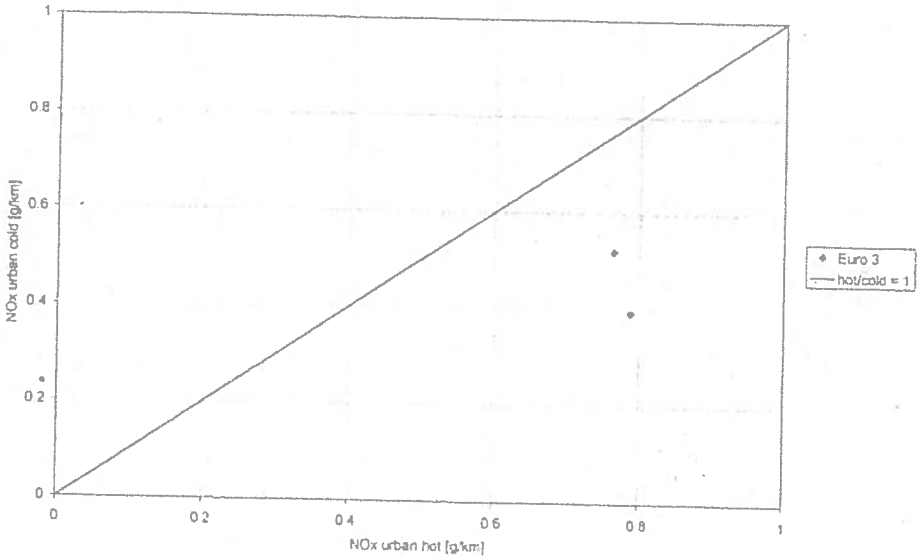

Figure 20 - UDC cold start emissions versus UDC hot start emissions for diesel vehicles: NO$_x$

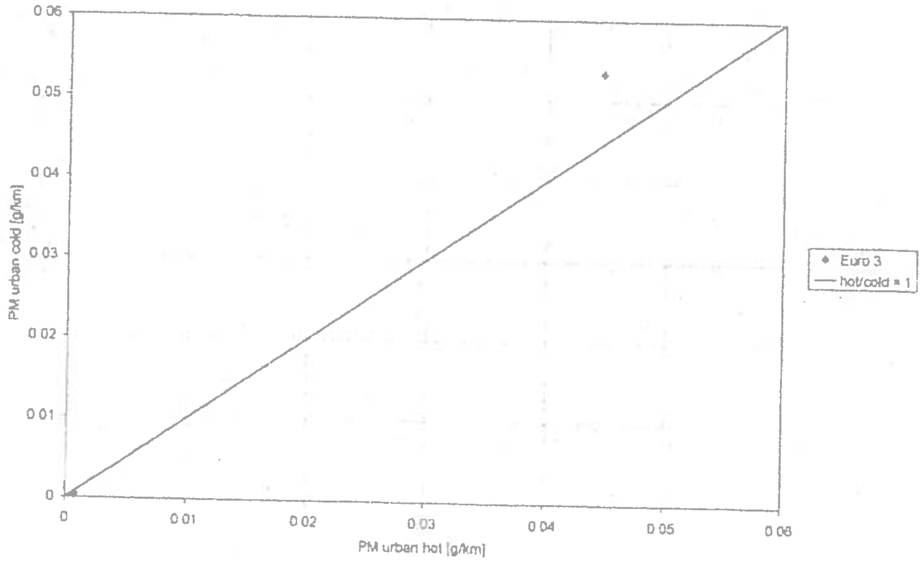

Figure 21 - UDC cold start emissions versus UDC hot start emissions for diesel vehicles: PM.

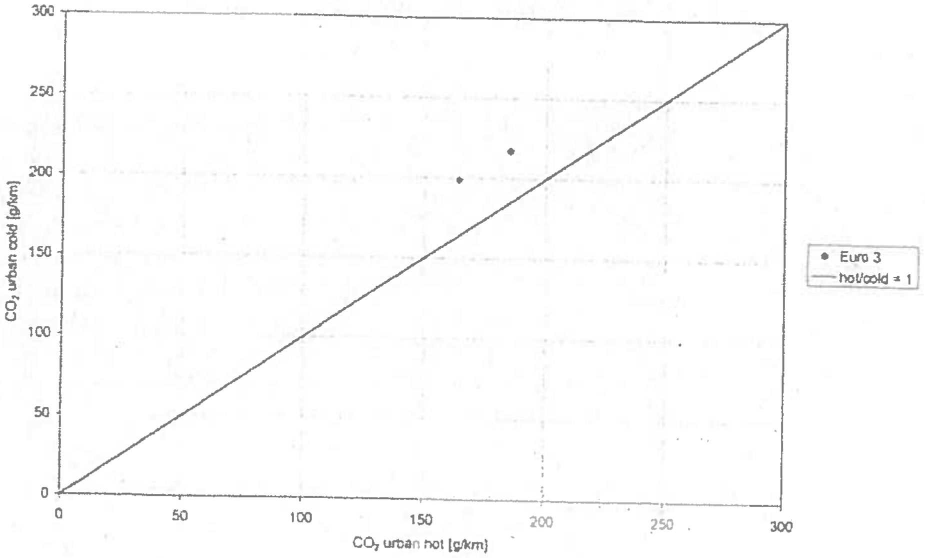

Figure 22 - UDC cold start emissions versus UDC hot start emissions for diesel vehicles: CO_2

From the cold start graphs it can be concluded that the HC and CO emissions of diesel cars when hot are always very low, but the cold emissions vary a lot. The cause for this is (in analogy with petrol vehicles) the period until light-off of the catalyst (in this case an oxidation type), during which products of incomplete combustion are not oxidised in the catalyst before being emitted. After light-off of the catalyst emissions drop to almost zero. For PM there appears to be almost no cold start increase of emissions which indicates that the combustion properties of modern diesel engines appear to be optimal directly after cold start. This can not be firmly substantiated as only two vehicle types were measured, but agrees with results from 2002.

NO_x emissions show a reduction by cold start. This is due to the lack of thermal aftertreatment system for NO_x in the tested vehicles that could be subject to heating up effects. The lower value is likely due to the lower intake air temperature during engine warmup. Future technology (NO_x-storage systems) will most probably be more affected by cold start, similar to the results affected by the oxidation catalyst heating.

The CO_2 emissions resulting from the cold start show consistent results. Both vehicles show an increase of 19%, likely caused by increased friction and heat losses directly after cold start. Fuel enrichment is no issue for diesel engines.

3.3 Summary of results for diesel vehicles

The Euro 3 diesel vehicle emissions proved to be within the limits. NO_x emissions are close to the allowable level, while other emissions components achieve the required levels comfortably. There were, however, insufficient vehicles tested to draw general conclusions, although the trends seen in recent years seem to continue. One vehicle tested was fitted with a PM filter; this vehicle had significantly lower PM emissions than the vehicle without. A discussion on more detailed tests with this vehicle can be found in Section 8.

4 Real-World Emissions

An important objective of the Dutch in-use compliance programme is to gather information on the real-world emission behaviour of vehicles on the road. With changing situations on the roads, and vehicle technology being able to adapt to these changed situations, the data gathered using the European type approval procedure is more and more losing its value as representative emission data. These data were not really meant to be used for this purpose, but have been used as (a basis for) emission factors for a long time, since little else was available and originally they could be used for this purpose without much error. The increasing discrepancy between type approval testing and real-world emissions has been acknowledged by TNO and other European research institutes, leading to a demand for real-world test procedures (starting with real-world test cycles). These test cycles have their origin in a large amount of real-world recorded trip data, which have been "compressed" to short test cycles to be driven on a chassis dynamometer.

For the purpose of deriving real-world emission factors for the Dutch national situation, in fact two things are needed: 1) Dutch real-world driving cycles, and 2) data of a representative Dutch vehicle sample. The second issue is easy to solve within the Dutch in-use compliance programme, since one of the main ideas behind the programme is exactly to test a sample that is representative for the Dutch fleet. The first issue is more difficult to address, since there is not yet a national full set of representative real-world driving patterns, although TNO Automotive is currently developing these cycles. It is expected that these cycles will be finished early 2005 so that they can be added to the 2005 programme.

The only option at this moment close to a national set, is a set of 11 different driving patterns that have been recorded on Dutch motorways in 1999 (Emissions and Congestion project) [1], [2], [3] and [4]. For the urban and rural part of real-world driving the Common Artemis Driving Cycles (CADC) are used. The CADC cycles have been developed in the European 5th Framework project Artemis in which all prominent European institutes participate. As a result, these cycles are considered representative for the average European real-world driving.

In summary, it was decided to use the following cycles for determining the real-world emissions of the Dutch car fleet:

1. the 'Emissions and Congestion' test cycles (11 different levels of highway traffic flow)
2. the Common Artemis Driving Cycles (CADC), for urban, rural and highway conditions

In practice this meant that from every vehicle type selected one vehicle was additionally tested on set 1, and another one was additionally tested on set 2. The results from using both sets of test cycles will be further discussed in the following section.

4.1 Emissions and congestion

On behalf of the Transport Research Centre of the Dutch Ministry of Transport and the Dutch Ministry of Housing, Spatial planning and the Environment, TNO executed a research programme in order to determine the effects of traffic congestion on exhaust gas emissions and fuel consumption of road vehicles on motorways. The need for information on this topic occurred when policy makers wanted to know what the benefits for emissions could be of decreasing traffic congestion by using traffic management measures. As a result an extensive research programme was executed in 1999 and 2000, that is described in the respective reports [1], [2], [3] and [4]. Important milestones in this project were the development of test cycles that represent Dutch motorway traffic and an extensive measurement campaign in which 19 vehicles were tested in the TNO laboratory on these test cycles. Table 6 shows the congestion categorisation used in the project.

Table 6 Congestion categorisation as used in the emissions and congestion study

Congestion category	Definition
1aa	Speed <10 km/h; 'stop and go'
1ab	Speed between 10 and 25 km/h
1a	1aa and 1ab combined, speed between 0 en 25 km/h
1b	Speed between 25 and 40 km/h
1c	Speed between 40 and 75 km/h
2a	Speed 75-120 km/h, traffic volume over 1000 vehicles per lane per hour, speed limit = 100 km/h
2b	Speed 75-120 km/h, traffic volume over 1000 vehicles per lane per hour speed limit = 120 km/h
2c	Speed 75-120 km/h, traffic volume below 1000 vehicles per lane per hour, speed limit = 100 km/h
2d	Speed 75-120 km/h, traffic volume below 1000 vehicles per lane per hour, speed limit = 120 km/h
2e	Speed over 120 km/h, independent of traffic volume
3	Traffic jam 'avoidance' route

When the emission results were weighted for the share of different vehicle types in the Dutch vehicle fleet of 1998, the following average 'bathtub-shaped' emission correction curves were constructed for the national Dutch vehicle fleet. Driving pattern 2C is set at 100% (see Figure 23).

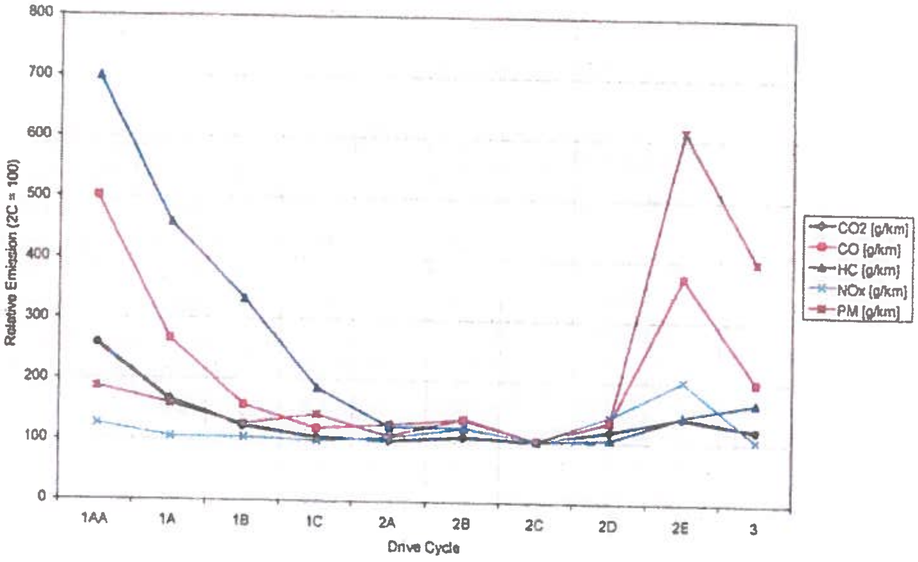

Figure 23 - Relative emission profile total Dutch fleet in 1998 (2C=100), including petrol, diesel and LPG vehicles.

The vehicle selection used in the study mentioned only consisted of cars up to Euro 2 and includes petrol, diesel and LPG vehicles. In order to gain more insight into the actual situation on the road and to make the predictions for the future more accurate, Euro 3 and Euro 4 vehicles from the selection in 2001, 2002 and 2003 have been tested on these real-world motorway test cycles in order to update these curves. Figures 24-26 show the overall relative results for the 2001–2003 vehicle selection for indirect injection petrol (average of 32 vehicles), DI-petrol (average of 2 vehicles) and diesel (average of 12 vehicles), respectively. Due to the limited number of DI-petrol vehicles tested, the DI-petrol results are not expected to be statistically significant.

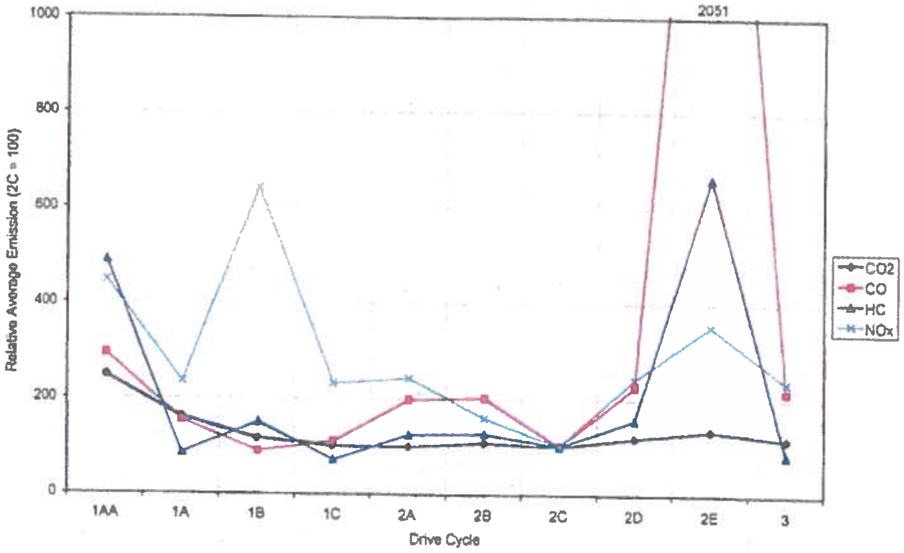

Figure 24 -Average emissions for Euro 3 and 4 petrol vehicles with indirect injection on the Emissions and Congestion driving cycles, relative emissions on the 2C cycle.

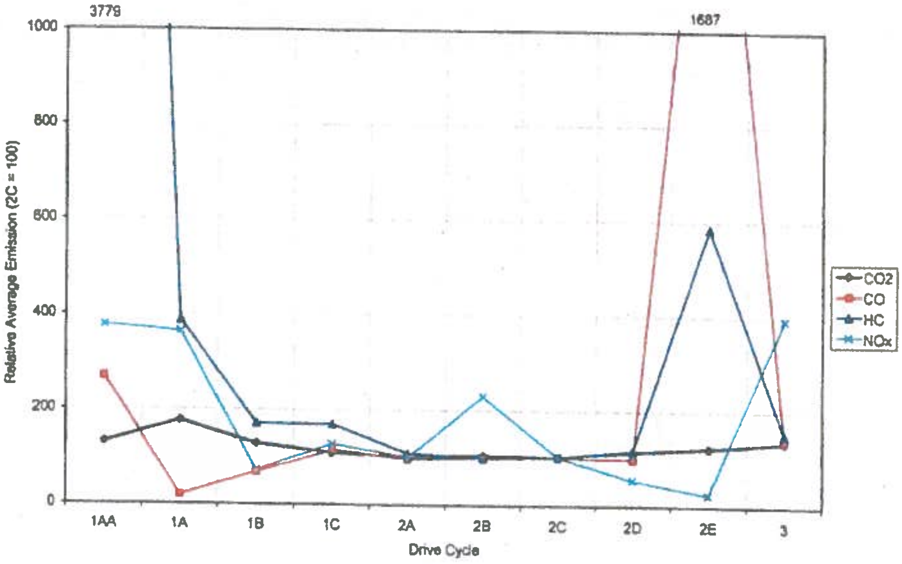

Figure 25 -Average emissions for Euro 3 and 4 petrol vehicles with direct injection on the Emissions and Congestion driving cycles, relative emissions on the 2C cycle.

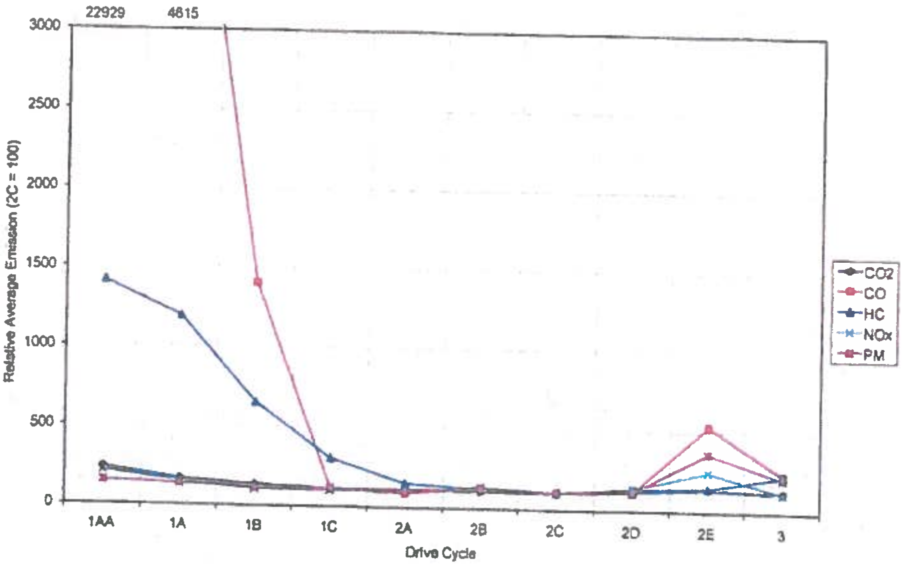

Figure 26 - Average emissions for Euro 3 diesel vehicles on the Emissions and Congestion driving cycles, relative emissions on the 2C cycle.

Based on the results for Euro 3 and 4 vehicles, the total Dutch fleet emission profile has been updated (Figure 27). The emission levels for the various vehicle types have been weighted for their share of the 2004 fleet.

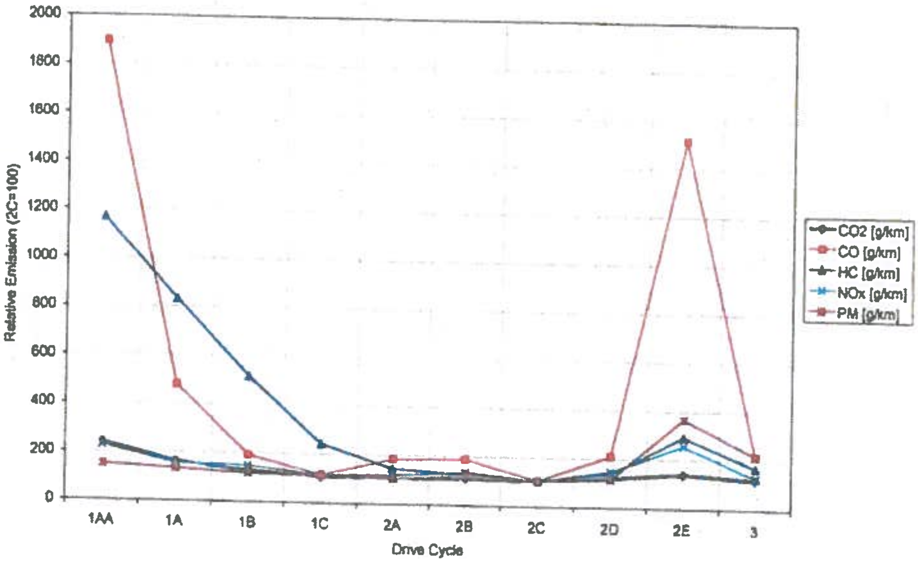

Figure 27 Relative emission profile total Dutch fleet in 2004 (2C=100), including petrol, diesel and LPG vehicles

The relative values show an appreciable change with respect to the previous results (Figure 23). This is especially true for the dramatic relative increase in CO and HC for the low speed cycles, and CO on the 2E (high speed) cycle.

The absolute values, however, are all reduced, some significantly (Figure 28). As certain emission components are reduced by a much lower factor on given drive cycles (especially CO), the emission level relative to the 2C cycle has increased. It can therefore be concluded that with the introduction of Euro 3 and 4, fleet emission levels are reduced under all conditions, but that this reduction is not the same under all driving conditions. The lowest reduction is seen by stop-and-go and high speed driving for CO and NO_x emissions.

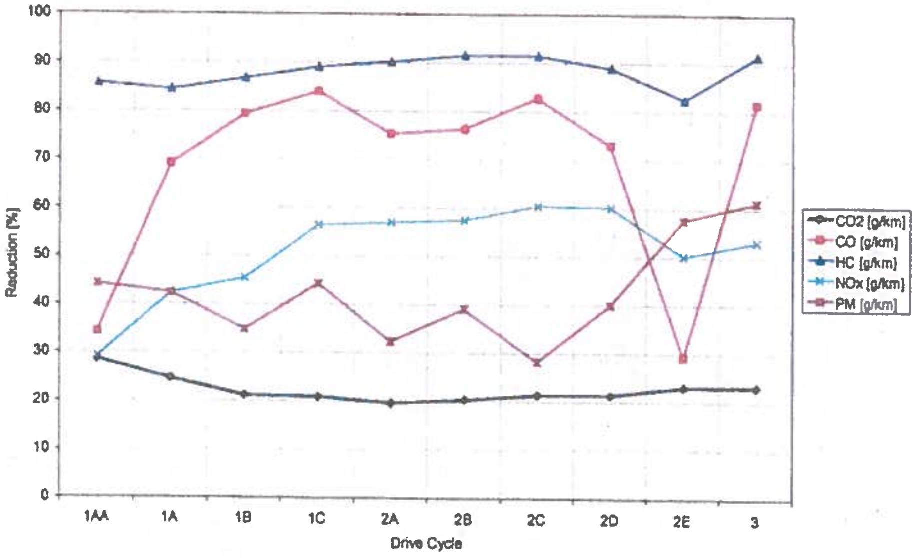

Figure 28 Percentage reduction of the 2004 fleet absolute emission levels compared with the 1998 fleet.

DI petrol vehicles have been tested for the first time. Compared to multi-point vehicles, the HC emission is much higher on the 1AA and 1A cycles, while the NO_x is lower for the 2D and 2E cycles.

More detailed results can be found in Appendix A.

4.2 Common Artemis Driving Cycles

The Common Artemis Driving Cycles (CADC) are used for producing information on the real-world emission behaviour of cars in comparison to the Type Approval (TA) testing. The CADC consists of an urban part, an extra-urban part and a highway part.

Comparing the data from the CADC-cycles with the TA test data gives relevant information on the transient behaviour of vehicle emissions outside the TA test window. This information is essential for emission modelling purposes.

Figure 29 shows the test results of the indirect injected petrol vehicle types from the 2002–2003 vehicle selection combined, compared with the urban (hot) part and extra-urban part of the standard TA test. The bars on the chart indicate the 1-σ limit of the emissions produced assuming normally distributed values, based on the 11 vehicles tested.

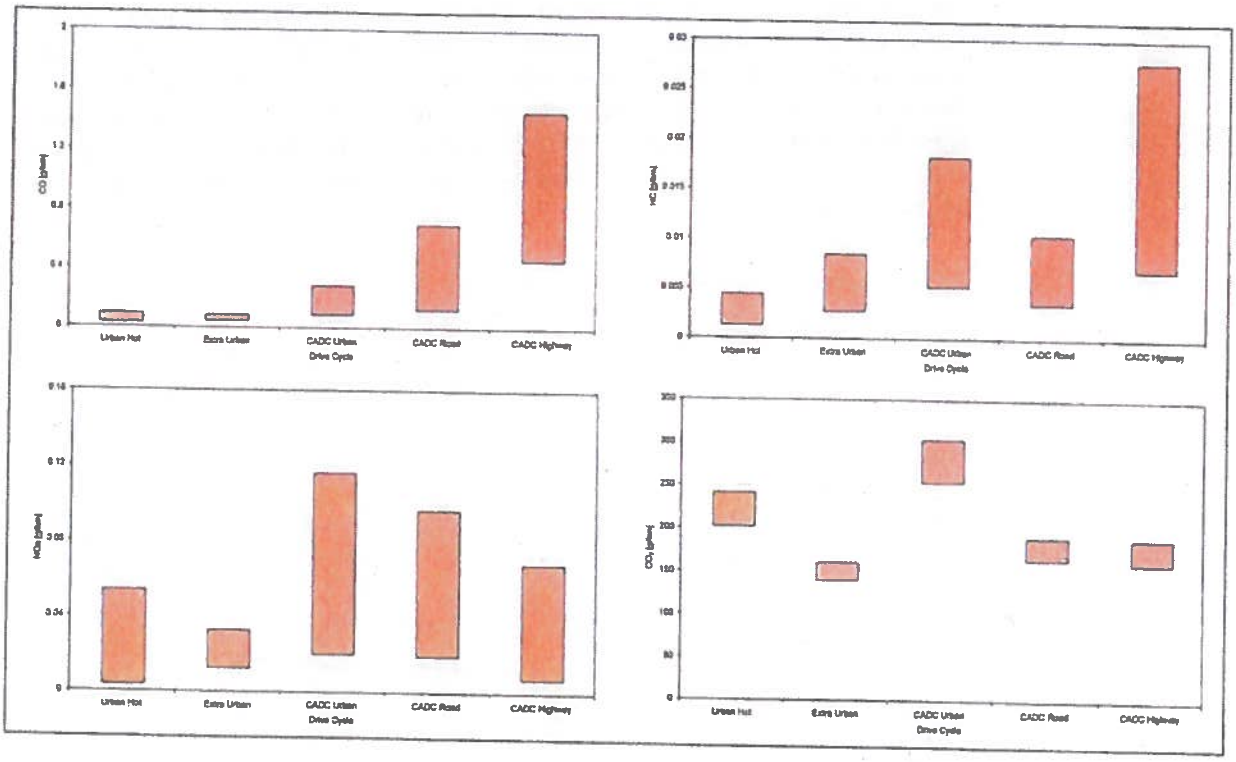

Figure 29 - 1-σ emission limits from the CADC cycles compared to the 'urban hot' and 'extra urban' ECE cycles for petrol vehicles with indirect injection.

Figure 30 shows the results for the petrol DI vehicles tested in 2003. Note that also the particulate emissions of these vehicles have been measured. The bars on the chart indicate the 1-σ limit of the emissions produced assuming normally distributed values, based on the 3 vehicles tested.

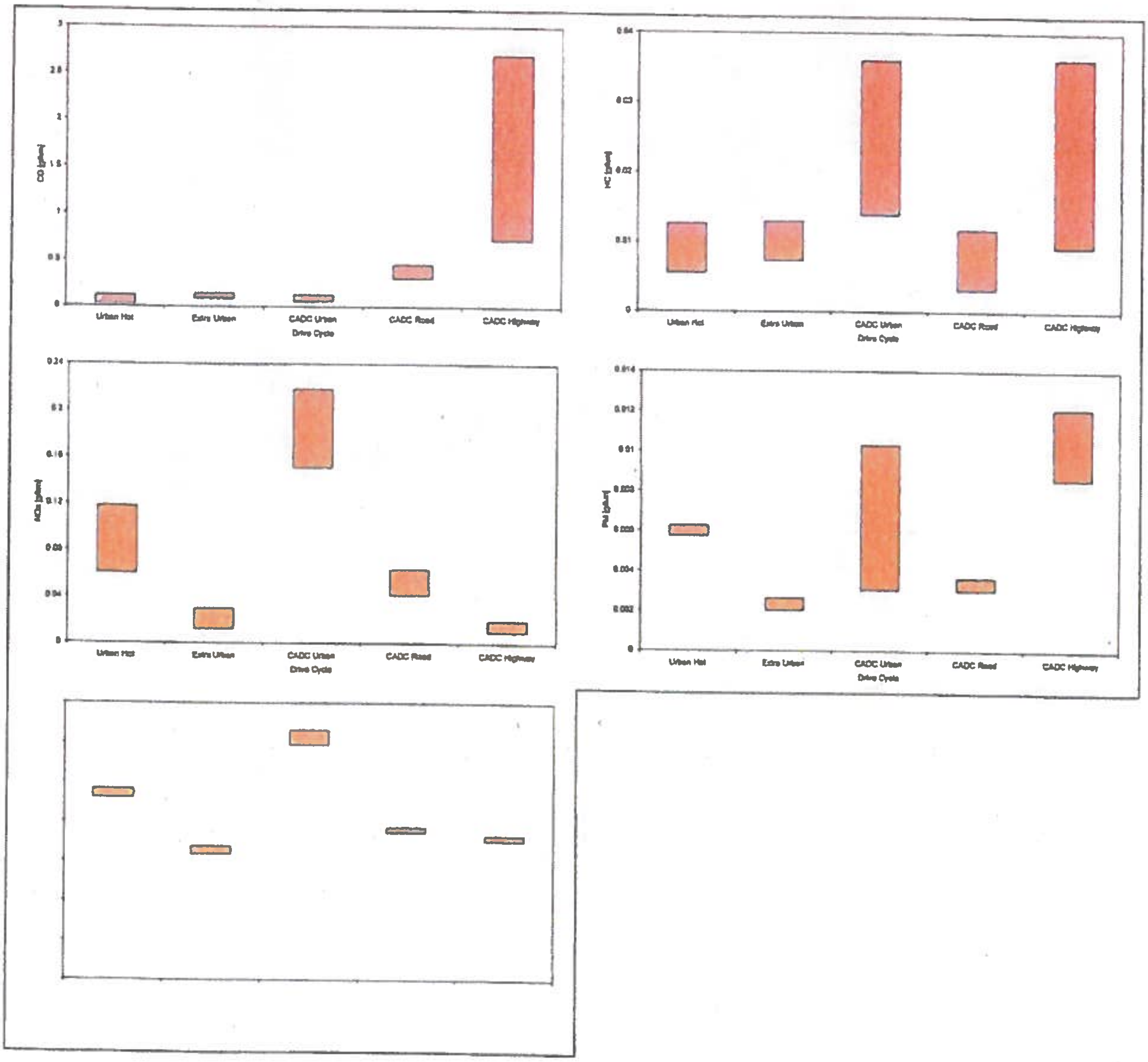

Figure 30 - 1-σ emission limits from the CADC cycles compared to the 'urban hot' and 'extra urban' ECE cycles for petrol DI vehicles.

Figure 31 shows the results for the diesel vehicles tested in 2002–2003. The bars on the chart indicate the 1-σ limit of the emissions produced assuming normally distributed values, based on the 6 vehicles tested.

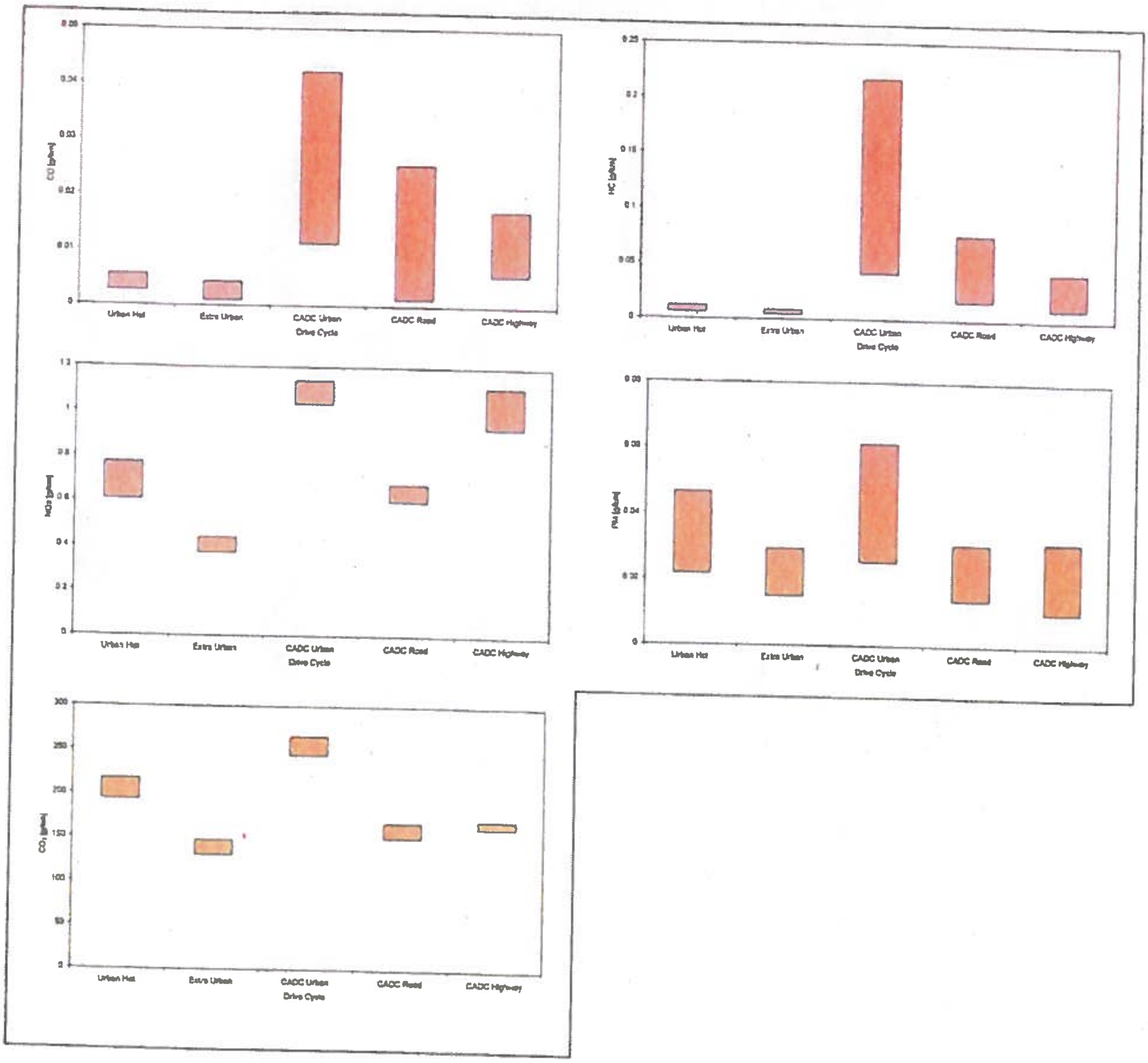

Figure 31 – 1-σ emission limits from the CADC cycles compared to the 'urban hot' and 'extra urban' ECE cycles for diesel vehicles

Similar to previous comparisons, the above shows that for all vehicle types, including DI petrol, the type approval test procedure seems to be no longer representative for real-world driving. The differences in emissions between real-world driving and the TA procedure are considerable and not constant.

The DI petrol vehicles show higher NO_x emissions on the urban hot and CADC urban cycles (due to lean operation at low engine speeds), but a reduction on the CADC highway cycle. For the CADC urban, the HC emissions of the DI petrol vehicles are higher, along with the CO on the CADC highway. This type of vehicle has measurable PM emissions which show a similar trend to that for diesel vehicles (with the exception of the CADC highway), although the absolute levels are a factor 2 to 5 lower. Further discussions on this topic are presented in Section 9. Care should be taken with drawing firm conclusions for the DI-petrol vehicles, as there was only a limited number tested.

5 Automatic Transmissions

In Europe, the fitment rate of automatic transmissions (ATs) is increasing. In addition, there is a large range of configurations for these transmissions. Traditional planetary gear train systems are common, along with more modern designs such as manual transmissions (MT) with automatic shifting and continuous ratio transmissions (continuously variable transmission, CVT). Due to the increasing number of these vehicles on the road, it is important to identify the effects of these systems on the environmental performance of the vehicle, especially considering real-world performance.

Within the Eurotest, vehicles with ATs are tested on a different cycle than MT vehicles. While essentially similar to the cycle used for MT vehicles, the AT cycle differs in that shift points are not specified (the transmission controller is free to determine which gear is selected at a given time) and accelerations are slightly milder (due to the absence of gear shift provisions in the speed-time profile of the cycle).

Due to the freedom to select gear ratios, gear shift patterns can be optimised to the driving situation. The techniques proposed by the programme 'The New Driving Force' can be partially enforced by the vehicle control system. The environmental performance of the AT vehicles on both the Eurotest and real-world driving cycles was therefore investigated and compared to the MT vehicles.

5.1 Initial tests

In order to assess the influence of various types of automatic transmissions on emissions performance, four vehicles were tested in AT and MT variants (Table 7). Each vehicle is certified to Euro 4 and has a different type of AT. With two of the vehicles, a mode is available allowing the driver to choose the selected gear ('hand-shifted'). For the driver, the gear shift is similar to that of an MT, but then without requiring manual clutch actuation.

Table 7 Vehicle types tested in 2003 (automatic transmission)

Vehicle make	Vehicle type	AT type and take-off element	Hand-shifted	# vehicles tested
Opel	Corsa Z1.2XE	EASYTRONIC (AMT), dry clutch	✓	3
Volkswagen	Polo 55kW	Stepped AT, torque converter	×	3
Audi	A4 96kW	Chain CVT, wet clutch	✓	1
Honda	Jazz 1.4i	Push-belt CVT, wet clutch	×	1

An overview of the transmission types is given in Table 8.

Table 8 Types of automatic transmissions

Abbreviation	Long name	Description
AMT	Automated Manual Transmission	Construction similar to conventional MT, shifting automatically controlled with hydraulic or electric actuation.
Stepped AT	Stepped Automatic Transmission	Conventional AT, whereby a series of planetary gearsets are used for power transfer. Shifting is performed with hydraulically actuated clutches and brakes between fixed ratios.
CVT	Continuously variable transmission	Transmission whereby any speed ratio can be selected between two extremes. Power is transferred between two conical pulleys with a push-belt (push-belt CVT) or chain (chain CVT).

The use of ATs has two major influences:

1. ATs have an intrinsically lower energy efficiency than an MT. The extent of this is dependent on the transmission configuration. Factors that reduce the efficiency include the use of a torque converter for the take-off element, extra parasitic loads for hydraulic systems and increased friction losses.
2. The manufacturer is free to select the optimal gear at any given instant of time via the shifting algorithm. A well-designed system therefore has the potential to increase overall powertrain efficiency by enforcing 'The New Driving Force' shift strategies. This is likely to also affect the emissions performance.

To separate the influence of these two effects, two vehicles were tested with AT on the Eurotest under the following conditions:

1. In 'D-range', whereby the vehicle is free to change gear on the cycle under its own discretion. The drive cycle for ATs was used (ECE R83 Annex 4 §2.3.3 or EU Directive 70/220/EEC Annex 3 §2.3.3).
2. Hand-shifted, where gears were shifted on the AT vehicle according to the prescribed gear-change regime from the test cycle. The drive cycle for MTs was used (ECE R83 Annex 4 Appendix 1 or EU Directive 70/220/EEC Annex 3 Appendix 1).

During these tests, the regulated emissions and CO_2 were measured.

It is important to note that as the AT and MT variants are different vehicles and every effort was made to obtain vehicles of similar specification, it is possible that different fitment levels are possible between these two variants. This can affect factors such as vehicle mass and accessory loading on the engine. In addition, automatic transmissions are in general heavier than their manual counterparts, which can lead to increased vehicle mass. Such an increase in mass may be slight, but enough to shift the AT variant up to the next vehicle inertia class. All these factors may influence the emission levels measured, but are not strictly due to the application of an AT.

Also to be noted is that the hand-shifted ATs and MTs may also not be identical, due to a different number of gears and possibly different gear and final drive ratios. These factors can all affect the work points of the engine on a given drive cycle, influencing emission levels.

The average emissions of all the vehicles tested of that type are shown in Figure 30.

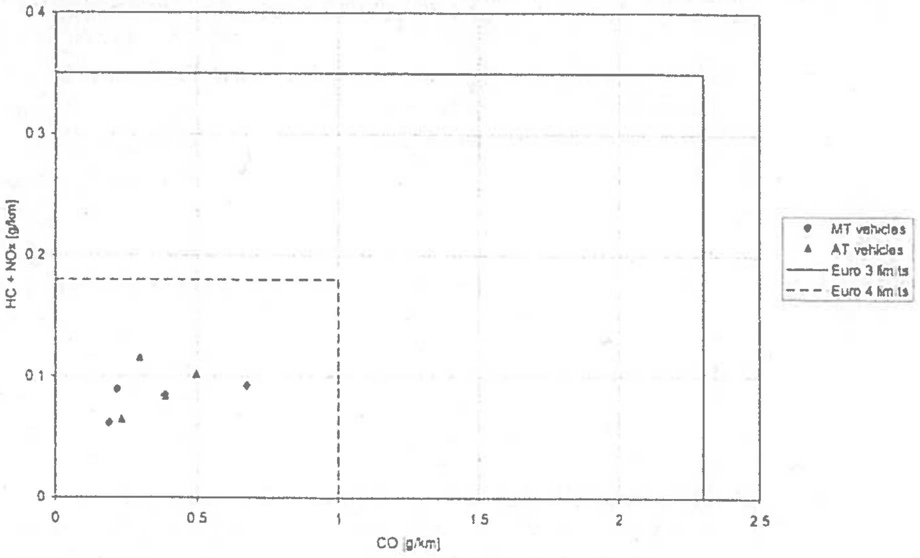

Figure 32 - Results of petrol passenger cars with manual transmission and automatic transmission in D-range on the standard type approval test procedure (average per vehicle type)

No clear trend can be observed when comparing an MT and the associated AT vehicle. The four vehicle types compare as shown in Table 9.

Table 9 Emissions results of AT vehicles compared to MT vehicles of same type

Vehicle	CO	HC	NO_x	Comments
Opel Corsa	–	=	=	
VW Polo	–	–	=	AT vehicle in higher inertia class
Audi A4	+	+	–	
Honda Jazz	=	=	=	

+) improved emissions (reduced level)
-) worse emissions (increased level)
=) emissions not affected

Results for individual vehicles are shown in Figure 33.

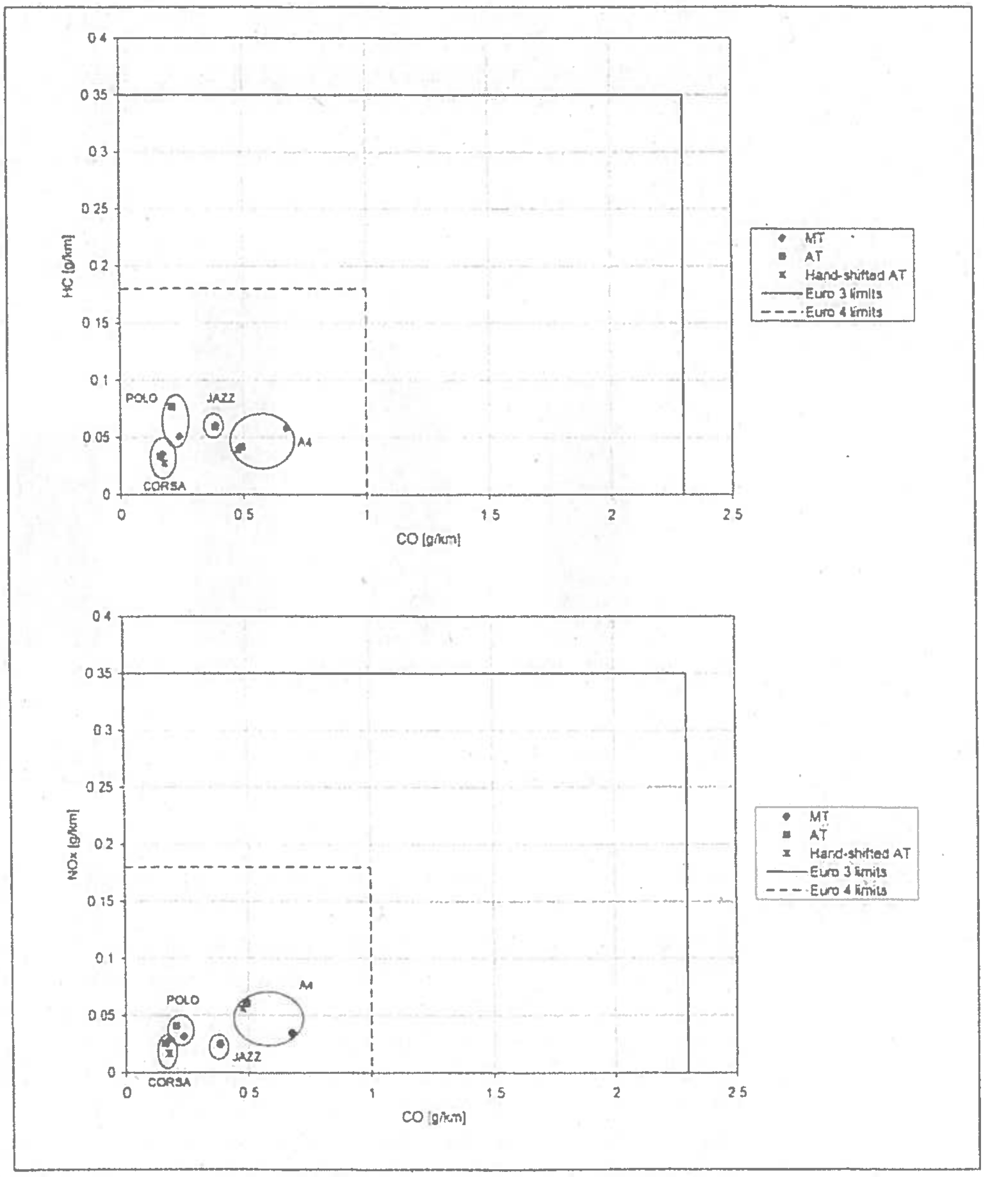

Figure 33 - Results of petrol passenger cars with manual, automatic and hand-shifted automatic transmission on the standard type approval test procedure (based on single vehicle tests). Automatic and hand-shifted automatic are identical vehicles, manual is the same type. Results of a given vehicle type are circled.

By hand-shifting the AT vehicles, slight improvements are seen for HC and NO_x emissions compared with the equivalent AT results. For one vehicle , CO was also slightly lower, for the other slightly higher. The differences are however small and may not be statistically significant. The increase in emissions of the Polo is most likely caused by the inertia class of the AT vehicle; this is one class higher than the MT. The A4 shows a reduction in both HC and CO, but an increase in NO_x. This may be caused by the increase in load on the engine due to increased losses, causing faster catalyst light-off but allowing higher levels of NO_x slip, or may be related to system control. For the Jazz; AT and MT emission levels are identical. This is likely due to the extra losses of the AT being balanced by the advantages of the free ratio selection possible with the design.

The CO_2 emissions for the tested vehicles are shown in Figure 34.

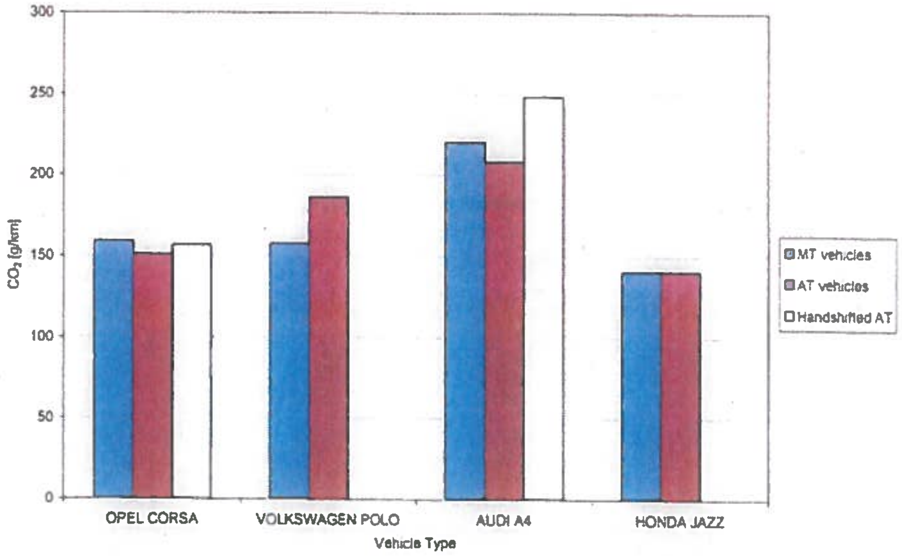

Figure 34 - Comparison of CO_2 emissions of single vehicles tested with manual transmission, automatic transmission and hand-shifted automatic transmission on the Eurotest.

For the various transmission types, the conclusions are shown in Table 10.

Overall, the stepped AT was the only system which showed a large increase in CO_2 emission results. This is partially due to the higher inertia class and the use of a 4-speed transmission. Both the AMT and chain CVT show improvements in the CO_2 emissions. For both, this is due to the shift strategy. Figure 32 shows that the chain CVT, when shifted manually, has a higher CO_2 emission than the standard MT, indicating a low efficiency on the drive cycle. The belt CVT shows equal CO_2 emissions for both MT and AT vehicles. It is likely that the efficiency losses of the CVT are overcome by improvements in efficiency due to the shift strategy. As a driveability-efficiency trade-off exists for CVTs, this may have been the design decision to not improve the CO_2 emissions further.

Table 10 Conclusions on CO_2-emissions for automatic transmissions

Vehicle	Transmission	ΔCO_2	Comments
Corsa	AMT	-3.2%	In AT mode, CO_2 emissions are reduced. When hand-shifting, the CO_2 returns to the level of the MT variant. This implies the AMT has roughly the same efficiency as the standard MT and the CO_2 improvement comes from the shift strategy.
Polo	Stepped AT	+18 5%	CO_2 is increased for the AT variant. This is partially due to the heavier inertia class compared with the MT vehicle and the AT being 4-speed.
A4	Chain CVT	-5.5%	The CO_2 emissions show a slight improvement compared with the MT vehicle. However, hand-shifting the CVT resulted in significantly worse CO_2 emissions. This implies that while the CVT shows worse efficiency than the MT, the advantages of the shift strategy are larger.
Jazz	Push-belt CVT	0%	The CVT vehicle achieved the same CO_2 result as for the MT. This implies that the expected efficiency losses of the CVT are counterbalanced by the chosen CVT shift strategy.

5.2 Cold start

In order to investigate the effect of the application of an AT on the cold start emissions, tests were performed with both MT and AT variants on the UDC cycle, with both a cold start from 20°C and a warm start.

Results of these tests are shown in Figures 35, 36, 37 and 38. These results are based on single vehicle tests per type, for two vehicle types (Polo and Corsa).

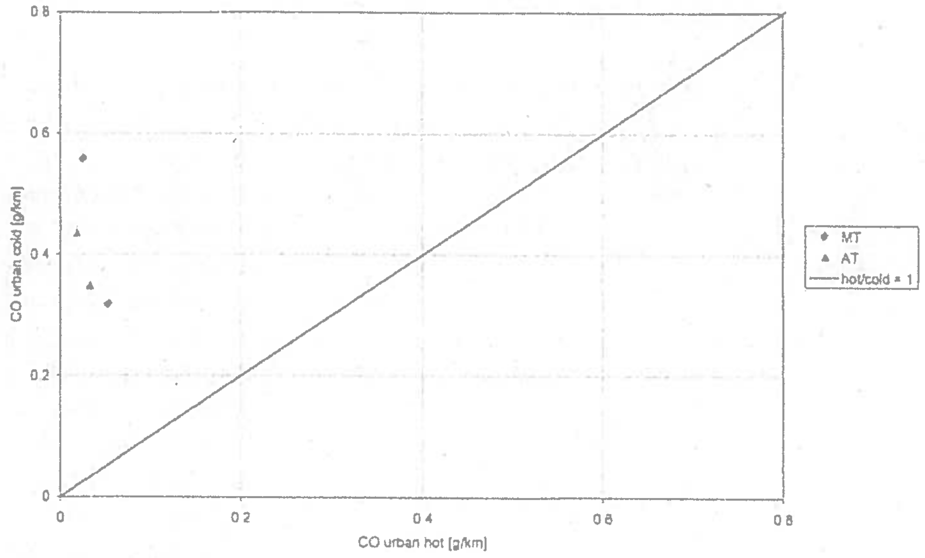

Figure 35 - UDC cold start emissions versus UDC hot start emissions: CO

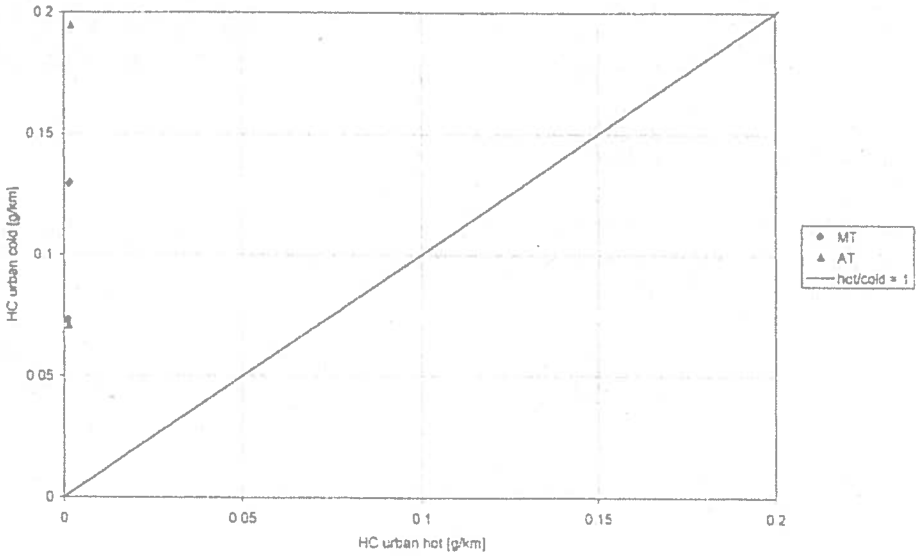

Figure 36 - UDC cold start emissions versus UDC hot start emissions: HC

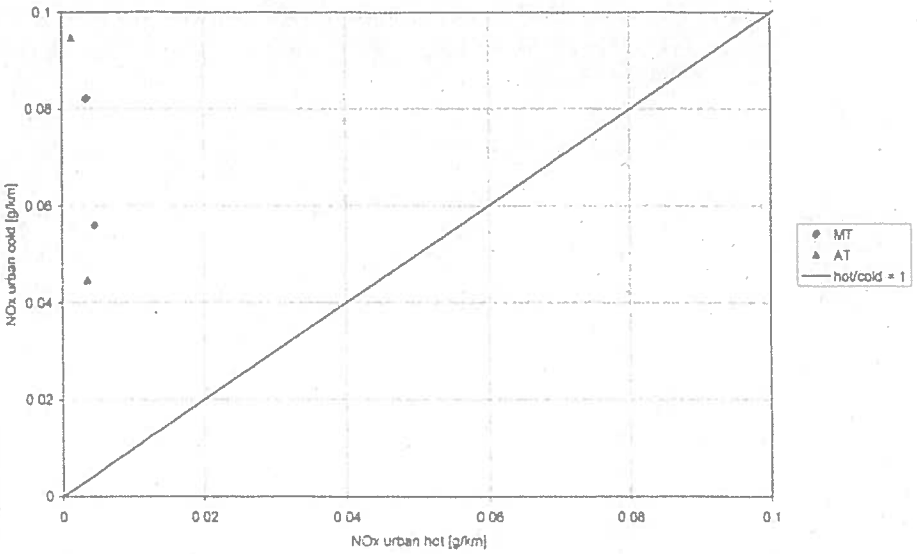

Figure 37 - UDC cold start emissions versus UDC hot start emissions: NO_x

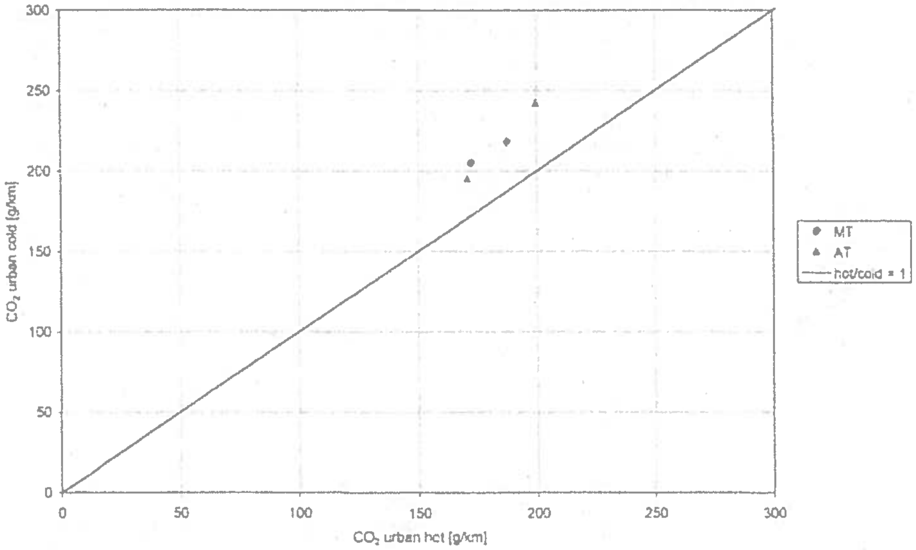

Figure 38 - UDC cold start emissions versus UDC hot start emissions: CO_2

For CO, HC and NO_x emissions, the effect of the cold start is as for the other petrol engine vehicles tested. However, there is no noticeable trend between the AT and MT vehicles. The CO_2 cold start penalty is also similar to that of other petrol vehicles tested, with a slight difference between AT and MT (respectively 18% and 17%). However, the sample size of vehicles tested is not sufficient to draw conclusions from this result.

5.3 Real-world emissions

The AT vehicles were also tested on the Common Artemis Driving Cycles to determine the emission performance under real-world conditions. These results are shown in Figures 39-42.

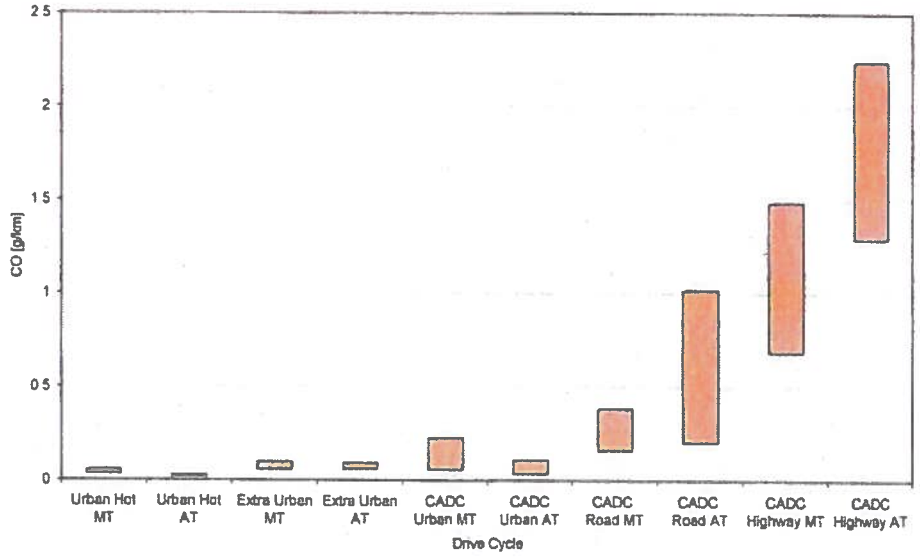

Figure 39 - CO-emissions on the CADC cycles compared to the 'urban hot' and 'extra urban' ECE cycles, MT vehicles and AT vehicles.

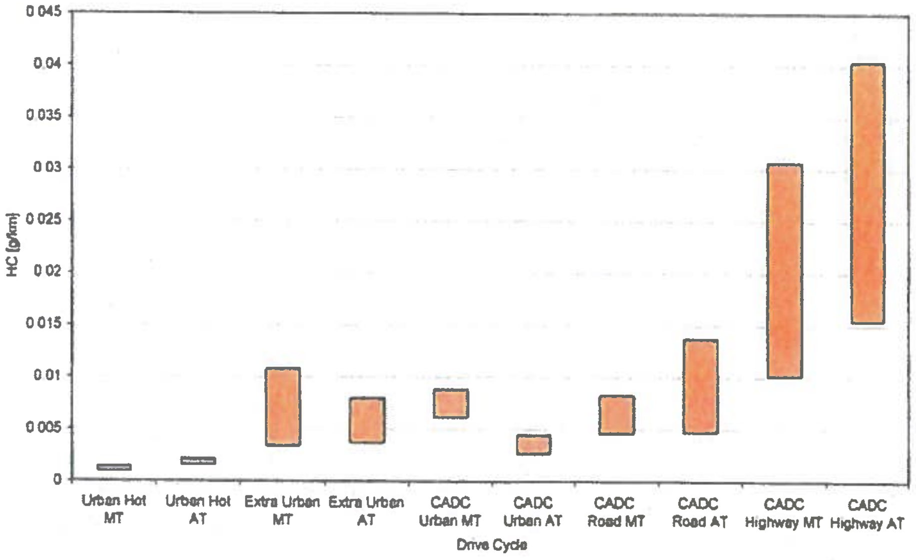

Figure 40 - HC-emissions on the CADC cycles compared to the 'urban hot' and 'extra urban' ECE cycles, MT vehicles and AT vehicles

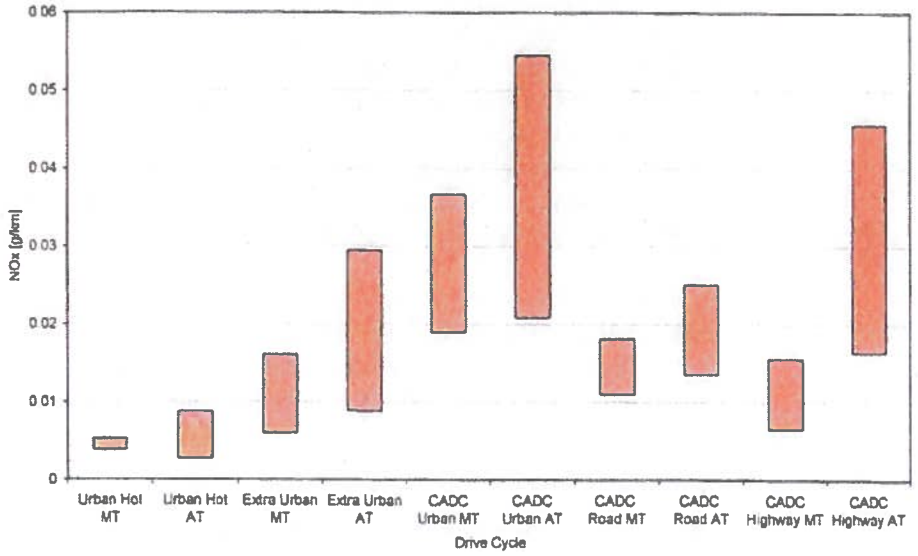

Figure 41 - NO$_x$-emissions on the CADC cycles compared to the 'urban hot' and 'extra urban' ECE cycles, MT vehicles and AT vehicles.

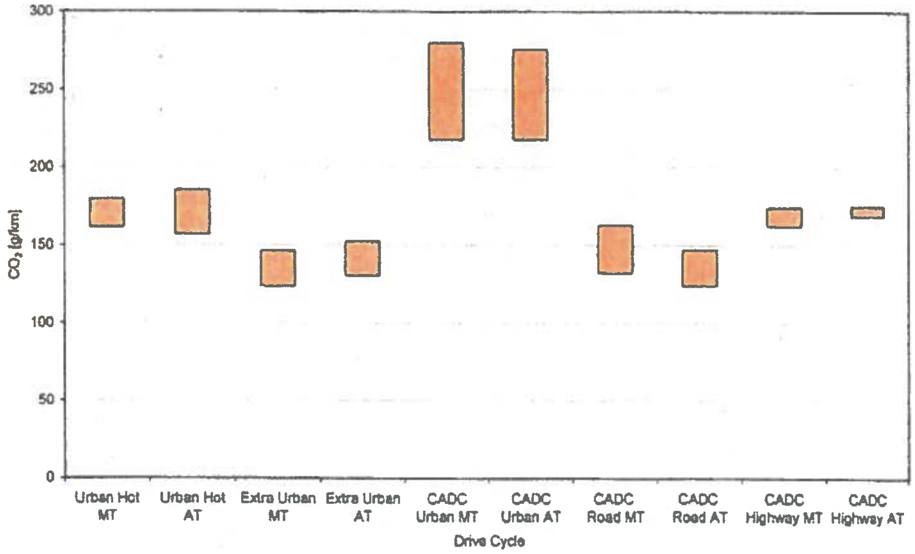

Figure 42 - CO$_2$-emissions from the CADC cycles compared to the 'urban hot' and 'extra urban' ECE cycles, MT vehicles and AT vehicles.

For CO emissions, the AT vehicles appear better than the MT variants on city cycles, but worse on the rural and highway cycles. Note that the EUDC cycle is not representative for real-world results obtained on the CADC Road and Highway cycles; ATs produce significantly higher CO levels on the real-world cycles compared with MTs, while this difference is not noticeable on the EUDC.

For HC emissions, the AT vehicles appear better on the CADC urban cycle only. On all other cycles the AT vehicles are equivalent to or worse than the MT vehicles. The differences between HC emissions between AT and MT variants on the UDC and EUDC cycles are not representative of the emissions on the CADC cycles. On the UDC cycle, the ATs produce a higher emission level than the MTs, while on the CADC Urban cycle the ATs produce lower emission levels than the MT variants. In addition, the higher emission level of the AT variants on the CADC Road and Highway cycles compared to the MTs are not seen on the EUDC cycle.

For NO_x emissions, the AT vehicles appear to be worse than for the MT vehicles on all cycles. The difference between MT and AT emission level on the UDC and EUDC show the same trend as the results on the CADC cycles, however the absolute emission levels are significantly different, especially when comparing the UDC and CADC Urban cycles.

For CO_2 emissions, there is little difference between the AT vehicles and the MT vehicles. The AT vehicles are slightly worse on the EUDC (extra urban) cycle, but slightly better on the CADC Road cycle, even considering the increased inertia class of the conventional AT vehicle tested. The difference between AT and MT vehicles on real-world cycles appears in general to be similar to that achieved on the homologation cycles, although in some cases the emission improvement can be larger on the real-world cycles than achieved on the EUDC cycle.

In general, it appears that the UDC and EUDC cycles are not representative neither for the absolute values of emission levels, nor for the relative difference between homologation and real-world cycles. These differences are dependent on the emission component and driving situation. Note however that the mix of technology in the vehicle fleet can have a significant impact on the environmental impact of a shift to more ATs on the road. For example, an increased number of conventional 4-speed ATs (in conjunction with an increase in inertia class) would likely lead to a net CO_2 emission increase, while application of 5-speed AMTs can lead to a CO_2 emission reduction.

5.4 Summary of results for automatic transmissions

The emission levels of the components HC, CO and NO_x do not show a clear correlation with the application of an automatic transmission. The AT vehicles can show better, worse or even equivalent emissions behaviour compared to MT variants. On a per vehicle basis, handshifting the AT's actually resulted in a slight improvement in the emissions behaviour of the vehicles tested.

Cold start behaviour was also similar to that of the MT petrol vehicles; no influence of the AT was noticeable.

The largest effect was found on CO_2 emissions. All AT vehicles except for one showed improvements in CO_2 emissions on the Euro 3 cycle compared with the MT variant. That one vehicle, however, was classified in a higher inertia class than its MT counterpart, in addition to being a conventional 4-speed transmission, which explains some of the result. In general, the influence of the AT can be divided into a negative influence (due to lower efficiency compared to a MT), and a positive influence (shifting patterns can be selected for optimal use of the engine). If correctly designed, the AT variant can provide a net reduction of CO_2 emissions, not only on the homologation cycles but also on real-world cycles. In fact, the improvement appeared larger on the CADC Road cycle than on the EUDC cycle.

On real-world cycles, the AT vehicles showed worse emission results on the highway and road CADC cycles. On other cycles, the results were mixed. In general, the results on the real-world cycles were not representative of the emission levels on the UDC and EUDC cycles.

6 Old-timers and Pre-Euro 1 Vehicles

With the continuous improvement in emission levels of new vehicles driven by ever stricter legislation, it is envisaged that the total emissions of the vehicle fleet will also be reduced by a similar level. However, many older vehicles remain on the roads. Scrappage legislation is one conceivable method to reduce the total vehicle fleet emissions. The emission levels of these older vehicles, compared with that of modern vehicles, is an important factor in determining the effectiveness of such legislation.

Therefore, eight 'old-timers' were tested to check the emissions behaviour of these older vehicles. The vehicles tested are shown in Table 11. All tests were carried out on the MVEG-A drive cycle (Eurotest with 40 seconds warm-up time, as used for Euro 2 certification). The vehicles tested can be roughly divided into two categories:

1. Vehicles from the 1980's that serve as daily transport and that still constitute a relatively large part of the Dutch vehicle fleet
2. Vehicles older than 25 years that have a recreational use, and that are also exempted from road tax in the Netherlands

It is important to note that pre-Euro 1 vehicles were type approved on the UDC cycle only, with 40 seconds between engine start and start of measurement. The full MVEG-A cycle was used in order to allow comparison with test results of modern vehicles.

Table 11 Vehicle types tested in 2003 (old timers)

Vehicle make	Vehicle type	Year	Fuel	Legislation category
1980's				
Citroën	BX 1.4	1984	Petrol	R15-04
Ford	Escort 1.8D	1989	Diesel	88/76 EEG
Citroën	BX 1.9D	1989	Diesel	88/76 EEG
Mercedes	230E	1983	LPG	R15-04
Older than 25 years				
Peugeot	504	1978	Petrol	R15-02
Alfa Romeo	GT 1600 Junior	1973	Petrol	R15-00
Opel	Manta	1974	Petrol	R15-00
Volvo	244	1975	LPG	R15-01

The test results are shown in Figures 43-46. Each vehicle is classified based on the emissions class that was in force in the year the vehicle was built. Because the emissions limits were defined at that time in grams per test, for the purpose of this report these limits were converted to g/km Eurotest-equivalent. Note that the emission levels R15-00 and R15-01 did not specify a NO_x limit, which is why the $HC+NO_x$ limit is lower than for later limits.

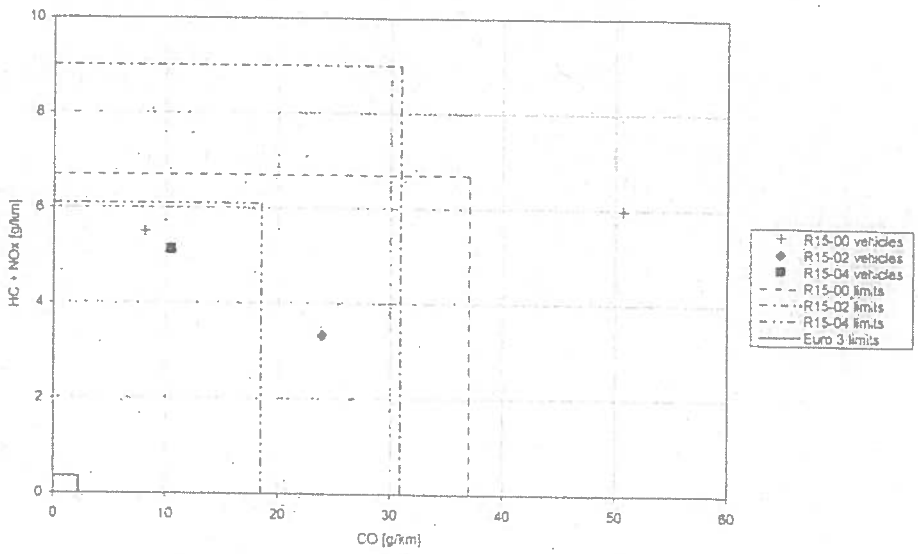

Figure 43 - Emissions of petrol 'old-timers' on the MVEG-A drive cycle (CO and HC + NOx).

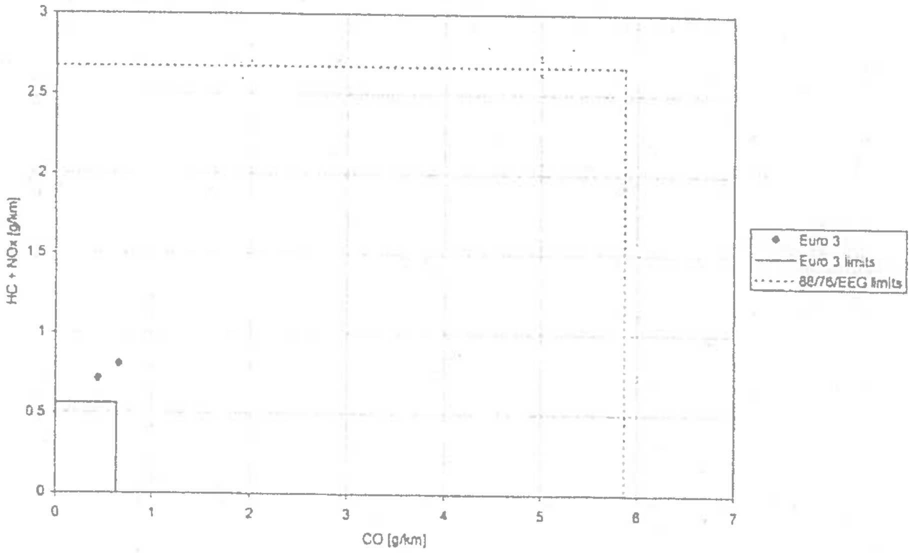

Figure 44 - Emissions of diesel 'old-timers' on the MVEG-A drive cycle (CO and HC + NO_x).

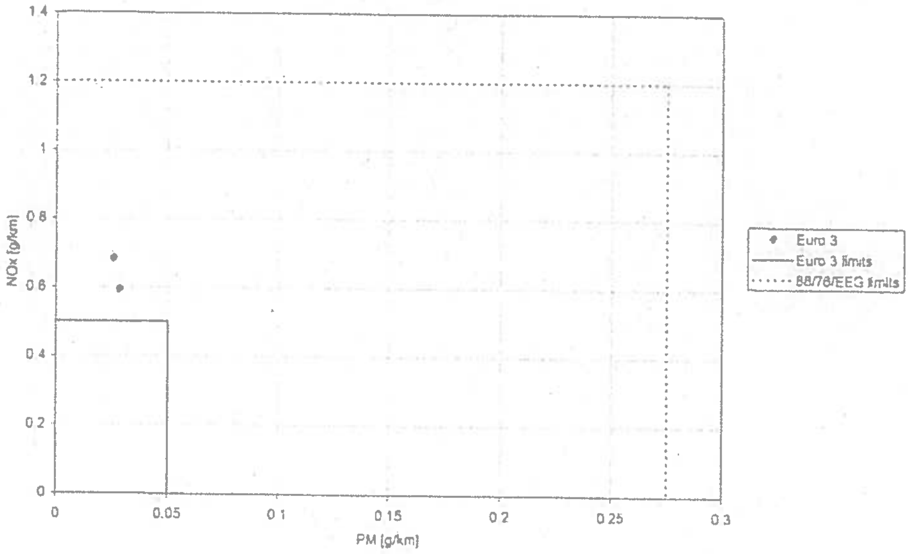

Figure 45 - Emissions of diesel 'old-timers' on the MVEG-A drive cycle (NO_x and PM)

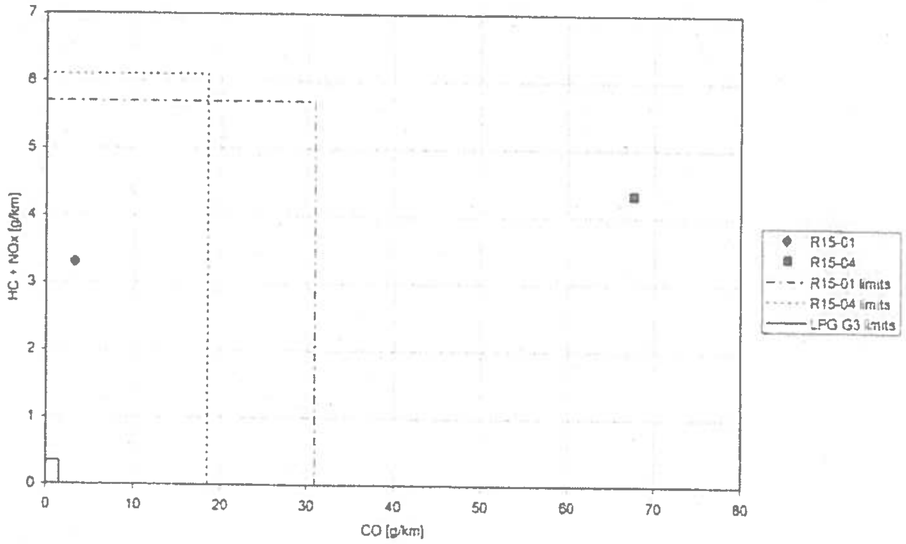

Figure 46 - Emissions of LPG 'old-timers' on the MVEG-A drive cycle (CO and HC + No_x)

For the petrol vehicles, the results show a very large variation. All vehicles except one conformed to the then valid emission limits. It's also remarkable that the 1974 R15-00 car performed almost as well as the 1984 R15-04 car. Apparently the state of maintenance for cars of this age becomes the dominant parameter over the legislative category that determines the emission level. Generally, the emissions are typically more than a factor 20 higher than new (Euro 3) vehicles.

The two diesel vehicles, both from the 1980's, performed well within the required limits and were even close to, but outside of, the Euro 3 limits. This is likely due to the manner in which the diesel limits were set when introduced (i.e., not technology forcing).

The LPG vehicles showed very different results, one being compliant with the appropriate emission requirement, and the other showing a large exceedance. This is probably another example of the importance of maintenance on emissions.

7 Durability

In order to assess the stability of emission levels during the lifetime of the vehicle, measurements have been performed on selected vehicles at various times during the vehicle life. This provides an indication of the increase or reduction of a vehicle's emission due to wear caused by continual use.

In 2003 three vehicles underwent emission durability testing:
1. Volkswagen Passat TDI 66 kW Euro 2.
2. Ford Mondeo D Euro 3
3. Volkswagen Passat TDI 74 kW Euro 3

In previous years an Opel Omega 2.5 Automatic Euro 2 was also tested; this vehicle has been removed from the test programme due to vehicle availability.

As the Passat 74 kW and Mondeo have only been tested once, the results will not be reported here as they provide no insight in the durability of the emissions of the vehicles. This is also the first time that the CADC cycles have been used to assess emissions durability and therefore also will not be reported here. These will be reported in the following report, when a second durability test has taken place.

The tests during the lifetime of the Volkswagen Passat TDI 66 kW were conducted at the intervals shown in Table 12.

Table 12 Odometer readings and date of durability tests for the VW Passat TDI 66kW.

Test Date	Odometer reading
19-11-2001	54 782 km
12-06-2002	75 427 km
24-04-2003	98 922 km

The emission results over the test duration are displayed in Figure 47.

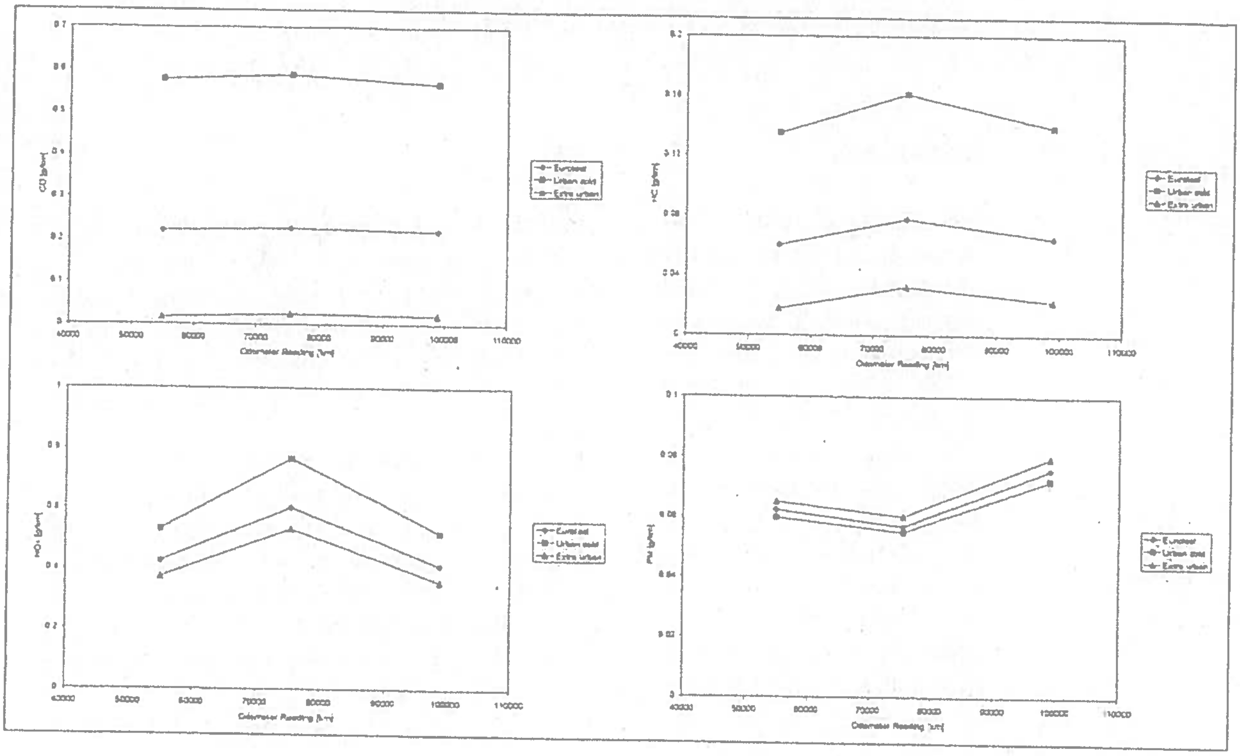

Figure 47 - Emissions over the lifetime of a Volkswagen Passat TDI 66 kW

The latest durability test results of the VW Passat show a reduction back to the level of the first test performed on the vehicle after an increase for the second test. The exception to this is the PM emissions, which increased to the highest level of the test series on this vehicle. These trends are stable for all 3 test types used. All emission levels are below the applicable Euro 2 limit values. It is possible that the change in emission levels between measurement 2 and 3 is related to a leakage in the turbocharger.

8 Emission testing of a vehicle fitted with a sequentially regenerating diesel particulate filter

8.1 Introduction

This chapter describes the emission tests that were performed on a Peugeot 307 HDi, a diesel passenger car fitted with a Diesel Particulate Filter (DPF). The DPF is a particulate trap system that regenerates according to the driving conditions. Since the emissions during regeneration may differ from those when not regenerating, a special procedure has to be applied to perform a type approval test. This procedure is described in the recently added Annex 13 of Regulation 83 on the exhaust gas measurement procedures of passenger cars.

The scope of the current investigation was to perform an emission test specified in Regulation 83, to gain experience in testing vehicles equipped with periodically regenerating devices. This test was executed within the framework of TNO Automotive's In Use Compliance program. Unregulated emission components were also measured. This was reported within the framework of the assessment of the environmental performance of vehicles running on petrol, diesel, LPG and CNG [5]. A comprehensive overview of the results of the unregulated emission component measurements can be found in [6].

8.2 The Diesel Particulate Filter technology of the Peugeot 307 HDi

8.2.1 Description of the DPF system

The DPF makes use of a Silicon Carbide (SiC) particle filter, that is periodically regenerated by a combination of employing the flexibility of the common rail injection system, together with a cerium-based fuel borne additive EOLYS [7]. The additive is stored in a separate tank, and added to the main fuel tank by a dosing system, managed by a separate ECU. The additive is used to decrease the combustion temperature of particulate matter with about 100°C, to approximately 450°C. This temperature, however, is still far much higher than the exhaust gas temperature of a modern fuel efficient DI diesel engine under normal operating conditions. To enable combustion of the particulate matter that is trapped in the DPF, the exhaust gas temperature and composition is changed temporarily by using post-injection. The catalyst must be sufficiently heated up to be able to oxidise the species coming from post-injection. Furthermore, to help increase the exhaust gas temperature, higher engine loads are created during regeneration, by switching on some electronic accessories.

8.2.2 *Types of regeneration*

Different types of regeneration can occur under various circumstances. Forced regeneration takes place either when a defined number of kilometres is reached after the last regeneration, or when the pressure drop over the filter exceeds a specific value. The pressure drop over the filter, continuously monitored, is a measure for the degree of filter loading (the accumulated mass of soot in the filter). Together with engine parameters defining the operational conditions, the engine ECU uses an algorithm to initiate and conclude the regeneration phase. During optimum operational conditions for instance, an efficient regeneration may occur, featuring shorter post-injection times and hence reducing the excess fuel consumption during regeneration.
Besides the forced regeneration, 'natural' regeneration can take place under optimum operational conditions of the vehicle that cause the exhaust gas to exceed the temperature at which the soot combusts. Note that the additive already lowered this temperature by approximately 100°C.

The cerium in the additive is not oxidised during regeneration, but accumulates in the filter. This influences the differential pressure in the course of time, and the engine ECU applies corrections for this. For the first generation of PSA vehicles that are equipped with the DPF system, the filter needs to be disassembled and cleaned after 80,000 km. For the current generation this is already 120,000 km, and for the next generation this will be 240,000 km, which is basically maintenance free.

8.3 Emission test procedure for vehicles equipped with a periodically regenerating device

For vehicles equipped with a periodically regenerating exhaust gas aftertreatment system, additional tests (to the standard Eurotest) have to be performed. Corresponding to the definitions in ECE Regulation No. 83, these vehicles should be tested according to the procedure described in Annex 13 of the same document [8]. In essence, the procedure calls for emission measurements to be performed both during the non-regenerative, and during the regenerative phase of operation:

- During the non-regenerative phase, a minimum of 2 Type I operating cycles must be performed: one immediately after regeneration, and one as close as possible prior to regeneration. Alternatively, the manufacturer may provide data proving that emissions remain constant within a bandwidth of 15% during the non-regenerative phase. In that case, a single Type I test during the non-regenerative phase is sufficient.
- During the regenerative phase, a Type I (20-30°C start) emission test must be performed, which includes the regeneration. If the regeneration requires more than one cycle, subsequent NEDC cycles must be driven.

The regulation also states that between two regenerative phases, the regenerative device has to be loaded by driving a consecutive sequence of operating cycles on the chassis dynamometer, until the filter is fully loaded.

The final emission result is a weighed average of the individual measurement results:

$$M_{pi} = \frac{M_{si} D + M_{ri} d}{D + d} \qquad (1)$$

Where:

M_{si} = mean mass emission of pollutant *i* in g/km without regeneration
M_{ri} = mean mass emission of pollutant *i* in g/km with regeneration
D = number of NEDC cycles between two regenerations
d = number of NEDC cycles required for regeneration

As prescribed by Annex 13, M_{si}, M_{pi}, D, d and the regeneration factor K_i for each pollutant *i* shall be recorded in the test report delivered by the technical service. The regeneration factor K_i is defined as:

$$K_i = \frac{M_{pi}}{M_{si}} \qquad (2)$$

8.4 Measurement set-up

The experimental set-up that has been used in this test to sample the regulated exhaust gas components and CO_2 is completely in accordance with the Directives of the European Union (96/69/EC).

To study the effect of regeneration on particle emissions, an extra sampling probe was inserted into the dilution tunnel, drawing sample flow through an Electronic Low Pressure Impactor (ELPI). The ELPI separates different particle size ranges based on their aerodynamic diameter. This enables tracing the different particle sizes during the cycle.

Additional sampling probes were inserted in the dilution tunnel to sample unregulated emission components. This was performed within the framework of the 'environmental performance of vehicles running on petrol, diesel, LPG and CNG' project. For a detailed description of the sampling and analysis methods that are used, as well as the measurement results, is referred to [5].

8.5 Vehicle and test conditions

For the current investigation a Peugeot 307 HDi 2.0 79kW (Euro 3 version), fitted with a DPF, was prepared by the vehicle manufacturer, PSA France, and put at TNO's disposal for emission tests.

Here some remarks are made concerning the vehicle preparation:

- The manufacturer provided the vehicle with a switch, to either prevent or trigger the particulate filter regeneration. With the switch in the "ON" position, and when the oil and coolant temperature reached a specific threshold value during the test cycle, engine settings would be changed to the regeneration mode, regardless of whether the DPF is full or not. This is detected by measuring the pressure drop over the filter.
  An unprepared vehicle would switch back from the altered engine settings when the filter is fully regenerated. For this particular vehicle, the engine remains in the regeneration mode during the entire NEDC cycle, even if the DPF is empty, because the switch to trigger the regeneration basically overrules the filter pressure drop signal. Consequently the excess fuel consumption and emissions over an NEDC are higher than for an unprepared vehicle during regeneration. The results obtained by these tests can therefore be considered as a worst case scenario.
- The DPF was loaded by the vehicle manufacturer, by driving a consecutive sequence of 70 NEDC cycles. The fuel that was used had a sulphur content of approximately 300 ppm. Hence a vast amount of sulphur was accumulated in the DPF.
- Prior to the tests at TNO, the fuel was changed to EN 590 diesel with a sulphur content of 35 ppm. Special effort was taken to ensure that the correct amount of EOLYS was added to the tank after draining and refuelling. This involved turning the ignition key to the "ON" position after the tank was drained, so that the engine ECU recognised the empty tank. After refuelling (the fuel refiller cap is provided with a contact), the engine ECU recognises the new level and adds the required amount of additive.
- Vehicle preconditioning was performed with the regeneration disabled.
- It was assumed that the regulated emissions would remain constant (within ±15%) between two regenerations. For that reason only a single emission test was performed between two regeneration phases.

In total, four emission tests were performed:

- First, a cold Type I test with the regeneration enabled was performed.
- Secondly, a hot emission test with regeneration enabled was performed, because the emission results from the first test gave rise to the suspicion that the DPF was not fully regenerated. For this additional test, the vehicle was preconditioned driving a single Eurotest cycle with the regeneration disabled, followed by 10 minutes of soaking. During the additional test, the online particle flow showed that the regeneration started sooner.
- Thirdly, a cold Type I test with the regeneration disabled was performed.
- Finally, a hot Type I test with the regeneration disabled was performed.

In this document, emissions tests with the regeneration enabled, are referred to as tests "with regeneration". For the tests between two regeneration phases, with the regeneration disabled, are referred to as tests "without regeneration". The weighed average of the emissions with and without regeneration, as calculated with Equation (1), is referred to as the "weighted emission result".

8.6 Results

8.6.1 Regulated emission components and CO_2

Table 13 presents the emissions of the regulated components and CO_2 that were measured on the NEDC. Results are included both for cold and hot tests, with and without regeneration.

Table 13 Regulated emission components for the Peugeot 307 HDi DPF, as measured on the Eurotest cycle with and without regeneration. Tests were performed both with cold and hot engine.

Cold	**With regeneration**		
[g/km]	UDC	EUDC	NEDC
CO	0.31	0.68	0.54
HC	0.06	0.01	0.03
NO_x	1.06	0.63	0.79
HC + NO_x	1.12	0.64	0.82
PM	0.289	0.278	0.282
CO_2	282.0	197.9	229.0
FC [l/100 km]	10.59	7.45	8.61

Cold	**Without regeneration**		
[g/km]	UDC	EUDC	NEDC
CO	0.38	0.00	0.14
HC	0.11	0.01	0.05
NO_x	0.33	0.26	0.28
HC + NO_x	0.44	0.27	0.33
PM	0.001	0.000	0.001
CO_2	198.7	116.4	146.7
FC [l/100 km]	7.48	4.36	5.51

Hot	**With regeneration**		
[g/km]	UDC	EUDC	NEDC
CO	0.09	0.10	0.10
HC	0.04	0.01	0.02
NO_x	0.79	0.61	0.67
HC + NO_x	0.83	0.62	0.70
PM	0.086	0.230	0.176
CO_2	337.3	187.5	243.1
FC [l/100 km]	12.64	7.03	9.11

Hot	**Without regeneration**		
[g/km]	UDC	EUDC	NEDC
CO	0.00	0.00	0.00
HC	0.03	0.01	0.02
NO_x	0.31	0.29	0.30
HC + NO_x	0.34	0.30	0.31
PM	0.001	0.001	0.001
CO_2	164.1	110.7	130.7
FC [l/100 km]	6.15	4.15	4.90

It was observed that the regeneration during the cold Eurotest initiated during the fourth elementary urban cycle. Hence the effect on regulated emission components will mainly be found in the EUDC part of the cycle. For the hot test with regeneration, the regeneration initiated in the second elementary urban cycle.
The best way to follow the occurrence of regeneration during a test cycle would be by using a CO-tracer. This was, however, not available during the tests. Therefore the initiation of the regeneration was observed differently, being in two ways. First, some of the electronic accessories are automatically switched on during regeneration, to create higher load conditions for the engine, as an aid to increase the exhaust gas temperature. Secondly, the online particle flow as measured by the ELPI showed sharp increases at the point where regeneration starts (see paragraph 8.6.2).

For the regulated emission components and CO_2, note that:

- For the cold start without regeneration, some CO was observed due to the cold start effect. In the EUDC part of this test, CO was below the detection limit. For the test with regeneration, the CO emission in the UDC was mainly caused by the cold start effect, while the CO emission in the EUDC can be attributed to the regeneration.

- For the hot tests without regeneration no CO was observed. For the hot test with regeneration, CO was both increased on the UDC and on the EUDC. This is caused by the earlier start of the regeneration.
- No effect of the regeneration is observed for HC. The higher HC emissions observed in the UDC are cold start effects.
- NO_x is higher for the tests with regeneration. This is caused by the fact that the EGR is turned off, to avoid exhaust gas temperature losses (used in this first generation of the DPF system). Next to this, the electronic accessories that are turned on during regeneration also slightly increase the engine load.
- The cold start PM is very low for the tests without regeneration. For the test with regeneration, it is not obvious which part of the PM emissions can be attributed to the cold start effect, and which to the regeneration.
- PM is obviously higher for both tests with regeneration. A visual inspection of the PM filters gave rise to the suspicion that it is most likely to be sulphur. The high sulphur content of the fuel that was used during the DPF loading phase can only back this up. From the type approval data as provided by PSA, the PM emission for a test with regeneration should normally be approximately ten times higher (see Table 14)
- Furthermore, note that the PM emission from the cold test with regeneration is much higher than for the hot test with regeneration, despite the fact that the regeneration in the hot test started sooner. It is, however, not a cold start effect. This is explained further in paragraph 8.6.2.
- The CO_2 emission results of the tests with regeneration are obviously higher. This is caused by the post-injected fuel, the combustion of the accumulated soot in the DPF, and the increase in fuel consumption caused by electronic accessories that are switched on during regeneration. The CO_2 emissions are even higher during the hot test with regeneration. This is caused by the earlier start of the regeneration.

Table 14 Type approval values for the PSA 2.0 HDi 79 kW engine

	With regeneration	Without regeneration	Weighted emission results	K_i
	[g/km]	[g/km]	[g/km]	[-]
CO	1.268	0.129	0.148	1.147
HC	0.073	0.024	0.025	1.034
NO_x	0.852	0.39	0.398	1.02
HC + NO_x	0.925	0.414	0.423	1.021
PM	0.011	0.001	0.001	1.167

Note: DPF loading was accomplished with 59 Type I operating cycles. The mass inertia that was used for these tests was higher than in the current tests.

From the results of the cold tests, the weighted emission results can be calculated, and the corresponding K-factors. They are presented in Table 15.

Table 15 Weighted emission results and K-factors for the cold Euro test

	With regeneration	Without regeneration	Weighted emission results	K_i	Euro 3 limit values	% of Euro 3 limit	Euro 4 limit values	% of Euro 4 limit
	[g/km]	[g/km]	[g/km]	[-]	[g/km]	[%]	[g/km]	[%]
CO	0.54	0.14	0.15	1.039	0.64	23	0.5	30
HC	0.03	0.05	0.05	0.996				
NO$_x$	0.79	0.28	0.29	1.025	0.5	58	0.25	116
HC+NO$_x$	0.82	0.33	0.34	1.021	0.56	60	0.3	112
PM	0.282	0.001	0.005	4.958	0.05	10	0.025	20
CO$_2$	229.03	146.74	147.90	1.008				

Figure 48 shows that the vehicle complies with the Euro 3 limit values. The vehicle also complies with the Euro 4 PM-limit. Note that the current vehicle is obliged to comply with Euro 3, and not Euro 4.

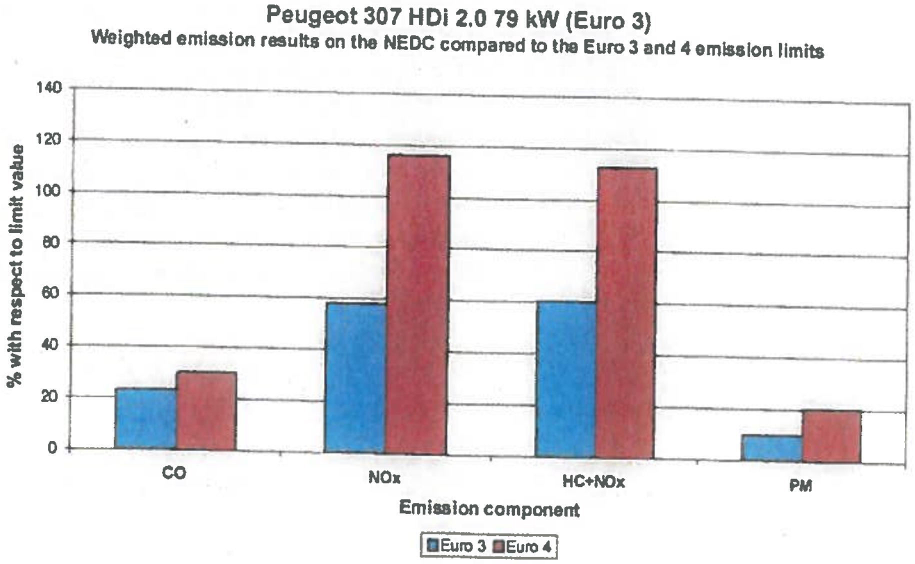

Figure 48 - Weighted emission results of the Peugeot HDi compared to Euro 3 and 4 limit values.

8.6.2 *Online particle flow measurements*

The online particle number as measured by the ELPI is an excellent tool to determine whether regeneration has started or not. Detailed results of these measurements can be found in Annex B. From Figure B.1 it can be seen that for the cold test with regeneration, no particles were observed during the first approximate 550 seconds, until the regeneration started. This coincided with the activation of some of the electronic accessories, as mentioned earlier. It was suspected that the regeneration phase was not finished after completion of one single NEDC. As prescribed by directive R83, consecutive NEDC cycles shall be driven if the regeneration requires more than one operating cycle. When complete regeneration is achieved, the cycle shall be completed.

As mentioned earlier (see paragraph 8.6.1), during the UDC part of the tests with regeneration, the cold test PM was much higher than the hot test PM. During the hot test, the regeneration started after 300 seconds (see Figures B.5 and B.6), while for the cold test it started much later, after 550 seconds. The high PM of the cold test, however, is not caused by the cold start. From Figure B.2 can be seen that at the end of the UDC part high peaks occur in the heavier stages of the ELPI measurements, especially from stage 6 (D_i = 432 nm, see table 16 for declaration of ELPI stages). Unlike the first stages, the higher stage numbers of the ELPI contribute significantly to the total particulate mass.

Table 16 Midpoint particle diameters for the ELPI stages.

ELPI stage #	D_i (nm)
1	27
2	39
3	70
4	144
5	261
6	432
7	724
8	1167
9	1855
10	2941
11	4914

During the tests without regeneration (see Figure B.3, B.4 and B.7) the particle flow was almost below detection limit for all stages. Some cold-start particles are observed during the first 150 seconds (see Figure B.3).

8.6.3 *Particle flow measurements and fuel sulphur content*

Combining the high particulate mass, the yellowish colour of the filters and the results from the particle flow measurements, it is concluded that the particles observed by the ELPI are sulphurous particles. This is caused by the high fuel sulphur content that was used during the loading phase of the DPF, leading to a high amount of sulphur accumulated in the filter.

Furthermore, it should be mentioned that especially the smaller stages of the particle size distribution measurement are prone to measurement artefacts. Dilution ratio, tunnel temperature and fuel sulphur content play an important role in this. Measurement phenomena such as spontaneous condensation, and coagulation (particles sticking together to form larger particles) may occur (see [5] for an explanation on these phenomena). High load conditions can cause a momentary low dilution ratio in the dilution tunnel. Especially when using high sulphurous fuel, this may lead to favourable conditions for spontaneous condensation of sulphurous components. This will be seen as sharp peaks in the smallest diameter range. If the concentration of these spontaneously formed particles is large, the collision probability of these particles will also be large, which may lead to larger particles due to coagulation. Some effects will therefore also be seen in higher ELPI stages.

The influence of high fuel sulphur content is also experienced in former measurements. In [7] is mentioned that fuel sulphur contents below 50 ppm are necessary to suppress the phenomenon of sulphur formation on the oxidation catalyst, leading to particulate matter emissions measured downstream the filter.

In the ACEA programme on emissions of fine particles from passenger cars [9], a Peugeot 607 HDi, equipped with a DPF was tested. In these tests fuel with a sulphur content smaller than 10 ppm was used. Particles were counted during regeneration, both with and without a thermodenuder[3]. The particles that were counted were almost all volatile, and in the range of 20nm.

8.7 Conclusions

- Due to the high sulphur content of the fuel that was used during the loading phase of the DPF, a high amount of sulphur was accumulated in the DPF. During regeneration, this was released. As a result the PM measurements were much higher than what was expected from the Type Approval value for this vehicle. Also, regeneration normally lasts shorter than experienced in the current tests. The results obtained are therefore regarded as a worst case scenario. Nevertheless, when calculating the weighted emission results according to Regulation 83, the vehicle still complies with the Euro 3, with PM being only 10% of the limit value.
- The test procedure as prescribed by Regulation 83 is very time-consuming and costly. Three emission tests need to be performed instead of one, and the loading phase of the DPF takes up a lot of time, due to the required consecutive driving of operating cycles. For future vehicles it is foreseen that the number of operating cycles to load the DPF will increase. Without the possibility for disabling regeneration, and without the co-operation of the vehicle manufacturer it is a very difficult procedure to execute. Cost and time consequences are huge in case of setback during the measurements.
- It is not obvious how to properly assess the emissions of a vehicle equipped with a periodically regenerating device under real-world circumstances, or on a cycle different from the Type I operating cycle. Similar to Regulations 83, the obvious method would be to load the DPF while driving consecutive real-world cycles. However, considering the various regeneration strategies that are stored in the engine ECU, it is likely that if the alternative cycle contains circumstances that are favourable to start the regeneration earlier, following the R83 procedure would yield an incorrect reflection of the real-world circumstances. It would be desirable to have an adapted methodology for in-use compliance testing as well as for assessing real-world emissions.

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3) A thermodenuder removes the volatile material condensed onto the particles, and the particles that are completely volatile.

8.8 Acknowledgements

TNO Automotive would like to thank [redacted] and [redacted] of PSA Peugeot Citroën (Centre Technique de la Garenne) in France, and [redacted] of Peugeot Nederland N.V., for putting a vehicle at our disposal and preparing it for this test. Special thanks to [redacted] and [redacted] for their kind assistance during the measurements and to [redacted] for his advice on the evaluation of the results.

9 Particle emission characteristics of direct injected petrol engines

9.1 Technology description

As described in chapter 2, emission measurements were performed on three vehicles that use petrol direct injection technology:

- Citroen C5 2.0 HPi
- Alfa Romeo 156 JTS
- Renault Laguna 2.0 16v IDE

The vehicles were all tested on the NEDC cold cycle, and on the CADC hot cycle.

To investigate the allegedly increased particulate emission of this technology, measurements of particulate mass and number emission were performed. An Electronic Low Pressure Impactor (ELPI), see also chapter 8, was used to monitor the particle number emission. Downstream the exhaust gas aftertreatment system a lambda sensor was mounted in the exhaust gas flow, to monitor the switch between the different combustion modes that can occur. During the heterogeneous combustion mode, the value of the lambda has no meaning as an absolute value, because areas with different lambda values exist inside the combustion chamber.

The vehicle manufacturers use different approaches in the petrol direct injection technology. Below a brief description is given:

1. *Citroen C5 HPi*
   The Citroen C5 HPi engine is a direct injected petrol engine, using stratified charged combustion up to 3500 rpm, and above homogeneous combustion. Up to 30% EGR is applied in the stratified charge mode. In the homogeneous mode, the mixture is either stoichiometric or rich.
   The exhaust gas aftertreatment system consists of an oxidation catalyst and a NO_x storage catalyst, that also functions as a three-way catalyst at $\lambda = 1$.

2. *Alfa Romeo 156 2.0 JTS*
   The Alfa Romeo 156 2.0 JTS uses stratified combustion up to 1500 rpm. Above this the engine operates in a homogeneous, stoichiometric combustion mode. The engine is trimmed for performance rather than fuel economy.
   The exhaust aftertreatment system consists of a three way catalyst, as the predominant stoichiometric operation does not require the use of a NO_x storage catalyst.

3. *Renault Laguna 2.0 16V IDE*
   The Renault Laguna 2.0 16V IDE operates always in a homogeneous combustion mode. The exhaust aftertreatment system consists of a three-way catalyst. The engine uses 3 preset EGR modes. Under light and moderate load conditions the EGR ratio may be up to 25%. The full load conditions use no EGR.

9.2 Measurement results

9.2.1 *Particle mass measurements*

Particle mass was measured separately for all the cycle parts. Table 17 shows the measurement results of the particulate mass measurements for the three direct injected petrol vehicles. In some cases large differences are observed between the urban and the extra-urban results. In the next paragraph this will be discussed in combination with the results of the particle number measurements.

Table 17 PM measurement results of the three direct injected petrol cars [g/km].

Cycle	**Citroen C5 HPi**	**Alfa Romeo 156 JTS**	**Renault IDE**	**Laguna**
UDC	0.004	0.015	0.010	
EUDC	0.002	0.002	0.003	
NEDC	***0.003***	***0.007***	***0.006***	
CADC urban	0.003	0.015	0.002	
CADC rural	0.003	0.004	0.003	
CADC motorway	0.010	0.014	0.007	
CADC	***0.007***	***0.010***	***0.005***	

9.2.2 *Particle number measurements*

9.2.2.1 *Citroen C5 HPi*

Detailed results from the particle number and lambda measurements can be found in Annex C.

NEDC

Figure C.1 shows that the particle concentration is during the entire test cycle approximately on the same level, dominated by the smallest particles (midpoint diameters are 27 and 39 nm for stages 1 and 2 respectively). Stages 6 to 11 have not been included in this figure , since the emissions of the heavier particles was below the detection limit.

The peaks observed in particle flow during the cold start were only slightly higher than during the remainder of the cycle, especially for particles with a higher diameter (ELPI stage 4).

From the lambda signal (Figure C.2) it can be seen that the engine operates in heterogeneous mode during the urban part of the cycle, except during accelerations. The cold start enrichment lasts until just after the first time the speed of 50 km/h is reached.

In the extra-urban cycle, during the acceleration from 70 to 100 km/h, the engine no longer operates in the heterogeneous mode, but switches to the homogeneous stoichiometric mode, as can be seen from the lambda signal. At this point there is a noticeable drop in particle concentration. Particle peaks are again seen during the brief 120 km/h part. A throttle release coincides with an infinite lambda value, in the figures cut off at a lambda value equal to 3.

CADC

- *CADC Urban*
  During the urban part, both the particle flow and lambda behave similarly to what is seen during the UDC (see Figures C.3 and C.4). From approximately 750 seconds onwards, no lean conditions are observed anymore, but lambda remains equal to 1 (mostly), despite the fact that there is no obvious change in the cycle pattern. Also the particle flow is lower from this point on.

- *CADC Rural*
  Figure C.5 shows that the particle flow during the rural part is lower than during the urban part, except at the steep acceleration in the end. Momentary changes to rich conditions (lambda $\lambda = 0.8$) are observed (Figure C.6), which coheres with the NO_x storage system. In the "constant speed" section, more about this is explained.

- *CADC Motorway*
  Figure C.7 shows the results from the motorway part. High peaks are observed in particle flow, for the first three stages of the ELPI. During the first part where the speed exceeds 120 km/h, the mixture is rich (lambda $\lambda = 0.8$) for a longer period of about 300 seconds. After that, it is stoichiometric again until the end of the cycle (Figure C.8).

  The rich condition arises to regenerate the NO_x storage system. Sulphur builds up on the catalyst surface, and rich conditions are required to remove this.

Constant Speed tests
The constant speed tests were performed, while monitoring the lambda signal and the particle flow. Figure 49 and 50 show the results.

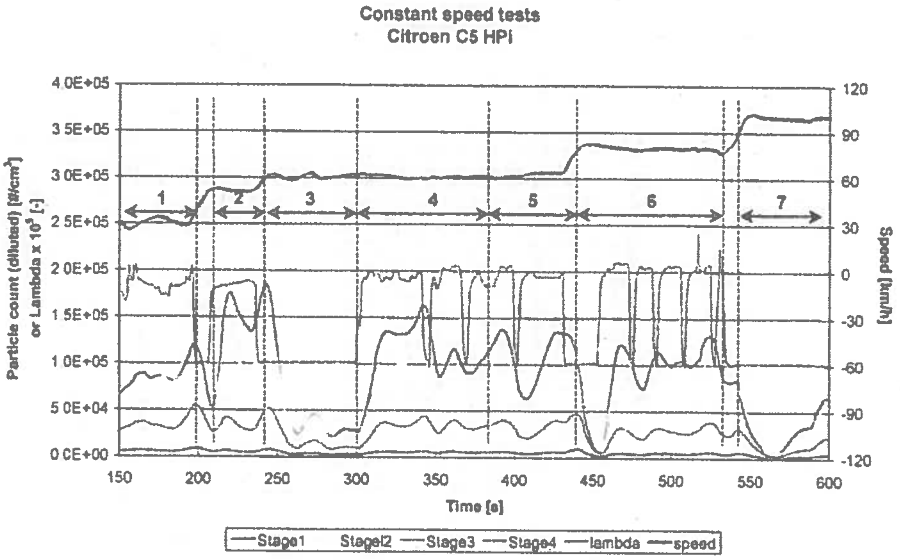

Figure 49 - Lambda signal and online particle flow as measured by the ELPI during various constant speed tests (index of numbers in Table 18).

Table 18 Various constant speeds, engine speeds, gear position and lambda signal as indicated in Figures 49 and 50.

	Speed	Engine speed	Gear	Combustion	Lambda
	[km/h]	[rpm]			[-]
1	30	2000	2	Stratified	Lean
2	50	3400	2	Stratified	Lean
3	60	4000	2	Homogeneous	Stoïchiometric
4	60	2700	3	Stratified	Lean
5	60	2000	4	Stratified	Lean
6	80	2600	4	Stratified	Lean
7	100	3500	4	Homogeneous	Stoïchiometric
8	120-100	3500-2900	5	Homogeneous	Rich
9	140	4000	5	Homogeneous	Rich

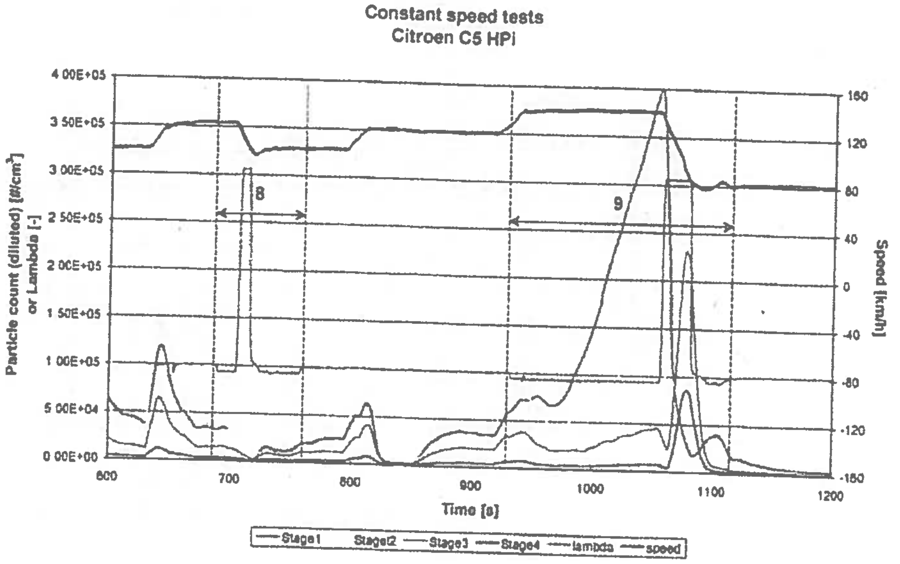

Figure 50 - Lambda signal and online particle flow as measured by the ELPI (index of numbers in Table18).

The measurement observations show that the combustion becomes homogeneous in the following conditions

- During accelerations, when excess engine power is required
- When the engine speed exceeds 3500 rpm.
- During heterogeneous (stratified) combustion the mixture switches periodically to homogeneous (stoichiometric) conditions for a short time. The interval is approximately 15 to 20 seconds.

From Figure 49 can be seen that there is a sudden decrease in particle flow when the mixture becomes homogeneous (stoichiometric).

It was also observed that the mixture can become rich during longer periods of time. These conditions occur when the NO_x storage catalyst needs to be disposed of sulphur deposits. High load conditions are favourable for this.

Figure 50 shows the influence of rich conditions on the particle flow. The first area with rich conditions (8) shows a relatively low particle count, while in the second area (9) the particle concentration increases until throttle release. It is likely that the particles are formed by the release of sulphur from the NO_x storage catalyst. The first attempt in Figure 50 may not have been long enough to release any sulphur.

Conclusions for the Citroen C5 HPi

- Heterogeneous, lean combustion is only observed in the Eurotest cycle and in case of real-world driving only in urban conditions. During lean combustion in stable operating conditions, the mixture becomes periodically stoichiometric, approximately each 15 to 20 seconds, to reduce the NO_x that is stored on the catalyst.

- During heterogeneous, lean combustion conditions, more particles are observed. This accounts especially for the first three stages of the ELPI.
- In rural and motorway situations the mixture is homogeneous, and mostly stoichiometric.
- During high load operating conditions, the (homogeneous) mixture can also become rich temporarily. This is to clean the NO_x storage catalyst of sulphur deposits.

9.2.2.2 *Alfa Romeo 156 2.0 JTS*

Detailed results from the particle number and lambda measurements for this vehicle can be found in Annex D.

NEDC - UDC

Figure D.1 shows that the particle concentration is approximately on the same level during the entire UDC, and is dominated by second and third stage of the ELPI (particle diameters between 31 and 50 nm for the second stage and 50 and 98 nm for the third stage). Particle peaks are mainly observed during idle, when the engine runs in stratified combustion mode.

As mentioned earlier, below 1500 rpm the engine switches to the stratified combustion mode. This can be seen from the lambda trace (Figure D.2), showing high values during idle. Note that the lambda is in this case the overall lambda of the mixture. While not idling, the mixture is still lean but closer to stoichiometric.

NEDC - EUDC

During the EUDC the particle concentration is considerably lower than during the UDC. During accelerations, some particles are observed, albeit significantly lower than during the UDC. The lambda trace shows that these emissions coincide with a switch to stoichiometric instead of lean combustion.

The PM as measured during the urban part of the Eurotest cycle is higher than during the extra-urban part (0.015 and 0.002 g/km respectively). The particle flow as measured by the ELPI confirms this. The higher ELPI stages contribute more in PM than the lower stages. High peaks as observed during the UDC in the fourth stage are absent during the EUDC. This explains the large difference between their respective PM values.

CADC

During the CADC cycle, large differences in particle flow and PM were observed for the three cycle parts.

- *CADC Urban*
  For the urban part of the CADC, peaks were observed that were similar in magnitude as for the UDC. The lambda trace is indicative for where the engine switches from heterogeneous (stratified) to homogeneous mode. Similar to the UDC, the particle peaks coincide with the stratified mode.

- *CADC Rural*
  During the rural part of the CADC, the particle flow was very low, except for a large peak in the first ELPI stage (particles from 24 to 31 nm), coinciding with the part where the highest cycle speed occurs.

- *CADC Motorway*
  During the motorway cycle the particle concentration builds up, especially for particles in the nano-size range. It is plausible that for this high load condition, sulphur that has been accumulated on the surface of the catalyst is released, and forms droplets.

Constant speed

The particle flow was measured during constant speed driving, at various speeds. Figure 51 shows the results of the first three ELPI stages. At all speeds particles were around the detection limit. Only during idling, when the combustion is stratified, some particles are observed.

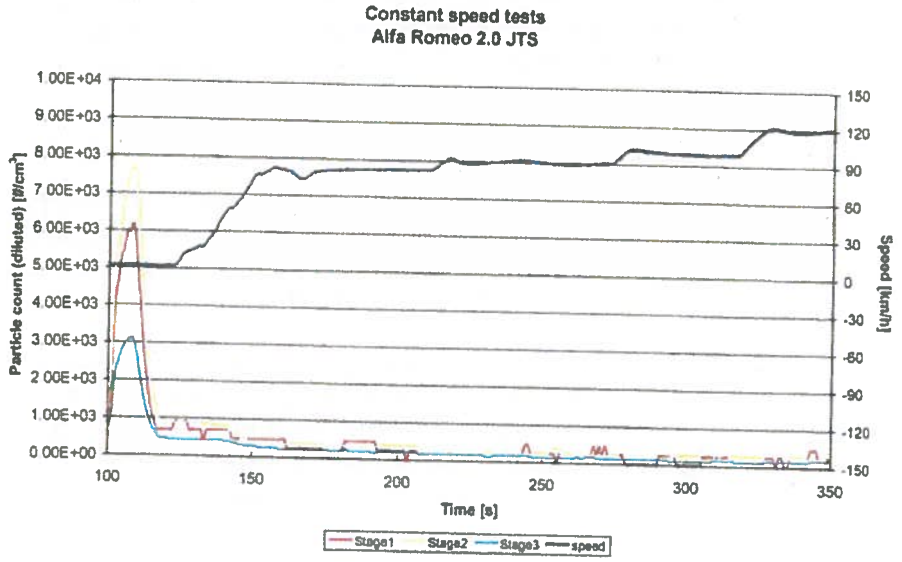

Figure 51 - Particle flow during constant speed driving, for the Alfa Romeo 156 JTS

Conclusions for the Alfa Romeo 156 JTS

- The engine of the Alfa Romeo 156 2.0 JTS switches from heterogeneous (stratified) to homogeneous combustion at an engine speed of 1500 rpm. During stratified combustion more particles are observed than during homogeneous combustion.
- Low and moderate load conditions are typical for urban driving conditions. Therefore, in urban conditions the engine of the Alfa Romeo 156 2.0 JTS is frequently in the stratified combustion mode. As a consequence, relatively many particles are emitted, and the PM values are higher than under extra-urban conditions.

9.2.2.3 *Renault Laguna 2.0 IDE*

For this vehicle, detailed results from the particle number and lambda measurements can be found in Annex E.

NEDC

Figure E.1 shows the results of the particle flow measurements of the first four ELPI stages, during the cold Eurotest. The flow is dominated by the second ELPI stage (particles in the size range from 31 to 50 nm). Due to the cold start, during the first elementary urban cycle the peaks are slightly higher compared to the rest of the UDC.

The lambda trace in Figure E.2 shows that the mixture is lean during constant speed driving and modest accelerations. During higher power demands, as in the EUDC, the mixture becomes stoichiometric. During idling, the mixture becomes very lean (in Figure E.2 values are cut off at lambda 3). This may be due to the high EGR ratio during low load conditions.

CADC

- *CADC Urban and rural*
  During the urban and rural part of the CADC, the particle flow is on a comparable level as during the UDC (see Figures E.3 and E.5). The lambda trace (Figure E.4 and E.6) shows that the mixture becomes stoichiometric during higher power demands, as already observed during the EUDC.
  During the steep acceleration in the rural part of the CADC, the lambda trace shows that the mixture becomes stoichiometric for a longer period of time. This coincides with some large peaks in particle emissions.
  In the rural part of the cycle, on very few occasions a small jump to rich conditions is observed. However, this does not coincide with high load conditions. It is not clear whether this is an intentional lambda-excursion or not.

- *CADC Motorway*
  During the motorway part of the CADC, the particle flow is again dominated by the second ELPI stage, as shown in Figure E.7. Unlike the other cycle parts, there are also more particles observed in the higher ELPI stages. This is confirmed by the larger PM value for the motorway compared to the urban and rural part (PM =

0.007 g/km for the motorway, and 0.002 and 0.003 g/km for the urban and the rural part respectively).
The lambda trace (Figure E.8) shows that lean conditions hardly occur any more, due to the high load conditions in the CADC motorway.

Conclusions for the Renault Laguna

- The Renault Laguna IDE has a homogeneous gasoline direct injected engine.
- During all test cycles, the particle flow is dominated by particles in the range of 31 to 50 nm.
- More particles are produced during high power demands, when the mixture becomes stoichiometric, instead of lean.
- During idle, the mixture becomes extremely lean, which may be caused by the high EGR ratio.

9.3 Comparison of DI petrol engines with modern diesel and petrol engines

From the online particle flow as measured during the NEDC, a particle size distribution can be constructed, yielding the number of particles per km for each ELPI stage.
In recent investigations at TNO, direct injected diesel passenger cars and multi-point indirect injected petrol cars were also measured using the same measurement set-up. The results of three vehicles that were comparable to the ones in the current investigation are averaged, for diesel DI and petrol IDI respectively. Also, the results of the three vehicles that are measured in the current investigation are averaged. Figure 50 shows the results. As can be seen, the direct injected petrol engines emit more particles than the conventional indirect injected petrol vehicles, but not as many as the direct injected diesel vehicles.
From Figure 52 can be seen that on the NEDC direct injected petrol engines emit approximately 10% of the particle number per km of direct injected diesel vehicles. Indirect injected petrol engines again emit approximately 10% of the particle number per km of direct injected petrol vehicles.

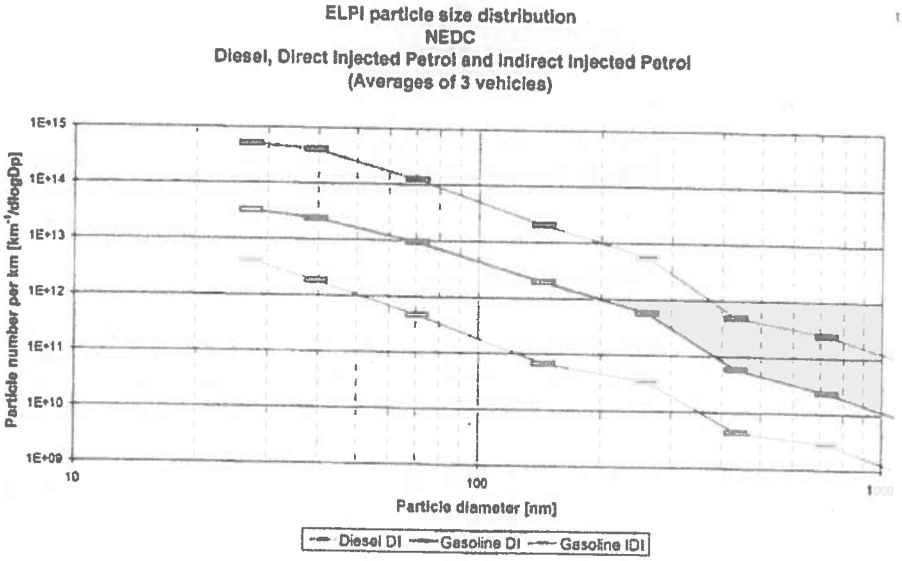

Figure 52 - Particle size distribution during the NEDC.

9.3.1 *Overall conclusions*

- A wide variety in direct injected gasoline engine strategies exists. Basically there is heterogeneous, stratified (lean) combustion, and homogeneous lean or stoichiometric combustion. Heterogeneous combustion is often only applied at lower and moderate power demands. At higher power demands, the engine switches to homogeneous combustion. Under high load conditions the mixture can also become rich.
- Generally, during heterogeneous combustion, more particles are observed than during homogeneous combustion under moderate load conditions. These are mainly particles in the range from 31 to 50 nm. The heterogeneous combustion mode occurs at low load conditions, for instance in urban situations. Particles in this size range do not contribute significantly in mass, therefore this effect is only observed with online particle measurements, such as with an ELPI.
- During high load situations, all technologies operate in the homogeneous mode, either stoichiometric or rich. In this case high particle counts are seen, in the range from 24 to 100 nm. This may be caused by the release of sulphur deposits on the catalyst surface, being released at high temperature.
- Direct injected petrol engines emit higher particle numbers than indirect injected petrol engines, but not as high as direct injected diesel engines. On the NEDC, direct injected petrol engines emit approximately 10% of the particle number per km of direct injected diesel vehicles. Indirect injected petrol engines again emit approximately 10% of the particle number per km of direct injected petrol vehicles.
- In the current investigation three different technologies were measured, amongst which one homogeneous and two heterogeneous stratified combustion engines, of which one with a NO_x storage catalyst. Only one vehicle was measured for each technology. The observed effects may therefore be vehicle specific to some extent, and conclusions regarding particulate emissions and the applied technology should be handled with caution.

10 Additional work

Apart from the work described in this report, several other topics were carried out in 2003 in the context of the In-Use Compliance Programme.

10.1 Taakgroep Verkeer en Vervoer

Just like previous years, in 2003 TNO Automotive participated in the "Taakgroep Verkeer & Vervoer", in which also the Dutch Institute for Public Health and Environment (RIVM) and the Dutch Statistics Institute (CBS) participate. The goal of this workgroup is gathering emission data on transport for the annual Dutch emission inventory. TNO Automotive delivers emission data for passenger cars, light duty vans and heavy duty vehicles. These data are derived from the emission results gathered in the In-Use Compliance programme.

Apart from its basic task, the workgroup also acts as a discussion forum for any topic on (transport) emissions.

10.2 DACH+NL

Germany, Austria and Switzerland also run In-Use Compliance programmes. In order to be able to exchange ideas and results between those countries and to increase the international harmonisation of emission factors, a discussion forum was set up in 1998. In 1999 the Netherlands also became a member of the group, that meets two or three times annually. In 2003 Sweden participated in one meeting as well.

10.3 Artemis

Unlike previous years, in 2003 the work under the 5th framework project Artemis unfortunately has come to a halt due to circumstances that are outside the scope of this report. Early 2004 the difficulties have been resolved and the participating institutes have resumed their work. The results from Artemis, being harmonised and integrated emission models for all transport modes are expected now for early 2005.

The work of TNO Automotive in Work Package 300 (on passenger cars) and Work Package 500 (on motorcycles) is co-financed by the Dutch Ministry of Housing, Spatial Planning and the Environment as part of the contract for the In-Use Compliance programme.

11 References

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A Emissions and Congestion: detailed results

Emissions and Congestion: detailed results

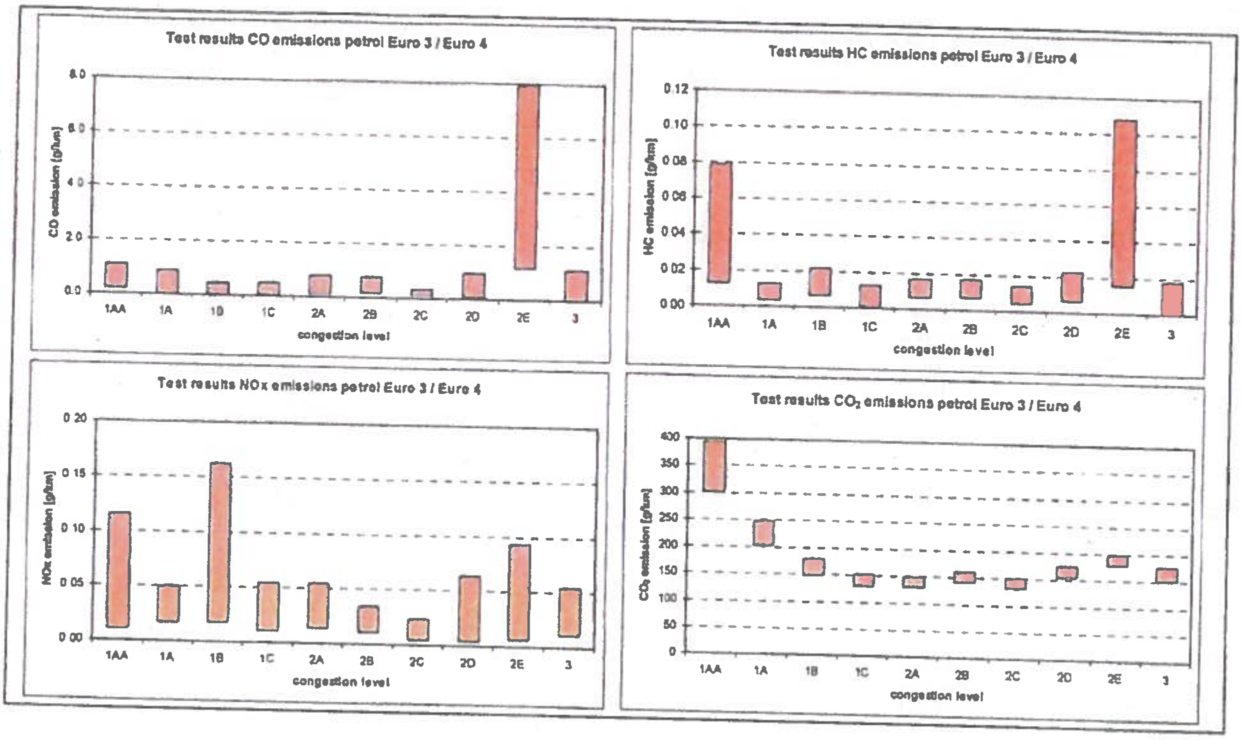

Figure A.1: Emissions and congestion: petrol vehicles Euro 3 and Euro 4.

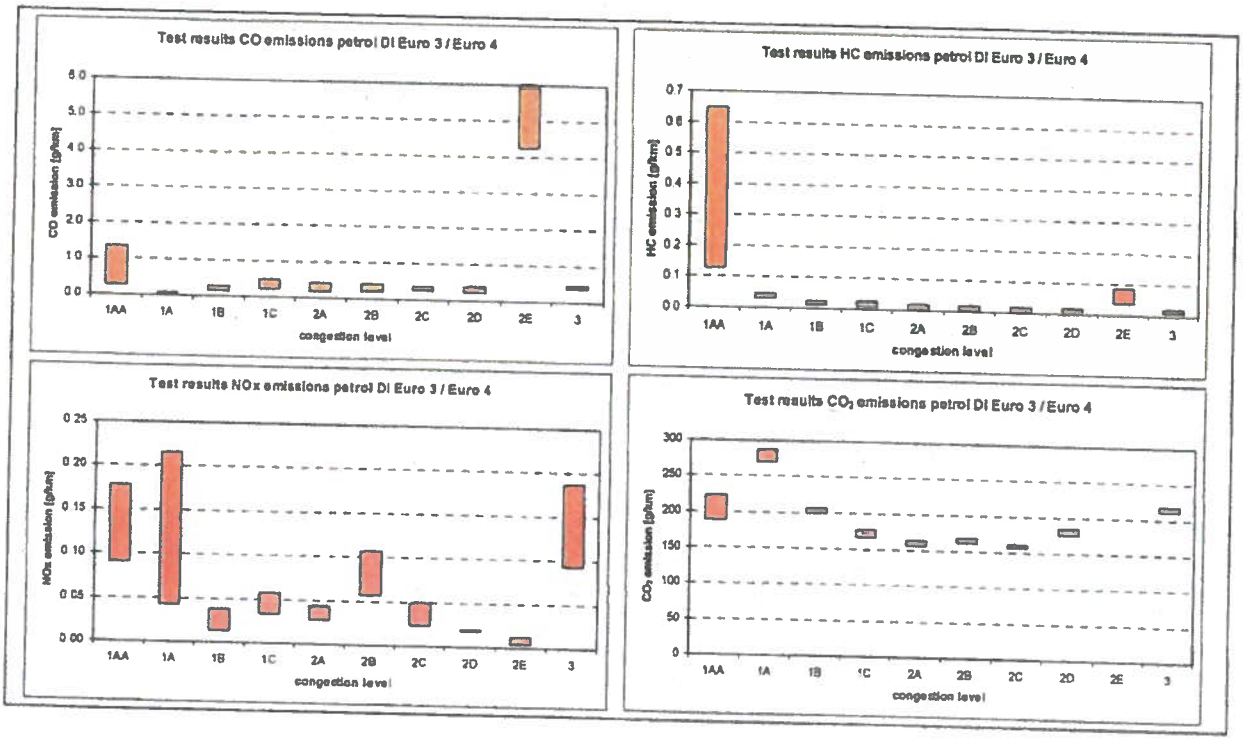

Figure A.2: Emissions and congestion: petrol DI vehicles Euro 3 and Euro 4.

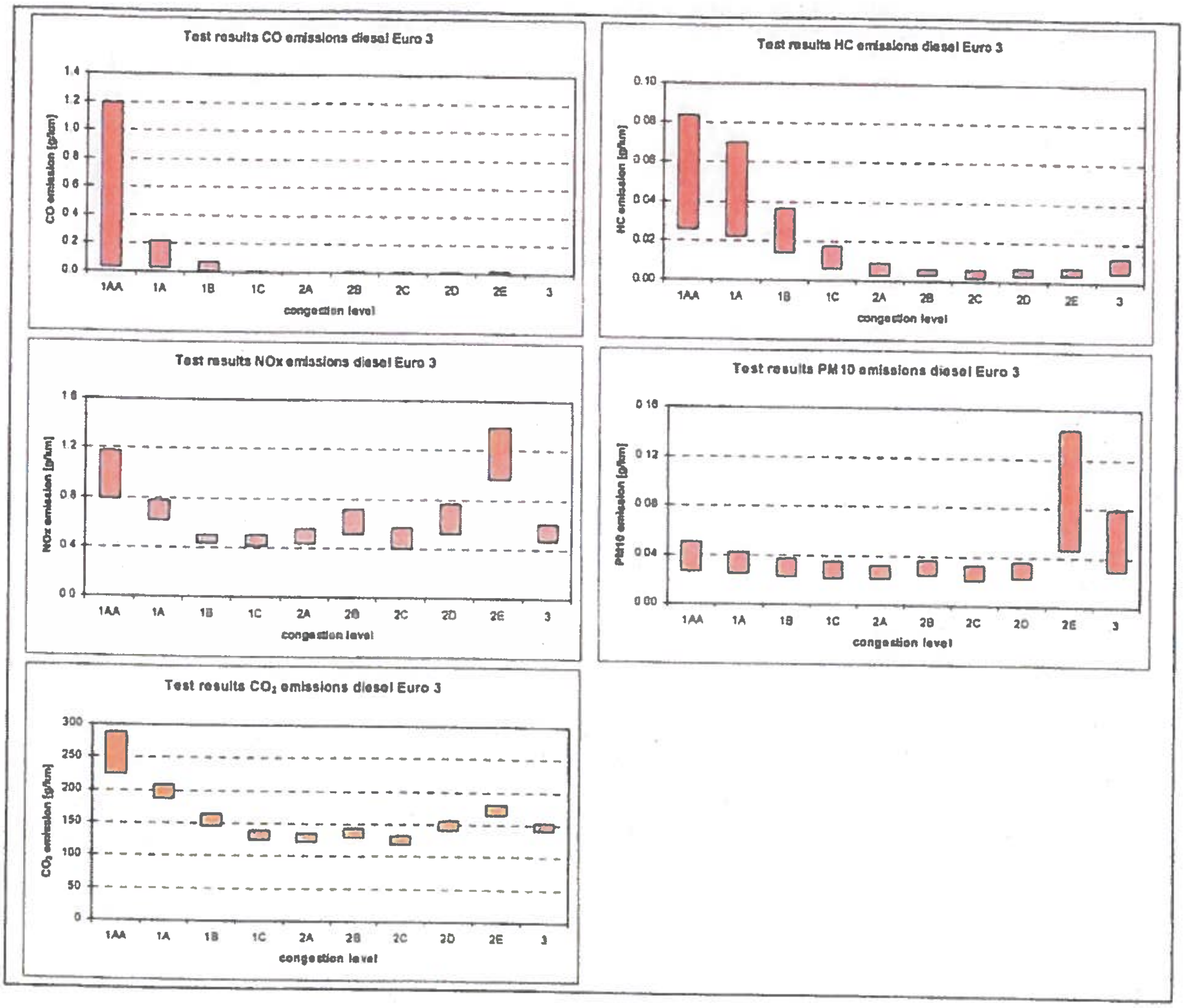

Figure A.3: Emissions and congestion: diesel vehicles Euro 3

B Online particle count measurements of the Peugeot 307 HDi with DPF

Online particle count measurements of the Peugeot 307 HDi with DPF

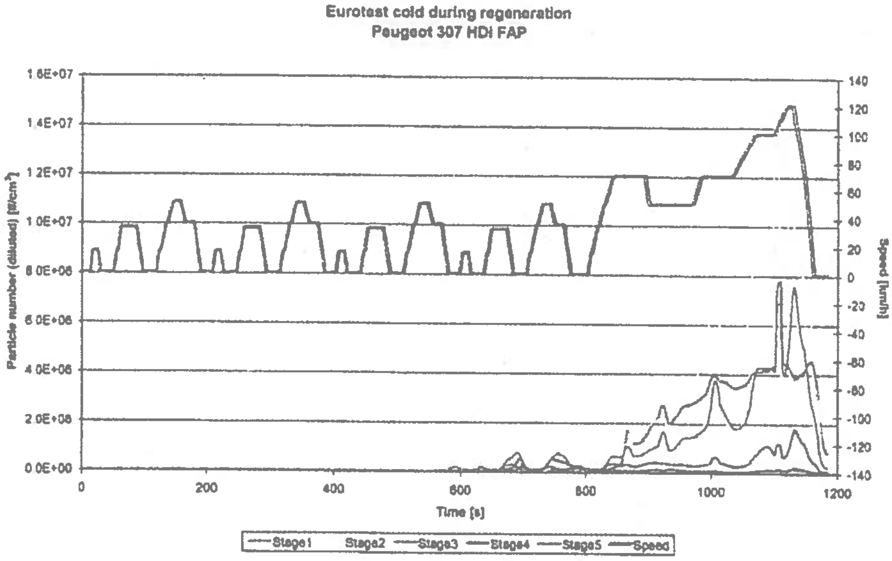

Figure B.1: Online particle count as measured by the ELPI during regeneration (cold start): stages 1 to 5.

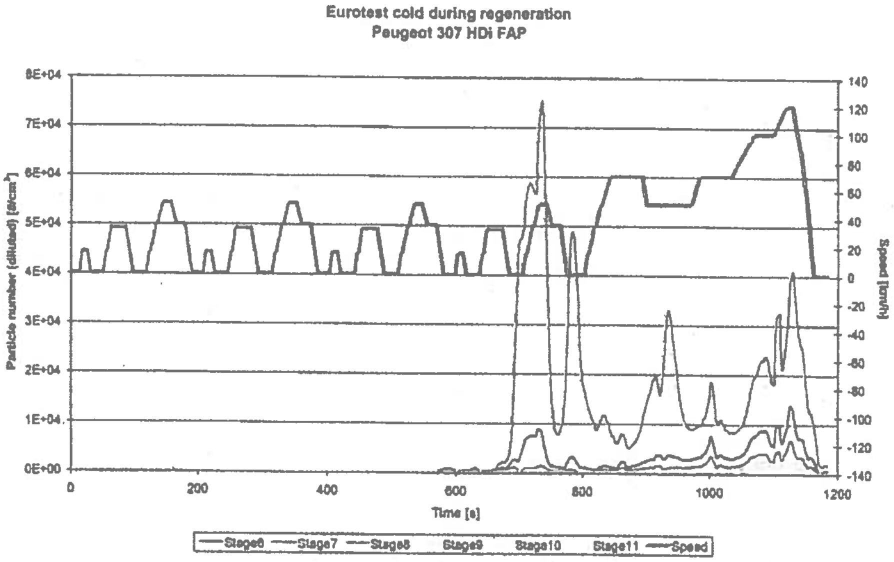

Figure B.2: Online particle count as measured by the ELPI during regeneration (cold start): stages 6 to 11

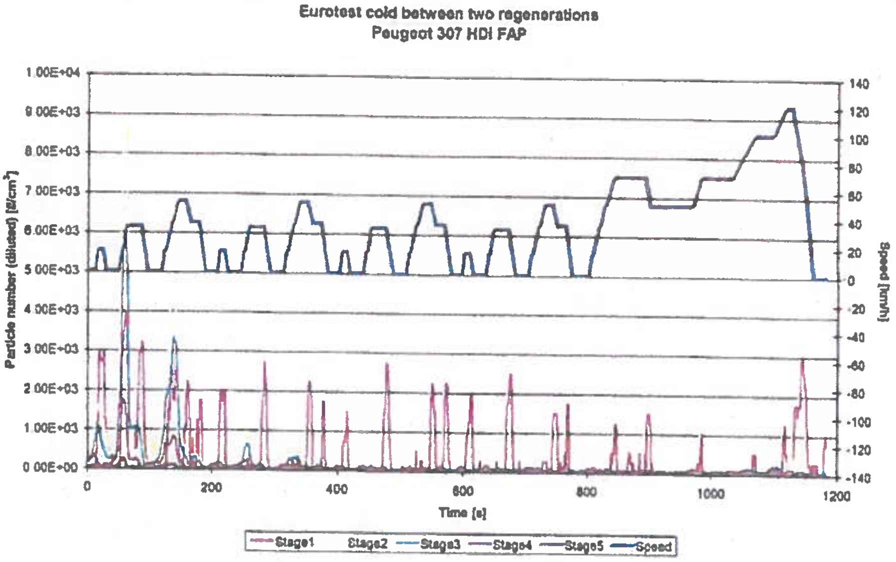

Figure B.3: *Online particle count as measured by the ELPI between two regenerations (cold start): stages 1 to 5*

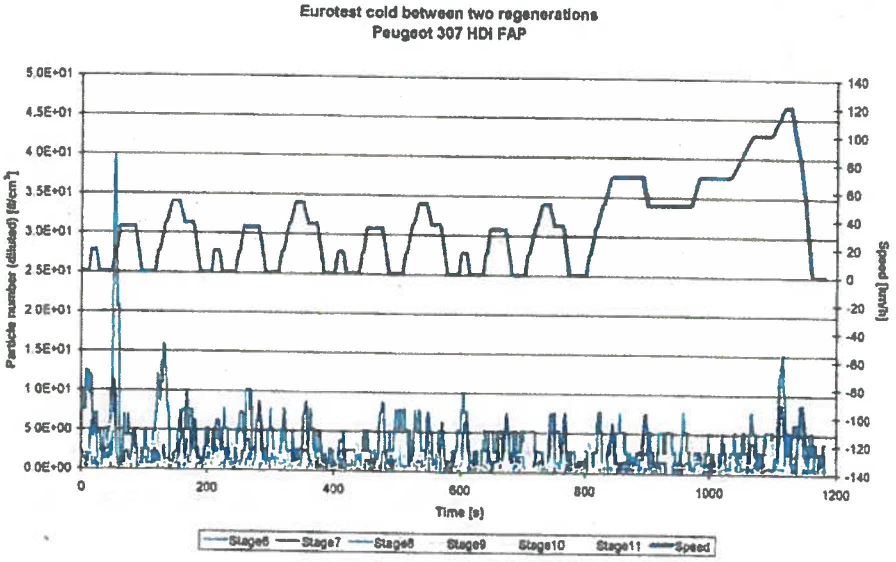

Figure B.4: *Online particle count as measured by the ELPI between two regenerations (cold start): stages 6 to 11*

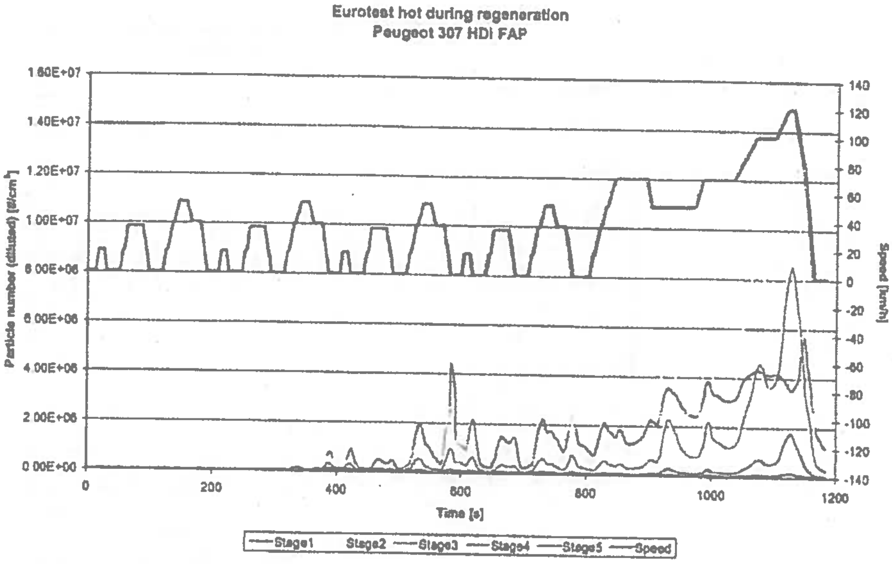

Figure B.5: Online particle count as measured by the ELPI during regeneration (hot start): stages 1 to 5

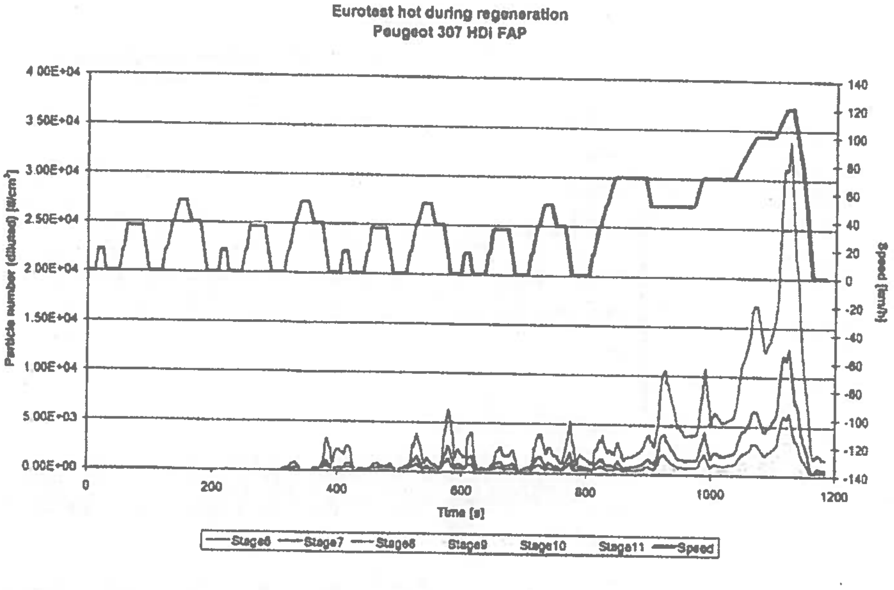

Figure B.6: Online particle count as measured by the ELPI during regeneration (hot start): stages 6 to 11

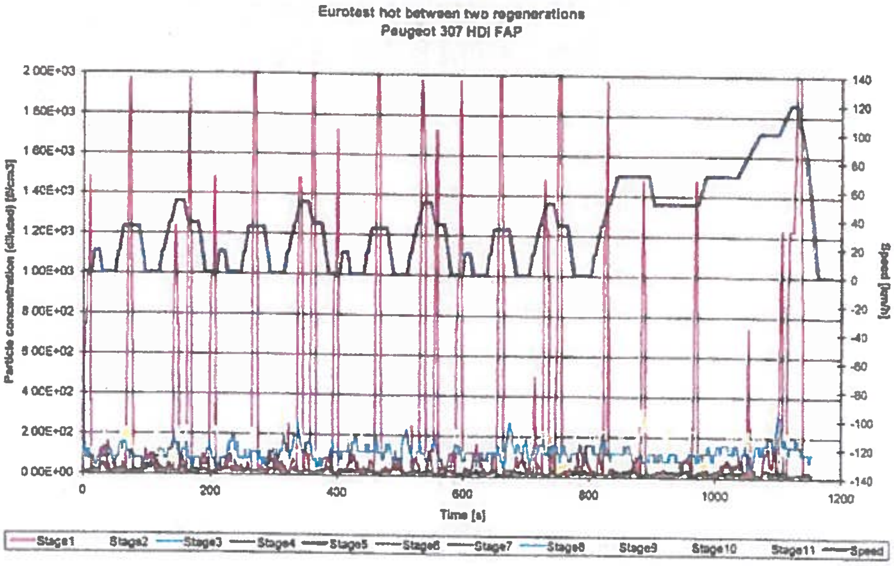

Figure B.7: Online particle count as measured by the ELPI between two regenerations (hot start)

C Online particle number and lambda measurements for the Citroen C5 HPi

Online particle number and lambda measurements for the Citroen C5 HPi

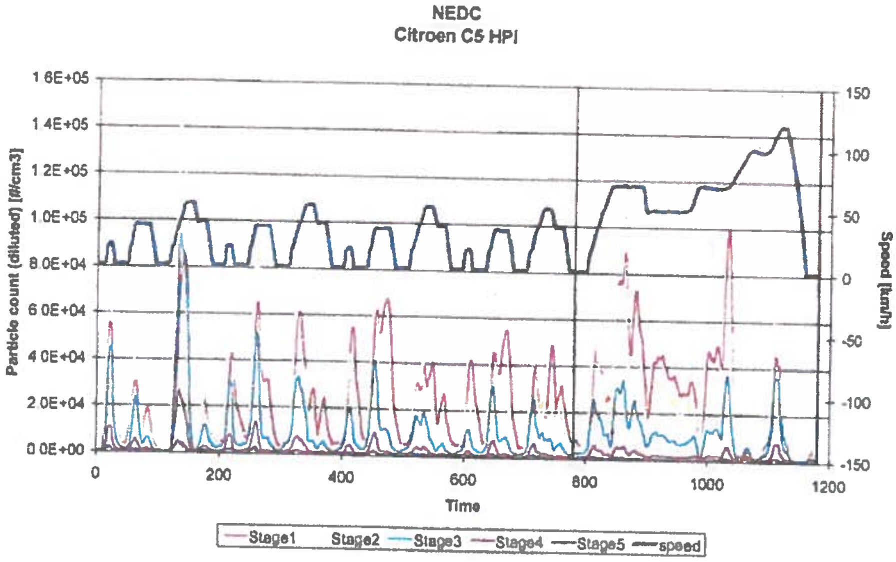

Figure C.1: Particle number during the Eurotest of the Citroen C5 HPi

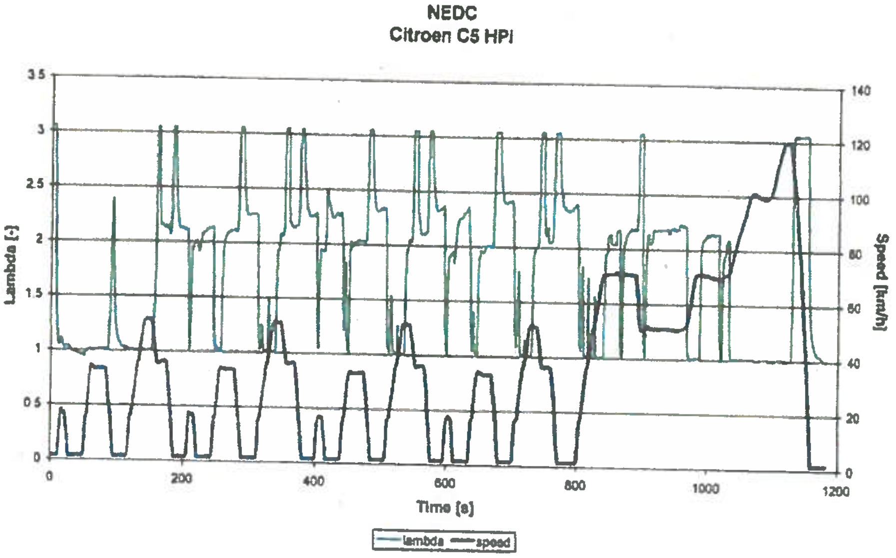

Figure C.2: Lambda signal during the Eurotest of the Citroen C5 HPi

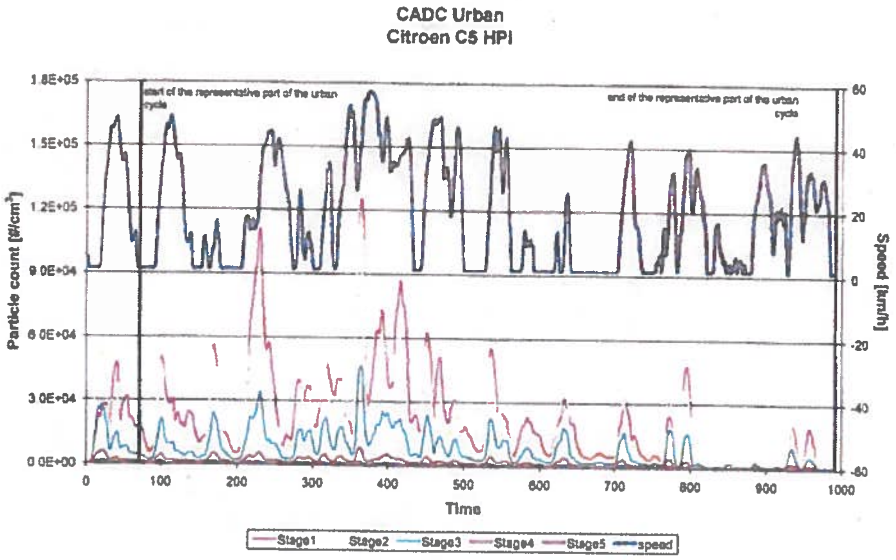

Figure C.3: Particle number during the CADC Urban cycle of the Citroen C5 HPi

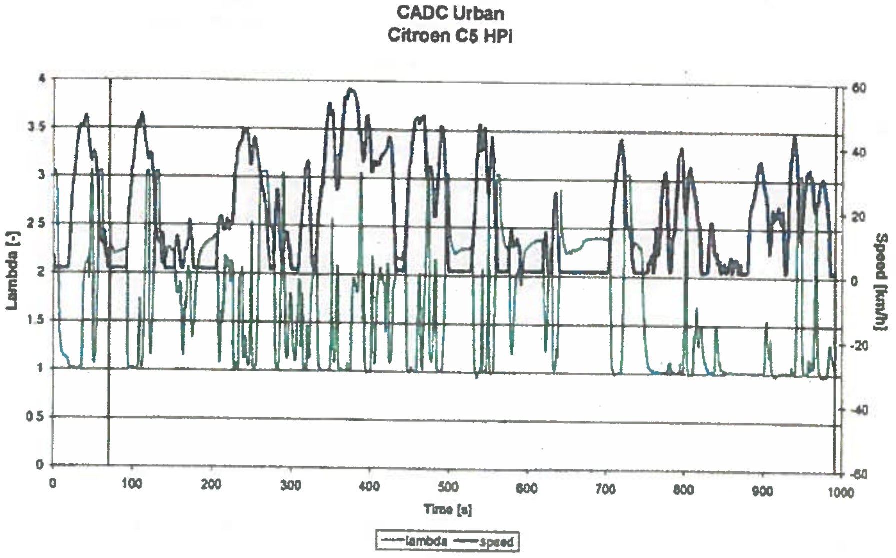

Figure C.4: Lambda signal during the CADC Urban cycle of the Citroen C5 HPi

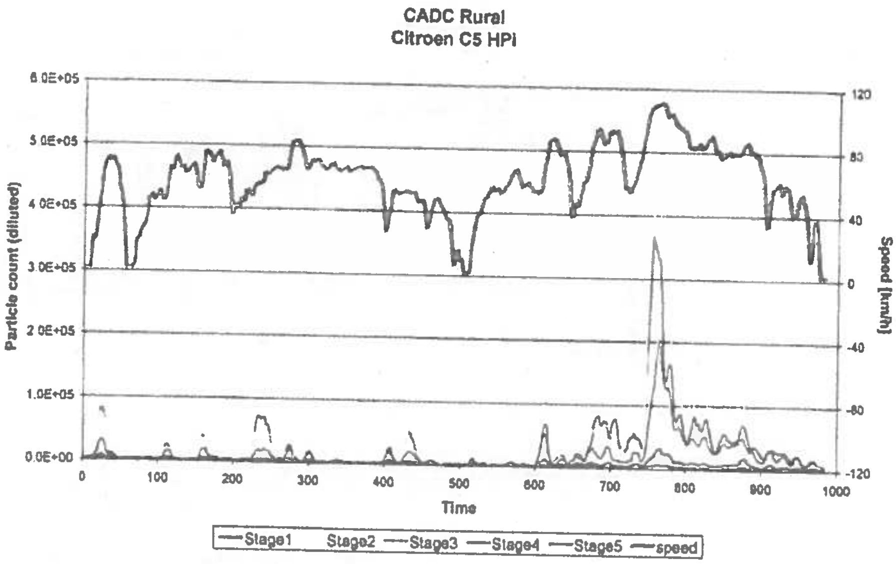

Figure C.5: Particle number during the CADC Rural cycle of the Citroen C5 HPi

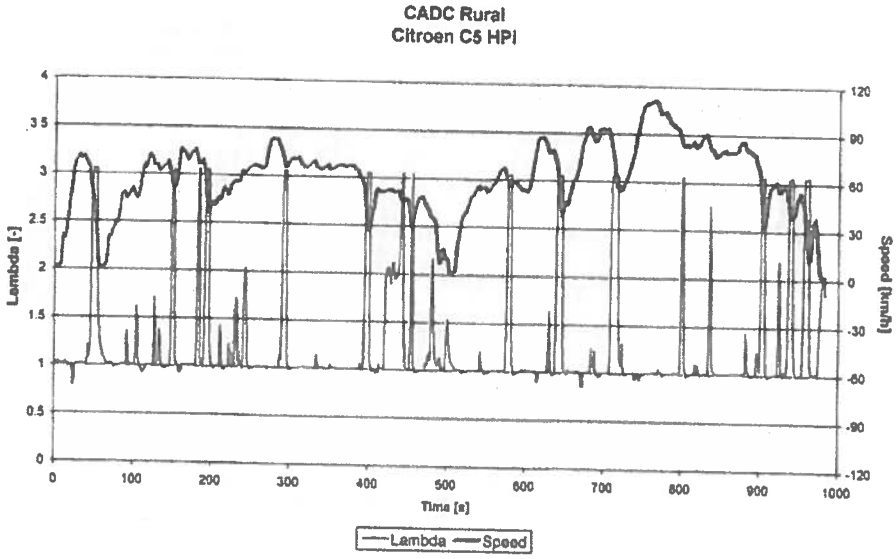

Figure C.6: Lambda signal during the CADC Rural cycle of the Citroen C5 HPi

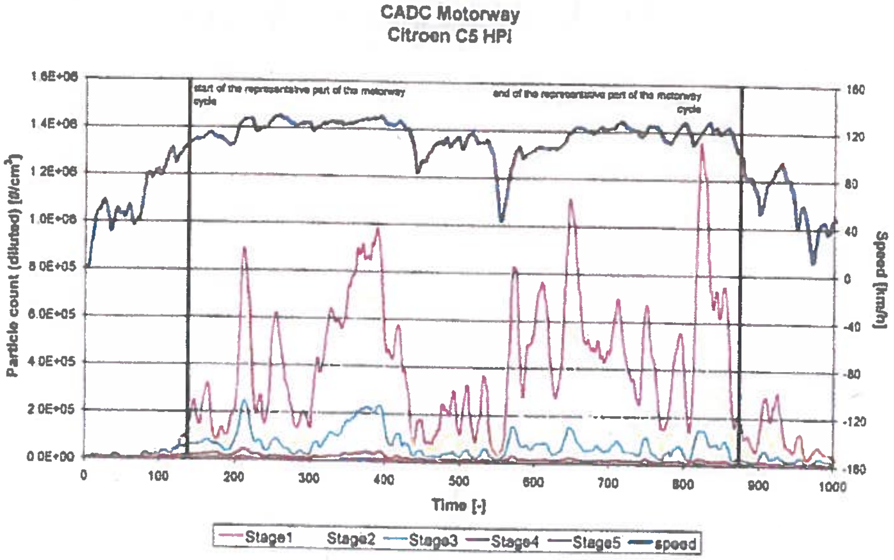

Figure C.7: Particle number during the CADC Motorway cycle of the Citroen C5 HPi

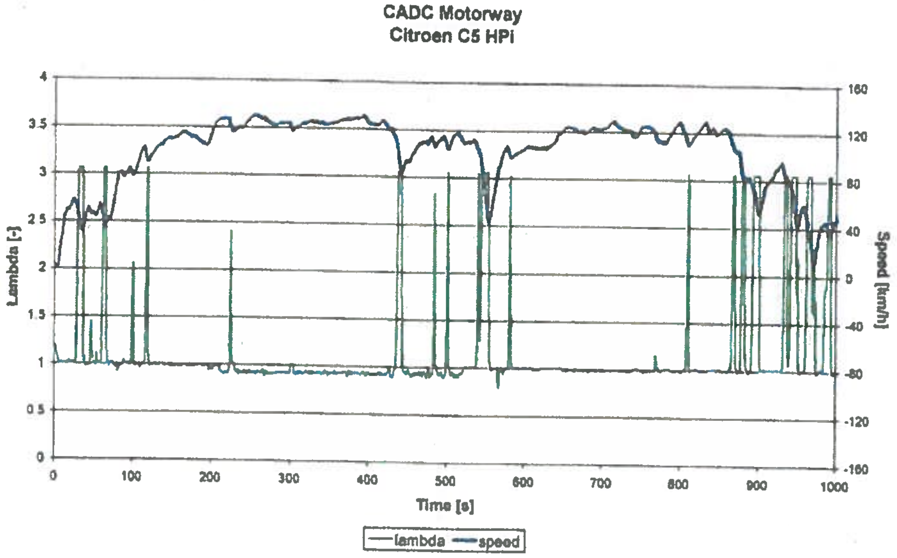

Figure C.8: Lambda signal during the CADC Motorway cycle of the Citroen C5 HPi

D Online particle number and lambda measurements for the Alfa Romeo 156 JTS

Online particle number and lambda measurements for the Alfa Romeo 156 JTS

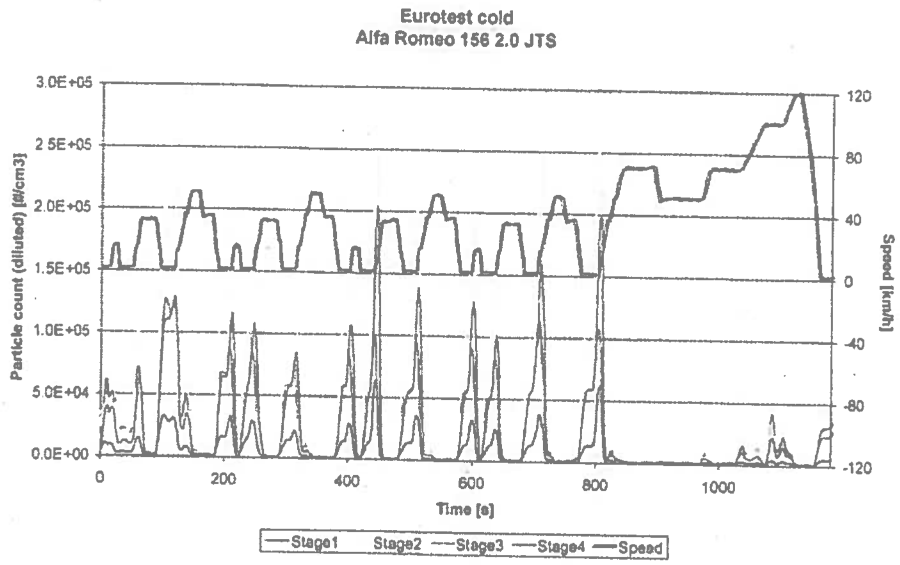

Figure D.1: Particle number during the Eurotest for the Alfa Romeo 156 2.0 JTS

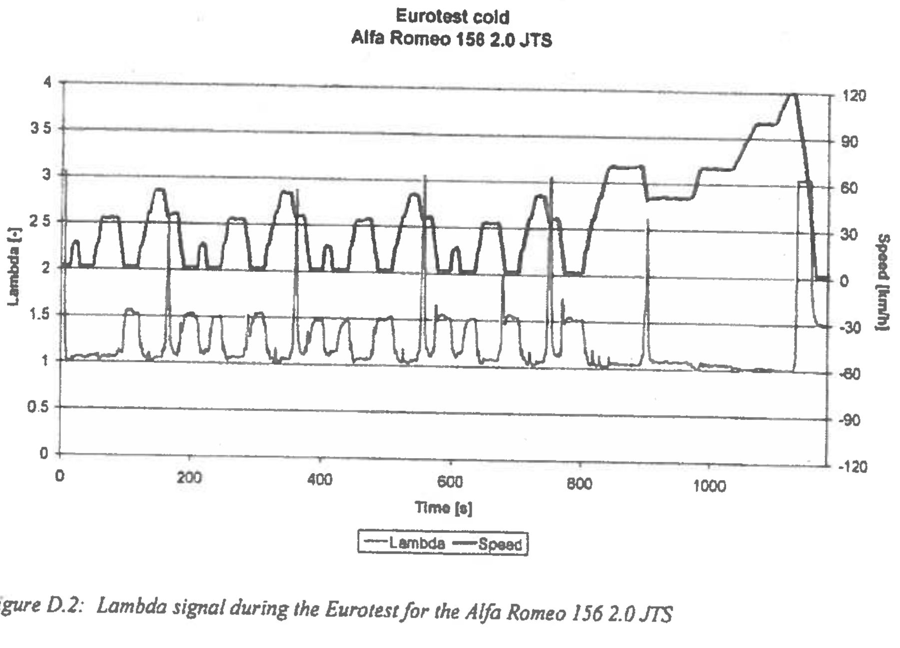

Figure D.2: Lambda signal during the Eurotest for the Alfa Romeo 156 2.0 JTS

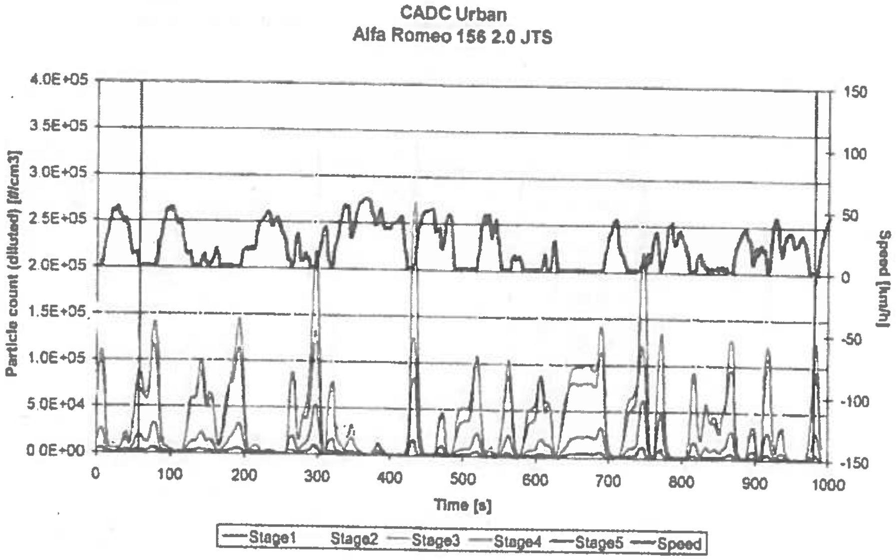

Figure D.3: Particle number during the CADC urban for the Alfa Romeo 156 2.0 JTS

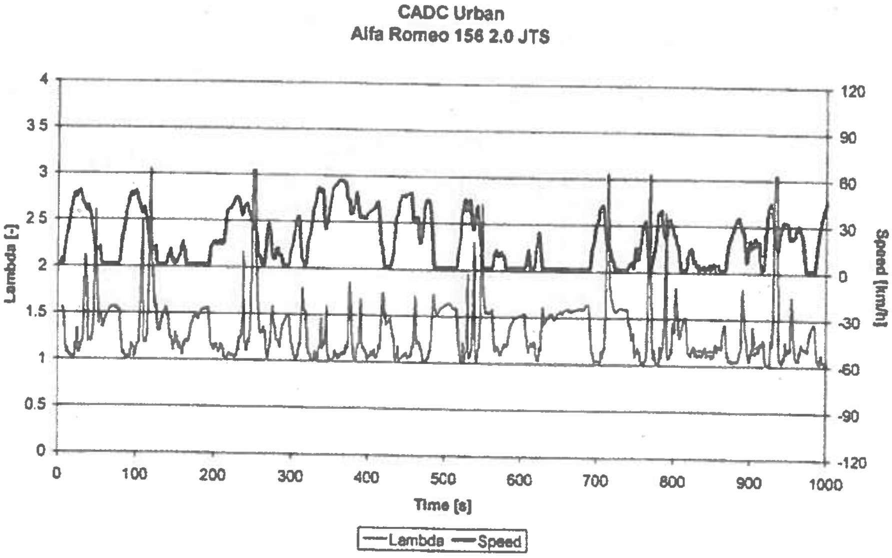

Figure D.4: Lambda signal during the CADC urban for the Alfa Romeo 156 2.0 JTS

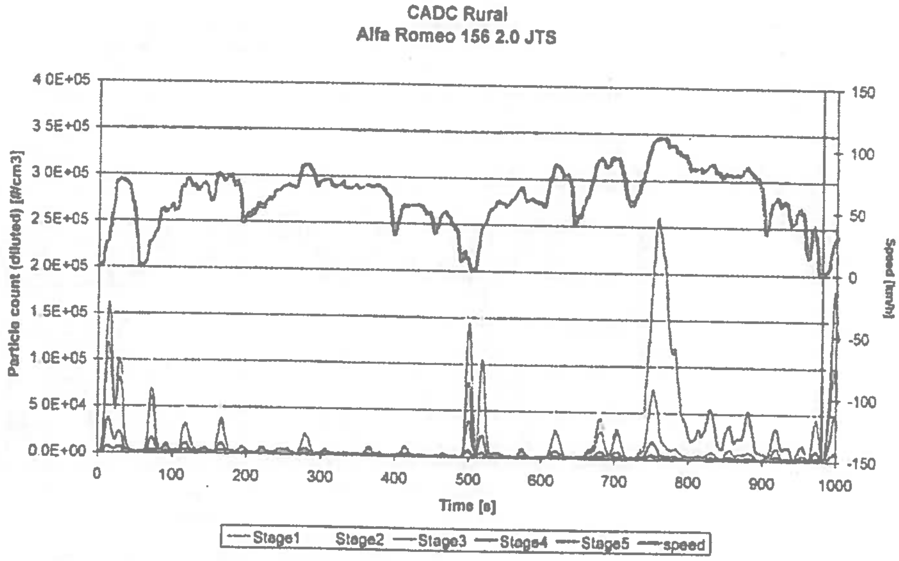

Figure D.5: Particle number during the CADC rural for the Alfa Romeo 156 2.0 JTS

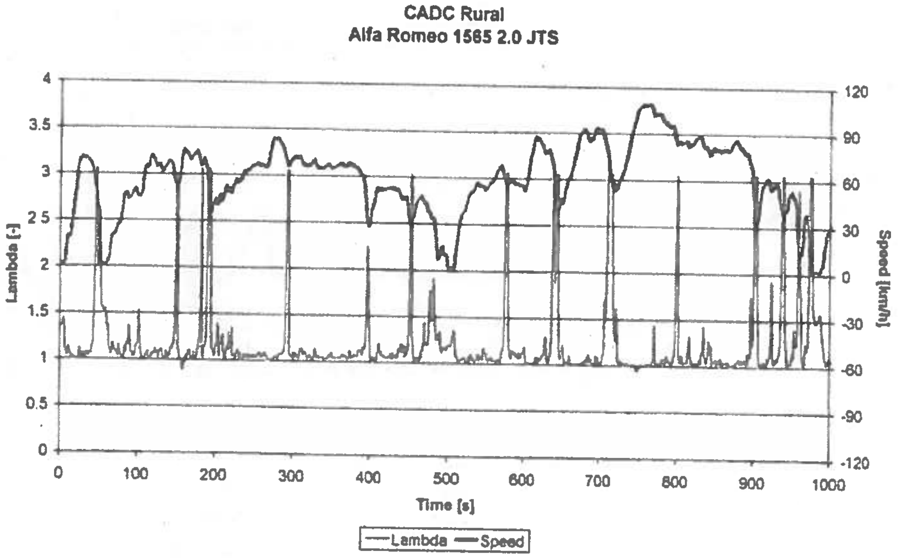

Figure D.6: Lambda signal during the CADC urban for the Alfa Romeo 156 2.0 JTS

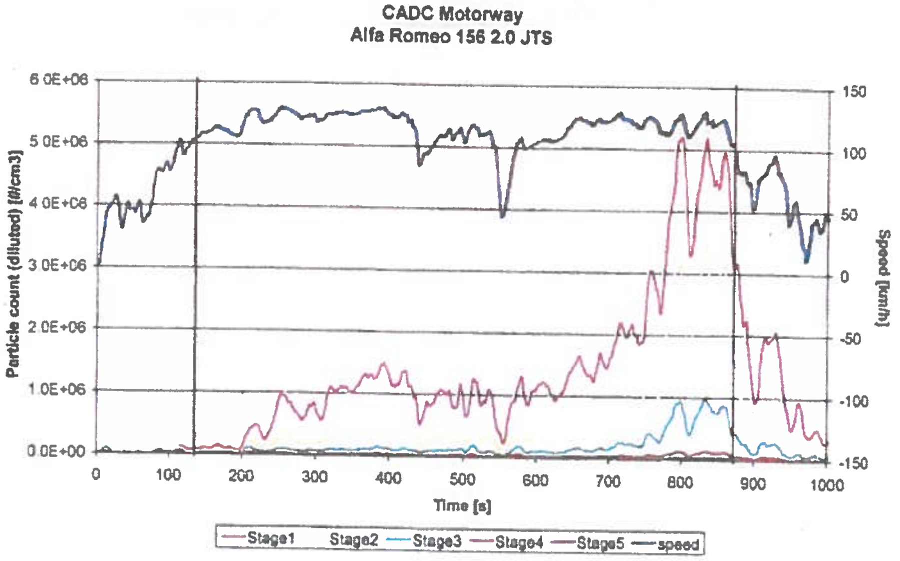

Figure D.7: Particle number during the CADC motorway for the Alfa Romeo 156 JTS

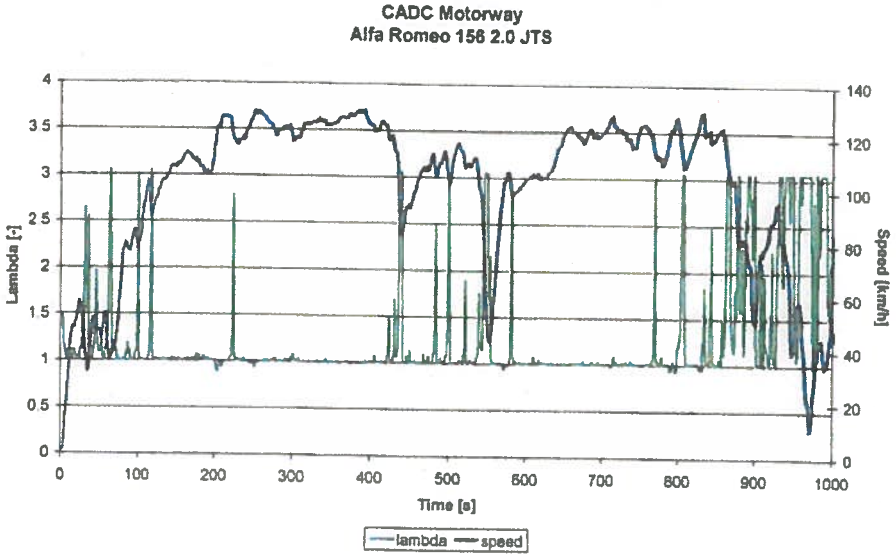

Figure D.8: Lambda signal during the CADC motorway for the Alfa Romeo 156 JTS

E Online particle number and lambda measurements for the Renault Laguna IDE

Online particle number and lambda measurements for the Renault Laguna IDE

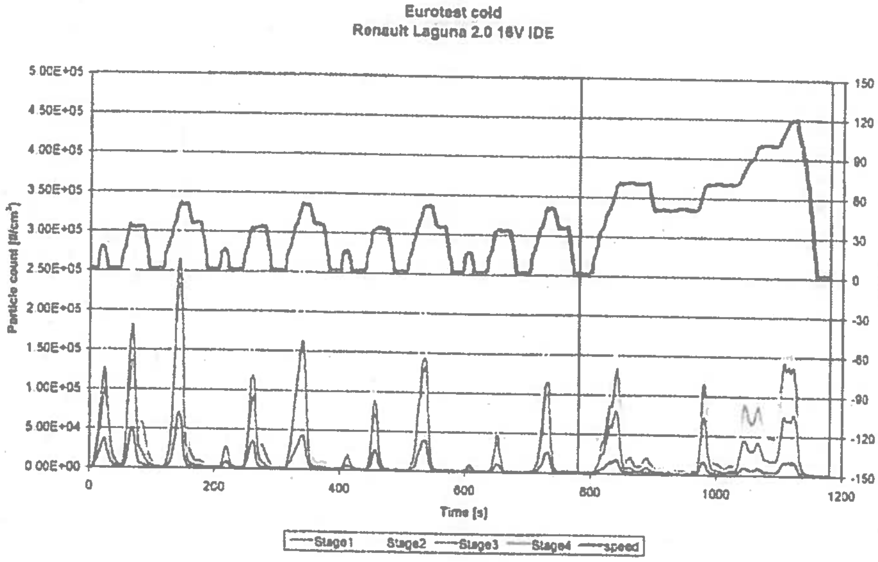

Figure E.1: Particle number during the Eurotest for the Renault Laguna

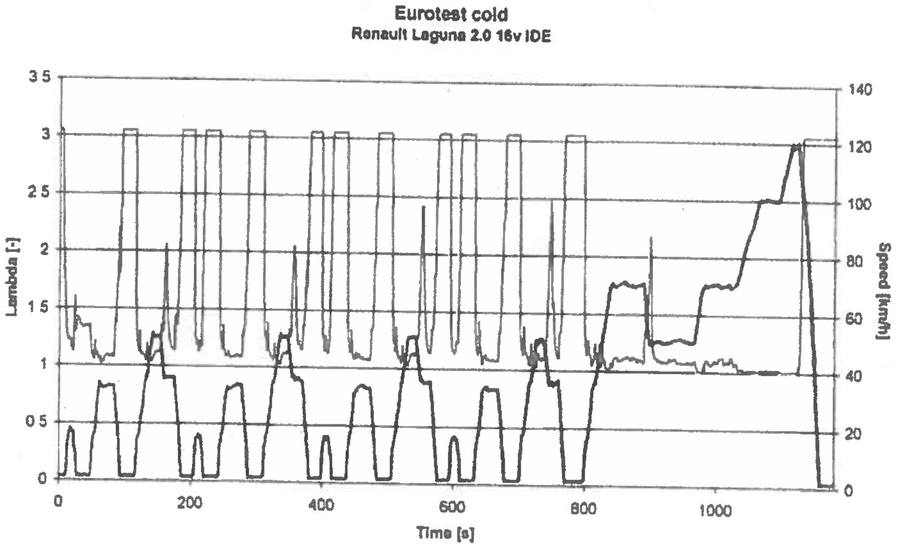

Figure E.2: Lambda signal during the Eurotest for the Renault Laguna

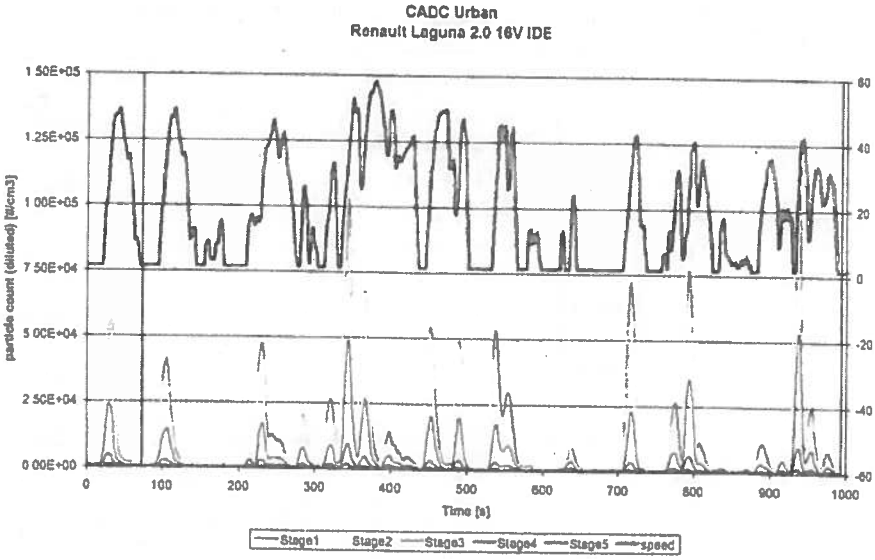

Figure E.3: Particle number during the CADC urban for the Renault Laguna

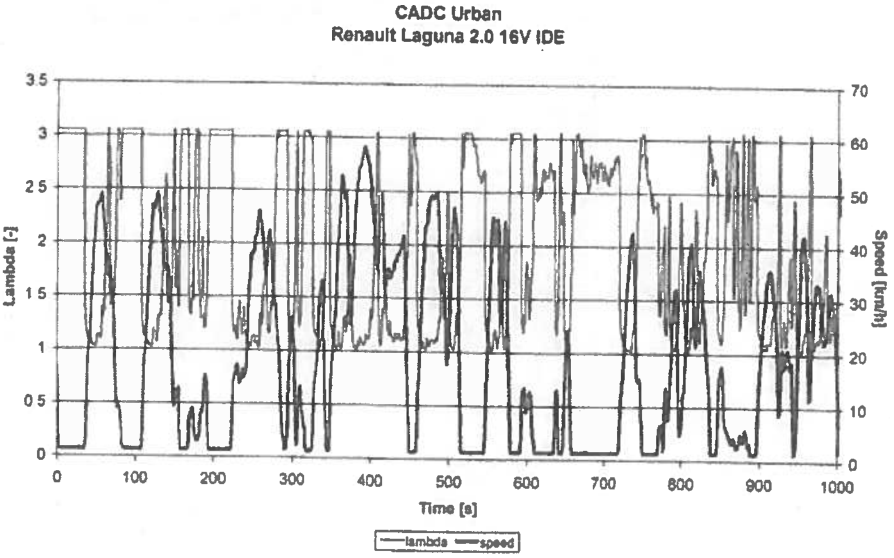

Figure E.4: Lambda signal during the CADC urban for the Renault Laguna

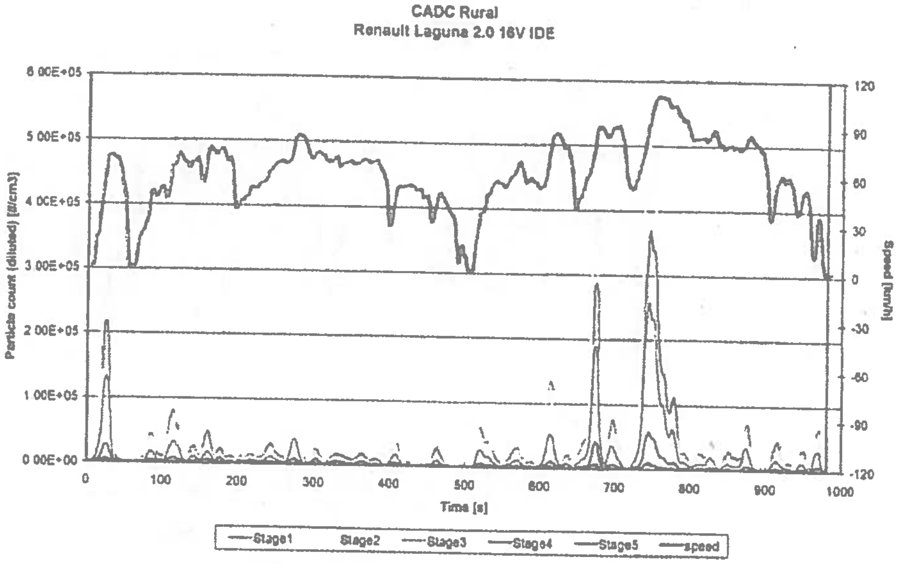

Figure E.5: Particle number during the CADC rural for the Renault Laguna

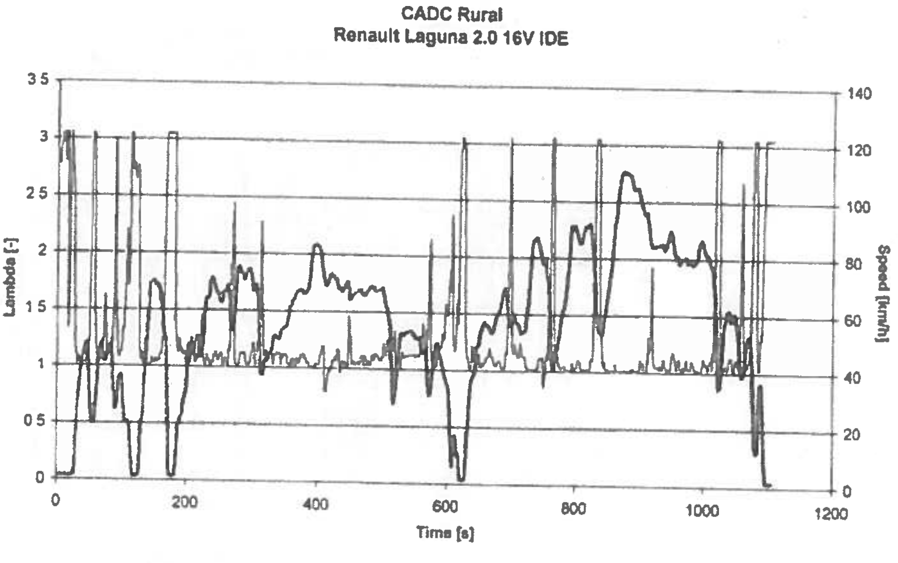

Figure E.6: Lambda signal during the CADC rural for the Renault Laguna

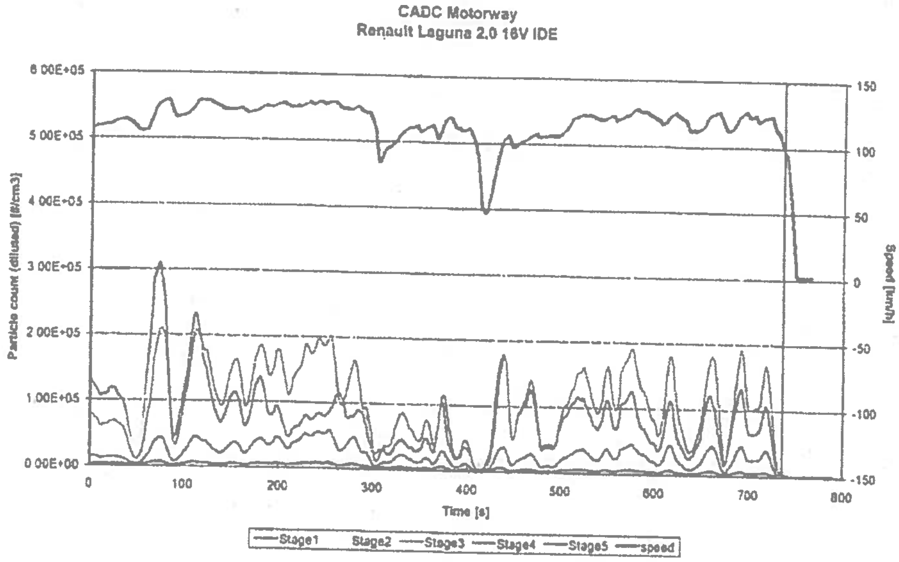

Figure E.7: Particle number during the CADC motorway for the Renault Laguna

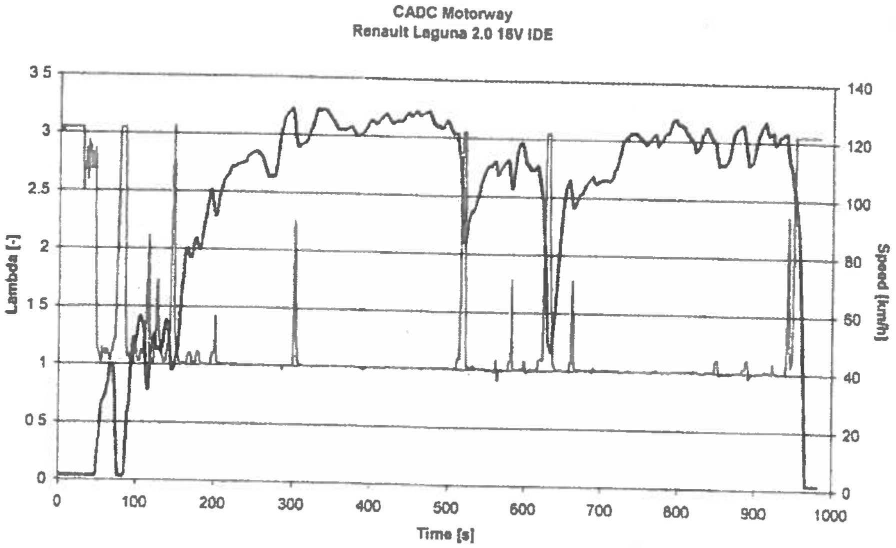

Figure E.8: Lambda signal during the CADC motorway for the Renault Laguna