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ENVIRONMENTAL AND HEALTH IMPACT FROM MODERN CARS

A comparison between two petrol and two diesel cars with varying emission control technology

Ecotraffic

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ENVIRONMENTAL AND HEALTH IMPACT FROM MODERN CARS

A comparison between two petrol and two diesel cars with varying emission control technology

A report for the

Swedish National Road Administration

Ecotraffic ERD^3 AB

Peter Ahlvik

May 2002

PREFACE

The transport sector contributes significantly to the air pollution and particularly influences the local air quality. Beside the question of air quality, the consumption of fossil fuels in the transport sector and the CO_2-emissions from this use is an issue of increasing importance.

For a long period of time, the emissions from light-duty vehicles have been in focus and a lot of measures have been taken to reduce the emissions from these vehicles.

The market penetration for light duty diesel cars has been increasing in the most markets in Europe and is now over 30 % (2001). In Sweden, however, the market share for diesel cars has decreased the last three years and is now slightly above 5 %.

The issue of whether petrol or diesel fuel should be used as fuel in passenger cars has been lively debated during the last years, particularly in Sweden. Especially the particle emissions from diesel cars have been in focus. This study is an attempt to contribute with some more facts to the subject.

The study presented in this report is built on new investigations of two petrol and two diesel cars with varying emission control strategies. Tests have been carried out both in the European driving cycle and in other driving cycles. Beside the regulated substances, analysis has been made on unregulated substances as well. The data has also been compared with data from earlier studies.

The report has been written by Peter Ahlvik, Ecotraffic ERD^3 AB. The author is liable to the results and the assessments in the report.

Borlänge, May 2002

Swedish National Road Administration, Vehicle Standards Division

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SAMMANFATTNING (SWEDISH SUMMARY)

Inledning och bakgrund

Transportsektorn bidrar påtagligt till luftföroreningarna och speciellt gäller detta för den lokala luftkvaliteten, eftersom fordon ofta används i tätt befolkade områden. I ett speciellt avseende har de lätta fordonen varit föremål för ett stort intresse under den senaste tiden och detta gäller partikelemissionerna från dieselbilar. Eftersom marknadsandelen för dieselbilar har ökat på de flesta marknaderna i Europa (till över 30% 2001) har denna fråga aktualiserats allt mer. Sverige har varit ett undantag i detta avseende. Här har marknadspenetrationen minskat långsamt under de 3 senaste åren och nu verkar den ha stabiliserats på något över 5%. För att fordonstillverkarna skall kunna klara sitt frivilliga åtagande att minska CO2 emissionerna i framtiden är en ökad marknadsandel för dieselbilar en möjlig väg.

Eftersom det finns relativt få data på icke reglerade emissioner från moderna dieselbilar, var det av speciellt intresse att generera sådana data. Det ansågs också av vikt att jämföra dessa data med de från moderna bensindrivna bilar. Efter diskussioner med Vägverket erhölls stöd för att genomföra projektet. MTC anlitades för att utföra den experimentella delen i projektet.

Metodik

Nedanstående 4 bilar valdes för undersökningen efter diskussioner med Vägverket, återförsäljare och biltillverkare:

- En dieseldriven Peugeot 307 2.0 HDi FAP, utrustad med partikelfilter
- En dieseldriven VW Golf 1,9 TDI (utan partikelfilter)
- En bensindriven Peugeot 307 med 1,6-liters motor
- En bensindriven VW Golf med 1,6-liters motor

Bilarna utlånades vänligen av de svenska återförsäljarna eller av tillverkaren i ett fall (Peugeot 307 HDi FAP).

Bilarna testades enligt den europeiska NEDC körcykeln vid temperaturerna +22°C och −7°C. Som komplement valdes den amerikanska US06 körcykeln, som har ett mer aggressivt körmönster än NEDC körcykel, för att representera denna typ av körning. Slutligen simulerades en omkörning av en långtradare för att generera data med en motorbelastning motsvarande full last.

Mätningar av reglerade och flera icke reglerade emissionskomponenter utfördes, inklusive toxiska föreningar och mätning av partiklarnas storleksfördelning.

Resultat

Eftersom en stor mängd figurer och resultat presenteras i rapporten visas endast några av de viktigaste resultaten och slutsatserna i denna sammanfattning. De emissionskomponenterna respektive effekter på hälsa och miljö från emissioner som speciellt lyfts fram i sammanfattningen är:

- HC emissioner
- NO_X emissioner
- Partikelemissioner (massa och totalt antal partiklar)
- Ozonbildningspotential
- Cancer risk index
- Försurning

Eftersom bilarna testades både vid ”normal” (+22°C) och lägre (-7°C) temperatur, visar några av diagrammen resultat för båda dessa temperaturer. I figurerna har följande beteckningar för bilarna använts:

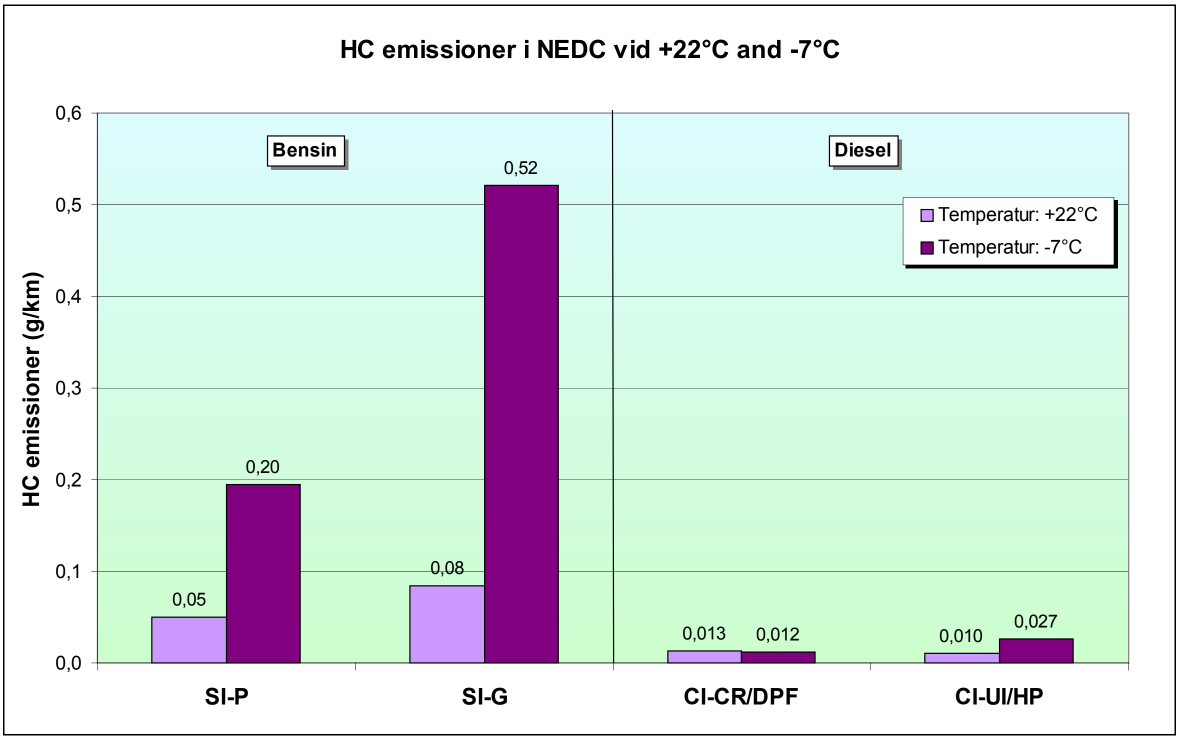
- SI-P: Den bensindrivna Peugeot 307
- SI-G: Den bensindrivna VW Golfen
- CI-CR/DPF: Den dieseldrivna Peugeot 307 med common rail (CR) insprutning och dieselpartikelfilter (DPF)
- CI-UI/HP: Den dieseldrivna VW Golfen med högtrycks insprutning (HP) med enhetsinjektorer (UI)

Valda emissionskomponenter

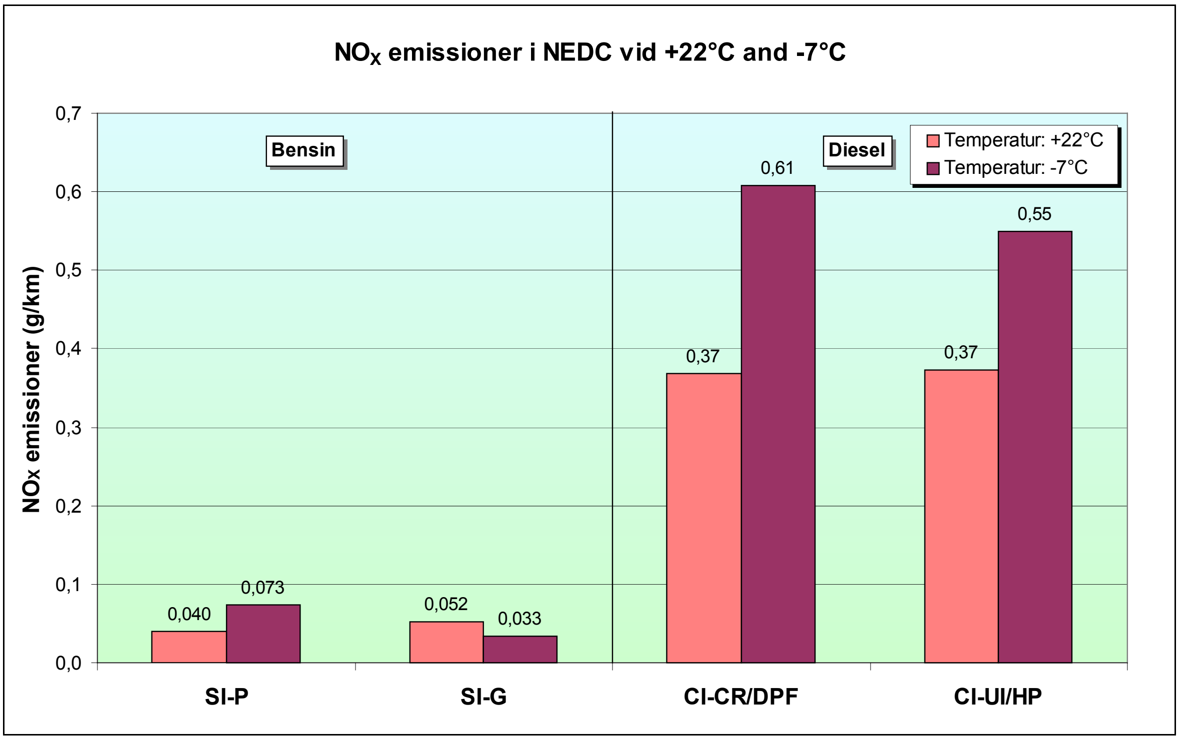
Från resultaten för HC emissionerna i **Figur S.1** framgår att nivån generellt är väsentligt högre för bensinbilarna än för deras dieseldrivna motsvarigheter. Dessutom påverkas HC emissionerna för bensinbilarna mer av temperaturen än vad som är fallet för dieselbilarna. En användning av avancerad teknik för att generellt minska kallstartemissionerna skulle kunna minska HC emissionerna väsentligt i framtiden.

De lägre nivåerna av HC emissioner för dieselbilarna indikerar också att emissionerna av toxiska flyktiga föreningar bör vara låga. Så var också fallet för de flesta av dessa emissionskomponenter.

Resultaten i **Figur S.2** för NO_X emissionerna – allmänt ansett som ett stort problem för dieselbilar – bekräftar förväntningarna om en högre nivå för dieselbilarna. Bensinbilarna kan utnyttja möjligheten att använda en så kallad trevägskatalysator (TWC) för att reducera NO_X emissionerna, medan de oxidationskatalysatorer som används till dieselbilar har en mycket ringa inverkan på NO_X emissionerna. Något förvånande var den avsevärt högre NO_X nivån vid den lägre temperaturen för dieselbilarna. Den endra rimliga förklaringen till denna trend är att avgasåterföringen (EGR) stängs av under kallstartdelen av testcykeln. *I framtiden kommer NO_X reducerande katalysatorer att vara nödvändiga för att dieselbilar* *skall kunna nå en NO_X nivå likvärdig den för bensinbilar.* Sådana katalysatorer utvecklas för närvarande.

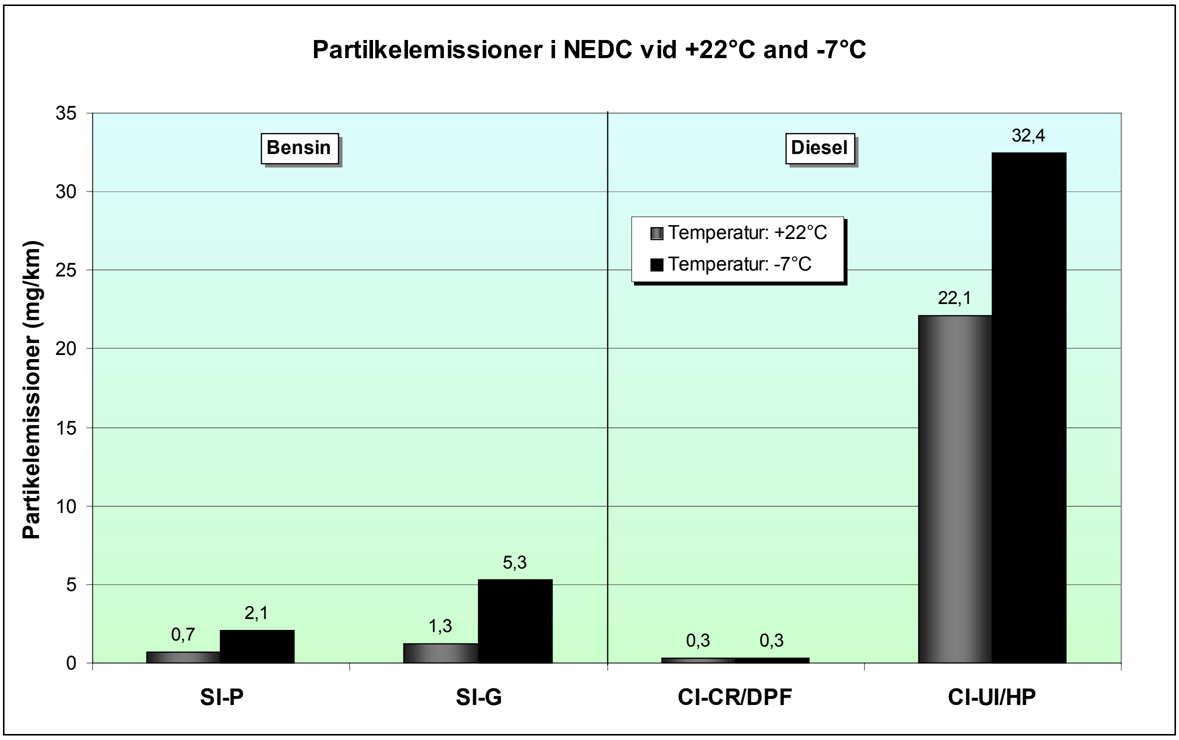


Figur S.1. *HC emissioner i NEDC*



Figur S.2. *NO_X emissioner i NEDC*

Partikelemissionerna anses vara ett stort problem för dieselbilar. Som förväntat var också nivån för partikelemissionerna högst för den dieselbil som inte hade något partikelfilter (**Figur S.3**), även om nivån för denna bilindivid faktiskt låg under Euro IV kraven. En ny motor med lägre partikelemissioner än den testade har introducerats under hösten 2001 och början av 2002. Partikelemissionerna var generellt lägre för dieselbilen med partikelfilter jämfört med bensinbilarna. Partikelnivån låg högre för bensinbilarna vid den lägre temperaturen än vid den ”normala” testtemperaturen. Emellertid var nivån vid den låga temperaturen väsentligt lägre än för tidigare resultat i litteraturen, vilket indikerar att en avsevärd förbättring har skett inom detta område.



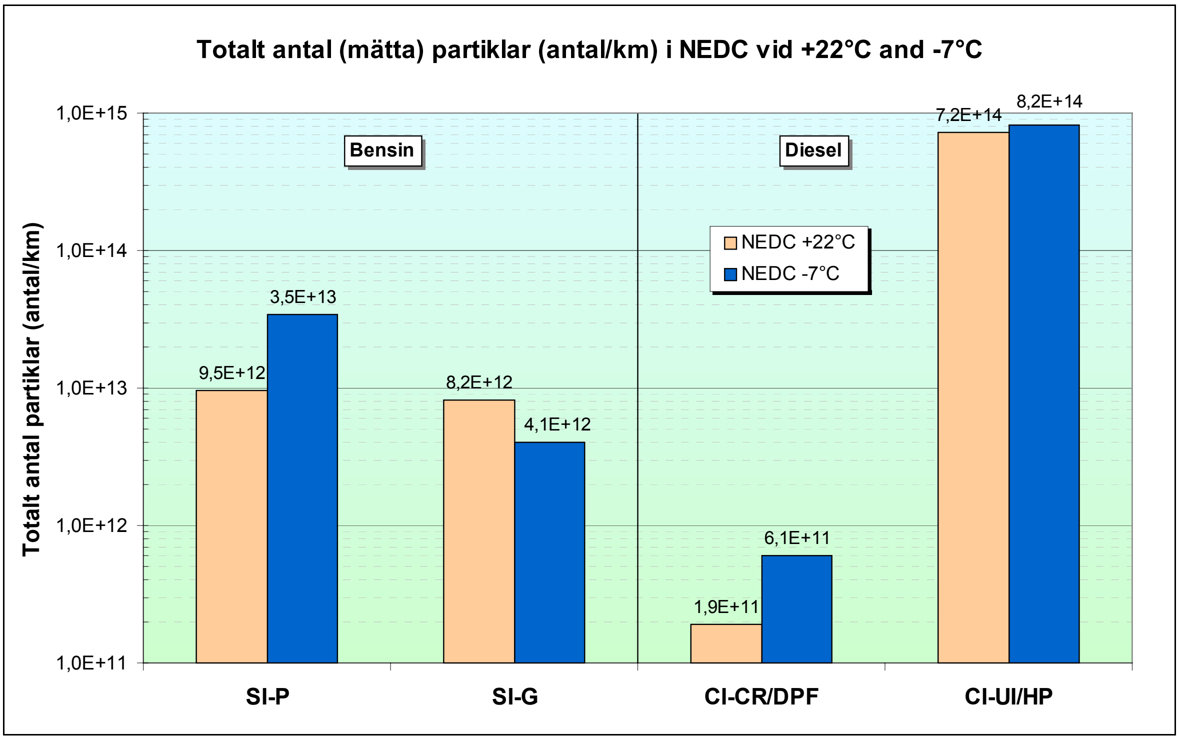
Figur S.3. *Parikelemissioner i NEDC*

Antalet partiklar och partikelstorleksfördelningen mättes med en elektrisk lågtrycksimpaktor (ELPI). Detta instrument kan mäta antalet partiklar av 12 olika storlekar för en aerodynamisk diameter mellan 7 nm och 6 µm. En av fördelarna med ELPI-instrumentet är att det kan mäta partikelemissionerna i realtid.

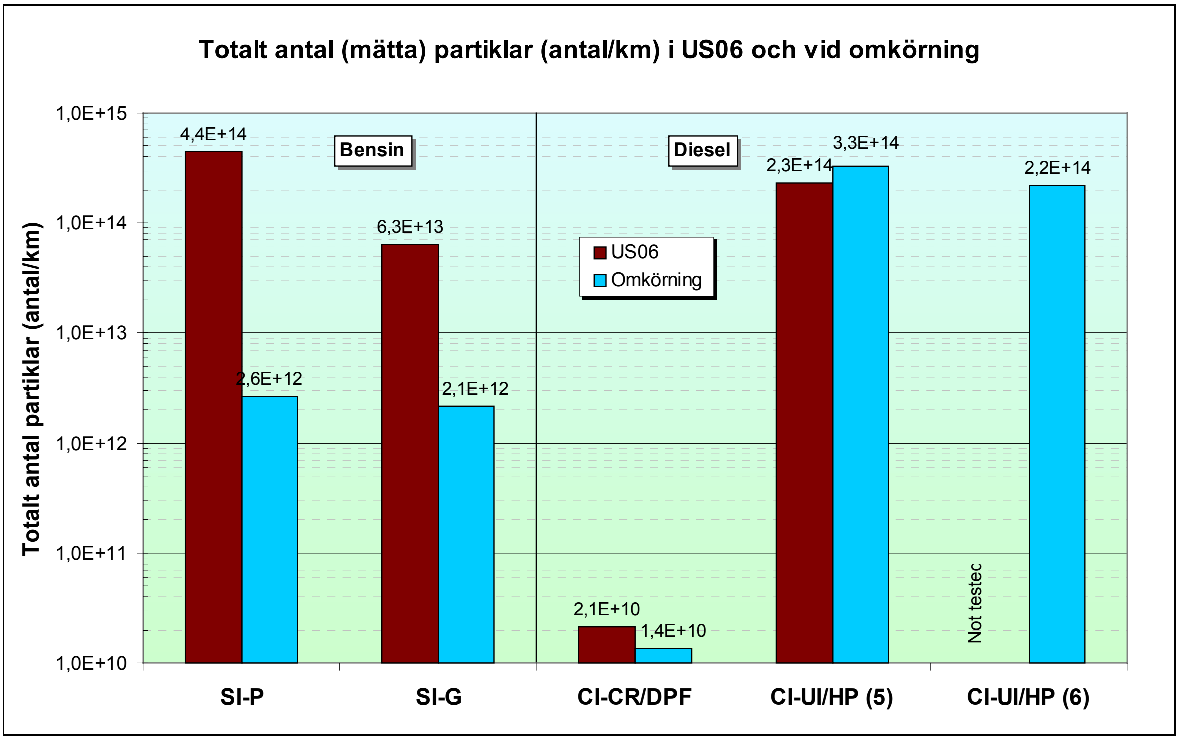
Resultaten för det totala antalet partiklar i NEDC cykeln visas i **Figur S.4**. Motsvarande resultat i US06 och vid omkörning visas i **Figur S.5**. Notera att båda figurerna har logaritmiska skalor på y-axlarna.

Antalet partiklar i NEDC cykeln (**Figur S.4**) var högst för dieselbilen utan partikelfilter. De två bensinbilarna låg ungefär 2 storleksordningar (dvs. 2 tiopotenser) lägre. Den lägsta nivån erhölls med dieselbilen med partikelfilter, dvs. ungefär en storleksordning lägre än för bensinbilarna.

I US06 körcykeln (**Figur S.5**) ökade antalet partiklar väsentligt jämfört med resultaten från NEDC körcykeln till en nivå ungefär lika hög som för dieselbilen utan partikelfilter. Nivån för omkörningstestet var lägre för bensinbilen än i US06. I båda testerna hade dieselbilen med partikelfilter en mycket låg nivå för det totala antalet partiklar, dvs. flera storleksordningar lägre än för de övriga bilarna.



Figur S.4. *Totalt antal partiklar i NEDC*

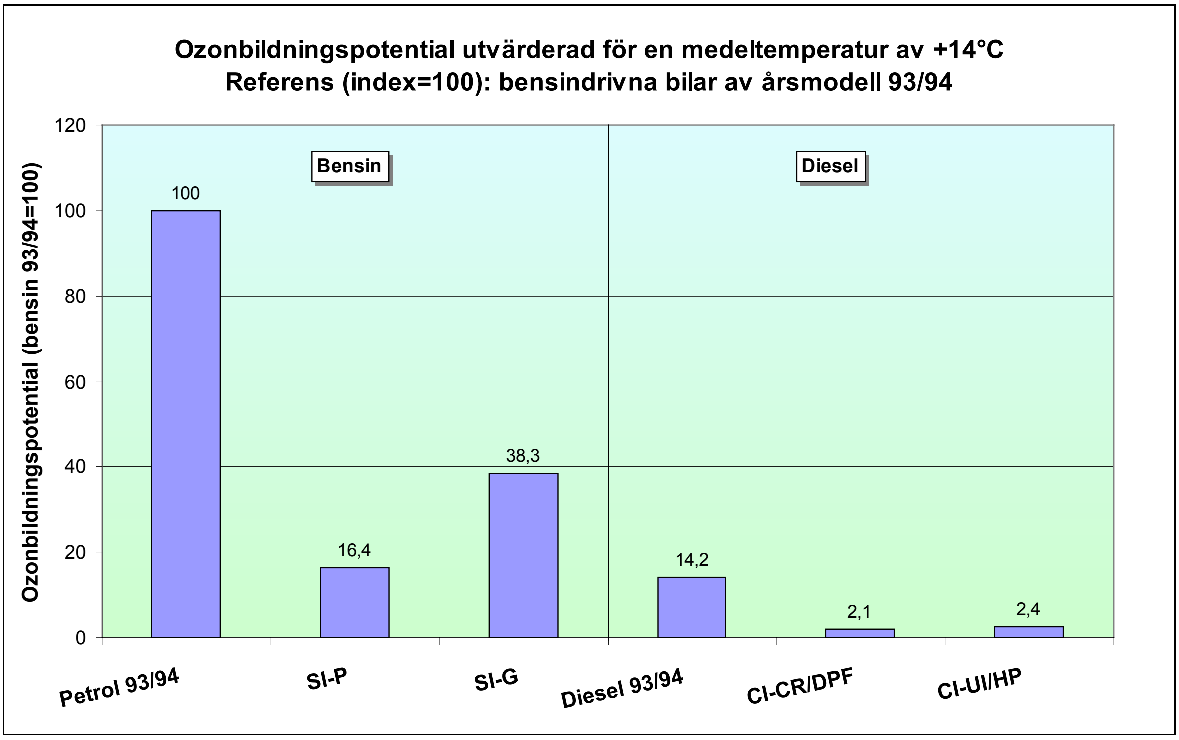


Figur S.5. *Totalt antal partiklar i US06 och vid omkörning*

Inverkan av emissioner på hälsa och miljö

I utvärderingarna av effekterna på hälsa och miljö har den årliga medeltemperaturen på +7°C använts i de flesta fallen. Enda undantaget var för ozonbildningspotentialen där en temperatur på +14°C användes i ställer. För att ge ett visst perspektiv på jämförelserna visas också resultaten för bilar av årsmodell 1993/1994 från en tidigare studie. För att förenkla presentationen av resultaten har ett index använts (referensnivå: bensinbilar av årsmodell 1993/1994).

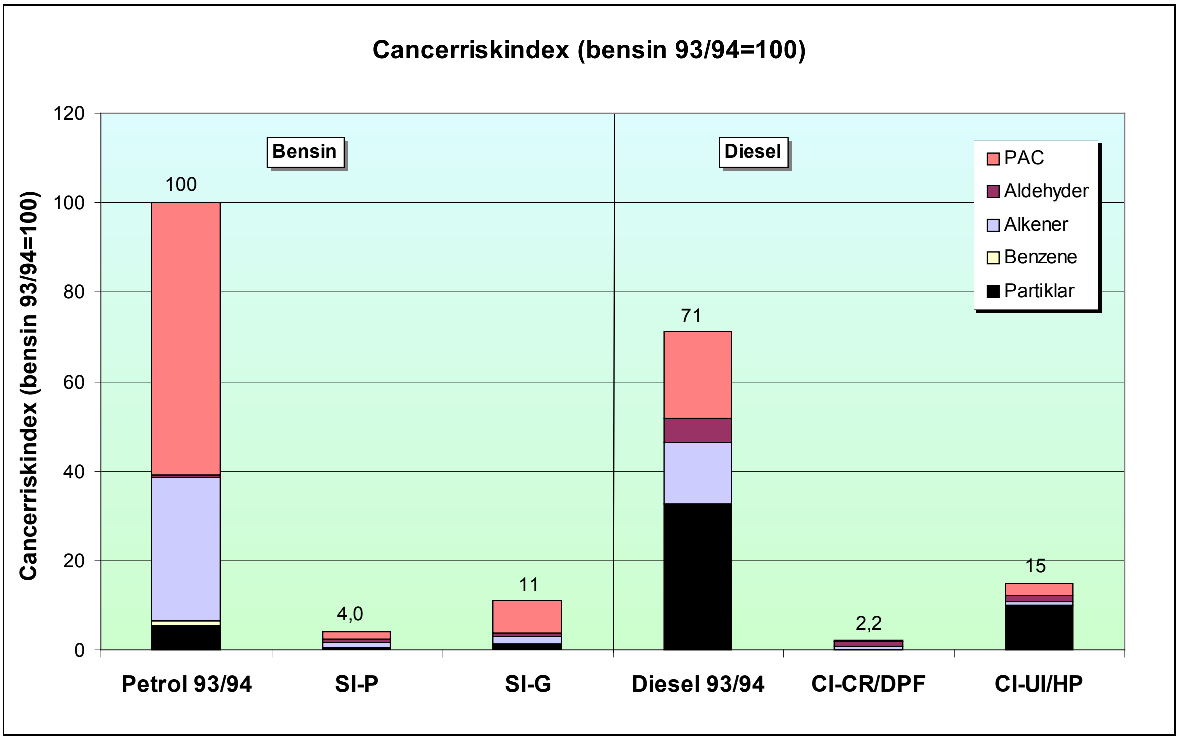
Ozonbildningspotentialen, som visas i **Figur S.6** var generellt lägre för dieselbilarna än för deras bensindrivna motsvarigheter. Orsaken är främst de väsentligt lägre HC emissionerna jämfört med bensinbilarna. Emellertid skall man också notera att nivåerna är väsentligt lägre för de nya bilarna är för de gamla oberoende av drivmedel.



Figur S.6. *Ozonbildningspotential (index: bensin 93/94=100)*

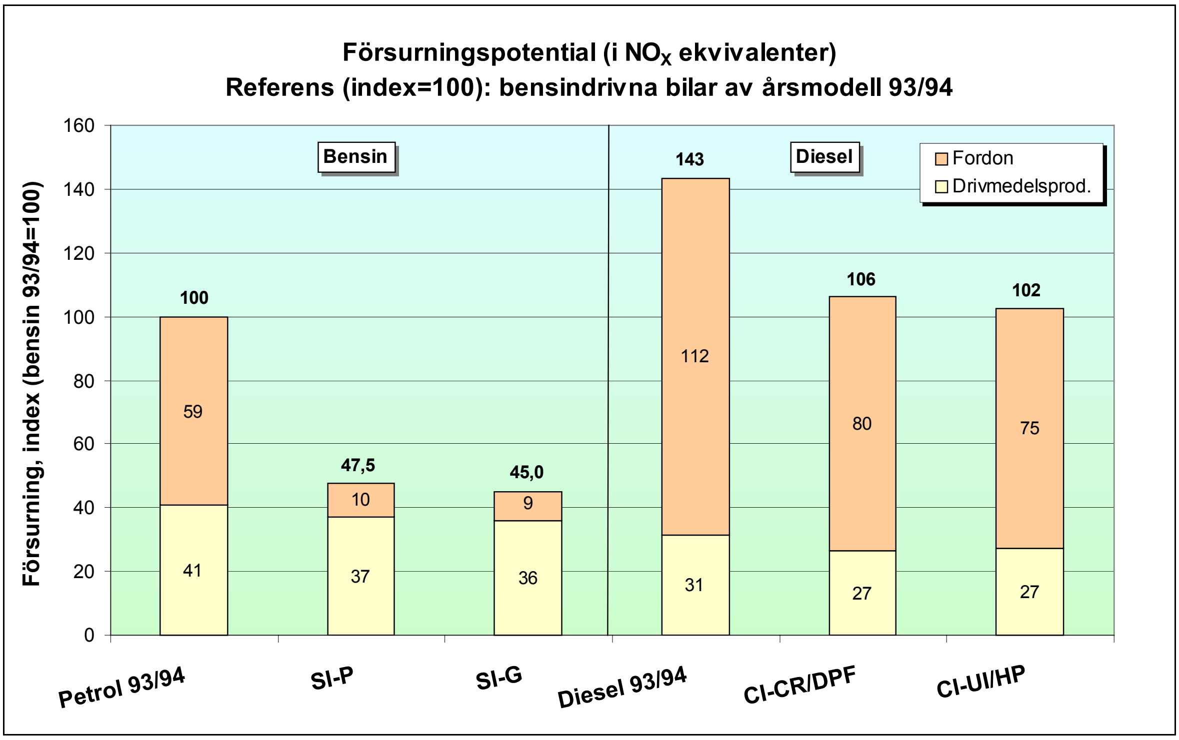
Resultaten för cancerriskindexet visas i **Figur S.7**. Riskfaktorer för de uppmätta föreningarna har använts som viktsfaktorer i beräkningen av cancerriskindexet.

Först bör man notera att nivån för bilarna som testades i denna studie var signifikant lägre än för de äldre bilarna (**Figur S.7**). På grund av de stora osäkerheterna för riskfaktorerna för varje enskild förening och spridningen mellan bilarna är det svårt att avgöra om diesel- eller bensinbilar har en lägre nivå. Bidraget till cancerriskindexet domineras av de polycykliska aromatiska föreningarna (PAC) för bensinbilarna. Dessa emissionskomponenter emitteras primärt vid låga temperaturer. För dieselbilar utan partikelfilter bidrar partikelemissionerna mest till cancerrisken. Den praktiskt taget totala elimineringen av partikelemissionerna när partikelfilter används har en avgörande inverkan på cancerriskindexet.



Figur S.7. Cancerriskindex (bensin 93/94=100)

Kväveoxider (NO_X) och svaveloxider (SO_X), liksom även ammoniak (NH_3), bidrar till försurningen. Emellertid måste även drivmedelsproduktionen tas i beaktande, eftersom försurningen kan anses vara en regional effekt. I **Figur S.8** visas resultaten för försurningsindexet.



Figur S.8. Försurningspotential (index: bensin 93/94=100)

En uppdelning i bidrag till försurning från drivmedelsproduktion och från fordonet har gjorts i **Figur S.8.** Eftersom NO_X nivån var mycket låg för bensinbilarna, samtidigt som svavelhalten i den bensin som användes var låg, domineras försurningen av drivmedelsproduktionen för de nya bensinbilarna. Dieselbilar har höga NO_X emissioner och detta är orsaken till den höga nivån för dessa bilar. I detta fall är bidraget från drivmedelsproduktionen lägre än för bensinbilarna.

Diskussion

Införandet av ny emissionsbegränsande teknologi har väsentligt minskat emissionerna från bensindrivna personbilar under det senaste decenniet. Efter introduktionen av trevägskatalysatortekniken (TWC) som avgasreningskoncept har fortsatta förbättringar av denna teknik minskat emissionerna ännu mer. Mot bakgrund av detta framsteg har emissionerna från dieselbilar blivit föremål för större uppmärksamhet från myndigheter och miljöorganisationer. Emellertid har inte emissionsproblemet för bensinbilar vid låga temperaturer heller lösts fullständigt. Man glömmer också ofta att emissionstester normalt genomförs i ett temperaturintervall av +20°C till +30°C. I det kalla nordiska klimatet måste också låga temperaturer beaktas. Trots allt uppvisar de testade bensinbilarna en avsevärt förbättring vid dessa temperaturer jämfört med äldre bilar.

Även om emissionerna från dieseldrivna bilar har minskat väsentligt under det senaste decenniet har den generella uppfattningen varit att dessa bilar emitterar väsentligt mer hälsofarliga emissioner än deras bensindrivna motsvarigheter. Resultaten i denna studie visar att flera icke reglerade emissionskomponenter från dieselbilar låg på samma nivå som för bensinbilar och i flera fall lägre. Två stora problem kvarstår − NO_X och partikelemissioner. I dag finns ingen motsvarighet till TWC reningstekniken för dieselbilar för att reducera NO_X emissionerna men sådan teknik håller nu på att utvecklas. Ny partikelfilterteknik har kommersialiserats av PSA och andra tillverkare kommer att följa detta exempel.

Beräkningen av inverkan på hälsa och miljö från avgasemissionerna ger en bättre insikt än att enbart redovisa resultaten för emissionskomponenterna. Emellertid bör det också noteras att i en del fall är indata för dessa beräkningar (t.ex. cancerrisk) ännu fullt utvecklade.

Slutsatser

Antalet bilar i denna studie var för få för att tillåta en generalisering av resultaten till att gälla för alla bilar. Urvalet av bilar gjordes med den förutsättningen att inverkan av ny teknik skulle kunna jämföras med tidigare genererade resultat från äldre bilar. Följande övergripande slutsatser kan dras:

- De reglerade emissionerna för alla bilar låg mycket nära certifieringsdata. Därför kan bilarna anses ha varit representativa stickprov för varje bilmodell. De två bensindrivna bilarna i denna studie visade sig ligga på samma nivå som några av de bästa bilar som tidigare testats vid MTC.
- Som förväntat var CO och HC emissionerna generellt sett lägre för dieselbilarna än för bensinbilarna medan resultaten för NO_X var de rakt motsatta. Partikelemissionerna var högre för dieselbilen utan partikelfilter jämfört med dess bensindrivna motsvarighet. Emellertid hade dieselbilen med partikelfilter lägre partikelemissioner än motsvarande bensinbil.

- Emissionerna av några kväveföreningar, som ammoniak (NH_3) och lustgas (N_2O) var låga för alla bilar.
- Emissionerna av aldehyder, ett välkänt problem för dieselmotorer, låg på eller under detektionsgränsen för dieselbilarna vid den högre temperaturen (+22°C). Vid den lägre temperaturen (−7°C) var nivån ungefär två gånger högre än detektionsgränsen. Detta indikerar att väsentliga förbättringar har gjorts inom detta område jämfört med äldre dieselbilar.
- Bensinbilarna hade högre emissioner av bensen, eten, propen och 1,3-butadien än deras dieseldrivna motsvarigheter, även om nivåerna för dessa emissionskomponenter var låga för alla bilar.
- PAC/PAH emissionerna är normalt låga för bensinbilar vid höga temperaturer. Eftersom nivån av dessa emissioner tidigare har varit högre för dieselbilar vid dessa temperaturer, har detta ansetts som ett stort emissionsproblem för dieselbilar. Det har sällan noterats att *nivån ökar väsentligt för bensinbilar när temperaturen sjunker*. PAC emissionerna för de bensinbilar som testades i denna studie låg väsentligt lägre jämfört med tidigare tester på äldre bilar vid låg temperatur. PAC emissionerna för dieselbilarna var generellt lägre än deras bensindrivna motsvarigheter vid den årliga medeltemperaturen +7°C. För dieselbilen med partikelfilter var PAC emissionerna en storleksordning lägre än för den bensindrivna bilen från samma tillverkare. En jämförelse med data för bilar av 1993/1994 års modell uppvisar en skillnad på mer än 2 tiopotenser. Även om dieselbilen utan partikelfilter hade lägre PAC emissioner än dess bensindrivna motsvarighet medför den stora variationen mellan bilarna att nya dieselbilar (utan partikelfilter) inte nödvändigtvid är bättre än nya bensinbilar i detta avseende.
- Dieselbilen utan partikelfilter emitterade i NEDC cykeln vid de båda testtemperaturerna ungefär 2 tiopotenser fler partiklar än dess bensindrivna motsvarighet. Dock låg antalet partiklar i US06 cykeln på ungefär samma nivå som för bensinbilarna. Ökningen av antalet partiklar för bensinbilarna i denna körcykel jämfört med NEDC körcykeln kan främst hänföras till en ökning av de minsta partiklarna (7 – 30 nm). Dieselbilen med partikelfilter var enastående i detta avseende då antalet partiklar för den var minst en storleksordning lägre än för bensinbilarna. Partikelfiltret var speciellt effektivt på att minska de så kallade nanopartiklarna. Jämförelser med tidigare data visade en minskning av partikelantalet för dieselbilen utan partikelfilter.
- Ozonbildningspotentialen var väsentligt lägre för dieselbilarna, dvs. en storleksordning lägre än för bensinbilarna. Detta beror främst på de låga HC emissionerna för dieselbilarna jämfört med bensinbilarna. Om förångningsemissionerna hade tagits hänsyn till hade den relativa skillnaden blivit ännu större.
- Cancerriskindexet var generellt lägre för de bilar som testades i denna studie jämfört med äldre bilar. Dieselbilen med partikelfilter hade ett lägre cancerriskindex än den bensindrivna motsvarighet. För dieselbilen utan partikelfilter var nivån något högre än för bensinbilen från samma tillverkare. Generellt sett erhölls den lägsta nivån för dieselbilen med partikelfilter, dvs. en nästan 98% lägre nivå än för bensinbilar av årsmodell 1993/1994. Det bör noteras att osäkerheten är hög när det gäller cancerriskindexet som följd av den stora variationen för riskfaktorerna beroende på vilken källa som används. Därför bör små skillnader inte beaktas.

- De miljöeffekter som är främst förknippade med NO_X emissioner, såsom NO_2 bildningspotential, försurning och övergödning, var större för dieselbilarna än deras bensindrivna motsvarigheter beroende på de högre NO_X emissionerna. Bidraget från bränsleproduktion var högre för bensinbilarna.
- Som förväntat var utsläppen av klimatgaser och energianvändningen lägre för dieselbilarna än för bensinbilarna. Detta beror delvis på en lägre energianvändning, delvis på en högre verkningsgrad i drivmedelsproduktionen.

Även om syftet med denna studie var att jämföra emissionerna från dieselbilar med emissionerna från bensinbilar, kan det inte undvikas att påpekas att fokuseringen var något större på resultaten från dieselbilarna. Detta beror främst på att de flesta data på icke reglerade emissioner har genererats på bensinbilar. Relativt lite är känt om inverkan av ny teknik i detta avseende. Som förväntat är NO_X och partikelemissionerna de största emissionsproblemen för dieselbilarna. Resultaten för partikelemissionerna visar att ett partikelfilter är mycket effektivt på att minska dessa emissioner. För båda de nämnda emissionskomponenterna har lösningar som kan minska dessa problem introducerats, eller kommer att introduceras på marknaden inom en nära framtid. Icke desto mindre, om dieselbilar förbättras i detta avseende så kommer också bensinbilarna att göra det. Testresultaten för de icke reglerade emissionerna, och de effekter på hälsa och miljö som utvärderats, visade lägre nivåer i några fall för dieselbilarna och högre i andra fall jämfört med bensinbilarna. Så småningom, när emissionerna från fordon som körs på båda typerna av drivmedel kommer att kunna minskas till försumbara nivåer, kommer framgent energieffektivitet och emissioner av klimatgaser att öka i betydelse.

EXECUTIVE SUMMARY

Introduction and background

The transport sector contributes significantly to the air pollution and in particular, this statement is valid for the local air quality, since vehicles often operate in populated areas. In one particular aspect, the light-duty vehicles have been subject much interest lately, and this is regarding the particulate emissions from diesel-fuelled cars. Since the market penetration of diesel cars has been ever increasing on most markets in Europe (to over 30% in 2001), this issue has become even more pronounced. Sweden has been an exemption in this respect. Here, the market penetration has been slowly decreasing during the last 3 years and now it seems to have stabilised at level of slightly above 5%. In order for the vehicle manufacturers to meet the agreement to reduce CO_2 emissions in the future, an increased market share of diesel cars is a possible route.

As there are relatively few data on unregulated emissions from modern diesel cars, it was of particular interest to generate such data. It was also considered important to compare these data with data on modern petrol-fuelled cars. After discussions with the Swedish National Road Administration (SNRA), funding for the project was granted. MTC in Sweden was commissioned to carry out the experimental part of the project.

Experimental

The following four cars were selected for the investigation after discussions with SNRA, the Swedish wholesalers and the car manufacturers:

- A diesel-fuelled Peugeot 307 2.0 HDi FAP, equipped with a particulate filter
- A diesel-fuelled VW Golf 1,9 TDI (without particulate filter)
- A petrol-fuelled Peugeot 307 with 1.6 litre engine
- A petrol-fuelled VW Golf with 1.6 litre engine

The cars were kindly lent by the Swedish wholesalers or by the car manufacturer in one case (Peugeot 307 HDi FAP).

The cars were tested according to the NEDC cycle at ambient temperatures of +22°C and −7°C. In addition, the US06, having a more aggressive driving pattern than the NEDC driving cycle was chosen to reflect this type of driving as well. Finally, overtaking of a lorry was simulated to generate data on full load operation.

Measurements of regulated and several unregulated emission components were carried out, including air toxics and particle size distribution.

Results

As a great number of figures and results are presented in the report, only a few of the most important findings are shown in this summary. The emission components or the specific impacts on health and environment from emissions that are particularly highlighted in the executive summary are:

- HC emissions
- NO_X emissions
- Particulate emissions (mass and total number)
- Ozone forming potential
- Cancer risk index
- Acidification

As the cars were tested at both "normal" (+22°C) and lower (−7°C) ambient temperatures, several of the diagrams show the results for both these temperatures. In the figures, the following denotations for the cars are used:

- SI-P: Petrol-fuelled Peugeot 307
- SI-G: Petrol-fuelled VW Golf
- CI-CR/DPF: Diesel-fuelled Peugeot 307 with common rail (CR) injection and diesel particulate filter (DPF)
- CI-UI/HP: Diesel-fuelled VW Golf with high-pressure (HP) unit injectors (UI)

Selected emission components

In **Figure ES.1**, the results on HC emissions show that the level was generally significantly higher for the petrol cars than for their diesel counterparts. Moreover, HC emissions from petrol cars were more influenced by the ambient temperature than are diesel cars. The use of advanced technology for reducing cold start emissions in general could reduce the HC level considerably in the future.

The lower HC emission level for the diesel cars generally also indicates lower levels of toxic volatile organic compounds. This was also the case for most of these emission components.

The results in **Figure ES.2** on NO_X emissions − generally considered as a main problem for diesel cars − confirm the expectations of a higher level for diesel cars. Petrol cars exploit reduction of the NO_X emissions in a so-called three-way catalyst (TWC), while the oxidation catalysts on diesel cars have very little influence on the NO_X emissions. Somewhat surprising was the considerably higher NO_X level at the lower ambient temperature for the diesel cars. The only plausible explanation for this trend is that the exhaust gas recirculation (EGR) is cut off during the cold start phase of the test cycle. *In the future, a NO_X reducing catalyst will be necessary for the diesel cars to achieve a NO_X level on pair with the petrol cars.* Such catalysts are currently being developed.

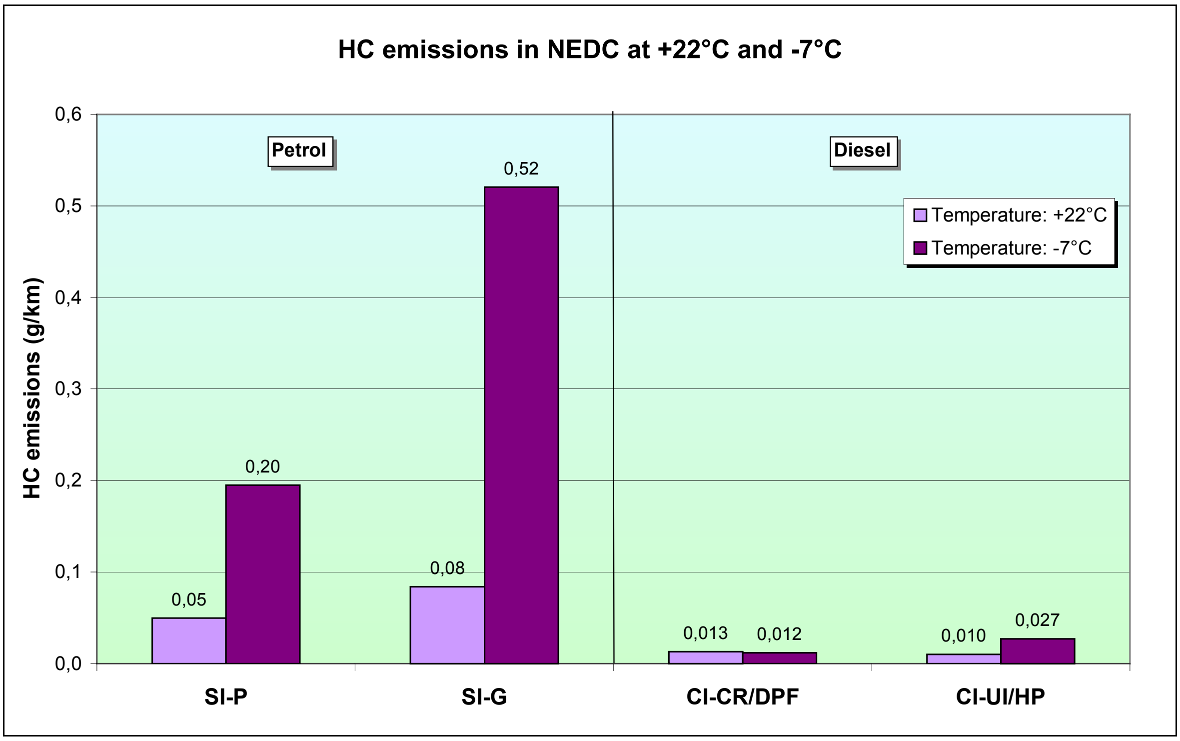


__Figure ES.1.__ HC emissions in NEDC

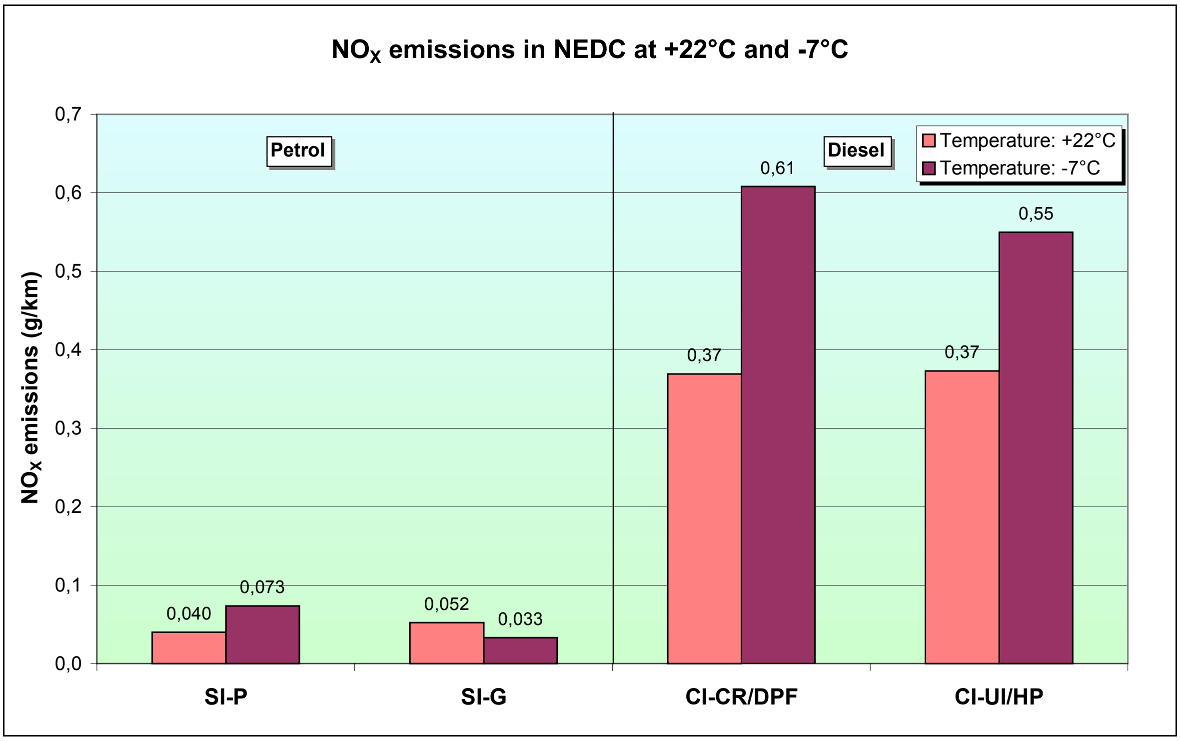


__Figure ES.2.__ NO_X emissions in NEDC

Particulate emissions are considered a major emission problem for diesel cars. As expected, the particulate level was also highest for the diesel car without a particulate filter (**Figure ES.3**), although the level for this car was actually lower than the Euro IV limit. A new engine with lower particulate emissions than the tested car has been introduced in autumn 2001 or early 2002. The particulate emissions were generally lower for the diesel car with a particulate filter than for the petrol cars. The petrol cars had a higher particulate level at the low ambient temperature than at the "normal" test temperature. However, the level at the low temperature was significantly lower than in previous results in the literature, indicating a considerable improvement in this area.

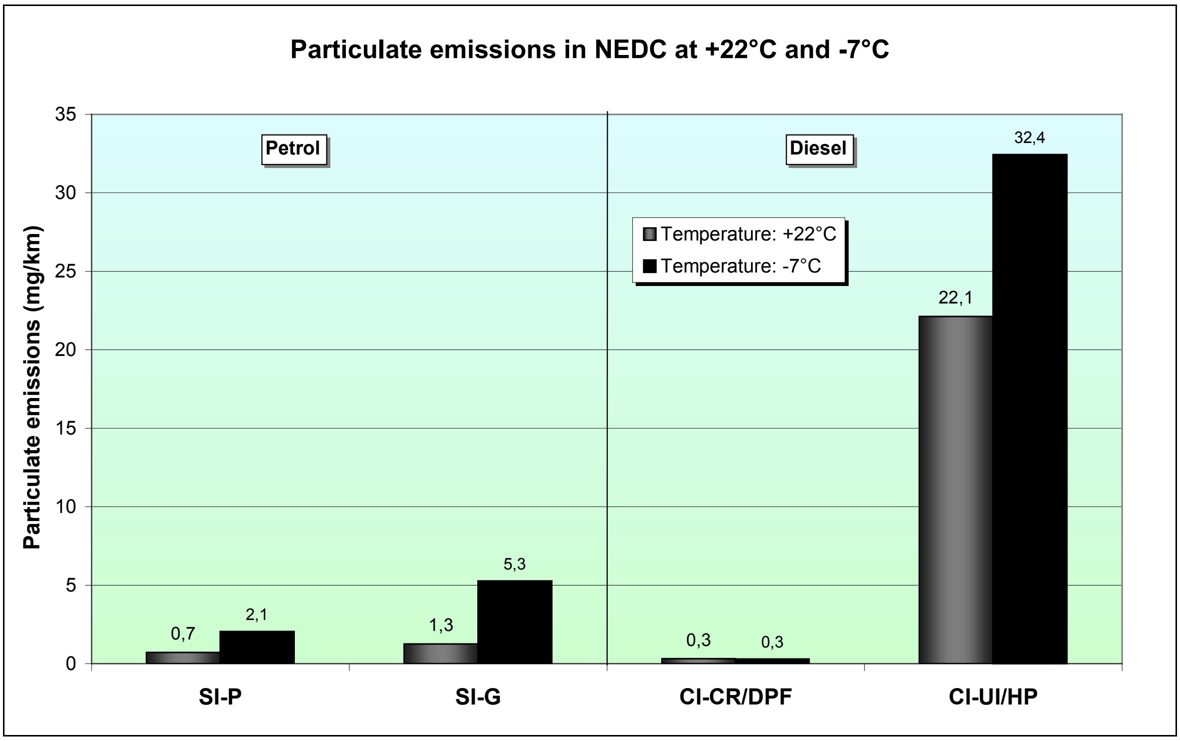


Figure ES.3. *Particulate emissions in NEDC*

The particle number and particle size distribution was measured with an electrical low-pressure impactor (ELPI). This instrument measures particle number at 12 stages for an aerodynamic particle size between 7 nm and 6 µm. One of the features of the ELPI instrument is that it can measure the particle emissions in real-time.

The results for the total particle number in the NEDC cycle are shown in **Figure ES.4.** The corresponding results in the US06 cycle and during overtaking are shown in **Figure ES.5**. Note that both figures have logarithmic scales on the y-axes.

The particle number in NEDC (**Figure ES.4)** was highest for the diesel car without a particulate filter. The two petrol cars had a level that was roughly two orders of magnitude lower. The lowest level was achieved by the diesel car with a particulate filter, i.e. about one order of magnitude lower than for the petrol cars.

In the US06 cycle (**Figure ES.5**), the particle number compared with the results in NEDC increased considerably for the petrol cars to roughly the same level as for the diesel car without a particle filter. The level during overtaking was lower for the petrol cars than in the US06. In both tests, the diesel car with a particulate filter had very low total number of particles, i.e. several orders of magnitude lower than the other cars.

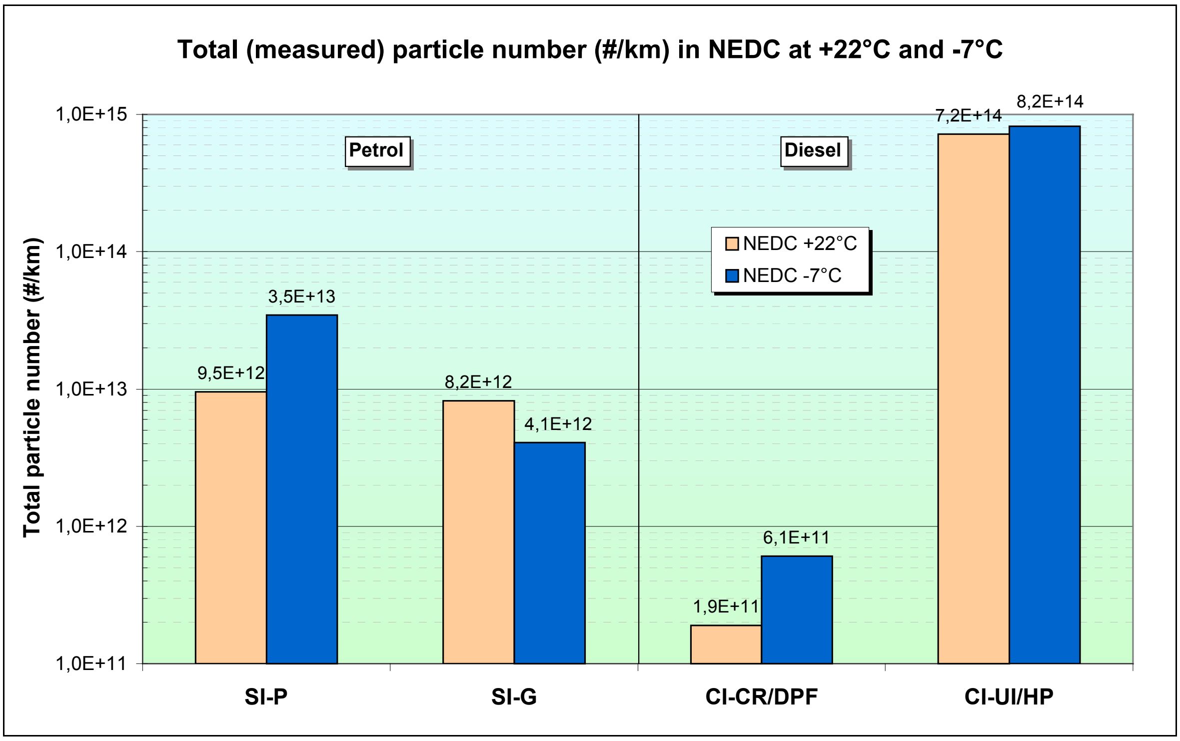


Figure ES.4. *Total particulate number in NEDC*

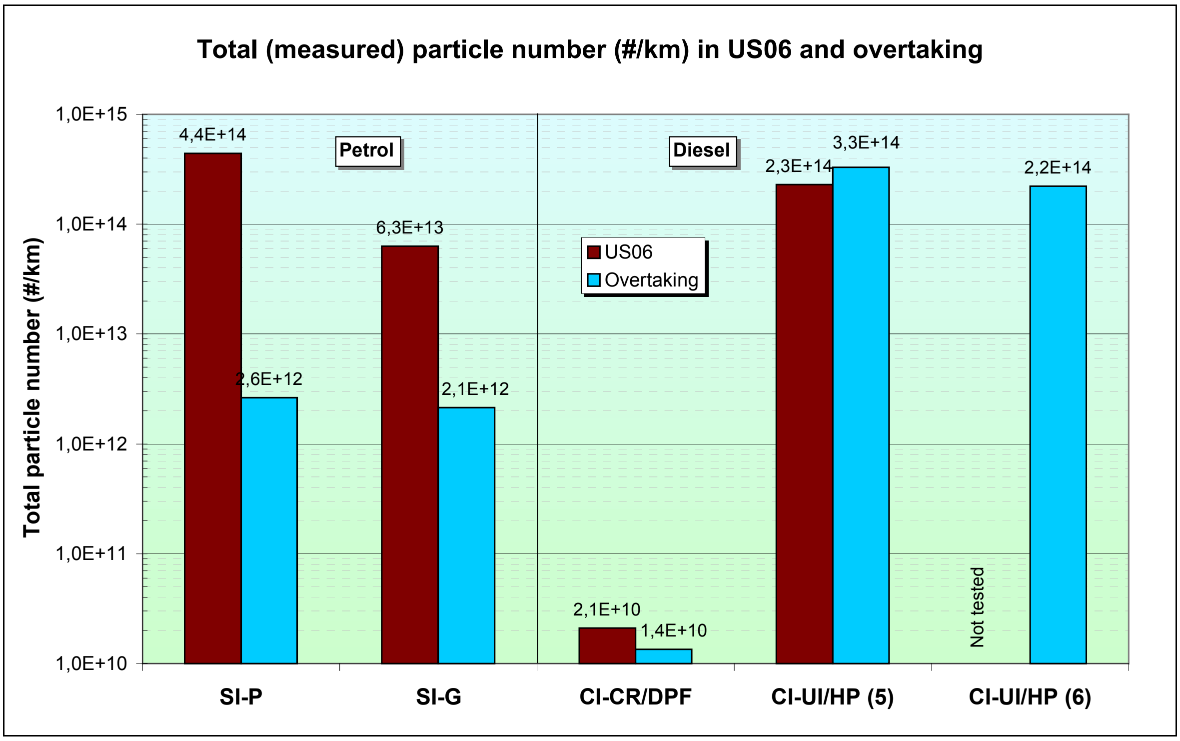


Figure ES.5. *Total particulate number in US06 and during overtaking*

Impact of emissions on environment and health

In the evaluation of the effects on environment and health, the yearly average temperature in Sweden of +7°C was used in most cases. The only exception was the ozone forming potential, where a temperature of +14°C was used instead. To provide some perspective for the comparisons, results from cars of model year 1993/1994 from a previous study are shown as well. To simplify the presentation of the results, an index has been used (base level: petrol cars of model year 1993/1994).

The ozone formation potential, as shown in **Figure ES.6** was generally lower for diesel cars than their petrol counterparts. The reason is primarily due to the significantly lower HC emissions in comparison to the petrol cars. However, it should also be noted that the level was generally considerably lower for the newer cars than for the older cars, regardless of fuel used.

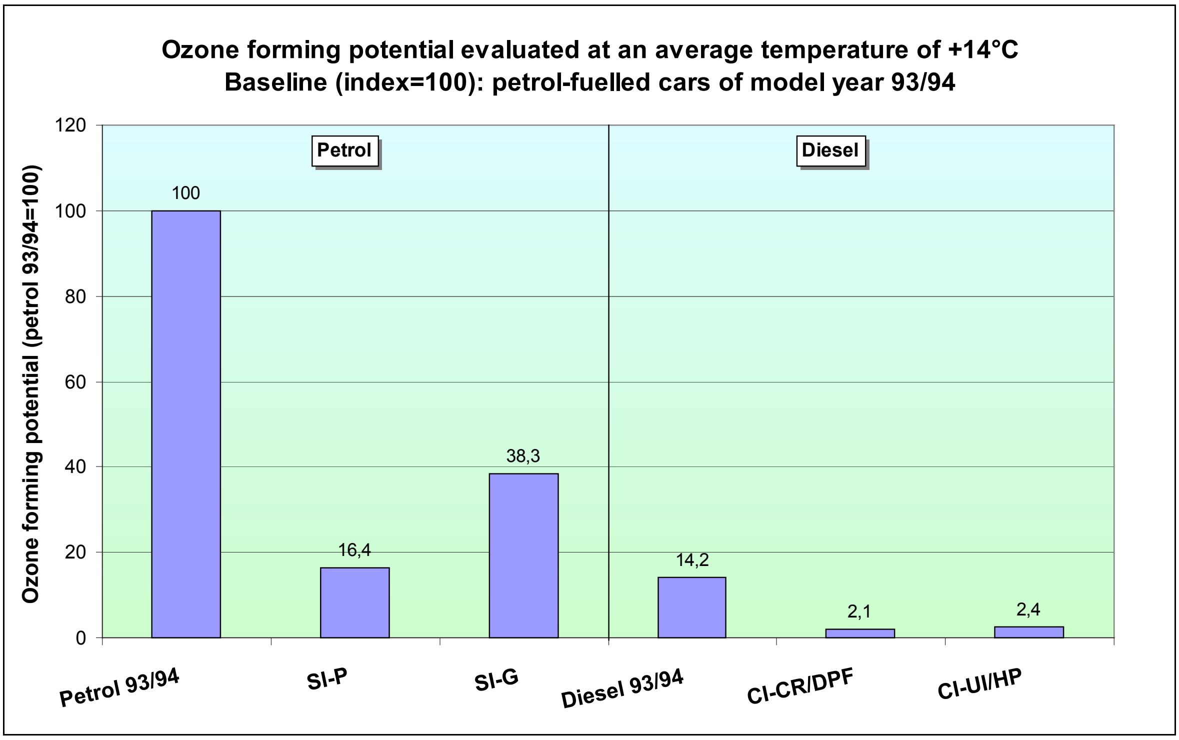


Figure ES.6. *Ozone forming potential (index: petrol 93/94=100)*

The results for the cancer risk index are shown in **Figure ES.7**. Unit risk factors for the measured emission compounds have been used as weighting factors in the calculation of the cancer risk index.

First, it should be noted that the level for the cars tested in this study was significantly lower than for the old cars **(Figure ES.7)**. Due to the uncertainty regarding the unit risk factor for each one of the emission compounds, and the scatter between the cars, it is somewhat difficult to conclude whether diesel or petrol cars have a lower level. The contribution to the cancer risk index was dominated by the polycyclic aromatic compounds (PAC) for the petrol cars. These emissions are primarily emitted at low ambient temperature. For diesel cars without particulate filters, particulate emissions contributed most to the cancer risk. The virtual elimination of the particulate emissions by using a particulate filter does had a considerable impact on the cancer risk index.

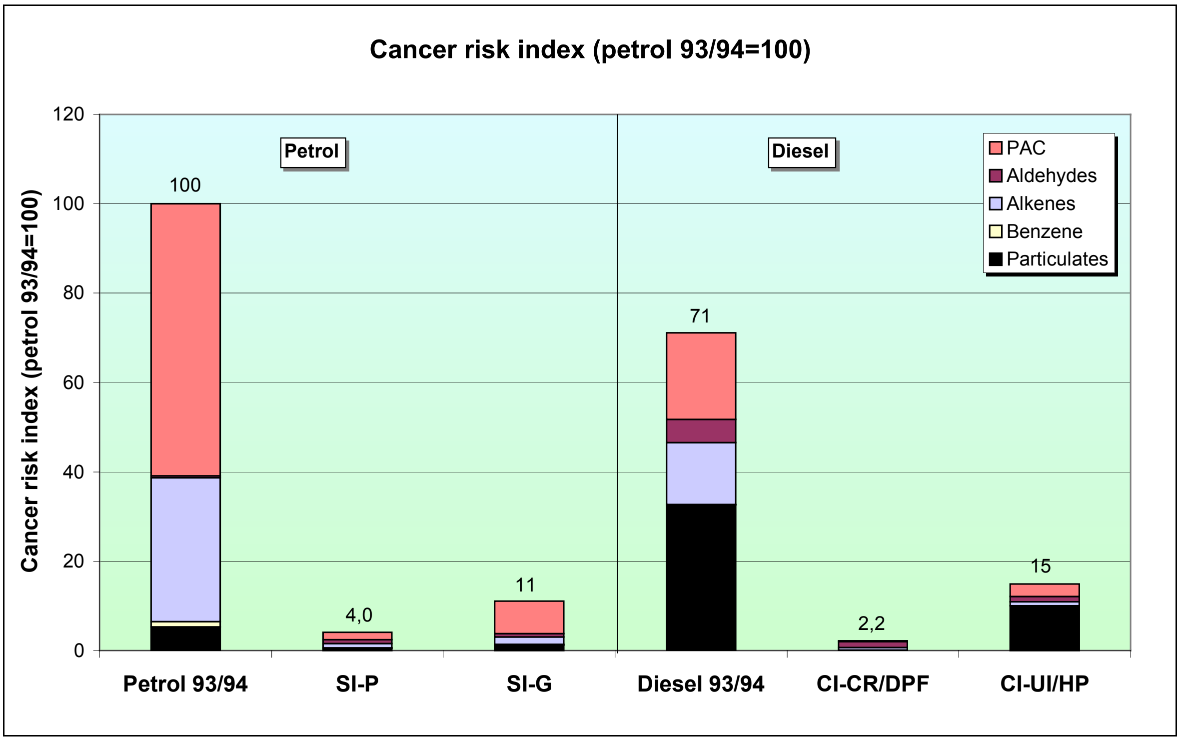


Figure ES.7. Cancer risk index (petrol 93/94=100)

Oxides of nitrogen (NO_X) and sulphur (SO_X), as well as ammonia (NH_3), contribute to the acidification. However, fuel production has also to be taken into account, as acidification could be considered as a regional impact. In **Figure ES.8**, the results for the acidification index are shown.

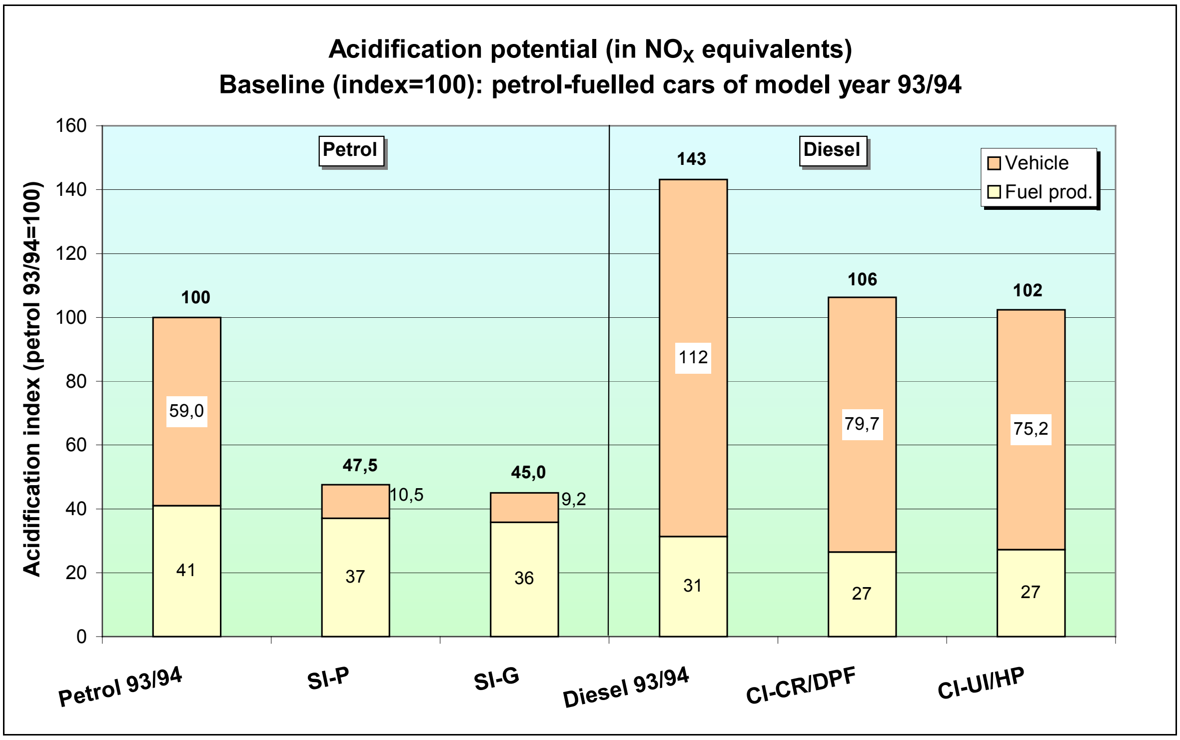


Figure ES.8. Acidification potential (index: petrol 93/94=100)

A split in fuel production and vehicle emissions has been made in **Figure ES.8**. As the NO_X level was very low for the petrol cars, as well as the sulphur level was for the petrol used, the acidification is dominated by fuel production for the new petrol cars. Diesel cars had a high NO_X level and this was the reason for the high level for these cars. In this case, the contribution from fuel production was lower than for the petrol cars.

Discussion

The introduction of new emission control technology has significantly decreased the emissions from petrol-fuelled passenger cars during the past decade. Since the introduction of the three-way catalyst (TWC) emission control system, subsequent improvements of this technology has decreased the emissions even further. In view of this progress, the emissions from diesel cars have received more attention from government authorities and environmental groups. However, the increase in emissions at low ambient temperatures from petrol cars still have not completely been solved, although this is often forgotten as emission tests are usually carried out in the +20°C to +30°C temperature interval. In the cold Nordic climate, low ambient temperatures must be considered. Eventually, the two petrol cars tested in this study showed a considerable improvement at such temperatures compared to older cars.

Although the emissions from diesel-fuelled cars have decreased considerably during the last decade, the general perception has been that these cars emit significantly higher quantities of harmful emissions compared to their petrol counterparts. The results in this study showed that several unregulated emission components from diesel cars are on the same level as from petrol cars, and in some cases, lower. Two major problems remain – NO_X and particulate emissions. Today, there is no equivalent technology to the TWC for diesel cars for reducing NO_X emissions but such aftertreatment is currently in development. Emerging particulate filter technology has been commercially introduced by PSA and other car manufacturers will follow this path.

The calculation of the impact on health and environment from exhaust emissions provide a better insight than only showing the results on the emission components. However, it should be noted that in some cases, the input data for these calculations (e.g. cancer risk) is not fully developed yet.

Conclusions

The number of cars in this study was too few to allow generalisation of the results for all cars. The selection of cars was made on the condition that the impact of new technology could be compared with previously generated results on older cars. The following main conclusions can be drawn:

- The regulated emission results on all tested cars were very close to the certification data. Therefore, they could be considered representative samples of each car model. The two petrol cars in this study proved to be on pair with some of the best cars that have been tested previously at MTC.
- As expected, CO and HC emissions were generally lower from diesel cars than from petrol cars, while the results for NO_X emissions was the opposite. Particulate emissions were higher from the diesel car without particulate filter compared to its petrol coun-

terpart. However, the diesel car with a particulate filter had lower particulate emissions than the corresponding petrol car.

- Emissions of some nitrogen containing compounds, as ammonia (NH_3) and nitrous oxide (N_2O), were low from all cars.
- The aldehyde emissions, a well-known problem for diesel engines, were at or below the detection limit for the diesel cars at high ambient temperature (+22°C). At the lower ambient temperature (−7°C), the level was approximately twice the detection limit. This implies that considerable improvements have been made in this area compared to diesel cars of the past.
- The petrol cars had higher emissions of benzene, ethene, propene and 1,3-butadiene than their diesel counterparts, although the levels of these emission components were low for all cars.
- PAC/PAH emissions are usually low from petrol cars at high ambient temperatures. As the level of these emissions has previously been higher for diesel cars at these ambient conditions, this has been considered as one of the main emission problems for diesel cars. It has seldom been recognised that *the level increases considerably for petrol cars when the ambient temperature decreases*. The PAC level for the petrol cars tested in this study were considerably reduced compared to previous tests on older cars at the low ambient temperature. The PAC levels for the diesel cars were generally lower than for their petrol counterparts at the average yearly temperature of +7°C. The PAC level for the diesel car with a particulate filter was one order of magnitude lower than the petrol car from the same car manufacturer. A comparison with data on 1993/1994 model years of petrol cars gives a difference of more than 2 orders of magnitude. Although the diesel car without a particulate filter had lower PAC emissions than its petrol counterpart, the great variation between cars implies that new diesel cars (w/o particulate filters) are not necessarily better than new petrol cars in this respect.
- The diesel car without a particulate filter emitted about 2 orders of magnitude more particles than its petrol counterpart in the NEDC cycle at both temperatures. However, in the US06 test cycle the number of particles was on roughly the same level as for the petrol cars. The increase in particulate number for the petrol cars in this cycle compared to the NEDC cycle was mainly attributable to an increase of the smallest particles (7 – 30 nm). The diesel car with a particulate filter was outstanding in this respect having particulate number emissions at least one order of magnitude lower than the petrol cars. The particulate filter was particularly effective in reducing the number of nanoparticles. Comparison with older data showed a reduction of the particulate number for the diesel car without particulate filter.
- The ozone forming potential was considerably lower for the diesel cars, i.e. roughly one order of magnitude lower than for the petrol cars. This is mainly due to the low level of HC emissions for diesel cars compared to the petrol cars. Should the evaporative emissions have been taken into account, the relative difference would have been even greater.
- The cancer risk index was generally significantly lower for the cars tested in this study compared to older vehicles. The diesel car with a particulate filter had a lower cancer risk index than its petrol counterpart. For the diesel car without a particulate filter, the level was slightly higher than for the petrol car from the same manufacturer. In general, the lowest value was obtained for the diesel car with a particulate filter, i.e. almost 98%

lower level than petrol cars of model year 1993/1994. It should be noted that the uncertainty is high for the cancer risk index due to the varying level for the unit risk factors, depending on which source is used. Therefore, small differences should not be considered.

- The environmental effects mostly related to the emissions of NO_X, such as NO_2 forming potential, acidification and eutrophication, were greater for the diesel cars than their petrol counterparts, due to the higher NO_X emissions. The contribution from fuel production was higher for the petrol cars.
- As expected, climate change and energy use was lower for the diesel cars than for the petrol cars. This is partly due to the lower fuel consumption, partly to the higher efficiency in fuel production.

Although the scope of this study was to compare the emissions from diesel cars with the emissions from petrol cars, it cannot be avoided to point out that the focus was shifted towards the results on the diesel cars. This is mainly because most data on unregulated emissions on new cars have been generated on petrol cars. Relatively little is known on the impact of new technology in this respect. As expected, the NO_X and particulate emissions are the main emission problem on diesel cars. The results on particulate emissions show that a particulate filter is very effective in reducing these emissions. For both emission components, solutions that can alleviate these problems have been introduced, or will be introduced on the market in the near future. Nevertheless, as diesel cars are improved in this respect, so will petrol cars. The test results on the unregulated emissions, and the effects on health and environment that were evaluated, showed lower levels in some cases for diesel cars and higher levels in other cases compared to petrol cars. Eventually, as the emissions from vehicles running on both types of fuels will be reduced to a negligible level, energy efficiency and the emissions of greenhouse gases will become more pronounced in the future.

1 INTRODUCTION

The transport sector contributes significantly to the air pollution and in particular, this is evident for the local air quality, since light and heavy-duty vehicles often operate in populated areas. Therefore, it has been of interest to reduce the exhaust emissions from these vehicles. First, in the late 1980´s, the focus was on light-duty vehicles but lately, the focus has shifted somewhat towards heavy-duty vehicles. The latest move is logical, as the share of this vehicle category (of the transportation emissions) seems to be increasing in comparison to the light-duty vehicles. However, in one particular aspect, the light-duty vehicles have been subject much interest lately, and this is regarding the particulate emissions from diesel-fuelled cars. Since the market penetration of diesel cars has been ever increasing on most markets in Europe (to over 30% in 2001), this issue has become even more pronounced. Sweden has been an exemption in this respect. Here, the market penetration has been slowly decreasing during the last 3 years and now it seems to have stabilised at level of slightly above 5%.

During the last years, climate gases (mainly CO_2) have also been much debated. It has become clear that the share of CO_2 emissions from the transportation sector is large and increasing. Therefore, a voluntary agreement has been made between the European car manufactures (represented by their organisation ACEA) and the EU commission about reducing the CO_2 emissions from the fleet of new cars by 25% from 1995 to 2008. Similar agreements has also been made between the car manufactures from Japan (JAMA) and Korea (KAMA) for 2009. Meeting this requirement is not easy. It has been speculated that increasing the share of diesel cars and cars with direct injection of petrol will be two of the main measures to meet this limit. Therefore, it is of interest to investigate the emissions from these two categories of engine/fuel technology in comparison to conventional petrol-fuelled cars.

In the EU, stricter emission limits for light-duty vehicles have been introduced subsequently during the last decade and in 2005/2006, the so-called "Euro IV" emission regulation will be enforced. However, there are already numerous petrol-fuelled cars that fulfil this regulation[1] and a few diesel cars can meet this emission level, although the late specification of the regulation in the latter case may have delayed actual certification of the cars. In the USA an in California, even stricter emission levels have been introduced (e.g. SULEV according to the LEV II programme). There are some petrol-fuelled cars available on the U.S. market that can fulfil these emission limits, implying that there is still considerable scope for future development in this area, if this technology could be applied extensively.

New diesel cars that can fulfil the Euro IV regulation are about to be introduced on a larger scale within the 2003/2004 timeframe. A 74 kW engine, thought to be a mainstream engine for many of the cars produced by for the VW group of auto manufacturers, was introduced in the autumn of 2001. Presently, this car fulfils the German D4 emission norm that has emission limits corresponding to Euro IV. However, it has not yet been certified to the Euro IV emission regulation. Although the recent development in this area has been encouraging, it has to be noted that the particulate level for diesel cars complying with Euro

[1] In some cases, cars have an emission level significantly below Euro IV but the cars are certified to Euro III anyway.

IV is still far higher than for a (modern) conventional petrol car. This conclusion is valid at an ambient temperature corresponding to the interval of +20 to +30°C used in the test cycle – the difference might be smaller at lower ambient temperatures.

The use of a particulate trap, which recently has been introduced on the market by one manufacturer (PSA), reduces the particulate emissions to practically the same level as for petrol-fuelled cars. Regarding the NO_X level, the situation is somewhat similar as for the particulate emissions, since the limit in the present Euro III directive and the future Euro IV directive is higher for diesel cars than for petrol cars. Due to the excess oxygen in the exhaust, reduction of NO_X by using conventional catalysts is not possible. New catalyst that seems to have a great potential are now being developed but the introduction of these catalysts are highly depending on the widespread availability of ultra low-sulphur diesel fuel (<10 ppm S). At present, such fuel is only available on a few markets in Europe.

Due to the objective to reduce the greenhouse gas (GHG) emissions, as mentioned above, direct injection of petrol has become a very interesting solution. With present technology comprising direct injection and a lean-burn combustion system, a reduction of the CO_2 emissions by some 12% (author's estimate) in comparison to a conventional petrol engine seems possible. The drawback of the technology mentioned is an increase of the NO_X emissions, as a conventional three-way catalyst (TWC) cannot be accomplished due to the excess oxygen in the exhaust. However, new catalyst technology is now being introduced on the market and this technology seems at least to partly overcome this problem. Another problem associated with direct injection of petrol is that the particulate emissions increase in comparison to conventional petrol engines. It seems likely that this problem could be alleviated by improved injection systems and control strategy, but the magnitude of this improvement potential is not clear. Although direct injection of petrol was of primary interest for this investigation, it was not possible to get access to a vehicle with the newest emission technology, and of comparable size to the other vehicles, within the timeframe of the project. However, such tests could be added later.

Separately, some of the facts not covered directly in the main body of the report, but information that could be of general interest, have been shown in separate boxes. In some cases, the discussion of these issues is also added in such boxes. An example of the box mentioned is shown to the right.

Ecotraffic's comments

Fact and discussion box

This is an example of a fact and discussion box. The data and opinion expressed here is not covered in the main report but this information is considered to be of general interest.

2 BACKGROUND

In Sweden, much of the emission research on vehicles and engines has been funded by the Swedish EPA (SEPA). During the initial phase of emission research, SEPA operated its own emission lab and the research organised in this form continued until 1989. For a period of 10 years after that, the responsibility for this activity was assumed by the Swedish Motor Vehicle Inspection Co. (ASB). The contract research carried out was managed through a 10-year agreement between the SEPA and ASB. The wholly owned subsidiary MTC (formerly Motortestcenter, a business area of ASB) of ASB carried out the research work under the agreement. The agreement was initially (1989) 10 million SEK per year, and as it was indexed, it amounted to approximately 16 million SEK in 1999 (approximately 1,5 million €). However, this agreement was ended in 1999 and in 2000, only a reduced programme was carried out. In 2001, very little research funded by the government (through SEPA) was conducted in this area.

During the latest years, a shift of some of the responsibility for controlling the air pollution from the transportation sector has been made from SEPA to the Swedish National Road Administration (SNRA). SNRA has also been funding some research in this area during the past years, although not up to the same level as by SEPA, as described above. It has been logical that SNRA has assumed more of the responsibility in this area than previously, as this authority now has the responsibility for the emissions from transportation sector (including off-road vehicles).

Besides the need for new emission factors for the regulated emissions, it can be concluded that the public domain database on unregulated emissions is not as comprehensive as for regulated emissions. As the latter is not very comprehensive either, it is conceivable that much more work is needed regarding the unregulated emissions. Particulate emissions and especially nanoparticles (<50 nm) have been much in focus due to the anticipated health effects, such as the probable cause of cancer and increased mortality and morbidity. Recently, “new” emission components, such as e.g. benzene and PAH (with benzo(a)pyrene as a marker of PAH), has also been of interest to include in future air quality standards in the EU. It is likely that the focus on exhaust emissions will broadened in the future to include several emission components that are not regulated today. In view of the trends mentioned, it is of interest to increase the public domain database in this area.

This project originates from preliminary discussions between Ecotraffic and SNRA in 1998. The first proposal for testing and evaluation of the data was modified several times in order to find a balance between the desire to investigate as much as possible and the current economical constraints. Due to the limited funding available at SNRA, the project could not be started before 2001.

In emission and health effects evaluations for various customers, Ecotraffic had identified the need for more experimental data in this field. In particular, data on vehicles with new emission control technology was found as principally important in this respect. Due to the emission research programme of SEPA, as described above, relatively comprehensive set of data are available on older vehicles. The exception is for some new emission components, e.g. small particles. Data on new vehicles are also necessary to generate in order to be able to make forecasts about the emission level from future vehicles. It does not make much sense to extrapolate trends for air pollution in the future using data from old vehicles as the basis for the forecast.

Since the need for new emission data was identified, it was decided to carry out the emission test programme and to evaluate the impact on health and environment from those emissions. Due to the economic constraints, relatively few cars could be tested, but is should also be recognised that it is possible to extend the testing in the future, when new emission control technology is introduced on the market.

3 METHODOLOGY

3.1 Literature survey

In previous work (e.g. [1][2]), the author has conducted literature surveys on regulated and unregulated emissions from cars fuelled with various fuels. Therefore, no dedicated literature search and assessment of this literature was carried out in this project. However, when necessary, literature is referred to for comparisons and for discussion of the results.

3.2 Selection of vehicle technology

Two main areas of interest were initially identified as interesting to investigate. The first area was the new direct injection technology for petrol-fuelled cars and the second area was the new diesel engines with high-pressure direct injection and/or particulate filters. In both cases, many variations of the technologies could be anticipated. Due to the importance of this issue, a brief overview of the various technologies is made below.

3.2.1 Conventional three-way catalyst (TWC)

The advance in conventional TWC technology has been tremendous during the last decade. When the LEV programme (1st version, or “LEV I”) was introduced in California in the 1990´s it was anticipated that new advanced technologies, such as e.g. electrically heated catalysts, would have to be used to meet the ULEV limits. Later it was found that improvement of the conventional technology made these solutions redundant, although they have now been developed to a commercial state. The new Euro IV emission limits are almost as though as the ULEV limits for the HC emissions, bearing in mind that the driving cycle is different in the two cases[3]. Some of the limits in the Euro IV directive (e.g. NO_X) are actually tougher than the ULEV. Somewhat surprising, it seems that most of the new petrol-fuelled cars introduced today are meeting the Euro IV limits, several years before the time schedule.

It is somewhat difficult in individual cases (i.e. a certain car model) to exactly pinpoint the improvements that have enabled the car manufacturers to meet the Euro IV limits without the use of the most sofisticated technology, as mentioned above. A recent overview by Audi of the technology applied for meeting the Californian ULEV emission level could be mentioned as an example of the introduction of low-emission technology [2]. Although this engine used a turbocharger, much of the emission control technology used is similar for naturally aspirated engines. Without going into much detail about the emission control on TWC engines, two major issues could be mentioned. First, it is of utmost importance to reach the light-off temperature for the catalyst as early as possible. Second, the air-fuel ratio has to reach stoichiometric ratio as soon as possible (reducing initial the phase of fuel enrichment). In the first case, the positioning of the catalyst as close to the engine manifold as possible is of importance. In some cases, a small light-off catalyst (with low thermal inertia) is used before the main catalyst. The improvement of the thermal stability of the

[2] Numbers in brackets indicate references that as listed in the reference section in the report.
[3] The weighting of the cold start is more prominent in the European driving cycle than in the US FTP-75 driving cycle.

catalysts has been crucial to enable the use of these technologies. Thermal insulation of the exhaust system (before the catalyst) to avoid heat losses, as well as strategies to raise the exhaust temperature during the cold start phase are also beneficial. Second, improvements in the combustion control (air-fuel preparation and combustion system) in combination with improved control strategy have enabled that the period without controlling the air-fuel ratio to stoichiometric condition has been shortened significantly. Ideally, this should be achieved in a shorter timeframe than the idle period in the test cycles. In the US FTP-75 test cycle, the idle period 23 seconds. This period is reduced to 11 seconds in the European NEDC cycle. It appears that advanced emission control technologies can achieve a light-off period shorter than the idle period in the NEDC cycle. Avoiding fuel enrichment in the first accelerations reduces the engine-out emissions considerably.

In order to reduce the fuel consumption of engines with TWC, one option is to avoid the throttling losses by utilising a fully flexible valvetrain. This type of valvetrain can limit the volumetric efficiency of the cylinder by closing the inlet valve early or late. Ideally, throttling can be totally avoided, thus reducing the fuel consumption considerably. This technology has recently been commercialised by BMW. The conventional TWC emission control can be retained by using this type of valvetrain and this is one of the principal advantages of this system in comparison to lean-burn direct injection technology (see below). In fact, some minor advantages for the emission control can be attributed to this valvetrain technology.

The remaining problems for the emission control with TWC technology are the ageing phenomenon (including total failures) and cold start at low ambient temperatures. As the first issue has not been investigated in this project, the second issue was considered to study.

3.2.2 Direct injection of petrol (SIDI)

Direct injection of petrol has gained considerable interest ever since the Mitsubishi GDI was first introduced on the European market in 1997 (1996 in Japan). Direct injection of spark ignition engines (SIDI) enables a significant decrease of the fuel consumption, which is the main advantage of the concept. This is primarily due to the reduction of throttle losses but also combustion phenomena, as well as heat losses are of importance. In a comparison of similar cars by the author, the advantage in fuel consumption for the direct injection engine (Mitsubishi GDI) was found about 10% in the NEDC cycle [3]. However, as the car with SIDI engine was relatively new during testing (it had a low odometer reading) compared to the conventional car, indicating that the real potential might be a few per cent higher.

Although the potential advantage in fuel consumption for the direct injection is appalling, there are also some problems with this technology. First, the excess oxygen does not enable the use of a conventional TWC catalyst system. Catalysts capable of reducing NO_X under lean conditions have been developed but so far, these catalysts do not have the same reduction capacity as the previously mentioned catalysts for the TWC system. The most recent technology, using storage and release type of catalysts (“NO_X traps”), has been introduced on the market. These systems seem to have the ability to meet the Euro IV limits and presumably, there is some further development potential for this technology. Another option could be to use a catalyst that uses hydrocarbons as a reducing agent and an assistance of non-thermal plasma (NTP), although this technology seems to have been of most interest for diesel engines.

Other issues with SIDI engines are higher HC and particulate emissions than conventional petrol engines. Today, it is not clear how great the development potential is in these fields but it is likely that the emission level of the newest cars should be lower than for the first generation of cars.

Although the investigation of a car with a SIDI engine was of interest in this project, it was not possible to receive a car with the newest technology within the timeframe of the project. Characterisation of the emissions from this technology remains to be included in further investigations.

3.2.3 Direct injection of diesel (CIDI)

Direct injection for diesel engines (CIDI[4]) in passenger cars was first introduced by Fiat, Rover and Audi in 1987-1989 timeframe as direct competition to the indirect injection engines (IDI). In the perspective of the subsequent market development, it should be noted that only the engine from Audi was a real commercial success during the first years. High noise and problems with emission control were two major problems initially but in both cases, the continuos development has alleviated these problems. The major advantage of the DI diesel engines is the reduction in fuel consumption by some 10 – 15% compared to the IDI diesel engines.

About mid 1990, the emission level for the DI engines was roughly comparable to the IDI engines and today, there is a considerable advantage for the DI engines. DI engines have higher NO_X emissions than IDI engines, without EGR in both cases, but the tolerance for exhaust gas recirculation (EGR) is higher in the former case. Thus, with optimum EGR, the DI engine seems to have an advantage. Furthermore, an increase of the injection pressure for DI engines, which per definition does not necessarily have to decrease the NO_X emissions, increases the EGR tolerance. Consequently, the higher injection pressure available with new injection equipment for DI engines and the subsequent development of the EGR system has shifted the emission advantage towards the DI engines. Injection systems with high injection pressure were first introduced in the 1997 – 1999 timeframe[5]. High-pressure distributor pumps, unit injectors (UI) and common rail (CR) injection systems are the three technologies available today. The second generation of the latter systems is now being introduced (CR gen. II), or is about to be introduced (UI gen. II), but it is anticipated that the use of rotary pumps will eventually be discontinued in the future.

Diesel cars meeting the Euro IV emission level are now being introduced on the market. However, as the permitted emission level for NO_X emissions in Euro IV is higher for diesel cars than for the corresponding petrol cars, the NO_X level is still higher for the diesel cars. In addition, the particulate level is higher implying that further development in this area is necessary. The other regulated emission components (CO and HC) are, in general, lower for diesel cars than for petrol cars.

A potential problem of the DI engines, and in particular engines that have high injection pressure, which has been discussed is the *potential* increase in nanoparticles[6] in comparison to IDI engines and DI engines with low injection pressure. However, there are little

[4] CIDI: Compression Ignition Direct Injection, i.e. a diesel-cycle engine with direct injection.
[5] It should be noted that high-pressure injection (>1 500 bar) had been used earlier on heavy-duty engines and on larger marine and industrial engines. However, the application of such technology was new on passenger car size of engines in the timeframe indicated.
[6] The definition of nanoparticles used in this report is particles with a diameter less than 50 nm.

data to support this hypothesis. A study conducted by this author did not find any significant difference between three cars with DI engines and two cars with IDI engines in this respect [4]. In view of the relatively little data available in this area (and the potential health effect), the generation of data on new vehicles was considered of high priority.

3.2.4 Direct injection of diesel (CIDI) with a particulate trap

The use of particulate traps on passenger cars is not new. In California, both Mercedes and VW had cars in production in the mid-1980's that were equipped with particulate traps. However, the durability of these systems was not satisfactory and consequently, the production of these systems was discontinued. At the same time, the public interest in diesel cars in the USA was declining rapidly, presumably as a response to the engine durability problems experienced by one US manufacturer. Concern about the potentially hazardous emissions from diesel cars was also raised by the US EPA. These issues led to a diminishing interest in diesel cars in the USA (that have continued until today). This could also have been a reason to why the development of particulate trap systems was given a very low priority by the car manufacturers for the subsequent period of (more than) 10 years.

In the 1980's, as future particulate limits were being discussed in Europe, it was found that the particulate emissions could be significantly reduced by further development of the engine ("internal measures"). By using such measures, the EU emission levels from late 1980 until Euro III (2000/2001) could be met with far less cost and complexity than using a particulate filter. When the Euro IV emission level for 2005/2006 was proposed, it was considered by many experts that this level could *not* be met without using a particulate filter. However, it has been shown that, in fact, this level can indeed be met without a particulate filter, at least on small to medium sized cars. On the longer term horizon − in particular, with respect to the future emission limits in USA and California − and for heavier cars, it seems that a particulate filter is the only viable solution[7]. Consequently, all car manufacturers and suppliers of exhaust aftertreatment devices are now developing this technology.

It should be noted that filtering the exhaust is not the main problem with particulate filters. Instead, regeneration of the filter (burning of the collected particulate matter) poses the main technical problem. Several technologies have been proposed for filter regeneration. Many of these require ultra-low (or zero) sulphur level in the fuel. As this fuel is not available all over Europe yet[8], the widespread use of this technology is not possible (cars can cross the borders). Some of the regeneration strategies are dependent on a catalyst that will convert SO_2 to sulphates[9]. As these sulphates will be collected on the sampling filter, and contribute to the particulate matter, the particulate emissions could actually increase under some circumstances.

One of the solutions that could be somewhat more sulphur-tolerant is the use of a fuel additive. In fact, the idea of using fuel additives is not new either, it was tested on vehicles in the USA (e.g. by VW) in mid 1980's. Copper, iron, cerium, strontium and other additives have been tested as means of reducing the regeneration temperature. During the past years,

[7] It should be noted that a combustion system without any soot formation is theoretically possible but the commercial success of this technology is not likely in the foreseeable future.

[8] Ultra-low sulphur fuel (<10 ppm) has been available in Sweden for more than 10 years and today, this fuel has almost the whole market for on-road diesel fuel.

[9] In addition, it could be mentioned that storage and release of sulphates from the catalysts and/or particulate filters is a particular problem in this respect.

this technology has been used on construction mining machinery and other non-road machinery of similar kind. However, the application of this technology on passenger cars has not been easy, primarily due to the low exhaust temperature experienced in this type of use. In 2000, a further development of this technology was commercially introduced by Peugeot on the model 607 HDi. The system has been described in a SAE Paper by Peugeot [5] and additional information about the development was provided in a SAE Paper by Faurecia [6] and in the Journal of MTZ [7]. As for many other regeneration technologies, the application on a passenger car is very difficult due to the low exhaust temperature. By utilising the possibilities of raising the exhaust temperature for a short period, regeneration can be initiated and consequently, this development is essential for a regeneration strategy. Modern CR injection systems provide this opportunity and consequently, the regeneration is intermittent. Using the strategy mentioned, the regeneration is completed in a relatively short time.

An important factor regarding durability is that Peugeot use silicon carbide (SiC) as monolith material in favour of corderite that is used in most applications today (e.g. heavy-duty vehicles). SiC is a much tougher material than corderite regarding the thermal stability. Needless to say, an electronic control of the regeneration process and diagnosis of the whole system is also necessary. The maintenance required for the system is that the additive has to be refilled and the filter must be cleaned from ash every 80 000 km (and possibly replaced after a longer period of use). The collected ash originates mainly from the lubricating oil and therefore, the formulation of low ash oil and a reduction of the oil consumption are important aspects for future development work.

Ecotraffic's comments

Filter maintenece and cost

The maintenance interval used today on the filter system by PSA might be acceptable but need improvement in the future. An ideal system should last the life of the engine without the need for maintenance or replacement. In addition, as the additive used shortens the interval, avoiding such additives would be of great importance in the future. The cost reduction by omitting the additive pump and control system would also be a driving force behind future development in this area. It is plausible that other possible routes but the system used currently by PSA will be explored in the future.

3.3 Experimental

3.3.1 Test facilities

The testing of the vehicles was carried out at MTC in Jordbro, about 20 km south of Stockholm. MTC has been accredited for emission testing according to EN 45001, since 1992.

The light-duty test cell at MTC used for this purpose is a climatic test cell capable of testing at an ambient temperature of down to –20°C[10]. The test cell used has a twin-roller electric chassis dynamometer, Clayton EIS 50. The dynamometer settings were calculated

[10] This is under relatively favourable conditions, i.e. during late autumn to early spring when the temperature outside is not so high. In the summer time the limit is approximately –15°C.

from coast down data provided by the car manufacturers. **Figure 1** shows an example of a typical test arrangement for a car on the chassis dynamometer.

***Figure 1**. Testing of the Peugeot HDi in the emission test cell at MTC (courtesy of MTC)*

3.3.2 Vehicles

In the preliminary discussion about vehicles of interest to study, several potential candidates were identified. First, it was decided to that a couple of principles should guide the choice of vehicles. These were:

- As low emissions as possible according to the European driving cycle, i.e. the fulfilment of Euro IV was preferred. If the vehicle was not certified to this emission level, it was still desirable that the emission level would be well below the Euro IV limits.
- Vehicle size should be about the average size (or weight) for European cars, i.e. somewhat smaller than the Swedish average size. It was also desirable that all cars should be about the same size and weight.
- The cars should have approximately the same performance. Using the acceleration from zero to 100 km/h as a benchmark, this would necessitate approximately the same engine power for cars of similar weight.
- The engines should have approximately the same cylinder capacity and number of cylinders. In general, the specific power for diesel engines has been lower than for petrol engines in the past. Recently, this difference has been diminishing, thus implying

that there should not be much difference in cylinder capacity for cars of similar performance.

- It was desirable that two corresponding petrol and diesel cars from the same manufacturer and of the same car model could be found. This would make the comparison between the two fuels more straightforward.

As described above, it was not possible to get access to a car with a SIDI engine of the desirable size category within the timeframe of the project. Therefore, it was decided to choose cars with conventional TWC emission control system instead. A car having a fully variable valvetrain to control engine power instead of using conventional throttling could presumably have been available from BMW. However, since this technology is not available from any other manufactures yet, it was not considered at this stage. Due to the constraints described, conventional TWC technology was considered the only viable option for the choice of the petrol cars. For cars of the size and weight, as described above, engines of a total cylinder capacity of some 1,6 to 1,8 litres would have an output of between 70 and 95 kW and provide the desired driveability for most customers. The offer of petrol-fuelled cars on the market meeting these criteria is vast, implying that the choice of car manufacturer and car model could be made with focus on the diesel counterparts instead.

Having determined that the availability of conventional petrol cars was not the limiting factor, potential diesel car test candidates were identified. During the summer of 2001, VW announced that they would initiate the production of an engine meeting the German D4 emission regulation (in practice, the same emission level as Euro IV) in the VW Golf size of cars. The power of that engine is 74 kW, i.e. within the desired power range. The engine is equipped with the latest version of Bosch Unit Injectors (UI-P1.1). However, even in this case it was not possible to obtain a vehicle within the timeframe of the project. Instead, a 96 kW TDI corresponding to Euro III emission regulations was chosen. This car was eventually the most powerful car of all the cars that were tested. A 74 kW Euro III version of the same engine has also been marketed in some car models in the VW group of companies. Since this engine is now being replaced by the previously mentioned new version having much lower emissions, it was not within the scope of the project to test the older version of that engine. Instead, the 96 kW engine was chosen.

The choice of diesels car having particulate traps is relatively limited today, as only PSA (Peugeot and Citroën) are offering such aftertreatment on their cars at the moment. A Peugeot 307, or possibly, a Peugeot 406 or a Citroën C5 was in the desired size range of cars. The particulate filter system (FAP) of PSA is offered on engines of 2,2 and 2,0 litre sizes today. In the latter case, the FAP system is only offered on the most powerful version of the 2-litre engine. After discussions with Peugeot, a 307 HDi with FAP was chosen. The power of this engine was 80 kW, i.e. lower than in the case of the VW Golf, but more in line with the petrol cars (see below). The car was kindly lent by Peugeot in France, as this car had not been introduced at the Swedish market at the time the test programme was initiated.

After the two diesel cars had been selected, the petrol versions of the same cars were also chosen. In both cases, 1,6 litre engines were the most obvious choices. The power level of 80 kW (Peugeot 307 1,6) and 77 kW (VW Golf 1,6) was on a similar level as the Peugeot 307 HDi (80kW).

Since the torque characteristics of naturally aspirated petrol engines and turbocharged diesel engines is vastly different, it could be anticipated that the passing acceleration without downshifting would be significantly quicker for the diesel counterparts. On the other hand, top speed usually is marginally higher for petrol engines of same power compared to the diesel counterparts due to selection of transmission and final drive ratios. It can be concluded that the criterion of selecting cars with the same performance was met, except in the VW Golf TDI case, where significantly better performance than from the other cars could be expected. It could be noted that the engine capacity is greater for the diesel engines than for the petrol engines. The ratio is 1,25 in the Peugeot case and 1,18 in the VW Golf case. For a couple of years, Ecotraffic has been continuously comparing the fuel consumption for petrol and diesel cars of similar performance (i.e. same acceleration 0-100 km/h) on the European market. The database comprised 103 cars of each type at the end of 2001. The average ratio of engine size (diesel/petrol) of all the cars was 1,15, implying that the difference for the cars tested in this study was slightly greater. One should also note that there are several other differences between petrol and diesel engines than size. For example, the petrol engines have 4-valve cylinder heads while the diesel engines only have 2 valves. This indicates that the technology level (in this respect) is still not quite as high for diesel engines as for petrol engines.

All the cars were kindly made available by the car manufacturers or the wholesales in Sweden. In one case (Peugeot 307 HDi), the car was transported from France but the other cars were chosen from the demonstration car pools of the wholesalers in Sweden.

In **Table 1**, the specifications of the cars are shown. Abbreviations for the vehicles are presented in the first row below the title of the table. The petrol cars are denoted “SI”, with the addition of “P” and “G” for Peugeot and Golf respectively. Likewise, diesel cars are denoted “CI”. The car with common rail injection and diesel particulate filter is designated “CR/DPF” and “UI/HP” is used for the car with high-pressure unit injector

Some comments can be made about the data in **Table 1**. As the cars were relatively new during the tests, the odometer reading was quite low. It was considered that the distance driven prior to the test should be greater than 3 000 km to avoid the so-called “green catalyst” effect, which results in particularly low emissions for a brand new car. On the other hand, the odometer reading should not be too high as the emission deterioration was not to be taken into account (this could be a separate issue for a follow-up project).

Table 1: Vehicle specifications

	Petrol cars		Diesel cars	
Parameter	**Peugeot 307 1.6**	**VW Golf Var. 1.6**	**Peugeot 307 2.0 HDi FAP**	**VW Golf 1.9 TDI**
Vehicle denotation.[a]	SI-P	SI-G	CI-CR/DPF	CI-UI/HP
Model year	2001	2001	2001	2001
Odometer reading (km)	12 205	3 358	7 632	4 677
Engine type	L4	L4	L4	L4
Certification	Euro III	Euro IV	Euro III	Euro III
Environmental Class[b]	C3/2000	C1/2005	C3/2000	C3/2000
Combustion system	SI otto	SI otto	DI diesel	DI diesel
Injection system	MPI	MPI	CR	UI
Displacement	1 587	1 598	1 997	1 896
Bore ∗ stroke	78,5 ∗ 82	76,5 ∗ 86,9	85 ∗ 88	79,5 ∗ 95,5
Compression ratio	10,8	11,5	17,8	19,0
Valves per cylinder (#)	4	4	2	2
Power (kW)	80	77	80	96
Rated eng. speed (r/min)	5 750	5 700	4 000	4 000
Maximum torque (Nm)	147	148	250	310
Max. torque spd (r/min)	4 000	4 500	2 000	1 900
Gearbox	5 speed	5 speed	5 speed	6 speed
Emission control concept[c]	TWC[c]	TWC[c]	EGR[d], OXD[e], DPF[f]	EGR[d], OXD[d]

Notes:

[a] The vehicle denotations in the table are used in the text and in figures and tables in the report. The denotations are: SI: spark ignition (P for Peugeot and G for Golf); CI: compression ignition; CR/DPF: common rail and diesel particulate filter; UI/HP: high-pressure unit injection.

[b] Sweden uses an environmental classification system for passenger cars. Previously this system had 3 classes, ranging from the basic EU level (class 3, or C3) to the class with the lowest emission level (class 1, or C1). In 2002, this system has changed to the corresponding year of introduction of the emission limits in Europe (i.e. 2000, 2005). For clarification, both denotations are shown in the table, although the classifications have changed this year.

[c] TWC: Three-way catalyst.

[d] EGR: Exhaust gas recirculation.

[e] OXD: oxidation catalyst for a diesel engine.

[f] DPF: Diesel particulate filter

3.3.3 Fuels

Commercially available petrol and diesel fuels corresponding to the Swedish Environmental Class 1 (EC1) was chosen in both cases. The reason for these choices was that such fuels have the highest market share on the Swedish market. Analysis of the fuel quality ensured that the fuel specifications were within the limits. The aspect of the influence of fuel quality should not be ignored when comparing these results to other results.

The petrol fuel used corresponded to the EC1 fuel specification for petrol. This fuel specification is similar to the EU specification for 2005. The petrol did not contain any ethanol, in contrast to the low blending of ethanol (5% vol.) that is common for the petrol distributed in the Stockholm area. It was anticipated that petrol fuel without ethanol additive would better represent a European perspective. The improved specification of this fuel compared to contemporary certification fuel should (presumably) also reduce the impact on the emissions causing adverse health effects.

The diesel fuel used corresponded to the EC1 fuel specification for diesel fuel. This fuel is considerably "cleaner" than the corresponding (current) specification for the European diesel fuel. The rationale for choosing this fuel was that it is totally dominating the market for diesel fuel for road transport in Sweden. The EC1 diesel fuel has a very low sulphur content (<10 ppm) and it is essentially free from polycyclic aromatic hydrocarbons (PAH). Therefore, the impact of this fuel on health related effects should be far less than for conventional diesel fuel (which has been proven on heavy-duty vehicles). *It is interesting to note that no testing of unregulated emissions from passenger cars running on this fuel has been carried out previously in Sweden.* This is in contrast to the heavy-duty vehicles, where this fuel quality has been the topic of numerous emission tests.

Ecotraffic's comments

Intercomparison

It should be noted that the purpose of the study was *not* to compare the products from various car manufacturers with one another. Instead, the objective was to show the impact of the two fuels and the various technical solutions used on the cars. Based on the results generated here it cannot be claimed that one carmaker is "better" than the other carmaker from any particular aspect. Instead, it should be noted that the outcome could have been vastly different if other car models had been compared instead. In some cases, general conclusions can be made about certain technologies or about the difference between the two fuels. From a general point of view, it should be noted that engine (and vehicle) development is a highly dynamic process and therefore, conclusions that are valid today might have to be changed in the near future.

3.3.4 Test matrix

In order to control the measurement accuracy and scatter, it would have been desirable to repeat the measurements several times, and (possibly) also to conduct a kind of back-to-back test. However, due to the limited budget available, this was not achievable. It should be noted that the differences in emissions between the two types of fuels (petrol and diesel) generally are relatively great for most emission components. Similar conclusions can be drawn about the difference between results for various test temperatures (-7 and +22°C). Thus, the differences that could be expected were, in general, relatively large compared to the absolute emission level. Therefore, it was decided to conduct only one test of each kind, unless some error would occur. Repeating the tests would have necessitated a reduction of the number of cars (from 4 to 2). Reducing the number of cars was not an issue, since additional cars would have been desirable instead in order to elucidate the impact of various technical solutions.

In order to control that the cars were in good condition and that the emission level was corresponding to the level from the certification data from the manufacturer, a comparison between these data and the measured data was made. After the first test was conducted, it was decided whether this car sample was representative or not. In all the four cases, the cars were considered to be very close to the certification data, as published by the certification agency VCA in the UK [8].

The following tests included in the test programme:

- NEDC test at +22°C
- NEDC test at –7°C
- US06 test
- Overtaking, 70 – 110 km/h (simulating overtaking of a lorry), including steady-state speed at 70 and 110 km/h (before and after overtaking)

All the latter two tests were conducted at “hot” conditions, i.e. a hot engine and at an ambient temperature of +22°C. A more thorough description of the choice of test cycles is made below.

3.3.5 Emission measurement

Most of the emission measurements were carried out in diluted exhaust from a full-flow dilution tunnel. Mass flow was kept constant using the principle of a critical flow venturi (so-called CVS, or Constant Volume Sampling).

In the overtaking test, emissions of the regulated gaseous emission compounds were measured in raw exhaust. The instantaneous (raw) exhaust mass flow was calculated using CO_2 measurements in undiluted and diluted exhaust to determine the instantaneous dilution factor.

Regulated emissions

The regulated gaseous emission components were measured with an emission instrument from the Horiba Mexa 9000 series (9400 D).

Particulate matter was collected on 47-mm Teflon coated glass fibre filters, conditioned in a climatic chamber, and weighed on a microscale.

Measurement principles for the emission components mentioned above are listed in **Table 2**.

Unregulated emissions

Of the unregulated emissions, as many compounds as possible were measured on-line. A mass-spectrometer (MS) was used for most of these emission components as shown in **Table 2**. The MS instrument used was a V&F Airsense 500, a soft ionisation mass spectrometer.

Table 2: Measurement methods for emissions

Emission component	Method of analysis
Total hydrocarbons (HC)	Heated FID
Carbon monoxide (CO)	NDIR
Oxides of nitrogen (NO_X)	Chemiluminescence (CLA)
Carbon dioxide (CO_2)	NDIR
Fuel consumption (FC)	Carbon balance[a]
Particulate matter (PM)	Gravimetric
Benzene	MS
Ethene	MS
Propene	MS
1,3-Butadiene	MS
Ammonia (NH_3)	MS
Nitrous oxide (N_2O)	GC/ECD
Acetaldehyde	HPLC
Formaldehyde	HPLC
Acrylamide	HPLC/DAD
PAH	GC/MS
Particle size	ELPI, SMPS

Notes:

[a] Exhaust gas analysis of CO_2, HC and CO is used to estimate the fuel consumption.

Nitrous oxide (N_2O) was analysed using GC/ECD. The aldehydes (acetaldehyde and formaldehyde) were analysed by HPLC and acrylamide by HPLC/DAD.

Sampling for off-line chemical analysis was made by using impingers. The collected samples were stored in a freezer, and the analyses were carried out in one batch for each emission component.

PAC emissions

The emissions of polycyclic aromatic compounds (PAC) comprise mostly of polycyclic aromatic hydrocarbons (PAH) but some compounds also contain other species but hydrogen and carbon, hence the denotation "PAC".

The PAC emissions were sampled from diluted exhaust on both particulate and semi-volatile phases. Sampling of the PAC emissions was carried out for the whole driving cycle. Particulate sampling was carried out using 150-mm Teflon coated glass fibre filters (Pallflex T60A20, Pallflex Inc. USA). The filters were cleaned prior to sampling as described in detail elsewhere [9]. Sampling of the semivolatile associated compounds was carried out downstream of the Pallflex filter using Polyurethane Foam plugs (PUF), which were also precleaned prior to sampling [9]. After sampling the filters and PUFs were stored in a freezer.

The filters were Soxhlet extracted with dichloro methane (DCM) and the PUF plugs were Soxhlet extracted with acetone. The crude extract was used for chemical analysis of PAC emissions. The PAC was analysed using gas chromatography mass spectrometry, as previously described [9]. Most of the previous analyses of PAC emissions have been carried out at the Stockholm University (R. Westerholm). Due to the time constraints for this project, the analysis was performed by Alcontrol Laboratories in Nyköping, Sweden. In the analysis, 12 tri+ PAC (3 or more rings) and 4 di+ PAH compounds were analysed. Previously, up to 29 tri+ compounds, and in some cases over 40 tri+ compounds, have been analysed [10].

In **Table 3**, a list of the compounds analysed is shown. A tickmark (x) indicates compounds that are similar to the set of 28 – 29 compounds analysed in previous studies. Note that the compounds from naphthalene to fluorene are di-aromatic compounds. As tri+ compounds have been found more mutagenic than di+ compounds, the former category has not been included in the sum of PAC emissions. In some cases, it has been of interest to compare the results from this study with previous results. To make the comparison of health effects (i.e. cancer risk) more correct, a correction has been made to take into account that fewer compounds were analysed in this study than in previous studies. The corrections used were derived from the results generated in a report by Almén et al. [11]. The results on the VW Golf diesel was chosen to correct the results on the diesel cars in this study. The Honda Civic corresponding to the Californian TLEV emission regulation (formerly used as classification for environmental class 1 cars in Sweden), was considered most representative car for the petrol-fuelled cars in this study.

Table 3. *PAC analysed*

No.	”29”	Compounds
di	-	Naphthalene
di	-	Acenaphtylene
di	-	Acenaphtene
di	-	Fluorene
1	x	Phenanthrene
2	x	Anthracene
3	x	Fluoranthene
4	x	Pyrene
5	x	Benzo(a)anthracene
6	x	Chrysene/Triphenylene
7	x	Benzo(b)flouranthene
8	x	Benzo(k)flouranthene
9	x	Benzo(a)pyrene
10	x	Indeno(1,2,3-cd)pyrene
11	x	Benzo(ghi)perylene
12	x	Dibenzo(a,h)antracene

Particle size and number emissions

Particle number and size distribution was carried out using two different types of instruments, measuring either the aerodynamic or the electrical mobility diameter.

The instrument used for measuring the aerodynamic diameter was an electrical low-pressure impactor (ELPI, by Dekati Inc. of Finland). Diluted exhaust is drawn through the ELPI instrument using a vacuum pump. Before entering the instrument, the exhaust gases are diluted in a second stage “dilutor” (after the dilution tunnel) in order to reduce their concentration. Prior to the first impactor stage of the impactor stack, the particles are charged using a unipolar charger. The particles are classified according to their aerodynamic diameter. Each stage of the impactor has a greased substrate (usually aluminium foil) where the particles are collected. The original ELPI impactor had 13 stages ranging from 30 nm to 10 µm. In the latest version of the instrument, the largest stage (PM_{10}) has been sacrificed to enable the inclusion of an absolute filter to collect particles between 7 nm and 30 nm. The particles collected on a specific impactor stage produce an electrical current that is recorded, in real-time, using a multichannel electrometer. The main advantage of the ELPI instrument in comparison to other instruments is its suitability for real-time measurements. In a transient driving cycle (such as the NEDC), it is essential to obtain good time resolution in order to follow the variations in the driving cycle. This was the main reason for choosing the ELPI instrument. The principle of the ELPI instrument has been described in more detail elsewhere [12].

Since previous measurements on diesel and petrol engines have indicated that the even smaller sizes of particles than 30 nm, possibly smaller than 10 nm, appear to be present in great numbers, it was considered necessary to measure even smaller particles. Although the newest version of the ELPI is capable of measuring particles down to 7 nm, it was of interest to extend the measurements even further towards smaller sizes. The Scanning Mobility Particle Sizer (SMPS) is an instrument that can measure particle size according to the electrical mobility diameter. The advantage of these instruments is the great number of channels (sizes) but the drawback is that a measurement event (measuring all channels) usually lasts a couple of minutes. Therefore, these types of instruments are best suited for steady-state measurements. To overcome this problem, the instrument was locked on a certain channel (size) to gain time resolution. In principle, repeating the measurements several times could have provided data on a number of sizes. Such kind of measurements are, however, very time consuming and, therefore, they are not considered practical. It was decided to measure the 5-nm size class only (according to the electrical mobility). The measurement interval for this channel was 4,7 – 5,2 nm. The use of more than one channel would have been imperative on the time resolution, so this option had to be omitted.

Since the ELPI measures the aerodynamic diameter of the particles, comparison between the results obtained using this instrument and other instruments, such as the SMPS/DMPS type of instruments, can be problematic. In order to be able to compare the results, the particle density as a function of the size, must be known. In a previous project the author has participated in, an evaluation of this kind was made [1]. The results for the intercomparison of the two instruments were quite satisfactory, on the condition that corrections were made for the varying particle density. However, one cannot assume that the particle density obtained from this experiment is universally applicable on the particulate emissions from all engines and fuels. Therefore, no recalculation of the electrical mobility diameter from the SMPS instrument to aerodynamic diameter was carried out. Thus, the results are not compared on the same diagrams either.

One important issue about particle size measurements to note is that the instrument set-up used in this study gives the total number of particles regardless of the composition of the particles. Due to the low sulphur content of the fuel, sulphate formation should be insignificant. On the other hand, volatile particles could be generated due to nucleation. Some experts claim, that only the solid particles pose a cancer risk. For example, this appears to be the hypothesis used in evaluations in Germany, as a study commissioned by German UBA and managed by the Fraunhofer Institute shows [13]. However, since this hypothesis is not generally accepted in the scientific community, it was chosen to measure all particles regardless of the nature of the particles. It should be noted that on-going work is trying to establish an accepted methodology for measuring particle number and size distribution. No such basic research was included in this study.

3.3.6 Driving cycles

The current driving cycle used in Europe is usually called NEDC (New European Driving Cycle). All the cars had been certified according to this test cycle so was plausible to use this cycle as one of the test cycles.

As the average load and the accelerations in the NEDC cycle are relatively low in comparison to a more aggressive driving style, it was considered of interest to choose another cycle in addition to the mentioned cycle. Several official and unofficial cycle candidates were considered. For example, the French Institute INRETS have developed several test cycles that are considered to represent modern driving style better than the current official test cycles. However, it was decided to use the US06 driving cycle instead of some of the unofficial cycle candidates. The US06 cycle comprises heavier accelerations than the NEDC cycle but it also contain microtransients in comparison to the NEDC, which has large portions of constant velocity. Another difference is that the US06 cycle is started with a hot engine. In summary, it could be anticipated that some emission components would be higher in the US06 cycle than in the NEDC cycle, due to the significant difference between the test cycles. Running an US06 cycle on a twin-roller chassis dynamometer sometimes cause problems[11]. In these tests, the tyres on the petrol-fuelled Peugeot 307 were skidding causing it to be outside the tolerance for a total time of 23 seconds in this test cycle. Although this period was relatively short, it cannot be excluded that the results were affected. A slight underestimation of the emissions from this car in US06 could be the result. There were no such problems in the tests on the other cars.

As none of the test cycles demands the maximum possible acceleration of the vehicle, it was decided to include measurement during an overtaking manoeuvre as well. The maximum speed limit in Sweden is 110 km/h (on highways). Some vehicles are limited to 70 km/h. Therefore, overtaking from 70 to 110 km/h is an example that is representative for Swedish driving conditions. In other countries in Europe, 80 to 120 km/h might have been more appropriate but this was not considered, as the maximum speed would be above the maximum speed limit in Sweden. During overtaking, the car would be run at the highest gear on full throttle without any downshifting. Since the gearbox of the VW Golf diesel has 6 gears, it was decided to test this car both in 5th and 6th gear.

In **Figure 2**, a schematic representation of overtaking a lorry is shown. It is anticipated that the overtaking starts 100 m before the truck. This corresponds to about 5 seconds at a speed of 70 km/h, although it is known that many drivers do not respect this distance as a proper safety margin. Since all the data in the overtaking test were logged it is, in principal, possible to evaluate an overtaking with a shorter (or longer) distance before the truck. The lorry is anticipated to be 24 meters long and the car is approximated to be 4,5 meters long. In total, this equals a distance of 152,5 meters. **Figure 2** shows a thin solid line for the distance travelled by the truck and two dotted lines representing the same speed with a gap before (100 m) and after (24 m + 4,5 m) overtaking respectively. The solid line shows the speed of the car, increasing from 70 km/h to 110 km/h in about 12 s and remaining constant after that. After about 17 s, the overtaking is completed.

[11] The use of single roller dynamometers is the preferred solution for aggressive driving cycles as this cycle.

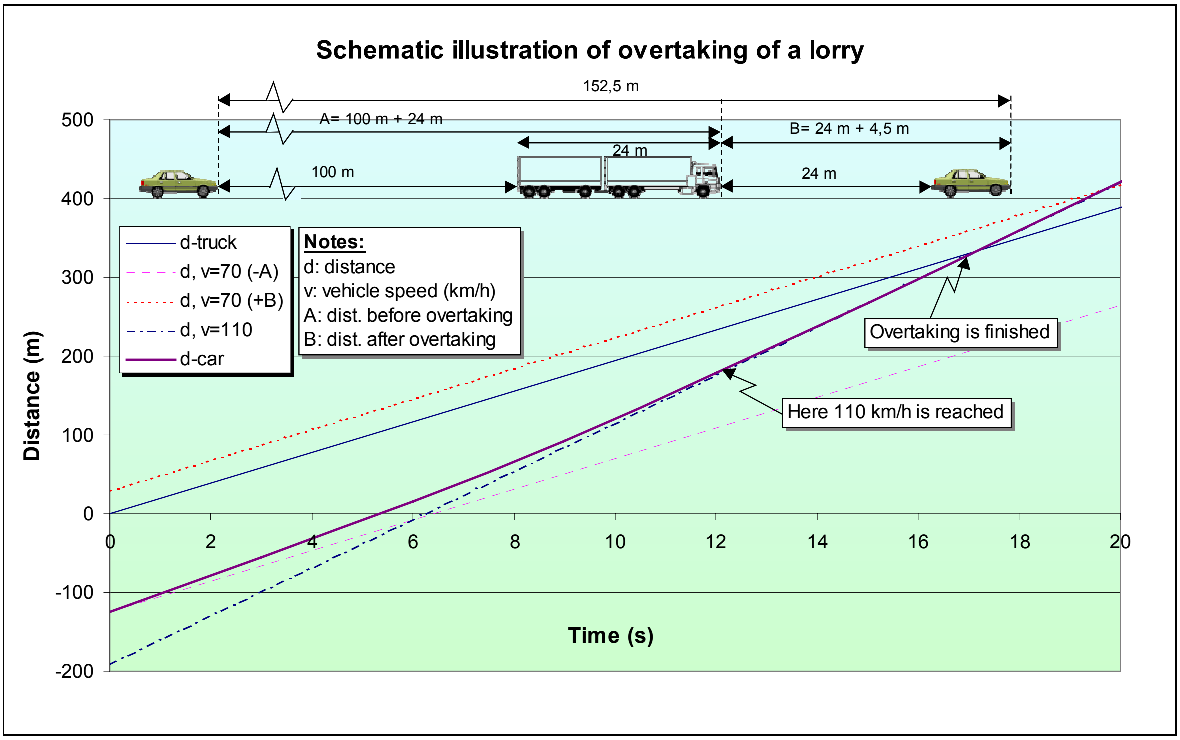


Figure 2. *Schematic illustration of overtaking*

3.4 Calculation of effects

To calculate the effects of the exhaust emissions, a methodology used previously by the author has been used also in this study. Since this methodology has been described in more detail elsewhere [1, 14], no more than a brief overview is provided here. However, in some cases modifications to the calculation scheme has been made and in these cases, a more detailed description is provided. As in the previous work, only the NEDC driving cycle has been used in the evaluation, although US06 and overtaking was included in this test programme.

The effects of primary interest have been grouped in local, regional and global effects along with the corresponding emission components. These effects are:

- Local effects, acute respiratory diseases
  - Ozone (O_3) forming potential (NO_X and organic gases)
  - Nitrogen dioxide (NO_2)
  - Organic gases such as, e.g. aldehydes
  - Particulate matter (PM)
- Local effects, cancer risk (numerous emission components)
- Regional effects
  - Vegetation injury (NO_X, SO_X and O_3)
  - Visibility (particulate matter and droplets)
  - Acidification (NO_X, SO_X and NH_3)
  - Eutrophication (NO_X, and NH_3)
- Global effects

- Climate change (fossil CO_2, CH_4, N_2O, etc.)
- Resource use

To simplify the presentation of the results, not all the effects listed above are covered in separate sections, since a certain emission component sometimes is responsible for several effects.

3.4.1 Lifecycle perspective

The effects mentioned above can be classified as *local, regional* and *global* effects. In order to obtain some life cycle perspective on the investigated effects, the fuel cycle emissions have also been included for the *regional* and the *global* effects. In those cases, the pollution from the vehicle and from the fuel cycle have been shown separately.

Data for the fuel cycle emissions have been collected from a previously published report by Ecotraffic, "Life of Fuels" (LoF) [15]. The emissions for vehicle production, scrapping, maintenance etc. are not included in the LoF report. However, it is anticipated that the difference between the investigated fuel/engine options is small in this respect.

3.4.2 Respiratory diseases – acute

Ozone forming potential

Ozone was identified as an irritant component in a Swedish governmental investigation on environment and health and a long-term target for the reduction of ozone has been set (80 $\mu g/m^3$, hourly avg.) [16]. Ozone formation in populated areas is generally limited by the VOC (volatile organic compounds) concentration.

In a previous investigation by this author, a reactivity adjustment factor (RAF) that was 1,32 times higher for diesel fuel than petrol was used. This factor was derived using input data from an investigation by Bach et al. at EMPA [17]. The RAF was obtained by interpolating data for +7°C. Other papers of interest in this area have been published by Decker et al. [18] and Neumann et al. [19], from VW in both cases.

Since ozone formation is higher during the summer than in the winter, a higher than yearly average temperature has been used in this study for evaluating the HC emissions. A temperature of +14°C was considered a reasonable average during the ozone season. Data by Bach et al. evaluated for +14°C gave a reactivity adjustment factor (RAF) that was 1,26 higher for diesel fuel than for petrol. However, the RAF data need to be corrected by taking into account the improvement of new petrol and diesel fuels qualities. No recent data for the Swedish fuel qualities have been published so the corrections had to be derived from data published elsewhere. The RAF for petrol was corrected by 0,977 in the re-evaluation of the 93/94 test results and by 0,94 for the cars tested in this study to take into account the potential improvement of petrol fuel. Both these corrections were derived from data by CARB in California. The factor mentioned later was valid for LEV cars and therefore, it was considered more appropriate for the new cars tested in this study. Since the reformulated petrol used in the USA also reduces the emissions of HC and VOC species, the (total) reduction of ozone formation is significantly *greater* than the reduction of the RAF. It could be mentioned that the RAF levels in the previously mentioned study by Decker was slightly different compared to the CARB data.

The paper by Neumann investigated the impact of Swedish EC1 diesel fuel on RAF and found a decrease by some 33% for the EC1 fuel in comparison to reference diesel fuel [19]. Considering this correction in addition to the corrections for petrol fuel, yields the RAF levels shown in **Table 4**. Petrol is used as reference in the left column and diesel is the reference in the right column.

Table 4. *Reactivity adjustment factor (RAF)*

Fuel	RAF	
Petrol	1,00	1,19
Diesel	0,84	1,00

Table 4 shows a relatively small difference in RAF level between the fuels and in fact, the level is lower for diesel fuel. This is due to that the relative improvement by reformulating the diesel fuel has been greater than in the petrol case. However, it should be noted that the reformulated petrol also reduces the HC emissions.

NO_2

Generally, the NO share of the total NO_X emissions is much higher than the share of NO_2. Since NO_2 is the more harmful component, a high share of NO_2 in the exhaust is not desirable. However, most of the NO_X is converted to NO_2 in the atmosphere. It has been shown that some catalytic aftertreatment devices, such as oxidising catalysts and DPFs used on heavy-duty engines, could increase the share of NO_2 under some driving conditions [20, 21]. Thus, the inhaled NO_2 from these vehicles could become higher than for vehicles that do not convert NO to NO_2. Unfortunately, the NO_2 emissions could not be measured separately on-line in this study. The total NO_X has been used the evaluation, as an indication of the *potential* NO_2 formation. Detailed simulation of the atmosphere chemistry would be necessary to refine the analysis.

Aldehydes

Of the organic gases, the aldehydes are particularly irritant components and therefore these emissions are compared separately in addition to the other components described above. There is a clear difference between formaldehyde and acetaldehyde in this respect, as formaldehyde appears to be much more potent than acetaldehyde.

Particulate matter

Particulate matter has been identified as a component causing respiratory diseases [22]. Several epidemiological studies have shown, by using statistical methods, that the daily mortality and morbidity correlate with increases in particulate air pollution. A paper by Pope et al. is one example of one of the first papers published in this field [23]. Thus, particulate emissions are considered one of the most important emission components to investigate.

3.4.3 Respiratory diseases – cancer risk

The cancer risk factors for the emission components of interest vary significantly depending on the sources used. It should be noted that the uncertainty regarding the data for cancer risk factor assessments is great. Therefore, the results for this effect also involve more uncertainty than the other investigated effects. Several sets of risk factors are also available from organisations such as, for example, U.S. EPA, CARB, CAPCOA and OEHHA of Cal. EPA [25 – 29]. A review draft version of the latest evaluation by EPA of cancer risk factors is available (July 2000), but the review has not yet been finalised [30].

Table 5. *Unit risk factors for cancer (*10^{-6})*

Component	Törnqvist & Ehrenberg	U.S. EPA 1990	OEHHA 1999
Particulates	70	70	300
Benzene	8	8	29
Ethene	50	(5)[a]	-[b]
Propene	10	(1)[a]	-[b]
1,3-Butadiene	300	300	170
Formaldehyde	100	10	6
Acetaldehyde	2	2	2.7
PAC	28 000[c]	4 000	1 100

Notes:

[a] EPA has not assigned any URFs for ethene and propene. The data shown in the table above have been calculated by Törnqvist and Ehrenberg assuming the same potency as 5% of the corresponding epoxides, hence the parenthesis.

[b] OEHHA has not assigned any URFs for ethene and propene.

[c] PAC in this case is defined as tri-aromatics+. These components are known to be the biologically most active components [24].

In this study, the unit risk factors (URFs) by the Swedish researchers Törnqvist and Ehrenberg [31] have been used extensively as the basis for the evaluation of cancer risk. One of the features of the risk factors by Törnqvist and Ehrenberg is that they also consider other forms of cancer than lung cancer and other routes of uptake besides inhalation (e.g. food chain). Their risk estimates have been the basis for SEPA in setting the reduction targets of hazardous compounds in ambient air. The URFs used in this study are listed in **Table 5** and compared to those by US EPA and OEHHA. The unit risk factors in **Table 5** are expressed as the individual mortality risk at a lifetime (70 years) exposure of 1 $\mu g/m^3$ for each component.

The risk estimate on particulate matter is based on the total particulate mass, as very little data is available on the impact by particle size on the cancer risk. In the previously mentioned study published by UBA [13] the mass of the insoluble particles were used. The share of the insoluble particles was based on estimations. In this study, no particulate analysis was performed.

Ethene and propene are included by Törnqvist and Ehrenberg among the components due to the proven metabolism similarity to that of 1,3 butadiene [31]. The URF for ethene and propene, which are active through their monoepoxides, have been derived by the dosimetry-rad equivalence method, using γ-radiation as reference standard. EPA and OEHHA use no URFs for ethene and propene.

The URF of formaldehyde is one order of magnitude or more in the evaluation by Törnqvist and Ehrenberg compared to the two other sets of URFs in **Table 5**.

In previous studies by this author, PAC has been defined as the sum of 29 different compounds. As the only 12 PACs were measured in this case, a correction was made to consider this. Most of the PACs are PAHs (Polycyclic Aromatic Hydrocarbons). The major difference between the URF for PAC is due to that Törnqvist and Ehrenberg (besides taking other forms of cancer than lung cancer into account) also considers other routes of uptake than inhalation (food chain).

3.4.4 Regional effects

Acidification

The NO_X emissions are the main contributor to the acidification from heavy-duty vehicles in Sweden, since all fuels in use (except diesel fuel quality according to the European specification) have very low sulphur content. The NO_X emissions from fuel production have been obtained from the LoF report [15], and the NO_X emissions from the vehicles have been collected from the compiled emission data, as described earlier.

The SO_X emissions have been calculated using the sulphur content of the fuels. In case of diesel fuel, the EC1 fuel has a limit of 10 ppm sulphur but since the industry average generally is much less than this limit, a level of 4 ppm has been used instead. This is considerably lower than the current European specification at 350 ppm. Petrol fuel according to the Euro IV (2005) and Swedish EC1 petrol fuel specification (<50 ppm S) was anticipated for the passenger cars and a level of 30 ppm was assumed for the calculation.

The level of NH_3 is generally low from diesel vehicles. For example, Almén found a level as low as 3 mg/km on two diesel-fuelled trucks [32]. The NH_3 emissions from petrol-fuelled cars vary from very low levels to high levels under certain driving conditions (high load and cold start). Since NH_3 was measured in this study, the data generated have been used in calculation of the acidification. When comparisons are made with older results, it should be noted that the contribution from NH_3 was not considered in the old data.

Eutrophication

Eutrophication comprises the impact of NH_3 and NO_X. In the evaluation, both these compounds have been used without any specific weighting factor for each component. N_2O was not considered, since it is not deposited at such a high rate as the two other emission components. Instead, the long life of N_2O in the atmosphere implies that its contribution to the climate change should be taken into account.

3.4.5 Global effects

Climate change

Most of the greenhouse gas (GHG) emissions can be attributed to fossil CO_2. In some cases, methane (CH_4) and NO_X can also be of significant importance. The data used in the calculations of climate change are shown in **Table 6**.

In total, six different emission components were used in the calculation of the total global warming potential (GWP). IPCC (Intergovernmental Panel on Climate Change) values for the GWP at a timeframe of 100 years were used for all components but NO_X and NMHC [33]. The same values as in the LoF report was used for these components. LoF used older IPCC data for the other components. Values for NO_X and NMHC (and HC) have not been included in later IPCC data, but the older figures were used here anyway. It was considered that the omission of these components would introduce even greater errors than using the old data. Speciation of HC/NMHC emissions and the use of GWP factors for each component could potentially improve the precision in the calculations but the limited data on speciated hydrocarbons available precludes this calculation.

Table 6. *Global warming potential (relative to CO_2)*

Component (GHGs)	Chem.	GWP
Carbon dioxide	CO_2	1
Oxides of nitrogen	NO_X	7
Carbon monoxide	CO	3
Non-methane hydrocarbons	NMHC	11
Methane	CH_4	24,5
Nitrous oxide	N_2O	320

Energy use

Energy use is closely linked to global warming when fossil fuels are used, as most of the climate change is attributable to CO_2. Consequently, the results on energy use and climate change can be anticipated to be relatively similar. However, there is a point in showing results on energy use as well, since the fossil fuel resources are limited. Moreover, the split between fuel production and end use could also be of interest.

4 RESULTS

Since the amount of data that can be shown from this study is vast, some delimitation has to be made. In some cases, it was also of interest to compare the results in this study with data from the previously mentioned study on emission impact [1]. As this would further increase the number of figures and tables, not every possible comparison is shown.

4.1 Regulated emissions

CO, HC and NO_X emissions are regulated for all fuels today. The particulate emissions are also reported in this section, although these emissions are not regulated for petrol-fuelled cars. CO_2 is also included in this section, although this emission component is only regulated indirectly through an agreement between the EU and the auto manufacturers organisations.

4.1.1 Emission comparison

First, it was of interest to compare the emissions from this study with available data from vehicle certifications. In **Table 7**, the certification data from the certification agency VCA in UK [34] are compared with the results obtained at the emission laboratory of MTC in this study.

Table 7. *Comparison of emissions with certification data (VCA)*

Car	**Model/fuel**	Source	CO	HC	NO_X	$HC+NO_X$	Part.	CO_2
Peugeot	307 1,6 110 hp	VCA	0,258	0,059	0,042	0,101	n.r.[a]	169
Peugeot	307 1,6 110 hp	MTC	0,241	0,050	0,040	0,090	0,0007	171,0
VW	Golf 1.6 petrol	VCA	0,504	0,083	0,047	0,130	n.r.[a]	170
VW	Golf 1.6 petrol	MTC	0,370	0,084	0,052	0,136	0,0013	167,6
Peugeot	307 HDi FAP	VCA	0,100	0,030	0,339	0,370	0,003	138
Peugeot	307 HDi FAP	MTC	0,031	0,013	0,369	0,382	0,0003	137,8
VW	Golf 1.9 TDI	VCA	0,081	0,016	0,376	0,392	0,029	146
VW	Golf 1.9 TDI	MTC	0,054	0,010	0,373	0,383	0,022	144,1

Notes:

[a] n.r.: Not regulated

As can be seen in **Table 7**, all the test results generated at MTC for the four cars were reasonably close to the certification data. First, it should be noted, though, that the certification data from VCA include deterioration factors[12], whereas the data from MTC do not. Usually, the deterioration factors are low, in particular for diesel cars.

The petrol-fuelled Peugeot was very close to the certification data for all emission components. The results for the petrol-fuelled VW Golf were also comparable, except for CO,

[12] The manufacturer can choose either to determine the deterioration factors or to use a set of fixed factors.

where a lower level was measured at MTC. The diesel-fuelled Peugeot had lower emissions of CO and HC but the NO_X emissions were somewhat higher. The most dramatic difference was for the particulate emissions, which were one order of magnitude lower at MTC. The use of Swedish virtually sulphur-free Swedish EC1 fuel and the fact that the measurements at MTC did not include any filter regeneration[13] are two plausible explanations. However, it should also be noted that particulate measurements are very difficult to perform at such low levels as in this case. The diesel-fuelled Golf had somewhat lower CO emissions at MTC but HC and NO_X were very close to the certification results. The particulate emissions were significantly lower, in fact below the Euro IV limit. As in the previous case, use of the EC1 fuel could be the main cause of the lower particulate emissions. For all cars, the CO_2 emissions were very close to the certification level.

Having noted that the emissions measured at MTC were very close to the certification level in most cases, one can conclude that the cars were in good condition and that they were representative samples of the vehicle models.

It is interesting to note that the two petrol cars could be regarded as some of the best cars ever tested at MTC. In a report by Eriksson [35] a Honda ULEV car from USA was tested at MTC when the car was new (odometer reading of 345 km). In **Figure 3**, the results from that study are compared with the results generated on the cars in this study (NEDC cycle in all cases).

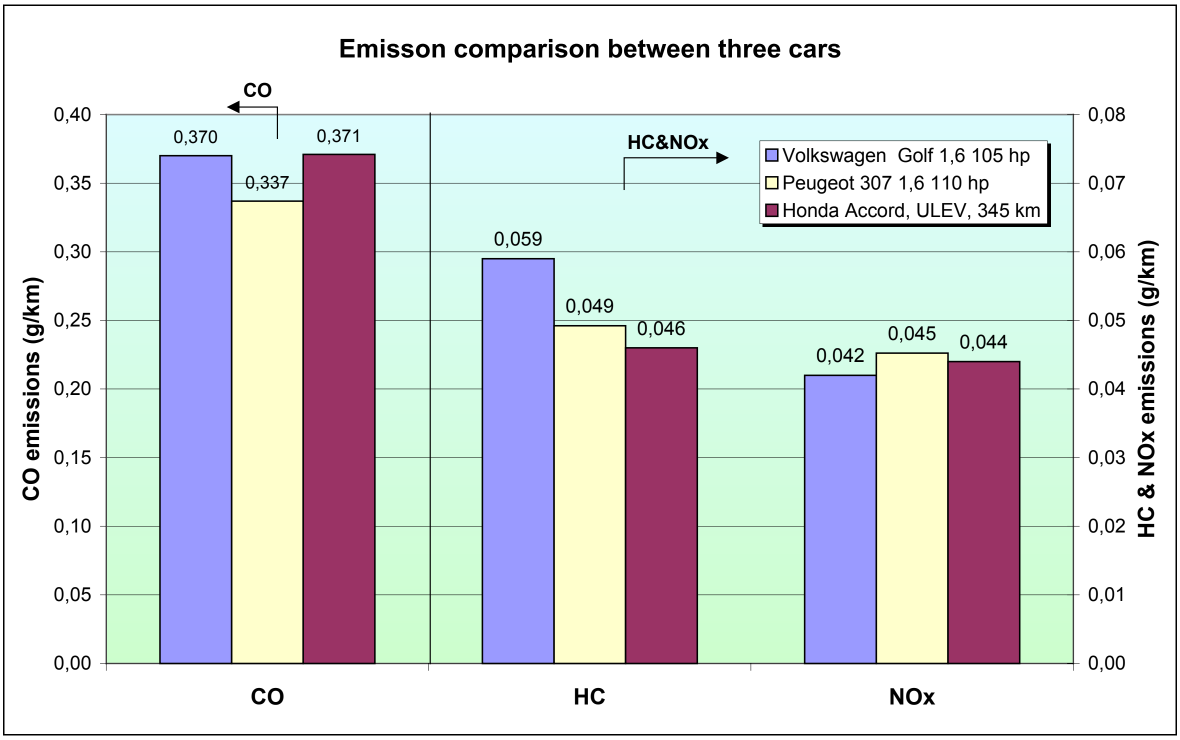


Figure 3. *Comparison of emissions with a Honda ULEV*

As can be seen in **Figure 3**, the two petrol-fuelled cars in this study were very close to the results generated on the Honda ULEV. It should be noted that the Honda probably had

[13] The particulate emissions increase under filter regeneration. However, this increase is relatively small.

been optimised for the US FTP-75 driving cycle, whereas the two petrol cars in this study had been optimised for the NEDC cycle.

To indicate the potential emission deterioration of new low-emission petrol-fuelled cars, the results from the study by Eriksson are compared with results that have been generated more recently by Lu Karlsson on the same car [36]. This comparison is shown in **Figure 4**.

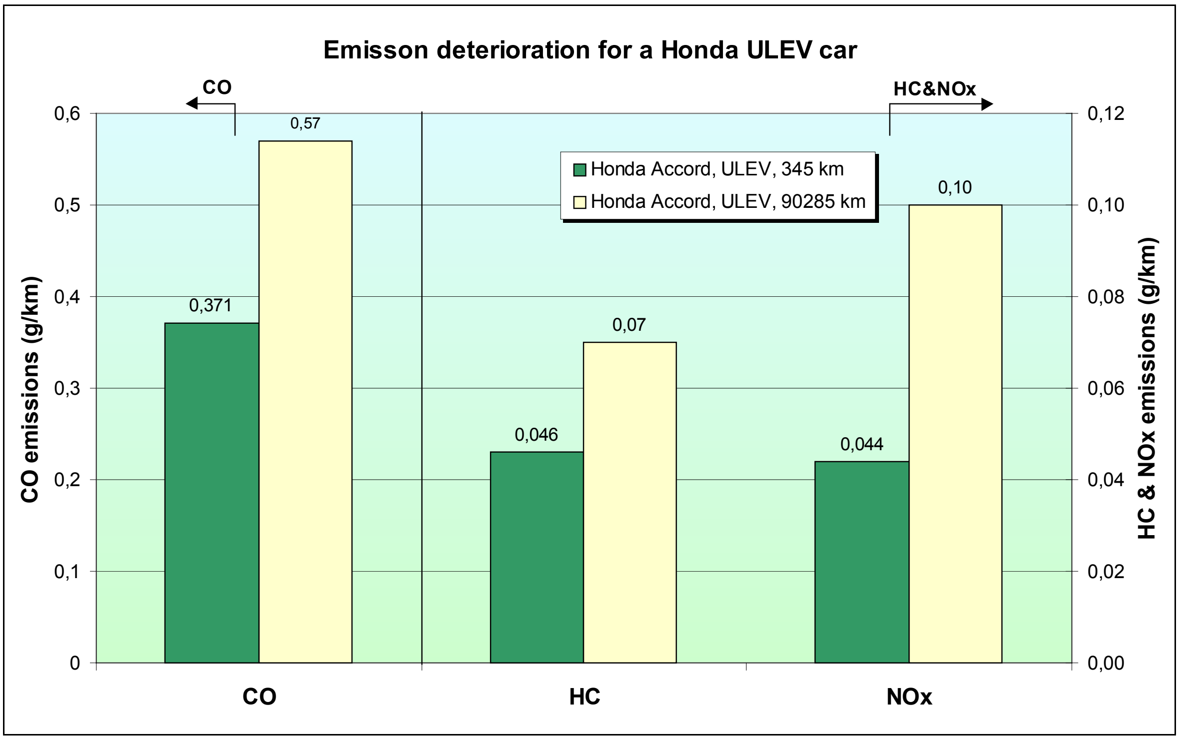


Figure 4. *Emission deterioration for the Honda ULEV*

The results in **Figure 4** show that a deterioration by approximately a factor of two, or somewhat less, could be expected for a mileage of 90 000 km, i.e. roughly half the useful life of the car. This is consistent with the factor obtained on older cars [1], although the initial emission level for new cars is considerably lower. Consequently, the deterioration in absolute numbers (g/km) is far less for new cars compared to old cars.

A few comments on the deterioration of diesel cars might be of interest to add. It could be anticipated that the deterioration for NO_X emissions would be very low for new diesel cars similarly to the results for old cars[14]. As the CO and HC emissions are largely influenced by catalyst efficiency for *new* diesel cars, the deterioration factor might be on a similar level as for petrol-fuelled cars. However, the deterioration in absolute numbers would be lower due to the low engine-out levels in this case.

As mentioned before, no estimate of deterioration has been made in this study. Therefore, the comparisons with older data, where deterioration has been taken into account, are more favourable than what could be expected if deterioration would be considered also in this case.

[14] The deterioration for an average fleet of diesel cars could be attributable to some extent to EGR failure on a percentage of cars, as the wear of engine components generally reduces NO_X emissions on diesel engines.

4.1.2 Structure of figures

Most of the figures shown below are organised in a similar way. Petrol cars are shown to the left in the figures and diesel cars to the right. However, in most of the discussion, petrol cars are compared to the diesel counterparts, as this comparison is more valid. The reader should also note that short vehicle denotations are used instead of long names. The denotations used in the figures are:

- SI-P: Petrol-fuelled Peugeot 307
- SI-G: Petrol-fuelled VW Golf
- CI-CR/DPF: Diesel-fuelled Peugeot 307 with common rail (CR) injection and diesel particulate filter (DPF)
- CI-UI/HP: Diesel-fuelled VW Golf with high-pressure (HP) unit injectors (UI)

4.1.3 CO emissions

The CO emissions in the NEDC test cycle at the two ambient temperatures (+22 and –7°C) are shown in **Figure 5**.

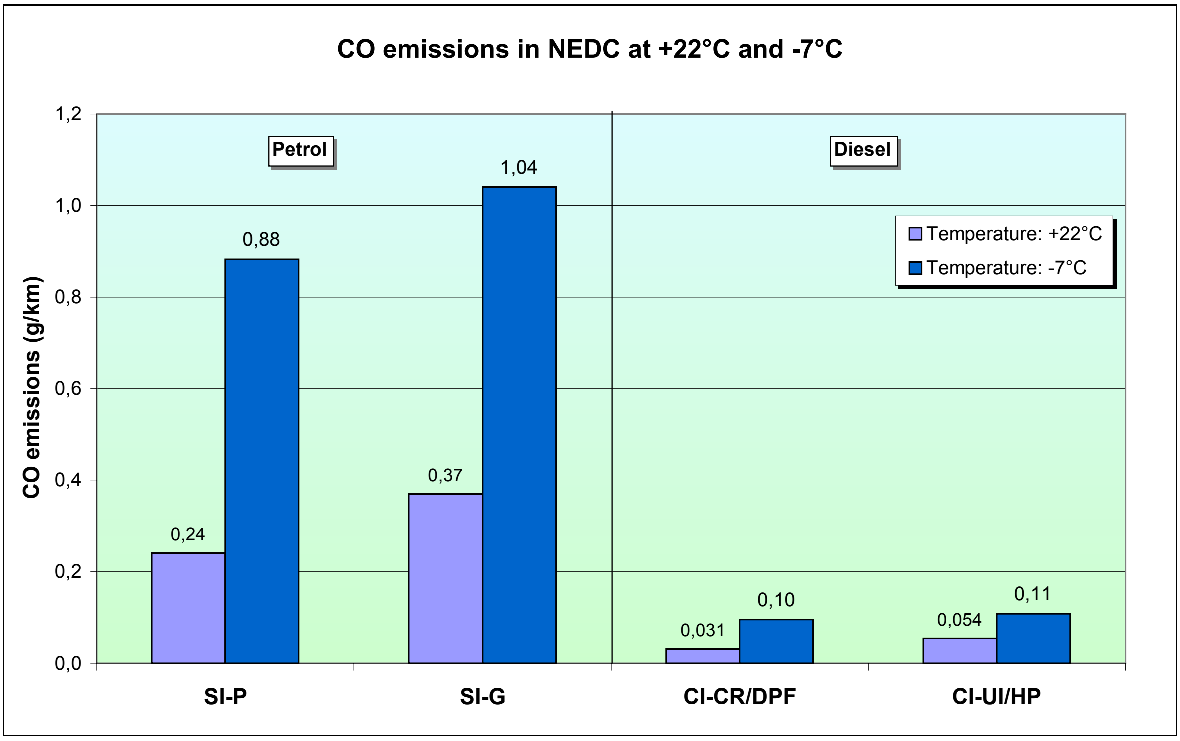


Figure 5. *CO emissions in NEDC at +22°C and –7°C*

As expected, the CO level was significantly lower for the diesel cars compared to their petrol counterparts (**Figure 5**). The ratio was almost one order of magnitude regardless of the ambient temperature. At the lower temperature, the CO emissions increased for both fuels. Since the level was generally higher for the petrol than for the diesel cars, the increase in absolute numbers by decreasing temperature was also greater.

In spite of the increase of CO emissions at lower ambient temperature, both the petrol cars were far below the cold start limit set at this temperature for the UDC part of the cycle in the current EU regulation. This supplement to the limits at "normal" test temperature is enforced in EU regulations from 2002. The CO emissions in UDC for these cars, at 1,9 and 2,8 g/km respectively, were 5 to 8 times below the limit of 15 g/km. This indicates a considerable margin to the limit value for this emission compound.

In **Figure 6**, the CO emissions in the US06 driving cycle and for the fictive overtaking of a lorry are shown. The emissions for both test cycles are expressed in g/km. As both tests are performed with hot starts, high catalyst activity on the CO emissions could be expected for petrol-fuelled cars. Note that the overtaking test was carried out in both 5th and 6th gear for the diesel-fuelled VW Golf.

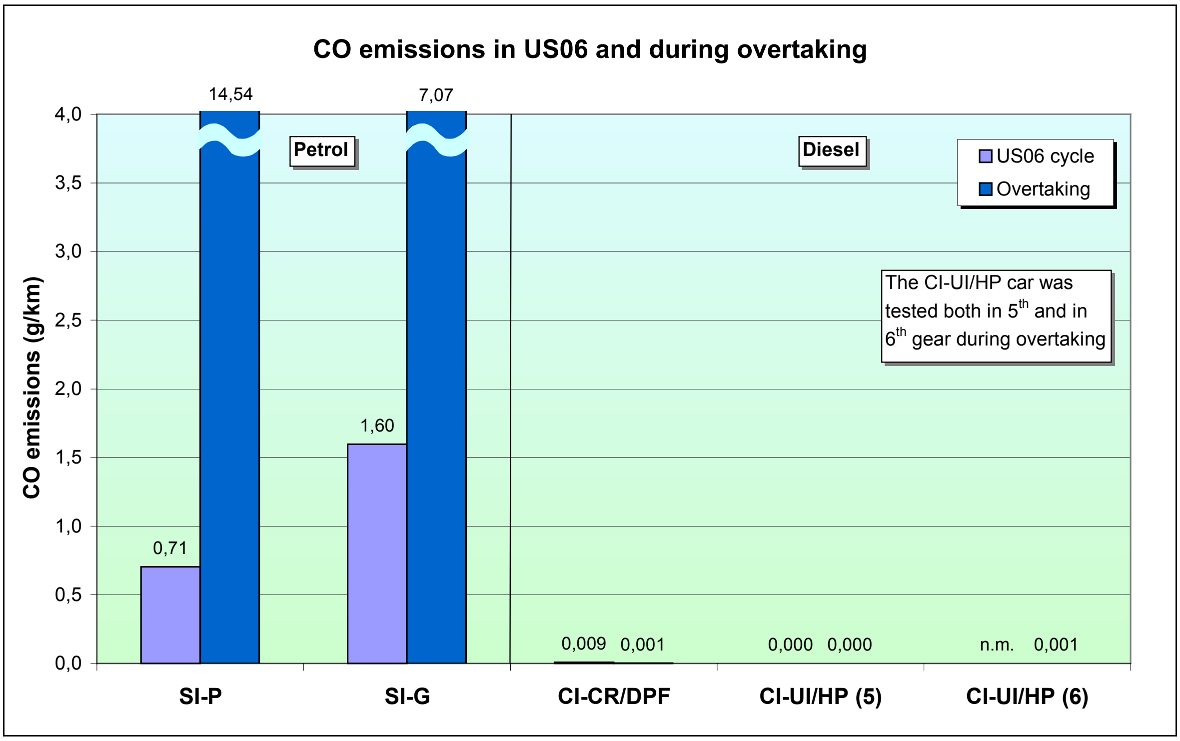


Figure 6. *CO emissions in US06 and during overtaking*

The CO levels for the petrol cars were higher in the US06 driving cycle than in NEDC, whereas the levels for the diesel cars were practically zero (**Figure 6**). The more aggressive driving pattern in US06 explains the higher CO level for the petrol cars, as fuel enrichment is likely to be used in some of the phases in the test cycle. A hot catalyst for the diesel cars practically eliminates the CO emissions. This is in contrast to the results from the NEDC cycle when the low engine load in the UDC phase causes a long period before catalyst light-off occurs.

The increase in CO emissions in the overtaking test was dramatic for the petrol cars (note that the bars are out of scale). The ratio of these emissions (in g/km) was 20 and 60 times higher respectively than in the NEDC test. As the overtaking proceed for about 0,5 km, this implies that the CO emissions during overtaking is equal to a distance of 10 and 33 km driven with the same emission factors as NEDC. As most of the CO emissions in NEDC are generated during the cold start, the relative difference would be even greater if a comparison would be made with the emission level for a hot start or at constant speed. However, as such comparisons often tend to become somewhat speculative and in some cases irrelevant, they are not included here[15].

In view of the relatively high CO emissions for the petrol cars at low ambient temperature, and in test cycles with higher accelerations, it is obvious that results from the NEDC test cycle cannot be generalised for all driving conditions. Much work would be needed to compile a new test cycle that is representative for all driving conditions.

It should be noted that the CO levels from new cars are decreasing due to the significant impact on CO emissions by the catalyst. As the non-catalyst cars are continuously being replaced, the health problems related to the CO emissions are gradually diminishing.

4.1.4 HC emissions

The HC emissions in the NEDC test cycle at the two ambient temperatures are shown in **Figure 7**. As expected, the HC emissions were higher for the petrol cars than for the diesel cars. By lowering the ambient temperature, the HC level increased by a factor of 4 to 6 for the petrol cars. Compared to the cold start limit of 1,8 g/km for the HC emissions in UDC, the level at 0,5 g/km was significantly less for one car. The other car, at a level of 1,4 g/km, was also below the limit. In both cases, the margin was less than for CO, as shown above.

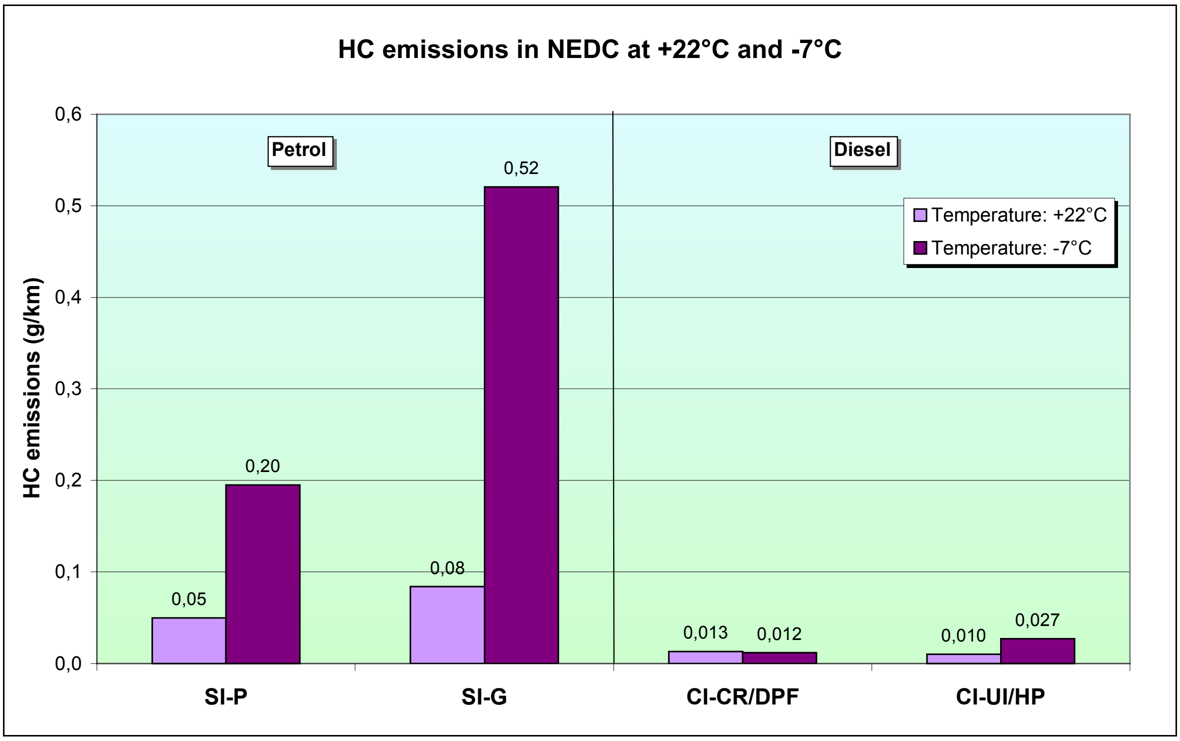


Figure 7. HC emissions in NEDC at +22°C and –7°C

As for the CO emissions, the level of HC emissions was generally lower for the diesel cars than for the petrol cars. Note that the HC level for the diesel cars was close to the detection level for contemporary instruments and test methodology used (measurement in diluted

[15] Data at constant speed at 90 and 110 km/h are available for such calculations if it would be of interest.

exhaust). One diesel car shows an increase by almost a factor of 3 by reducing the temperature, whereas the level seems unaffected by temperature for the other car.

As the emissions of toxic volatile organic compounds (VOC) is somewhat related to the HC level, further decrease in the HC level for the petrol cars – particularly at lower ambient temperature – would be desirable. There are many technical solutions available on the development stage (an on a commercial stage in some cases) that would enable this decrease of HC emissions. Although many of these measures could be applied to diesel cars as well, the absolute difference would probably decrease if the comparison (on future cars) would be made on a technology neutral level.

In **Figure 8**, the HC emissions in the US06 and overtaking tests are shown. Compared to the HC emission level in NEDC at +22°C, the level in the US06 was lower for both categories of fuels. Although fuel enrichment plays a decisive role for the CO emissions for petrol cars, the impact on HC emissions appears to be significantly less. The hot start and the fact that modern catalysts tend to crack hydrocarbons, are the likely major causes of the much more favourable results for the HC emissions.

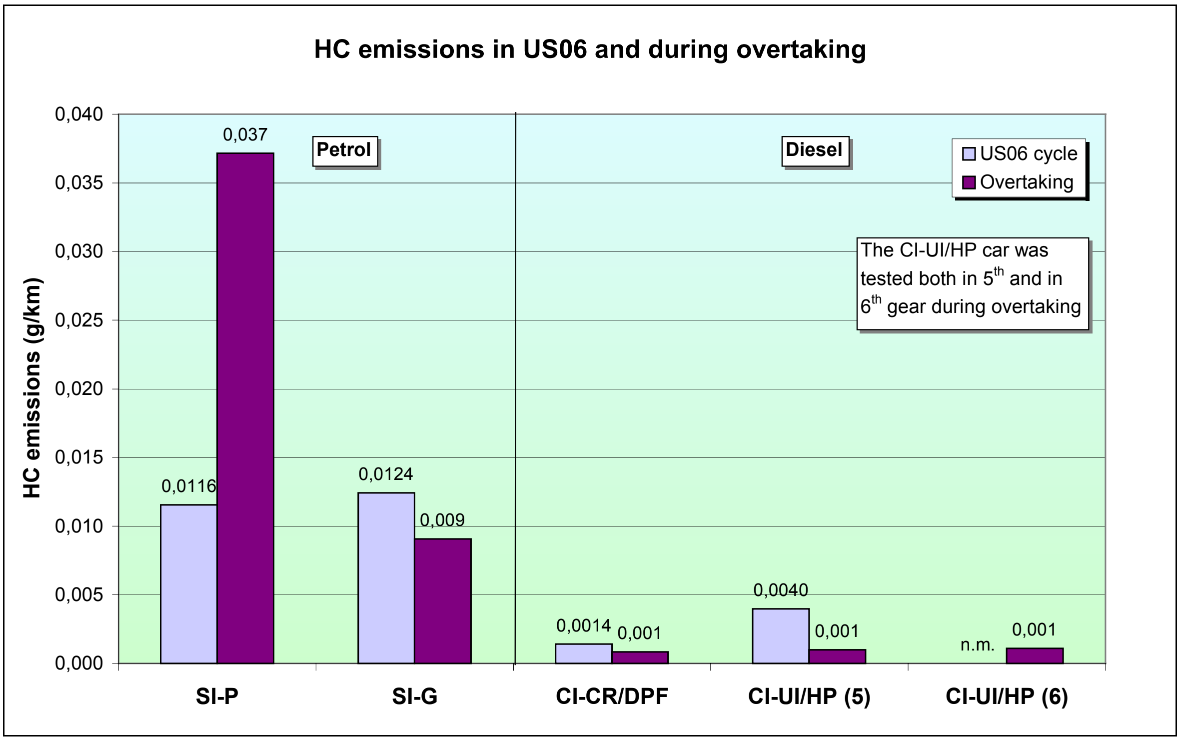


Figure 8. *HC emissions in US06 and during overtaking*

One petrol car had higher HC emissions during overtaking than in the US06, whereas the difference was insignificant in the other case. As the former car also had higher CO emissions, a higher rate of fuel enrichment is probably the explanation to the increase in HC emissions.

The HC emissions for the diesel cars were on the detection level in both test cycles. There was a trend to a lower level in the overtaking test, although the limitations of the measurement methods make such conclusions somewhat speculative. However, it is worth noting that the HC emissions were measured in raw exhaust in the overtaking test compared to diluted exhaust in the other test cycles. Consequently, the detection level should be about one order of magnitude lower than for the measurement in the other test cycles, which were carried out in diluted exhaust.

4.1.5 NO_X emissions

The NO_X emissions in the NEDC test cycle at the two ambient temperatures are shown in **Figure 7**. Contrary to the results for CO and HC emissions, the NO_X level at +22°C was significantly higher (a factor of 7 to 9) for the diesel cars compared to the petrol cars. NO_X emissions from petrol cars are not much affected by temperature and consequently, one petrol car had higher NO_X emissions at –7°C than at +22°C, while the other car showed the opposite trend.

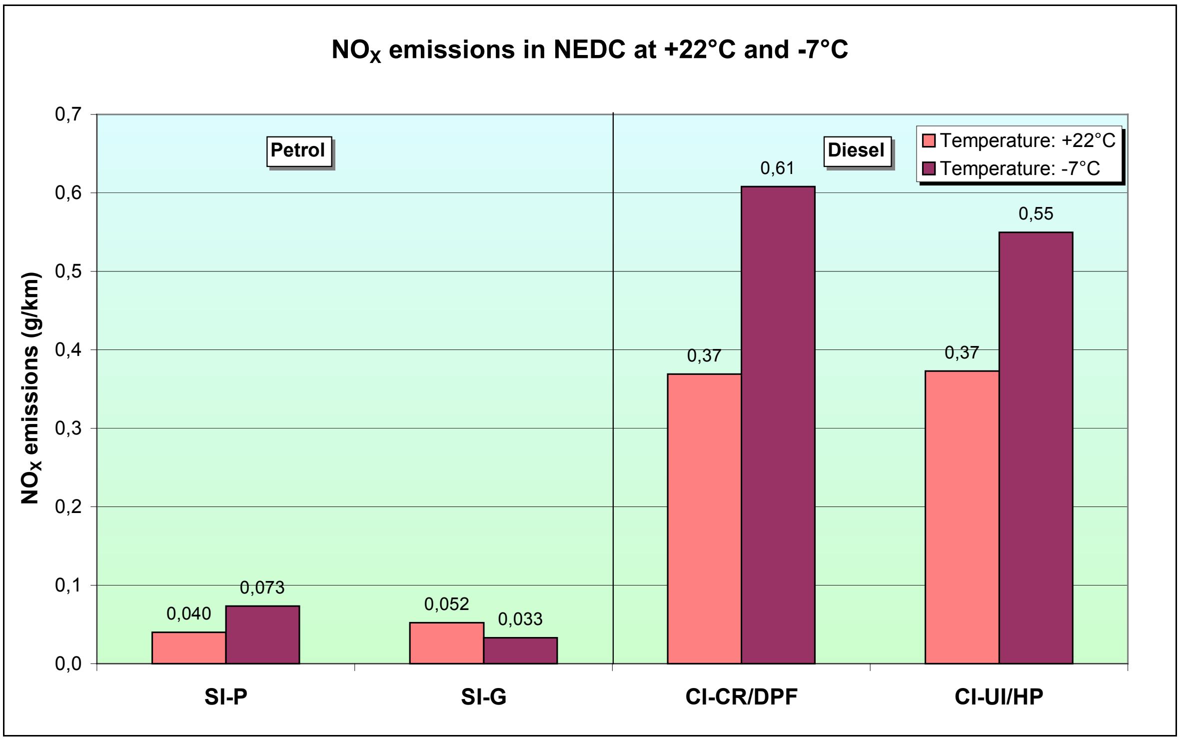


Figure 9. *NO_X emissions in NEDC at +22°C and –7°C*

The temperature impact on the NO_X emission from the diesel cars was considerable. This might not be expected at first glance, as NO_X formation decreases with decreasing temperature and an oxidation catalyst has very little effect on NO_X emissions. The increase in fuel consumption due to increased friction, higher idle speed and heat losses at lower temperatures should increase the NO_X emissions but the impact of temperature is predominant. For example, results by Demel et al. (Audi) showed some 10% *decrease* in NO_X emissions at –7°C compared to +22°C on an Audi 100 2,5 TDI [37]. A graph presenting the results from this study is shown in **Figure 10**.

The most likely reason to the *increase* in NO_X emissions for the cars tested in this study is the EGR strategy used at cold start. EGR plays a crucial role in reducing the NO_X emissions from diesel engines. Limiting (or cutting off) EGR at low ambient temperatures could result in higher NO_X emissions than at the higher temperature. The NO_X emissions in the two first cycles (UDC 1+2) of the NEDC cycle were some 2 times higher than in the two subsequent cycles (UDC 3+4) and this exemplifies the importance of the cold start strategy. As the difference in fuel consumption was far less than a factor of 2, the contribution from more fuel being burnt is of less importance than the EGR strategy.

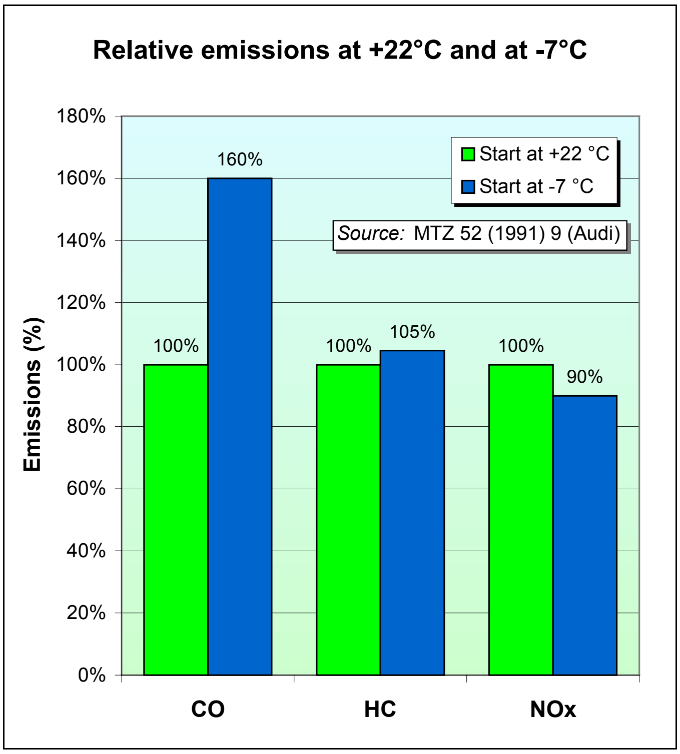


Figure 10. *Comparison of emissions at +22°C and at −7°C (source: Audi, MTZ [37])*

Higher NO_X emissions from cars with DI diesel engines at low ambient temperatures have been reported in a previous project carried out by this author [4]. In this case, a Volvo 850 TDI showed about 50% higher NO_X emissions at −7°C compared to +22°C. That particular car was equipped with a more recent version (Euro II) of the same engine as in the tests on the Audi, as mentioned above. The risk for condensation (including freezing) and corrosion are two factors that might limit the use of EGR under cold ambient conditions. In general, introducing *hot* EGR during a cold start *should be beneficial* in reducing CO and HC emissions (as well as NO_X) on the condition that the ignition delay can be reduced by introducing hot exhaust gases. *In view of the significantly higher NO_X emissions from diesel cars compared to petrol cars, the increase in NO_X emissions at lower ambient temperatures must be addressed in the future.*

In **Figure 11**, the NO_X emissions in US06 and overtaking tests are shown. As expected, the NO_X level was generally low in the US06 test cycle for both petrol cars. The catalyst temperature is high in this test cycle but the exhaust mass flow is not high enough to cause significant NO_X breakthrough in the catalyst. However, one petrol car showed considerably higher NO_X emissions during the overtaking test. High catalyst temperature and low air/fuel ratio should not result in high NO_X emissions, so catalyst breakthrough was probably the issue in this case.

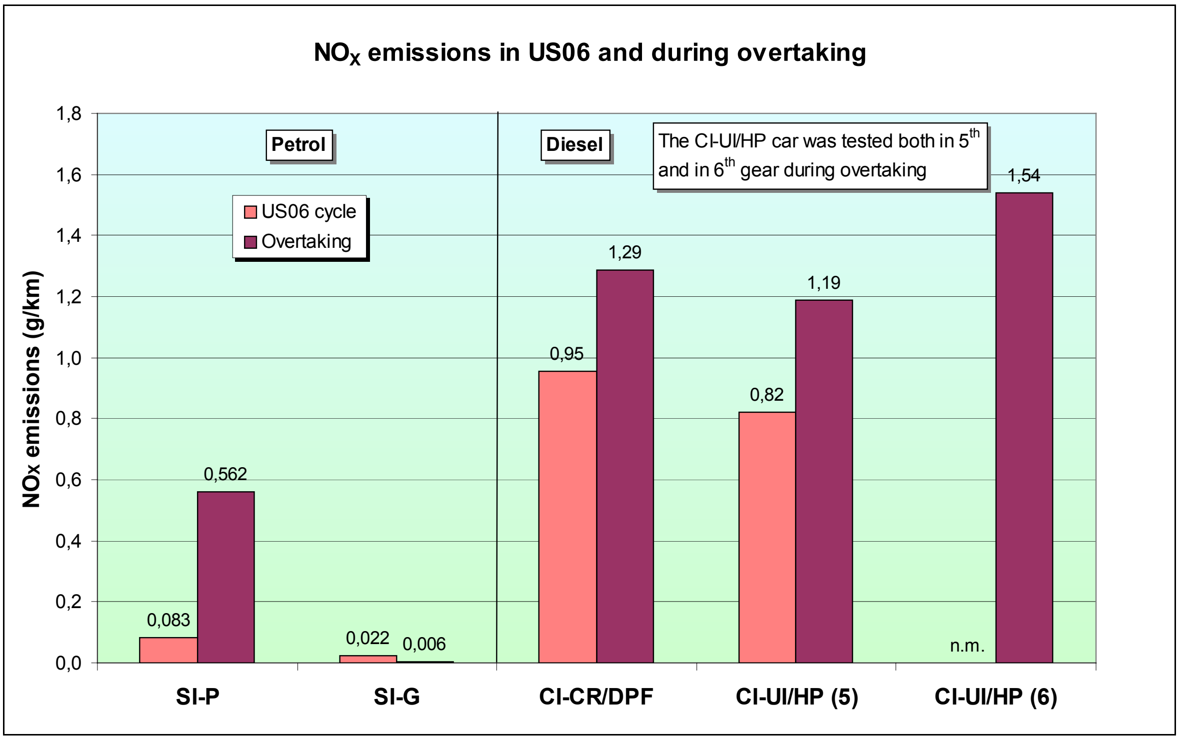


Figure 11. *NO_X emissions in US06 and during overtaking*

In contrast to the petrol cars, the diesel cars had significantly higher NO_X emissions in both driving cycles above compared to the NEDC. The increase ranged from a factor of 2 (US06) to 4 (overtaking, 6^{th} gear for the Golf TDI). EGR is normally cut off at high load on light-duty diesel engines due to the decrease of excess air by increasing load. DI engines are more dependent on EGR to reduce the NO_X emissions than IDI engines[16]. Hence, the relative increase in NO_X emissions by increasing load should be more pronounced for DI engines. Cooling the EGR and increasing the boost pressure enhance the possibilities to increase the area in the load and speed range where EGR is used. However, this is counteracted by the desire to increase the specific output of the engines. The drawback with increasing NO_X emissions at high-load driving cycles cannot be overcome unless NO_X after-treatment is introduced and/or a new combustion system that alleviate this problem is developed.

4.1.6 Particulate emissions

In **Figure 12**, the particulate mass emissions in the NEDC test cycle at the two ambient temperatures are shown. Note that the scale used is expressed in mg/km in contrary to g/km, which is the common practice.

[16] DI engines also tolerate higher EGR rates than IDI engines. Thus, the NO_X emissions can be lower for DI engines although the engine-out emissions are higher. However, at very high load, IDI engines often have lower NO_X emissions as no EGR is used in either of the engines.

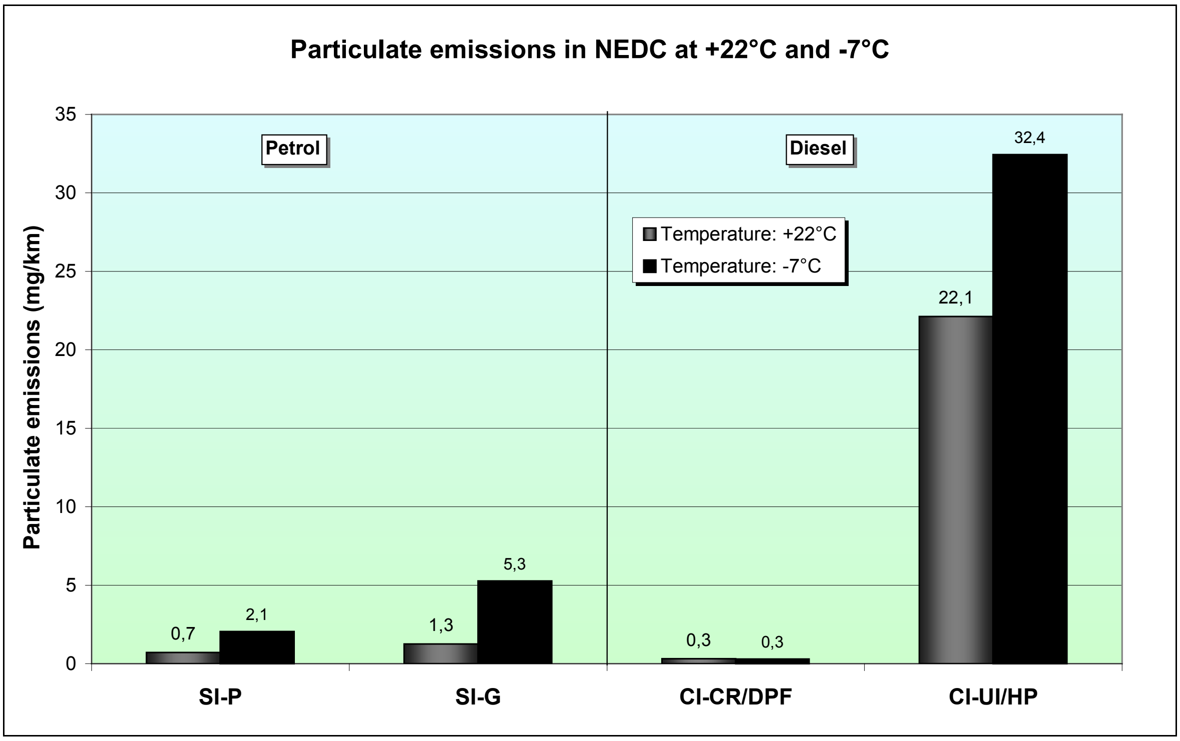


Figure 12. *Particulate emissions in NEDC at +22°C and –7°C*

The results in **Figure 12** confirm the general perception that particulate emissions from petrol cars are very low at high ambient temperatures. Somewhat surprising is the fact that the increase in particulate emissions at the lower ambient temperature was relatively small, i.e. significantly less than on tests with older cars (more details are provided below). The explanation to this behaviour can probably be derived from the observation that the CO and HC emissions were relatively low (especially in comparison to the cold start limits) for these two cars at −7°C. Consequently, the fuel enrichment during the cold start phase must have been low, which also should have a positive impact on the particulate emissions. Improved petrol quality could also have had an influence on the particulate level (see further discussion below).

The diesel car without a particulate trap had particulate emissions at +22°C that were *below* the Euro IV limit of 25 mg/km. As the particulate emissions were lower than the certification level as well, the Swedish EC1 diesel fuel was probably the main cause of the favourable results in this case. The particulate level at –7°C was significantly higher than at +22°C implying that the cold start has an impact on the particulate level on this car. The particulate level for this car at +22°C was more than one order of magnitude higher than for its petrol counterpart. At –7°C the factor was reduced to about 6. It has been shown that the particulate level can be reduced below the Euro IV limit[17] by internal engine measures. Such engines (3 and 4-cylinder TDI engines) are in production now by the VW group, but as explained before, a car with this technology could not be included in this test programme. Certification data have not yet been found in the open literature by the author, but

[17] To the knowledge of the author, the cars have not been certified according to Euro IV, due to the necessity of an OBD system. However, the German D4 regulation, having the same emission level, should be met. Several other car manufacturers, including the PSA group, have announced that they will introduce cars with an emission level below Euro IV in the near future.

in a special edition of the journal of MTZ provided by VW, a diagram shows a particulate level of about 15 mg/km [38]. Recognising that the use of Swedish diesel fuel would further somewhat reduce this level, it could be anticipated that the level of 22 mg/km in this test could be reduced by about 50%. However, this level would still be considerably higher than for new petrol cars with TWC.

The diesel car with particulate trap shows extremely low particulate levels in the NEDC cycle at both test temperatures. Assuming an engine-out particulate level of 0,03 g/km, the filtration efficiency would be some 99%. The level measured in this study was lower than the certification level. Two factors could play an important role. First, filter regeneration was not taken into account in this study, although this impact of regeneration has been shown to be relatively small [10]. Second, the Swedish diesel fuel might also have an impact, even on this low particulate level. It could also be anticipated that the low ambient level of particulates in the countryside outside Stockholm (and in Sweden in general) compared to the levels on the European continent might have some influence on the measured particulate level. Furthermore, the test cell air is filtered to a very low particulate level.

In **Figure 11**, the particulate emissions in the US06 driving cycle is shown. No gravimetric particulate emission measurements were carried out in the overtaking test, as the governing of the sampling period – varying from vehicle to vehicle – was considered a difficult obstacle to be overcome. Furthermore, the short sampling period was anticipated to give too low particulate mass on the sample filter anyway.

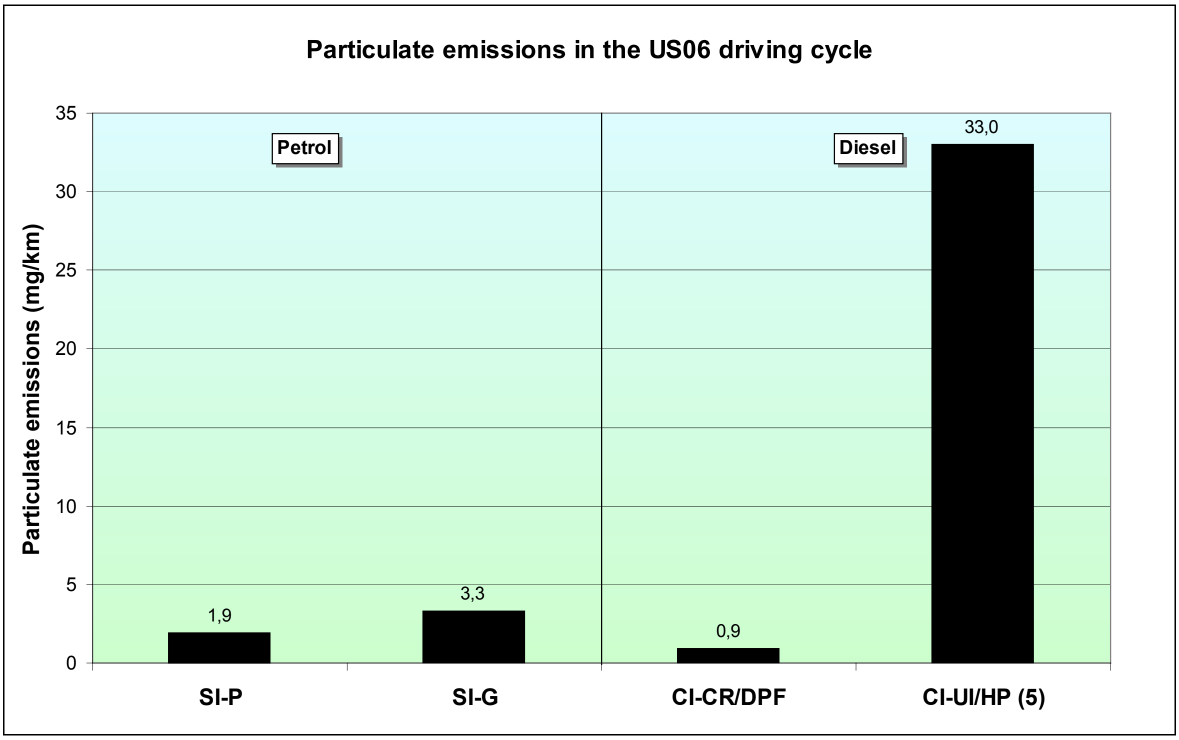


Figure 13. *Particulate emissions in US06*

Figure 11 shows that the particulate mass emissions for the petrol cars in the US06 cycle were low, i.e. not much higher than in the NEDC cycle at +22°C. However, the majority of the particulate emissions in the NEDC cycle are generated during the cold start phase, whereas the US06 does not include a cold start. Consequently, the particulate emissions must be generated under completely different conditions in the US06 cycle than in the NEDC cycle. Fuel enrichment could play an important role in the US06 case.

The diesel car without a particulate trap had higher particulate emissions in the US06 cycle than in the NEDC cycle at +22°C. Higher engine load in the former cycle is probably the main cause for this behaviour.

As in the previous cases, the particulate level of the diesel car with particulate trap was very low. The higher exhaust temperature in the US06 cycle might cause sulphate formation in the particulate filter, but as the Swedish EC1 diesel fuel is practically sulphur-free, this should not be an issue in this case.

The particulate emissions from diesel cars without a particulate filter are generally considerably higher than from petrol cars with TWC emission control and cars with particulate filter. As this difference will remain although the Euro IV particulate limit is met, further reduction of the particulate level will be necessary in the future on the condition that particulate matter is considered as a health hazard. *Therefore, the use of particulate filters and/or the introduction of a new combustion system that drastically would reduce the particulate level are the two options for the future development of diesel engines.*

Comparison of particulate emissions from petrol cars in other studies

It might be of interest to discuss the particulate emissions from petrol-fuelled cars in some more detail. As the particulate emissions at the yearly average temperature of +7°C in Sweden are of main interest, some results interpolated for this temperature have been compiled. The author has been participating in two studies analysing the particulate level on petrol vehicles corresponding to the Euro I emission level. The first study calculated the particulate level from tests in the US FTP-75, making corrections for the lower weighting factor of the cold start in this test compared to European driving pattern [39]. The second study evaluated the particulate emissions from tests in the NEDC cycle [1]. It is also of interest to mention two additional studies. In a study at MTC, the average particulate level measured on three cars was reported [4]. Fortum and VTT in Finland have conducted a study on the impact of petrol fuel quality on the particulate emissions that has been summarised in an SAE paper [40]. From this study, three cars with TWC have been chosen. In **Figure 14**, the results from the studies mentioned are summarised and compared with the level from the two cars in this study.

The results in **Figure 14** show that the level in the two KFB reports and the SAE paper on EU 2000 fuel were on a roughly similar level (14 – 18 mg/km). Improved fuel quality (RFG) reduces the particulate emissions by almost 50%. The fuel quality has presumably had some impact in the MTC 9708B report as well, since these tests were run on ordinary Swedish petrol that should be better in this respect than the reference fuel. However, the particulate level measured in this study is outstanding. First, it could be anticipated that the further improved fuel quality of the Swedish fuel that now corresponds to the EU 2005 fuel specification could have had a positive impact. Second, the petrol cars in this study were new, and it cannot be excluded that ageing has some impact on the particulate level. The odometer reading for the cars in the other studies were greater and in the two first mentioned studies the evaluation was made for an average odometer reading of 80 000 km. However, even if the fuel quality and odometer reading might explain some of the apparent reduction of the particulate emissions, the improved technology on the new cars in this study should also have had a decisive influence on the results.

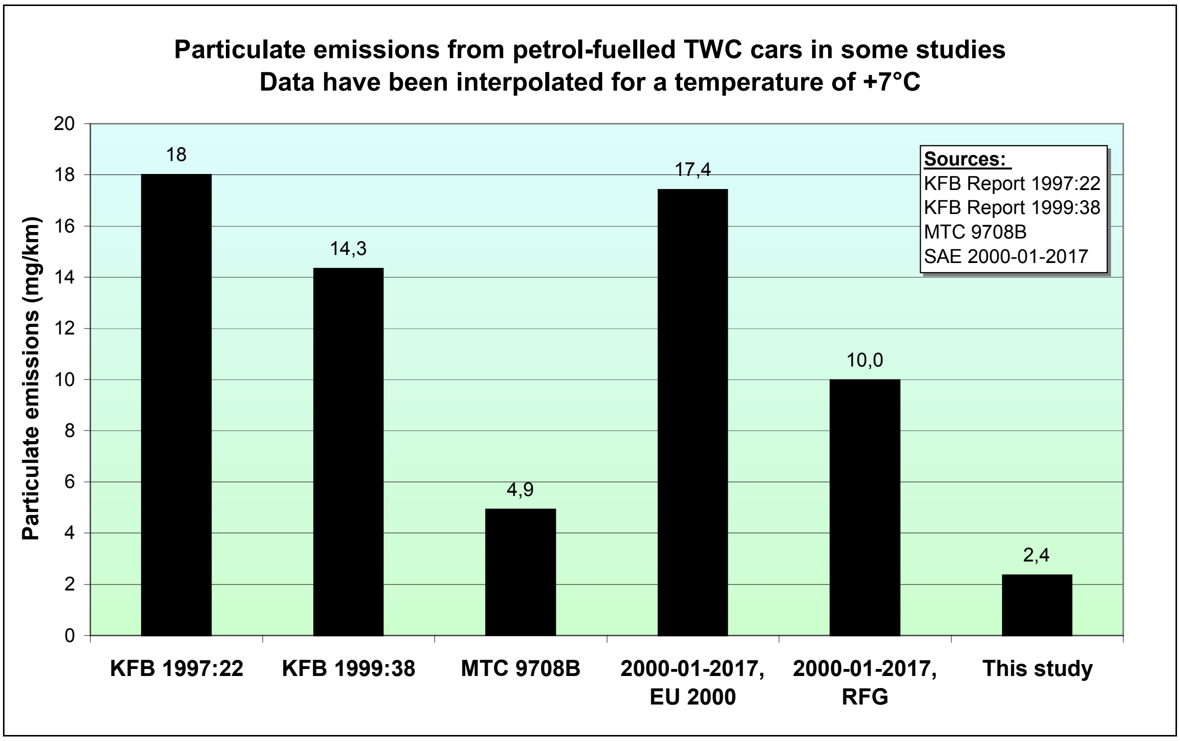


***Figure 14**. Particulate emissions from petrol cars with TWC*

It is also of interest to compare the particulate level for the petrol cars with cars that use direct injection of the fuel. The previously mentioned study by Fortum and VTT conducted measurements on a car with direct injection of petrol (Mitsubishi GDI). A study by this author also carried out measurements on a similar car [3]. As in the previously shown figure, the results for +7°C have been interpolated from data at +22°C and −7°C. The results from these calculations are shown in **Figure 15**.

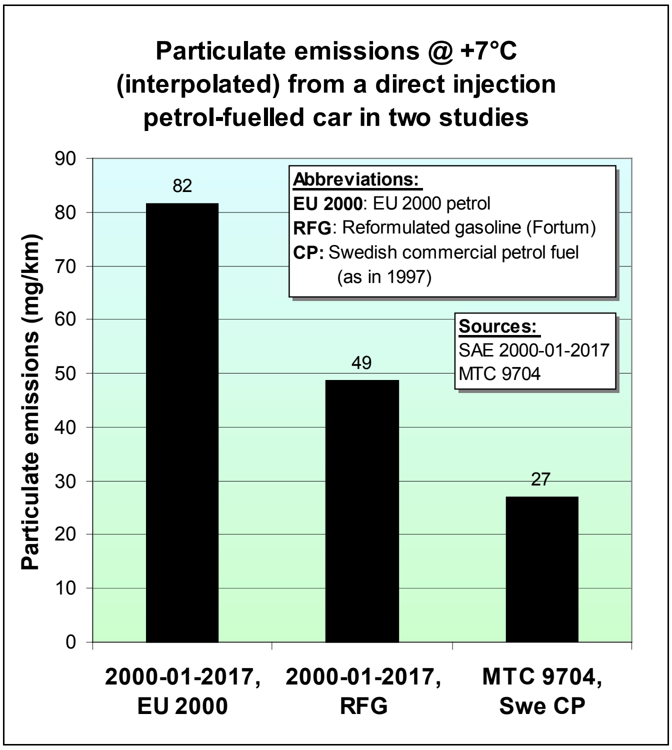


***Figure 15**. Particulate emissions from a direct injection petrol car in two studies*

As can bee noted from the results in **Figure 15**, the particulate emissions were significantly higher in this case than for the TWC cars shown in **Figure 14**. In fact, in the Fortum/VTT study, the level was higher than for the diesel car without a particulate filter in this study. In the MTC study, the level was similar to the diesel car without a particulate filter that was tested in this study.

Before drawing too drastic conclusions on the results shown here, it might be noted that the Mitsubishi GDI was the first car introduced on the European market with this technology. Furthermore, the car was apparently optimised for the EDC driving cycle, as the emission level was generally higher in the NEDC cycle. Therefore, it is likely that the particulate level could be significantly reduced on more advanced concepts. However, it is still plausible that the particulate level on direct injection petrol cars will be higher than on cars with TWC.

Considering the reduction of the particulate level that will be made on Euro IV diesel cars, the particulate level on cars with direct injection of petrol could be on a roughly similar level. Consequently, diesel cars with a particulate trap would have a considerable advantage over direct injection petrol cars in this respect. *In view of the development outlined above, (tougher) particulate limits for cars running on all types of fuels should be considered in the future.*

4.1.7 CO_2 emissions and fuel consumption

Carbon dioxide (CO_2) is the largest contributor to the climate change. The climate gases are reported in section 4.3.4 but it might be of interest to discuss the CO_2 emissions from the cars separately as well. In **Figure 16**, the CO_2 emissions in the NEDC test cycle are shown.

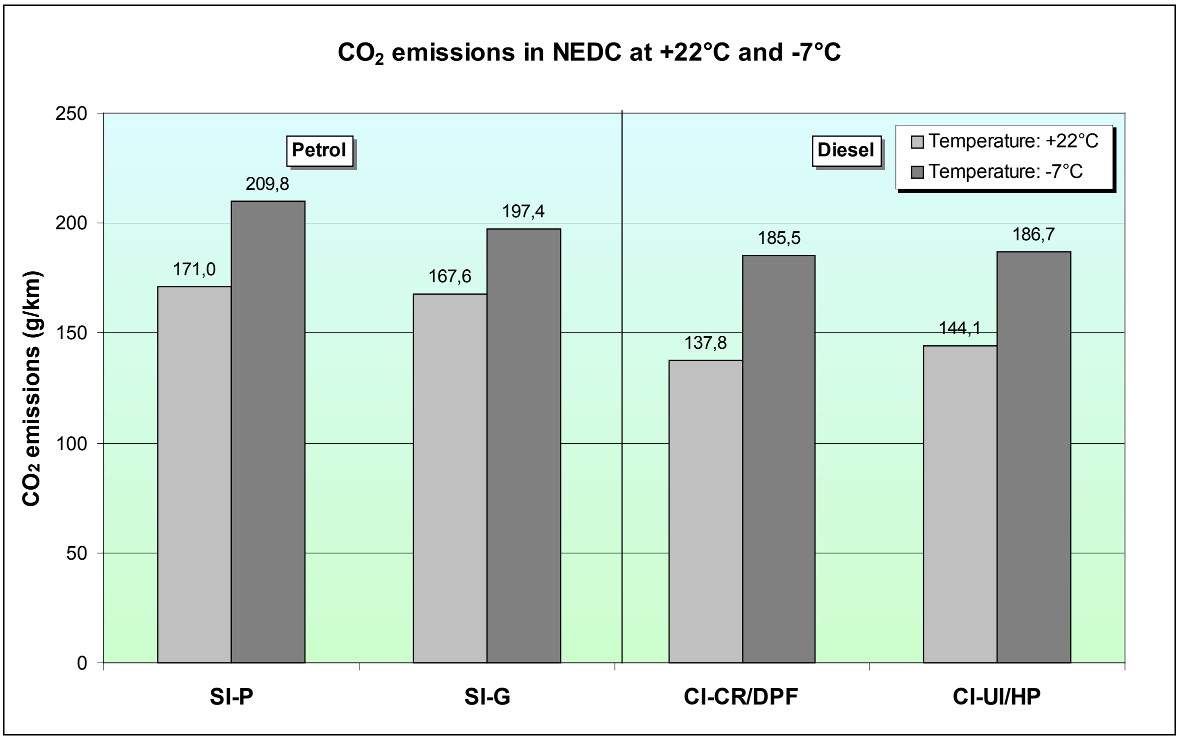


***Figure 16**. CO_2 emissions*

The data in **Figure 16** show that the CO_2 emissions were lower from the diesel cars than from their petrol counterparts at both temperatures.

The supplement to the CO_2 results presented above with data on fuel consumption, as shown in **Figure 17**, concludes the presentation on this subject.

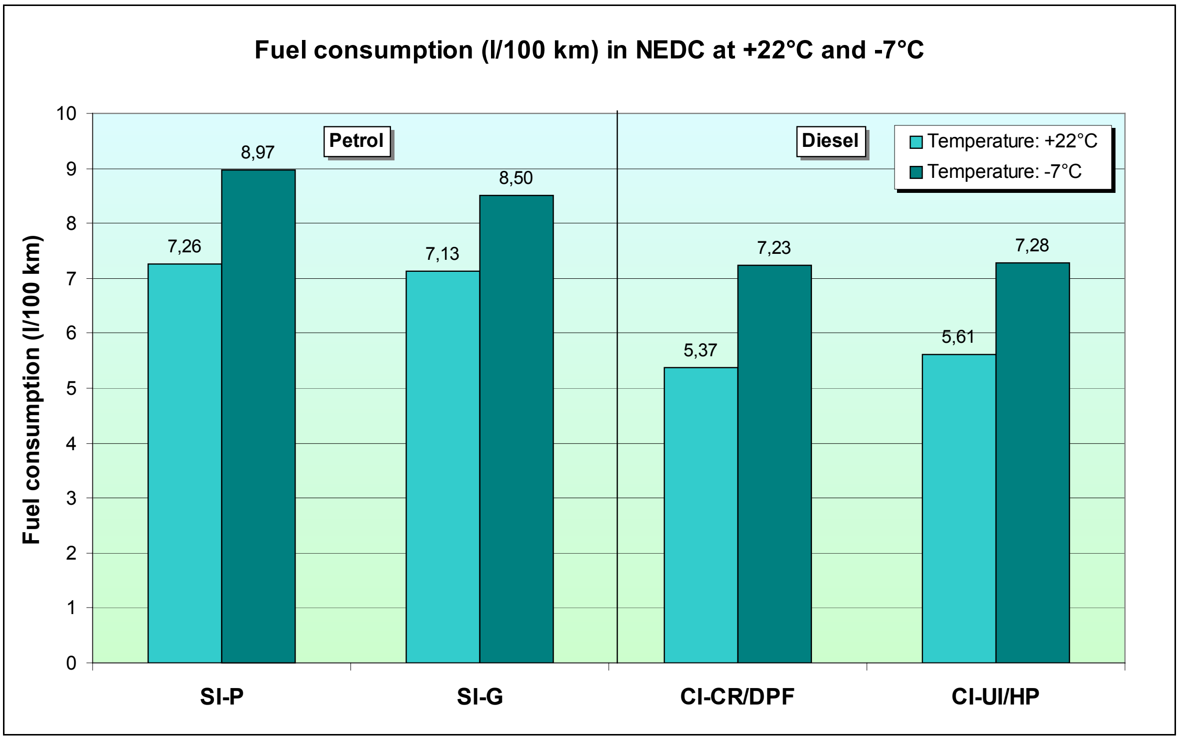


***Figure 17**. Fuel consumption*

As can be seen in **Figure 17**, there are similarities with the results for CO_2 in **Figure 16**, except for the greater difference between petrol and diesel fuel. Although the density of Swedish diesel fuel is lower than for diesel fuel according to the European standard and the H/C ratio is higher, the carbon content is still higher per litre than for petrol fuel. This explains the mentioned difference between the two figures.

An interesting observation shown in the figures for CO_2 and fuel consumption is that the relative increase in fuel consumption by reducing the temperature was greater for the diesel cars (factor of ~1,3) than for the petrol cars (factor of ~1,2). Evaluations of results on older cars have usually shown the opposite trend when cars using IDI diesel engines have been compared with petrol cars. One factor of importance is that the fuel enrichment for the petrol cars at cold start in this study appears to be small due to the relatively small increase in CO and HC emissions. It is well known that DI diesel engines have lower heat losses to the cooling water than IDI engines do. This increases the period of high engine friction during the cold start. Cars with DI diesel engines often use some complementary compartment heating and this should have an impact on the fuel consumption at low ambient temperatures. However, using common practice, no compartment heating was used in the tests at low ambient temperatures. Another important piece of information provided by Peugeot is that the idle speed for their diesel car is increased at low ambient temperatures [41]. Higher idle speed increases comfort and driveability during the cold start phase[18]. Consequently, the fuel consumption increases. Since only two cars of each type were tested in this study, any firm conclusions cannot be drawn but it is recommended to investigate this matter further.

[18] It is likely that the idle speed at low ambient temperatures for petrol cars has been *decreased* during the last years compared to the strategy used previously. However, the author does not have any concrete evidence to confirm this hypothesis.

4.1.8 Complementary results from overtaking

Since the overtaking test is not an official test procedure, some additional data from these tests might be of interest to show. In **Figure 18**, the vehicle speed traces are shown. The common ripple for a speed signal from a chassis dynamometer is clearly seen, as well as the difficulties in maintaining the desired constant speed after the acceleration. The diesel-fuelled Golf, having the highest engine power and torque (although the total drivetrain ratio also has an impact) provided the greatest acceleration in the 5th gear. In 6th gear the difference between this car and the petrol counterpart (in 5th gear) was smaller. The Peugeot diesel also had a more brisk acceleration than its petrol counterpart.

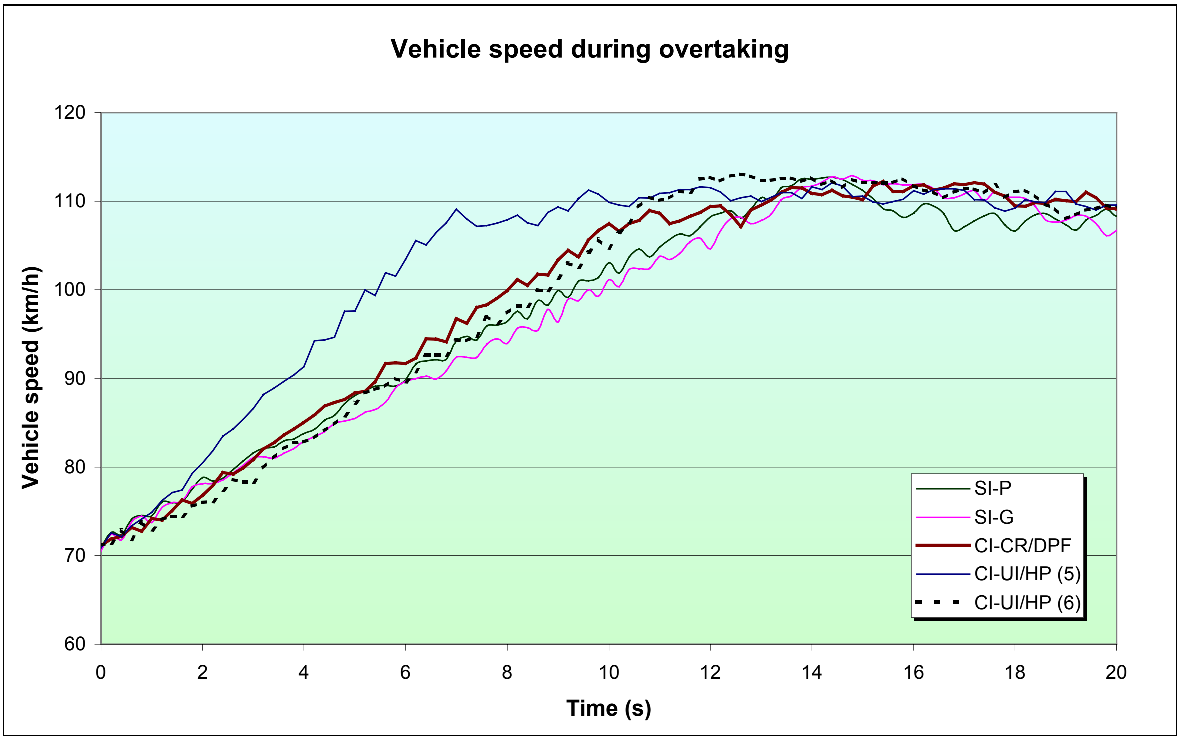


Figure 18. *Vehicle speed traces during overtaking*

Although the time for completion of the overtaking was measured, the distance driven is of greater importance. A graph with these results is shown in **Figure 19**. As can be seen in **Figure 19**, the diesel cars were faster than their petrol counterparts. The difference for the diesel-fuelled Golf in 5th and 6th gear could also be noted.

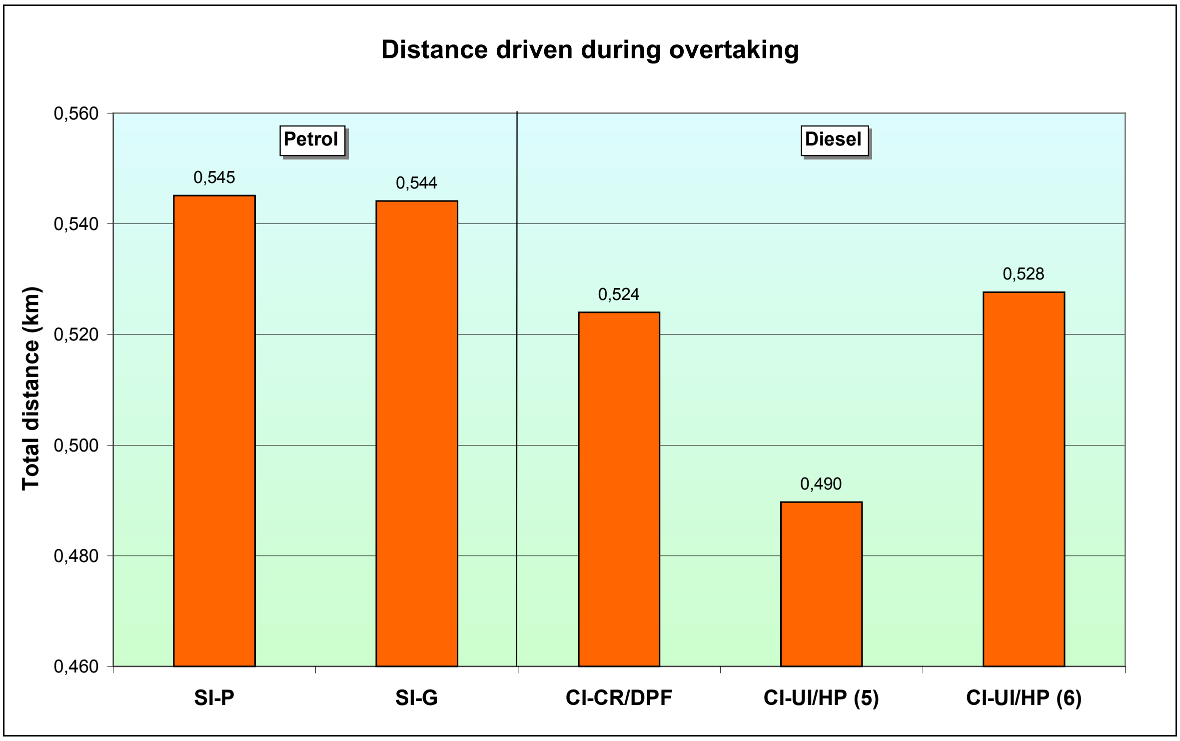


***Figure 19**. Vehicle distance driven during overtaking*

4.2 Unregulated emissions

In this section, the results on the unregulated emissions are presented and discussed. It should be noted that the uncertainty for the measurement of several of these emission components is considerably greater than for the regulated emissions. Likewise, the public domain database on the unregulated emissions is smaller than for the regulated emissions.

4.2.1 Nitrogen containing compounds

Nitrous oxide (N_2O)

The emissions of nitrous oxide (N_2O) are shown in **Figure 20**. Somewhat surprisingly, the N_2O level was higher for the diesel cars. Older petrol cars, and in particular cars with aged catalysts, usually have higher N_2O emissions than petrol cars with catalysts, implying that N_2O formation in the catalyst is higher than the N_2O conversion. A recent study at MTC [36] showed significantly higher N_2O emissions (in the NEDC cycle) for all the tested petrol cars than the cars in this study. The N_2O level ranged from about 24 mg/km to 87 mg/km. The newest cars showed the lowest level. Diesel-fuelled vehicles generally have relatively low emissions of N_2O. In view of other published results on N_2O emissions, some scepticism regarding the results obtained in this test series must be expressed. Considering that the results for the petrol cars were on a level that could be expected from the diesel cars, and vice versa, it cannot be excluded that some mix-up has been made in the sampling or analysis process. However, MTC has investigated this issue without having found any explanation.

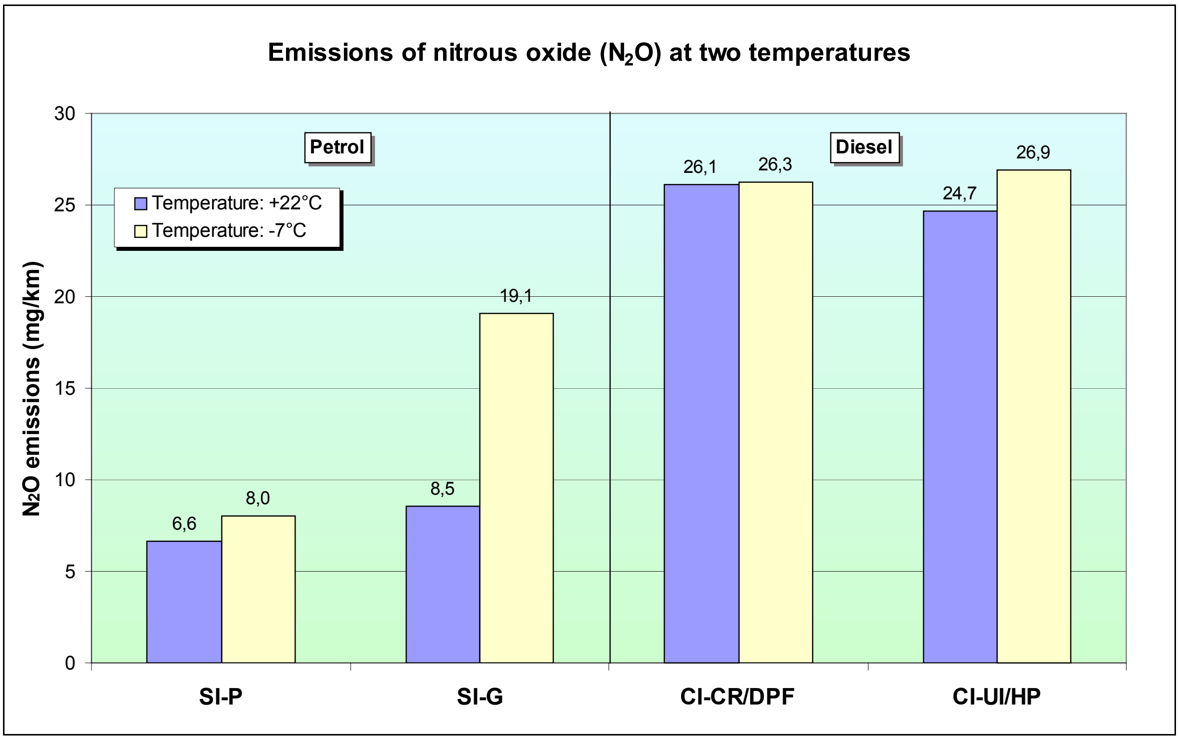


***Figure 20**. N_2O emissions*

Ammonia (NH_3)

The emissions of ammonia (NH_3) are shown in **Figure 21**. Ammonia can be formed in the catalyst under low air/fuel ratios. The ammonia emissions were generally low for the petrol cars and below the detection level for the diesel cars. The measurement trace from the MS instrument (in real-time) oscillated around the zero level for the diesel cars during the whole test cycle, implying that no ammonia could be detected in the exhaust from these vehicles. This is plausible, since diesel engines generally operate with air excess and ammonia is formed under rich conditions. An increase in ammonia emissions can be noted for the petrol cars at the lower ambient temperature. However, the level at this temperature was also low.

4.2.2 Light aromatics

Of the light aromatics, only the benzene emissions were measured. Benzene is a known carcinogen that is usually found in the emissions from petrol cars, since petrol contains benzene. However, the benzene level in petrol has been considerably reduced and in this study, petrol corresponding to the EU 2005 petrol specification was used (<1% benzene). Benzene can also be formed from higher aromatics in the fuel.

In **Figure 22**, the benzene emissions in NEDC at the two temperatures are shown. As expected, the level was higher for the petrol cars than for the diesel cars, although it should be noted that the level for all cars was low. All cars, but the diesel car with a particulate trap, showed a distinct increase of benzene by lowering the temperature. The increase was roughly proportional to the increase in HC emissions for the petrol cars when the temperature was reduced.

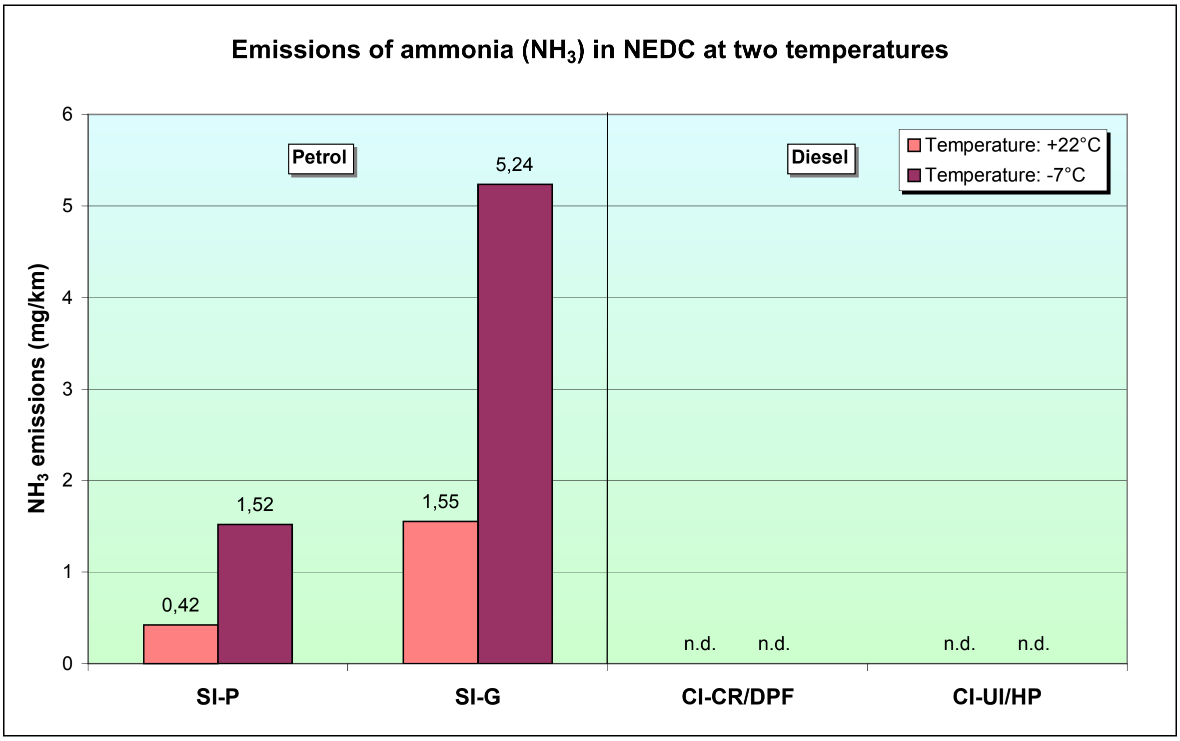


Figure 21. *Emissions of ammonia (NH_3)*

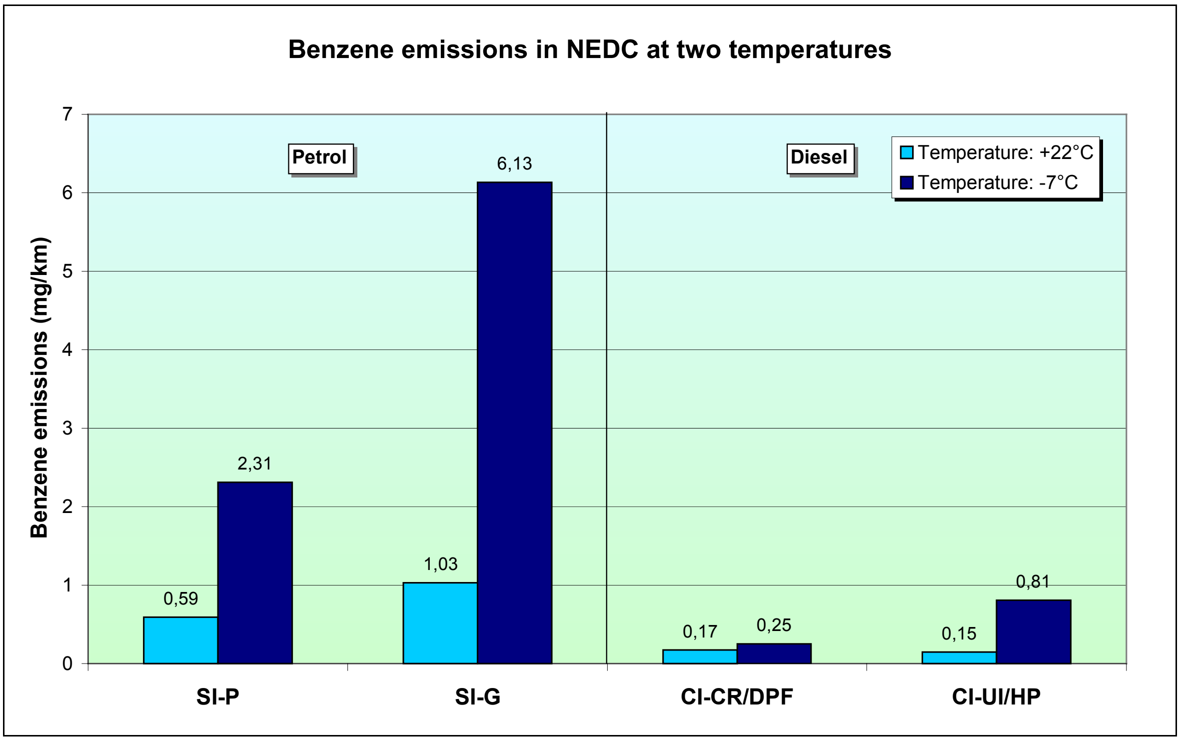


Figure 22. *Benzene emissions*

4.2.3 Aldehydes

Aldehydes are generally considered a problem for diesel engines. **Figure 23** shows the results on aldehyde emissions in the NEDC cycle. No aldehyde emissions could be detected at any of the test temperatures for the petrol cars[19]. One of the diesel cars had a formaldehyde level slightly above the detection level at +22°C.

At the low ambient temperature, the aldehyde emissions from the diesel cars increased to a level about two times higher than the detection level. However, this level must also be considered as a low level in comparison to emission levels on older cars. For example, May et al. have reported results on an Audi 80 TDI[20] in the EDC test cycle [42]. The formaldehyde level was about 20 mg/km and the acetaldehyde 25 mg/km, i.e. more than an order of magnitude higher than the level of 1,5 mg/km (or less) found at +22°C in this study. Even compared to the results at –7°C in this study, the level on the older Audi 80 TDI was 7 – 8 times higher. However, it could be noted that the VW Vento TD with an IDI engine had about 50% lower aldehyde emissions than the Audi 80 TDI, implying that the DI engine had a disadvantage in this respect. The higher aldehyde level for the car with the DI engine also corresponded to a higher HC level. The previously cited paper by Neumann et al. reported a level of about 11 mg/km for the sum of 13 aldehydes and ketones [19]. The levels on formaldehyde and acetaldehyde were not reported explicitly.

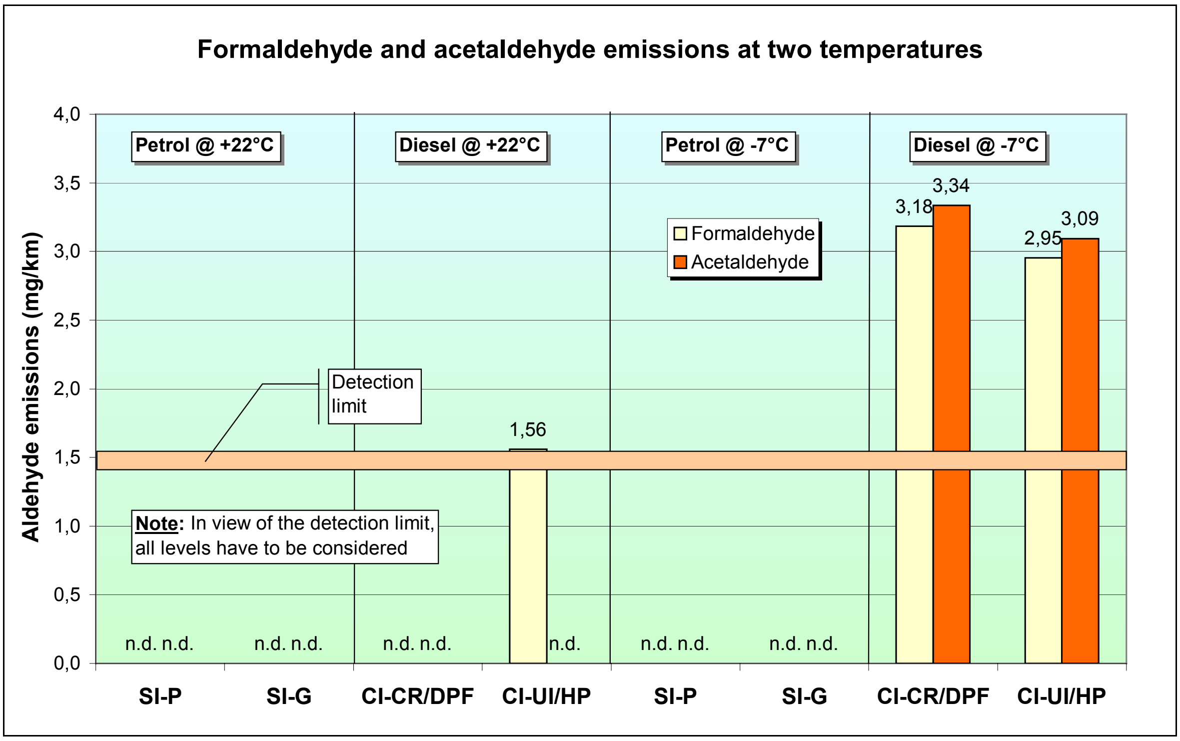


Figure 23. *Aldehyde emissions*

Although the aldehyde emissions from the diesel cars in this study appeared to be relatively low, the potential for further reduction should be mentioned. Using close coupling of

[19] The detection level recalculated from concentration level to engineering units (mg/km) was about 1,5 mg/km.
[20] Presumably, this was a car certified to the Euro I regulation, although this was not reported explicitly.

a light-off catalyst (potentially even located before the turbocharger) closely followed by a main catalyst should be significantly better than an underfloor catalyst in this respect. With low-sulphur fuel, sulphate formation of close-coupled catalysts would not be a problem (as it is to some extent today). Consequently, a very active catalyst formulation could be used for the close-coupled catalyst. Conversion of NO to NO_2 could be an issue with an active catalyst but using a NO_X reduction catalyst would handle this problem anyway. Catalytic coatings on particulate filter are also discussed, and this could have some impact on the aldehyde emissions as well. In view of the future development indicated above, aldehyde emissions from diesel cars could be practically eliminated in the near future.

4.2.4 Alkenes

First, it should be mentioned that the MS instrument appeared to have a zero drift for some of the tested emission components. In general, the emissions of the alkenes were high during the cold start but decreased rapidly to a very low as soon as the cold start period was over. In some cases, additional emissions were emitted during the EUDC phase. Due to the zero drift, the integrated value sometimes *decreased* considerably over time after the cold start phase, which must be an artefact. The problem is illustrated in **Figure 24**, where a correction of this apparent error is also shown. The correction was simply made by excluding negative values. It might be possible that the zero drift could have increased the level in some cases but this is somewhat difficult to determine. Since no correction was made in these cases, a slight overestimation of the level might be the result.

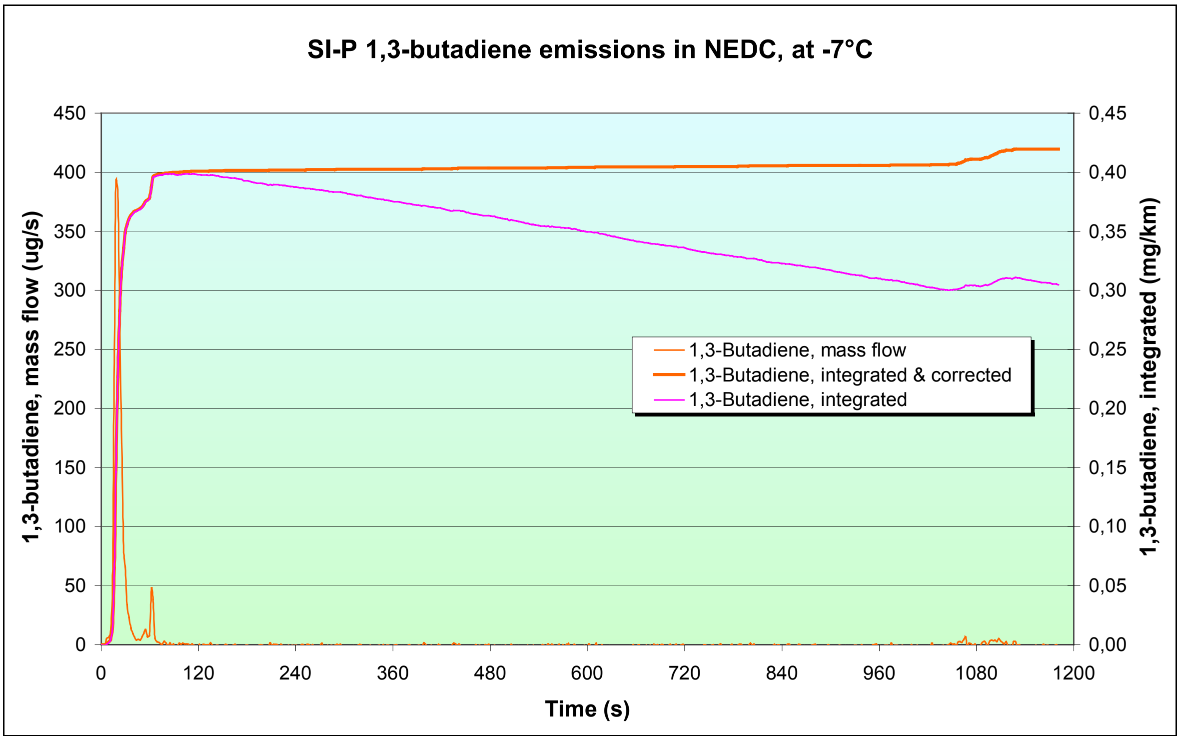


Figure 24. 1,3-butadiene emissions (corrected and uncorrected) at +22°C

In **Table 8**, the measurements where the values for the alkenes were corrected are shown. In three cases, corrections were considered necessary.

Table 8. Corrections for some of the alkenes

	Emission compound correction			
Vehicle	Temp.	Ethene	Propene	1,3-buta
SI-P	+22	No	No	No
SI-P	-7	No	No	No
SI-G	+22	Yes	No	Yes
SI-G	-7	No	No	Yes
CI-CR/DPF	+22	No	No	No
CI-CR/DPF	-7	No	No	No
CI-UI/HP	+22	No	No	No
CI-UI/HP	-7	No	No	No

The emissions of the alkenes (ethene, propene and 1,3-butadiene) at +22°C are shown in **Figure 25**.

Figure 25 shows that the ethene emissions at +22°C were roughly similar for the petrol and diesel cars respectively from each car manufacturer. The propene emissions were considerably lower for the diesel cars in comparison to their petrol counterparts. The 1,3-butadiene emissions were about 50% lower in one case (diesel with particulate trap) but the difference was small in the other case.

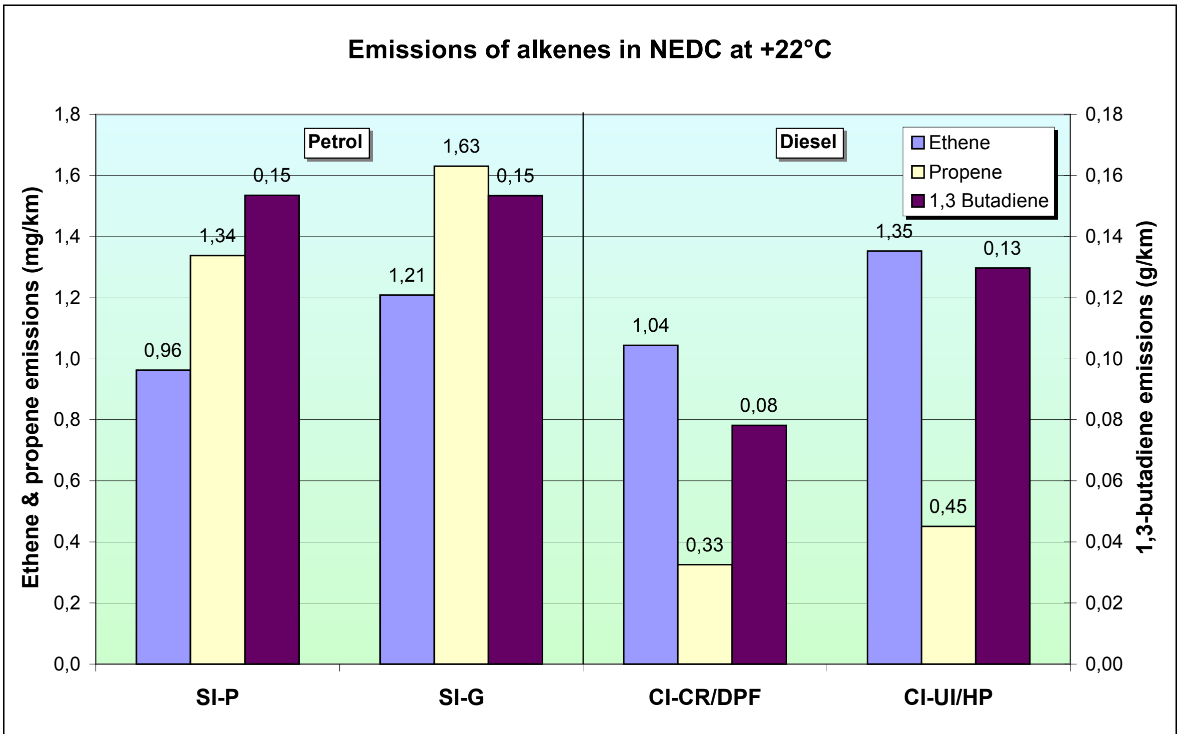


***Figure 25**. Emissions of alkenes at +22°C*

The emissions of the alkenes at -7°C are shown in **Figure 26**. Compared to the previous results in **Figure 25** at +22°C, the emissions of the alkenes increased considerably for the petrol cars at the lower ambient temperature. This is plausible since also the HC emissions increased significantly by reducing the ambient temperature. The increase of the alkene emissions due to reducing the temperature was somewhat lower for the diesel cars, although the trend is not quite clear. The relative difference between the two fuels was generally greater at the lower ambient temperature, even if the smallest difference was no more than a factor of two.

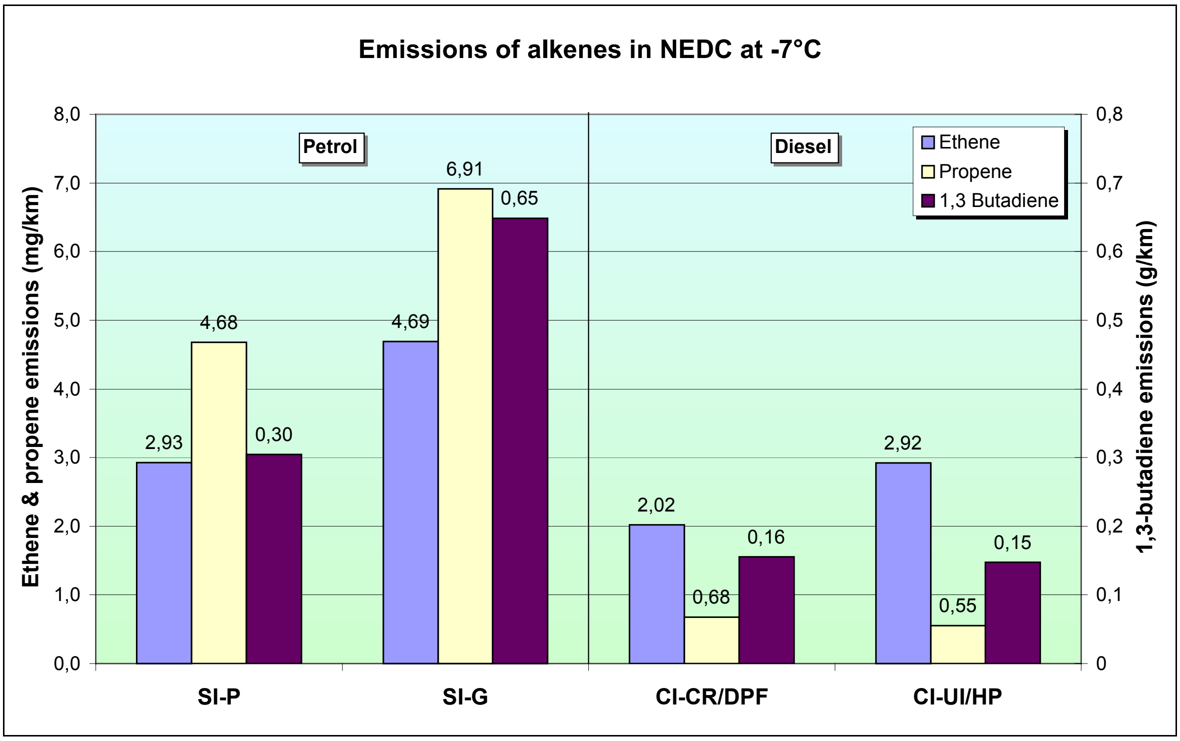


***Figure 26**. Emissions of alkenes at -7°C*

1,3-butadiene is considered a suspected carcinogen. There is also some evidence that ethene and propene might cause cancer but the unit risk factors are considered significantly lower in these cases. 1,3-butadiene that is considered the most important of the alkenes has generally been lower in measurements on diesel cars compared to results on petrol cars. Neumann et al. found that the level of 1,3-butadiene was virtually undetectable for the two cars tested in that study [19]. The results by Almén et al. generated on a VW Golf TD of MY'93 were somewhat inconclusive [11]. At –7°C a level of 9 mg/m was measured but with a high scatter of ±7mg/km. No value was noted at +22°C in the report but in the calculation of the cancer risk index, a very high contribution from 1,3-butadiene was shown. In view of other results in the literature, some errors in these measurements and/or the evaluations could be anticipated for the higher temperature. A later study by Almén found a level of 7 ±4mg/km for the same car at –20°C [43]. The level on the 3 petrol cars in the same study was considerably higher, ranging from 13 to 41 mg/km (also at –20°C).

4.2.5 Polycyclic aromatic compounds (PAC)

As mentioned in section 3.3.5, 12 tri+ aromatic PAC and 4 di-aromatic PAH were measured. As some previous results include additional compounds, a direct comparison should not be carried out without considering this fact. PAC (and PAH) emissions have generally been considered as a major problem for diesel engines. However, the use of aftertreatment devices and improved fuel quality can significantly reduce this level, which has also been the case for petrol engines. At low ambient temperatures, the PAC emissions tend to increase more for petrol cars than for diesel cars. Very high PAC emissions at low ambient temperature have been shown for petrol cars in a couple of reports, e.g. [11, 43, 44].

The results on PAC emissions are shown in **Figure 27**. The results have been divided into PACs associated with the particulate fraction (PM) and the semivolatile (PUF) fraction. In addition, the total PAC is shown.

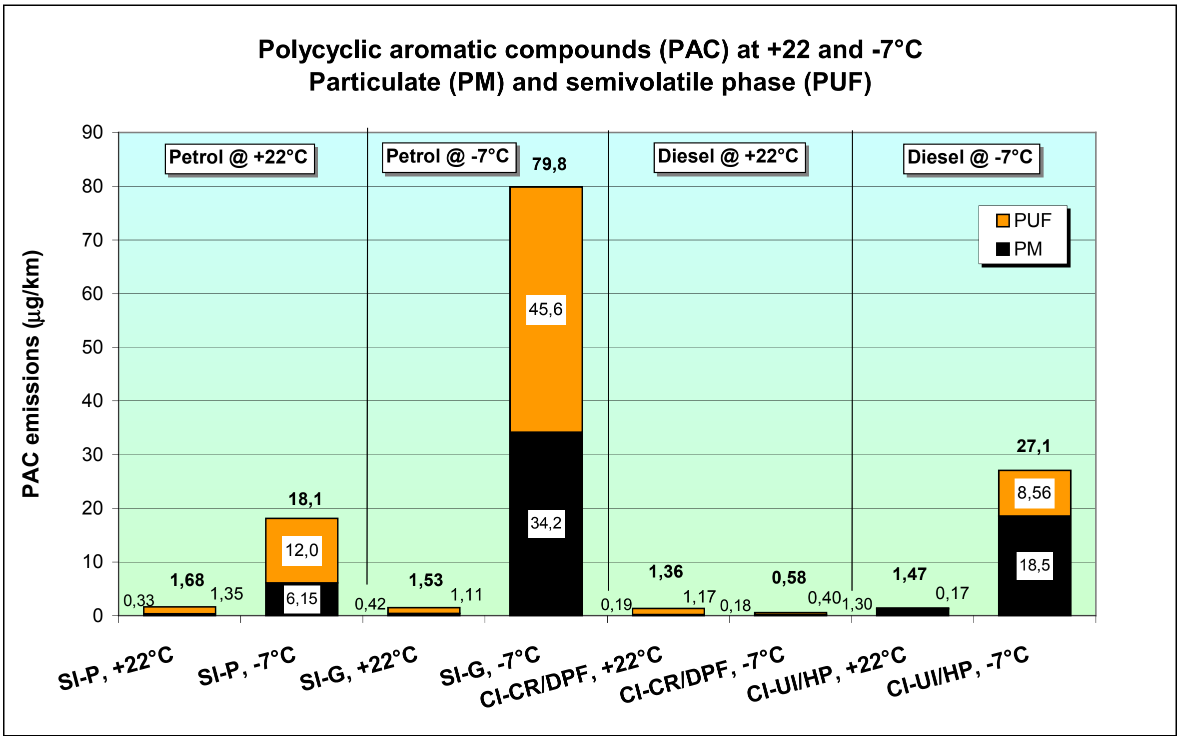


***Figure 27**. Emissions of polycyclic aromatic compounds (PAC) at +22°C and –7°C*

As expected, all cars had very low PAC emissions at +22°C regardless of fuel type (**Figure 27**). The PAC in the semivolatile phase (PUF) was higher than in the particulate phase for the petrol cars, as generally is the case for petrol cars. The diesel car without particulate filter had very little PAC in the semivolatile phase at this temperature. On the contrary, the diesel car with the particulate trap had very little PAC in the particulate phase – in fact; both the percentage and the absolute level were lower than for the petrol cars. The most plausible explanation is that the removal of condensation nuclei increases the semivolatile share of the PAC emissions. This trend has been seen before with a particulate trap on both light-duty [10] and heavy-duty vehicles [20]. The question remains whether PAC in the particulate phase poses more health hazard than PAC in the semivolatile phase, or vice versa.

At the lower temperature, the PAC emissions increased considerably for the petrol cars but this trend could also be seen for the diesel car without a particulate filter. The level on the diesel car was exceptional in this respect; i.e. it tended to decrease with decreasing temperature. However, it should be noted that the level at both temperatures was very low and in fact, since the PAC emissions were on the detection level in this case, one cannot draw any firm conclusions on the temperature impact. Both diesel cars had lower PAC emissions than their petrol counterparts. However, the petrol car with the lowest PAC emissions had lower PAC emissions than the diesel car without a particulate trap. It could also be noted that the share of particulate bound PAC emissions tend to increase for the petrol cars at the lower temperature and with a higher total PAC level in general.

Since the differences for the PAC emissions was so great regarding the impact of temperature, the interpolated average for +7°C is shown in **Figure 28**. The diesel cars had lower PAC emissions than their petrol counterparts, as PAC was dominated by the emissions at the lower ambient temperature. *The diesel car with particulate trap has PAC emissions that were one order of magnitude lower than its petrol counterpart.* For the cars from the other car manufacturer, the difference was about a factor of 3. As the difference between the two petrol cars was great (as is the measurement scatter, in general), it cannot be concluded without doubt that a diesel car *without* a particulate filter has lower PAC emissions than average petrol cars.

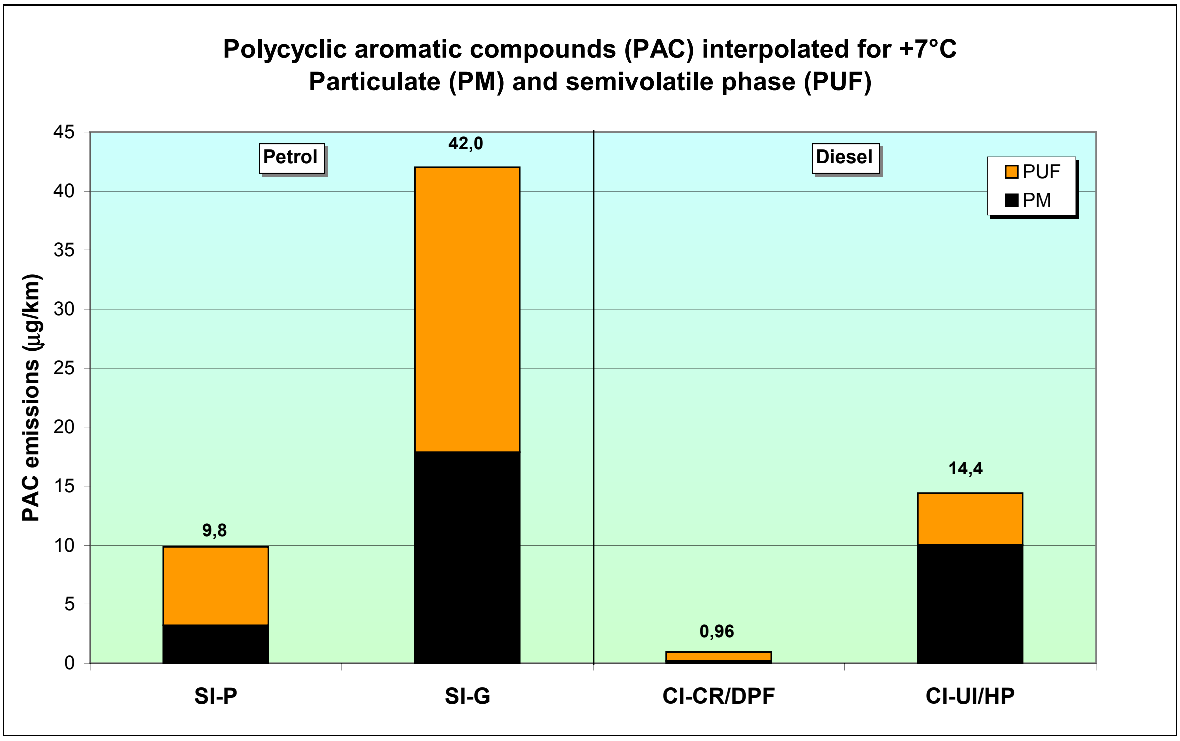


***Figure 28**. Emissions of polycyclic aromatic compounds (PAC) at +7°C*

It might be of interest to discuss the temperature impact on PAC emissions in little more detail. As mentioned above, there are some measurements available at various temperatures [11, 43]. In **Figure 29**, PAC emissions vs. temperature are shown for two petrol cars and one diesel car (note the different scale compared to the previous figures). Although the measurement scatter is generally great for PAC measurements (only the *average* of 3 measurements is shown in **Figure 29**), it is clear that the petrol cars were affected much more by low ambient temperature. The Honda Civic corresponded to the former Swedish Environmental Class 1 (equals Calif. TLEV) limit. This car had significantly lower PAC emissions than the diesel car at +22°C but it had much higher PAC emissions at the lower temperatures.

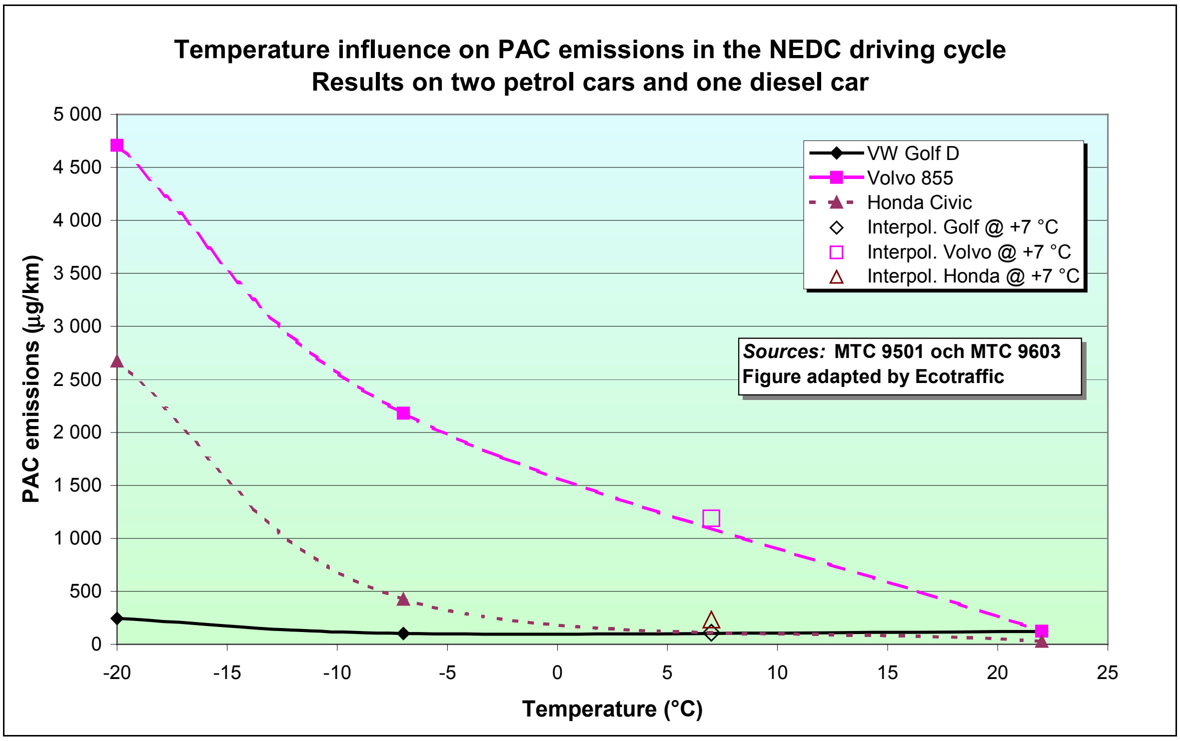


***Figure 29**. PAC emissions at various temperatures for two petrol cars and one diesel car*

In view of the results in this study and the results in **Figure 29**, it can be concluded that a significant decrease of PAC emissions at low ambient temperatures has been achieved on the petrol cars in this study. The Honda, being a TLEV car, had relatively low HC emissions at –7°C compared to the Volvo that was certified to an older emission regulation. Thus, the "knee" for increase in PAC emissions at low temperature seems to have been shifted to lower temperatures as well. It could be anticipated that this trend would be even more pronounced for the petrol cars in this study. This could explain the significant decrease in PAC emissions at –7°C compared to the older results.

The low PAC level for the diesel car with a particulate trap is very impressive in comparison to the old cars. The difference was about two orders of magnitude even if the fact that fewer compounds were analysed in this study is taken into account. The average PAC level for the diesel car without a particulate filter at +7°C has been improved by almost one order of magnitude compared to the results on the older diesel car (**Figure 29**). However, the *relatively* large increase in PAC emissions by reducing the temperature remains to be explained. Previously, it has been noted that the HC emissions increased by almost a factor of 3 in the NEDC cycle by lowering the temperature, whereas the other diesel car did not show any increase (**Figure 7**). However, the increase in PAC emissions was almost a factor of 20. More tests would be necessary to reveal if this is a general trend, or if there could be some artefacts in the measurement. (Only a single measurement was carried out on each car.)

4.2.6 Acrylamide

Acrylamide has been noted in Sweden as a compound causing health hazards from the use (or misuse) in tunnel construction. Leaking of acrylamide in spill waster caused poisoning of the water supply in the Hallandsåsen area. Acrylamide is considered neurotoxic and it is anticipated to be a *possible* human carcinogen (IARC class B2). Acrylamide has also recently been found in food in a Swedish study [45]. Heating of the food during frying seems to be the cause of the formation of acrylamide. Acrylamide has also been found in cigarette smoke.

In an article in a Swedish newspaper "Aftonbladet" in June 16, 2001, the consultant company Rototest claimed to have found acrylamide in automobile exhaust [46]. Besides this information, no publication of data from these tests is known to the author. Rototest claimed to have found acrylamide in the exhaust at high engine load (fuel enrichment). Another possible, somewhat similar, engine operating condition could be cold start at low ambient temperatures but this was not analysed in the mentioned study. To limit the number of samples to be analysed in this study, it was decided to carry out the analysis of acrylamide in US06 and in the overtaking test only. The results on acrylamide emissions are shown in **Table 9**.

Table 9. *Emissions of acrylamide*

Car	Test cycle	Acrylamide (mg/km)
SI-P	US06	<0,3
	Overtaking	n.d.[a]
SI-G	US06	<0,3
	Overtaking	n.d.
CI-CR/DPF	US06	<0,3
	Overtaking	n.d.
CI-UI/HP	US06	0,6
	Overtaking 5th	n.d.
	Overtaking 6th	n.d.

Note:

[a] n.d.: not detectable. Recalculation of the detection limit to mg/km is not valid in this case, as the sampling period was not constant in the overtaking test.

In all cases except one (CI-UI/HP), the acrylamide level was below the detection limit. The detection limit of acrylamide was 5 µg/litre of water in the sampled volume. The sampled gas volume was between 6 and 14 litres depending on the test cycle and car. The detection limit in **Table 9** has been recalculated from concentration in the sample to mg/km. The detection limit was approximately 0,3 mg/km in the US06 test cycle. As the sampling during overtaking was made for a longer period than the actual overtaking to avoid problems with timing of the sampling, recalculation of the detection limits is not as straightforward as for the US06 cycle. Therefore, these levels have been omitted in **Table 9**. In general, the detection limit is higher in this test than in the US06.

As mentioned previously, only one car in **Table 9** had a higher level of acrylamide than the detection limit. As this level was only a factor of 2 higher than the detection limit, it is somewhat uncertain whether any acrylamide was emitted by this tested car either. An increased sampling volume in general and supplemental testing at low ambient conditions is recommended for future investigations in this area.

4.2.7 Particle number and particle size distribution

It is worth noting that all figures presented in this section use logarithmic scale on the y-axis and in some cases, on the x-axis as well (for particle size distribution). As the possible number of comparisons that could be shown is vast, some limitations have been made.

It should be noted that "total" number of particles refers to the particles that have been measured with the sampling, dilution and instrumentation used. It is possible that smaller particles than the smallest size that could be detected were emitted. It could also be possible that particles were generated (e.g. through nucleation during dilution) in the lab that are not generated in ambient air. This again, would lead to an overestimation of the particle number. The opposite is also possible, i.e. an increase in size of particles in the laboratory in contrast to nucleation in ambient air. It was not within the scope of the project to investigate the measurement methodology, since such work is currently going on in many laboratories around the world.

Total particle number

The "total particle number" per km was obtained by dividing the integrated total number of particles in the test cycle divided by the distance. In **Figure 30**, the total particle number in the NEDC cycle is shown for the two temperatures.

The impact of temperature (**Figure 30**) was different on the two petrol cars, i.e. an increase by reducing the temperature in one case and a decrease in the other case. The impact of temperature on the diesel car without particle filter was negligible, while the car with a particulate trap showed an increase (although the level was very low at both temperatures). The level for the petrol cars was roughly 2 orders of magnitude lower than for the diesel car without a particulate trap. These results are consistent with many other results in the public domain literature. The diesel car with a particulate filter had more than one order of magnitude lower particle emissions than its petrol counterpart. The difference compared to the diesel car without a filter was some 3 orders of magnitude, implying that the particulate filter had a dramatic impact on the particle number, as well as on the particulate mass.

In **Figure 31**, the total particle number in the US06 and overtaking tests are shown. Compared to the results in NEDC above (**Figure 30**), the results in this case were totally different.

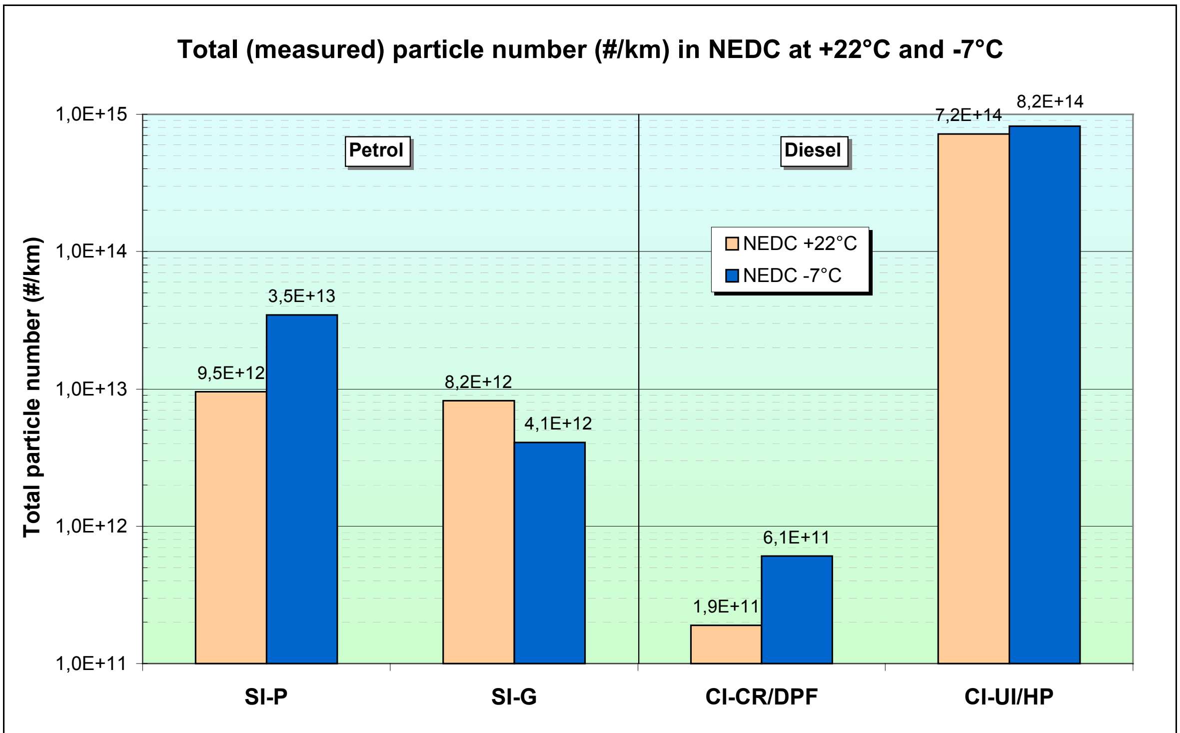


***Figure 30**. Total particle number emissions in the NEDC cycle*

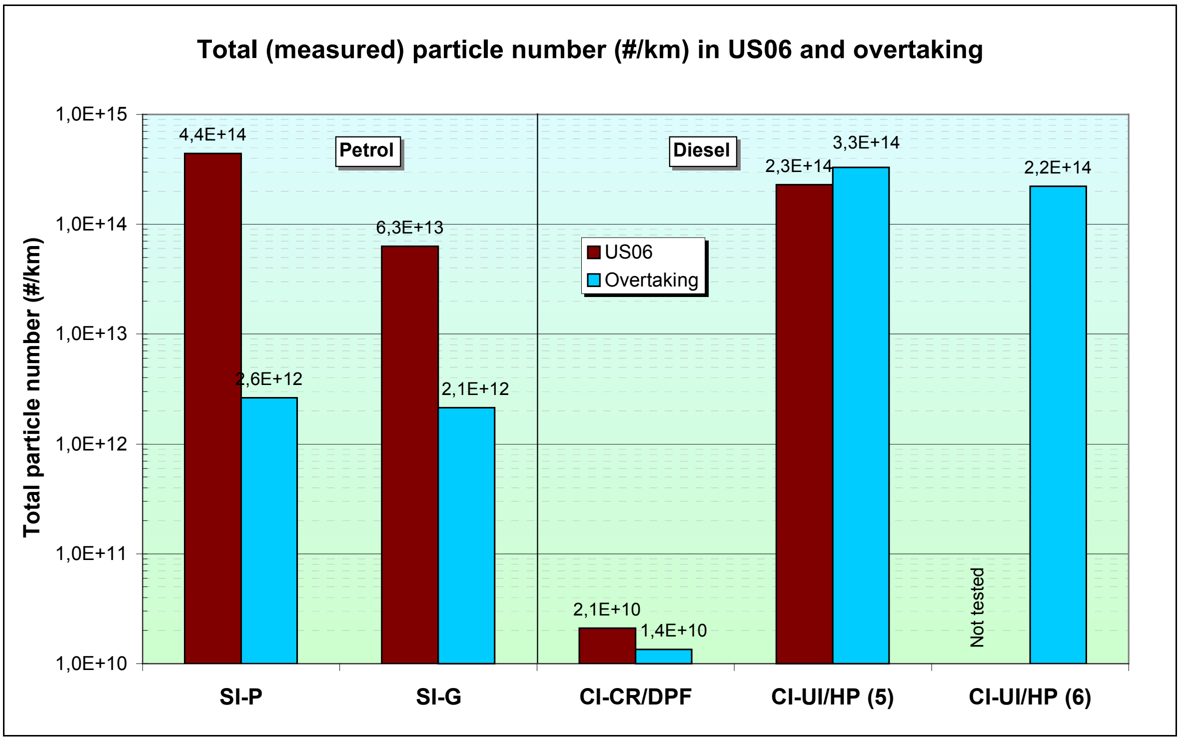


***Figure 31**. Total particle number emissions in the US06 and overtaking tests*

In US06, the particle number for the petrol cars increased substantially, i.e. approaching the level for the diesel car without a particulate trap in one case and reaching an even higher level in the other case (**Figure 31**). The level for the diesel car with the particulate filter decreased with one order of magnitude compared to the results in NEDC. Thus the relative advantage of this car compared to the other cars was more pronounced in this driving cycle than in the previous case.

The results in the overtaking test were obtained by integrating the total particle number from the start of the acceleration from 70 km/h until a stable steady-state level was obtained at 110 km/h. As it was found that this period was about 50 seconds for the petrol-fuelled cars, the distance corresponding to this period was chosen and then this distance was used for all cars. It should be noted that increasing the averaging period from about 20 seconds that the overtaking lasted to 50 seconds in this case could significantly change the results for some cars. For example, the petrol cars showed an increase in the particle number during acceleration but as the period for averaging is increased, the average level will decrease. However, it was considered that this methodology was more realistic than choosing a period too short for reaching a steady-state level at 110 km/h.

The particle number for the petrol cars was considerably lower during overtaking than in the US06 (**Figure 31**). The level was also lower than in the NEDC driving cycle. The diesel car without a particulate trap had about the same particle number during overtaking (in both 5^{th} and 6^{th} gear) as in US06 and the difference compared to the results in NEDC was also small. The diesel car with the particulate filter had a remarkably low level during overtaking as well as in the US06 driving cycle.

Real time particle number results

A unique feature of the ELPI instrument is its ability to measure particle number in real time for up to 12 size classes. Thus, the traces of the particle number for each of the 12 channels can be recorded and plotted to reveal interesting phenomena that are related to the operating conditions in the driving cycle. To limit the number of graphs, only the traces of the total number of particles has been shown here but it should be noted that the particle size distribution sometimes shift in real time.

In **Figure 32**, the results for the real time measurements in NEDC at +22°C are shown for the Peugeot cars. As can be seen in **Figure 32**, both cars had higher particle number emissions during the cold start phase of the cycle. It is also apparent that the petrol car had much higher spikes, i.e. up to two orders of magnitude higher than for the diesel car. The level of these spikes was much higher than at a steady state-speed of 70, which was recorded in the overtaking test. Consequently, this appears to be a transient effect. Whether the level is a "true" transient effect or simply the effect of some storage and release phenomenon (e.g. outgassing of stored volatile compounds) remains to be investigated. The high spikes for the petrol car appears to be the main reason for the significantly higher number of particles (i.e. more than one order of magnitude) averaged for the whole driving cycle, as shown in **Figure 30** above. Both cars have higher particle number at the high-speed portion at the end of the EUDC cycle.

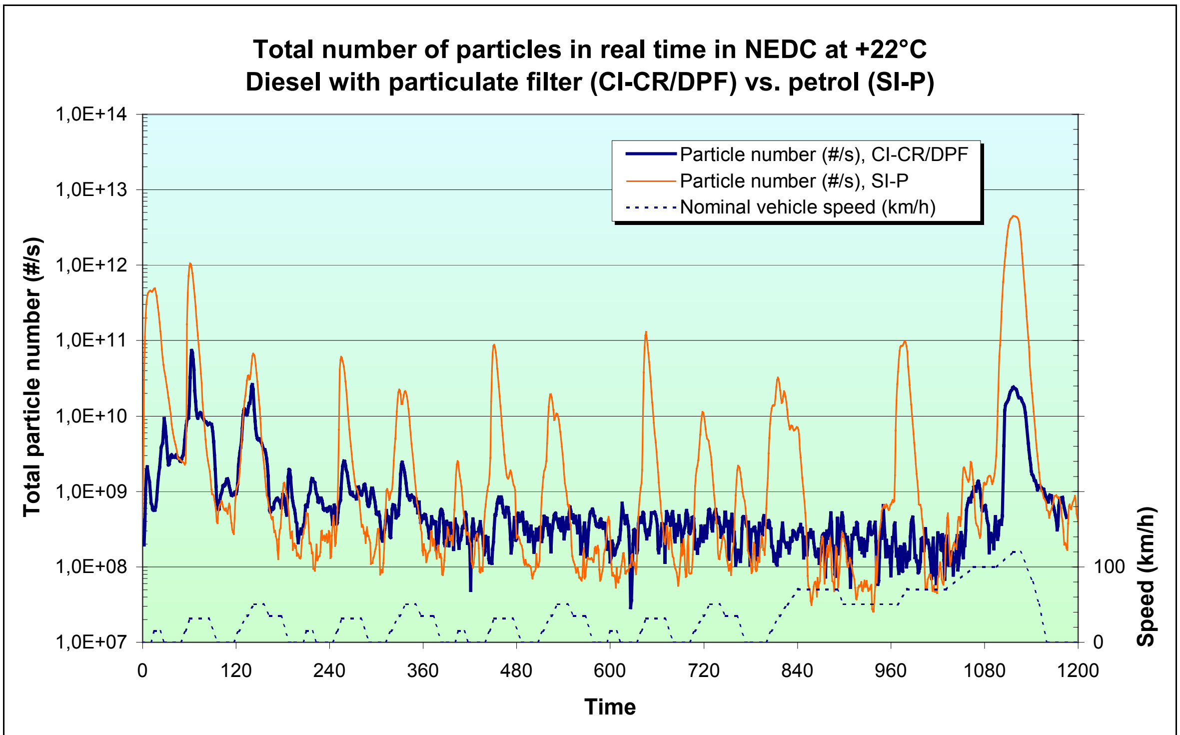


Figure 32. Real time particle number (#/s) traces in NEDC at +22°C, Peugeot

In **Figure 33**, the results for the real time measurements in NEDC at +22°C are shown for the VW Golf cars. In this case, the level for the diesel car was significantly higher than the level for the petrol car. It was only for a short period during the cold start phase of the cycle that the particle number for the petrol car was on an approximately equal level to the diesel car. In general, the variation was much greater for the petrol car, as could also be noted in the previous figure. The petrol car showed a notable impact of the cold start period (as for the previously discussed petrol car) but the diesel car remained more or less unaffected by the cold start.

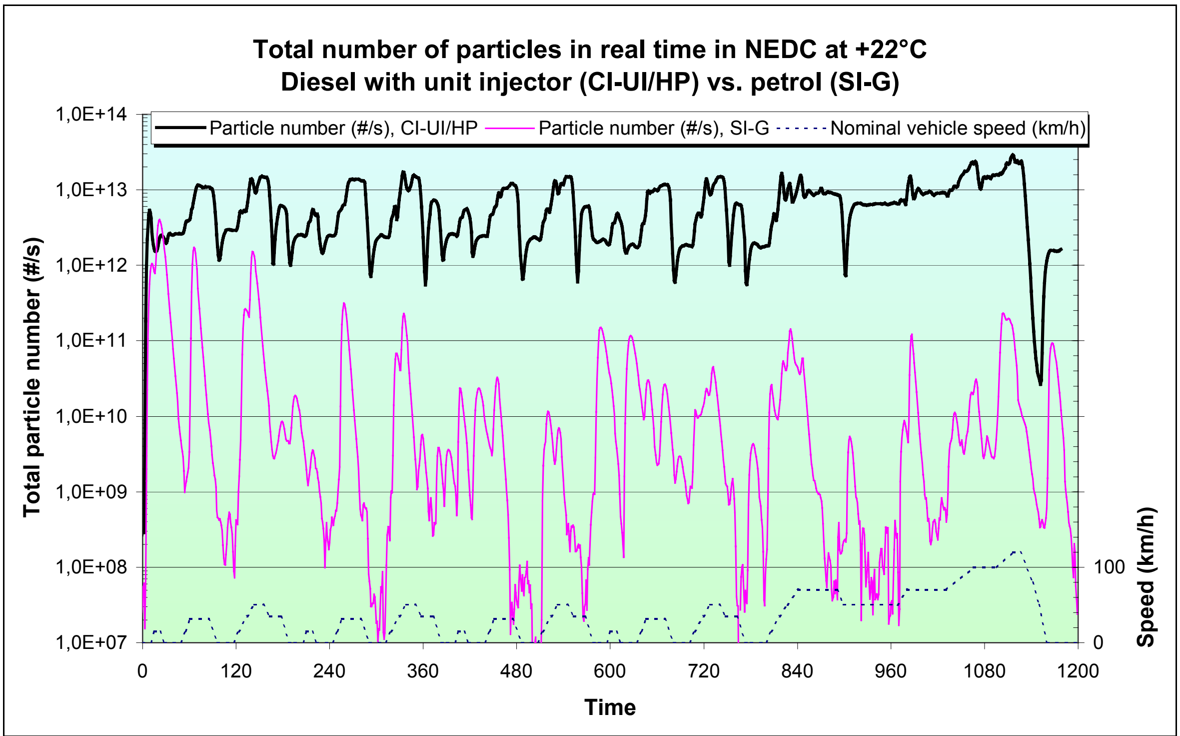


Figure 33. *Real time particle number (#/s) traces in NEDC at +22°C, VW Golf*

In **Figure 34**, the results for the real time measurements in US06 are shown for all the cars. In general, both diesel cars maintained a more stable level than the petrol cars, although the difference between these two cars was vast. The petrol cars showed a great variation that was following the pattern of the driving cycle during approximately 3 minutes in the beginning of the driving cycle. After this period, the level was increasing to reach (SI-P) or exceed (SI-G) the level of the diesel car without a particulate filter (CI-UI/HP). Apparently, the high-speed portion of the US06 increase the particle number significantly for the petrol cars. One petrol car (SI-P) remains on the high level of the diesel car without a particulate filter at the end of the cycle, whereas the other petrol car (SI-G) shows a decreased level.

Astonishingly, the diesel car with the particulate filter has low particle number emissions during the whole driving cycle in contrast to all the other cars. This indicates a high trapping efficiency of the filter and low sulphate formation. In the SAE Paper describing the development of the particulate filter system, Salvat et al. showed high particulate mass emissions at a steady-state speed of 120 km/h with high sulphur fuel (500 ppm), indicating that sulphate was formed [5]. The mass emissions and number of particles was significantly reduced with low-sulphur fuels (10 & 50 ppm). Evidently, the low-sulphur Swedish EC1 diesel fuel used in this test does not contribute significantly to the formation of particles at the high-speed part of the US06 driving cycle, as no increase in total number can be seen. As previously discussed, the particulate mass emissions were also very low in the US06 driving cycle.

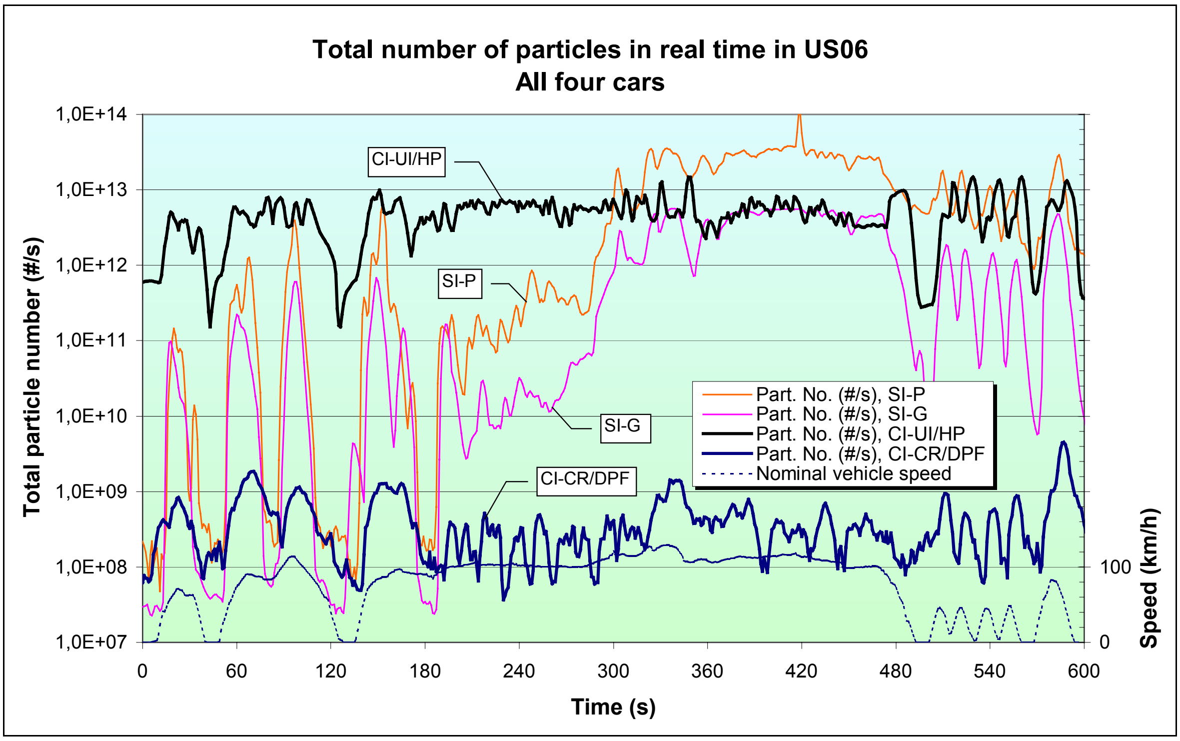


Figure 34*. Real time particle number (#/s) traces in US06, all cars*

In **Figure 35**, the results for the real time measurements in the overtaking test are shown for the all cars.

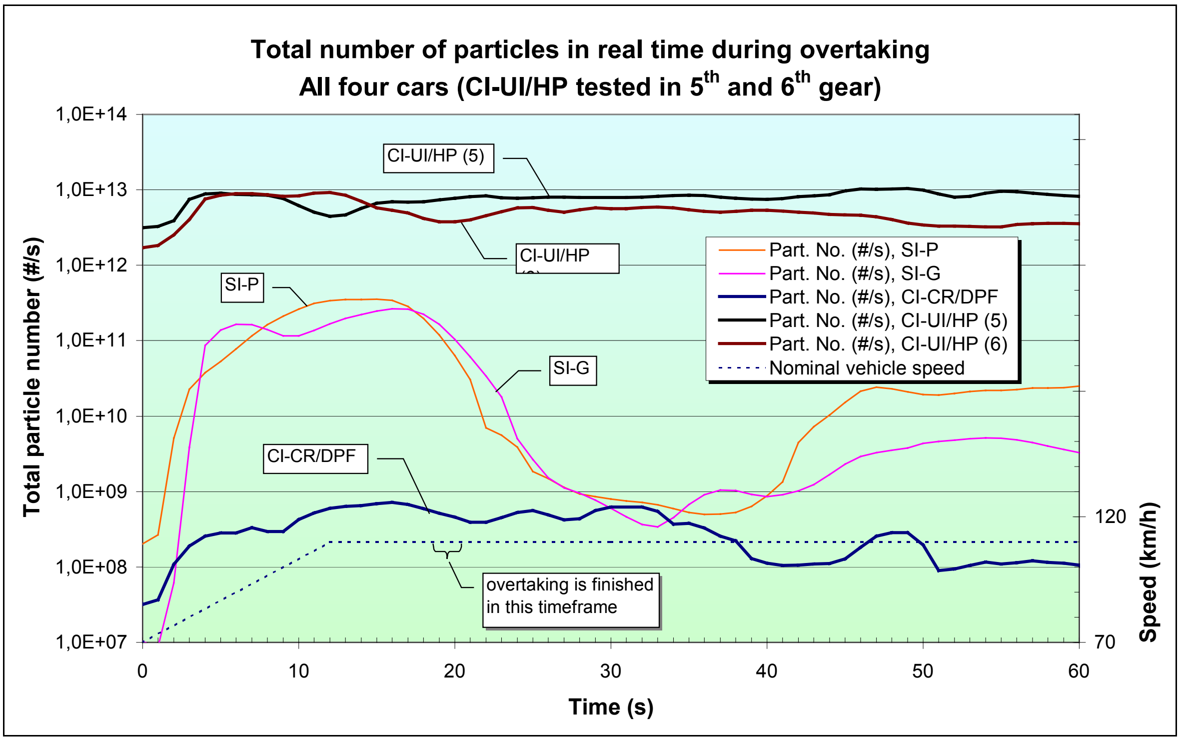


Figure 35*. Real time particle number (#/s) traces during overtaking*

As in the previous case (**Figure 34**), the diesel cars in **Figure 35** showed relatively small variation during the whole test. The peak in particle number during acceleration was 3 to 4 orders of magnitude higher for the petrol cars compared to the steady-state level at 70 km/h. The difference between this peak and the steady-state level at 110 km/h was smaller but still, it was one or almost two orders of magnitude. As for the previous results, the impact of the particulate filter was great.

Comparison of total particle number with other studies

As petrol-fuelled cars previously tested at MTC have showed great variation of particle number in the NEDC cycle, it can be concluded that the level presented here for the two petrol cars is in line with the previous findings. This is on the condition that the upgrading of the ELPI instrument used in this study (by adding an absolute filter as the smallest channel) is considered.

A report by Färnlund et al. presented and discussed results from measurements on 45 light-duty vehicles performed at the emission laboratory of Rototest [47]. The fuel, engine and aftertreatment technology studied were:

- Cars with DI turbocharged diesel engines (without particulate filter)
- One car with a particulate filter (Peugeot 607 HDi)
- Cars with naturally aspirated (NA) SI petrol engines
- Cars with turbocharged SI engines
- Cars with direct injected SI petrol engines.

An ELPI instrument of the same type as in this study (including the smallest filter stage) was also used by Rototest. However, the Rototest chassis dynamometer is of the steady-state type compared to a conventional chassis dynamometer that can handle transients (vehicle inertia simulation). Thus, the particle number was measured at 18 different engine-operating points; some of these were at full load. Weighting of the generated test data can "simulate" various driving cycles (albeit without transient effects).

The authors concluded that the number of particles for petrol engines tended to increase as the air/fuel ratio decreased below stoichiometric condition (λ<1). An increase with higher specific torque was also seen. An example was that, at full load, a naturally aspirated SI engine could produce the same amount of particles during 0,16 seconds as during one minute at 90 km/h. The corresponding factor would be 375, i.e. roughly in line with the increase seen in this study for the peak in the acceleration test compared to the steady-state speed of 70 km/h. The factor in this study was lower when the comparison is made between the peak and a steady-state speed of 90 km/h.

The report by Färnlund et al. also evaluated results for "moderate mixed" and "gentle mixed" driving styles. It is interesting to note that the total particle number for the car with a particulate filter was higher than for the NA SI cars for both evaluated driving styles. Similarly, the difference between this car and the diesel cars without a particulate filter was (only) about a factor of 5. According to the authors, regeneration of the filter was included in the results but no details on under which conditions this occurred and how this could have influenced the results was provided in the report.

The vast differences in testing conditions and tested vehicle types between this study and the study by Färnlund et al. makes a direct comparison of the results difficult. However, two general conclusions could be drawn. First, the particle number for petrol cars could increase significantly at higher loads (i.e. for more aggressive driving cycles, as well). This conclusion is confirmed in both studies. Second, the diesel car with particle filter tested in this study showed significantly greater reduction in particle number in relation to the diesel car without the particle filter than the corresponding comparison in the study by Färnlund et al.

Particle size distribution

Particle size distribution is shown as logarithmic "bar" diagrams where the number of particles has been divided by the width of the channel (i.e. dN/dlogDp is shown). Thus, the area under the "curve" is proportional to the total number of particles. This recalculation is particularly important for the updated ELPI instrument, since the width of the 1st channel is greater than for the other channels.

In **Figure 36**, the particle size distribution for the Peugeot cars in NEDC at an ambient temperature of +22°C is shown. By scrutinising the results in **Figure 36**, it is evident that the level for the diesel car with a particulate filter was about one order of magnitude lower than for its petrol counterpart except for the smallest particle size. The difference in the latter case was more than 3 orders of magnitude. Evidently, the particulate filter was effective in reducing the emissions of all sizes of particles.

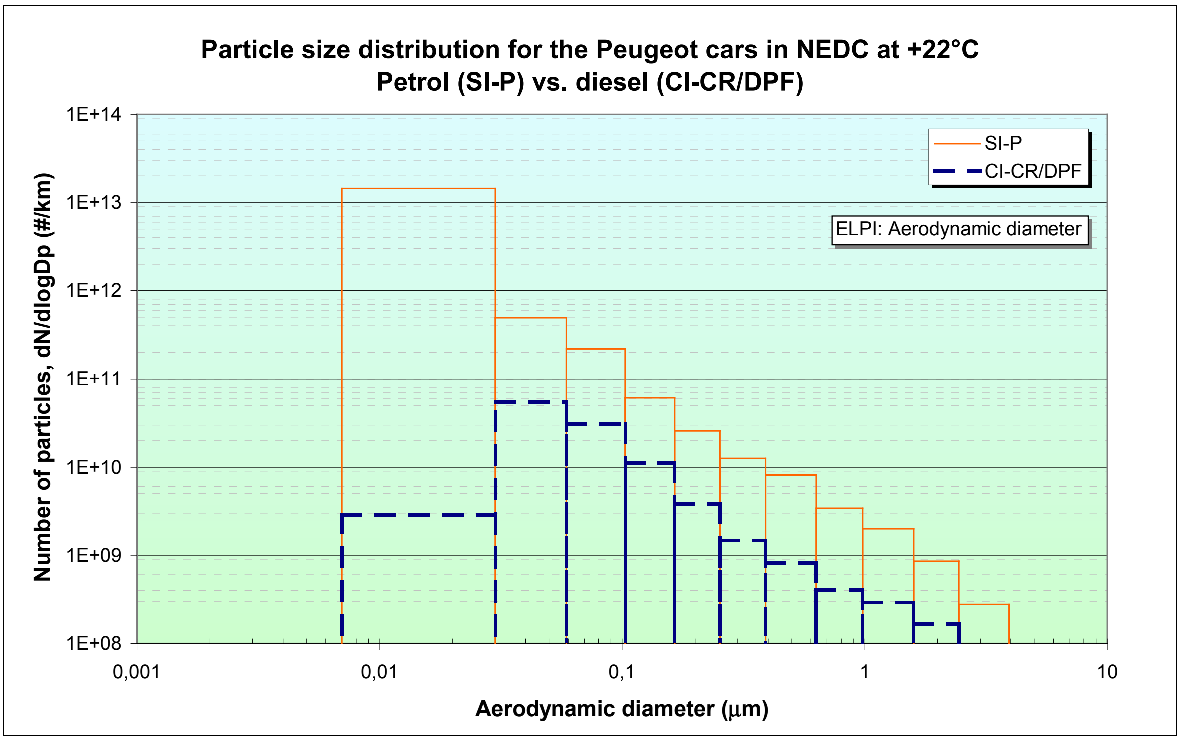


***Figure 36**. Particle size distribution in NEDC, Peugeot cars at +22°C*

The results in **Figure 37** at –7°C confirm the observation in **Figure 36** for the larger particles. However, the difference for the smallest size class was smaller at –7°C than at +22°C. The higher level of the smallest particles was the main reason for the increase in total number of particles by lowering the temperature, as previously shown in **Figure 30**. One possible reason for a higher level of the smallest particles for the diesel car with the particulate filter at –7°C compared to the level at +22°C could be an increase in the number of "wet" particles.

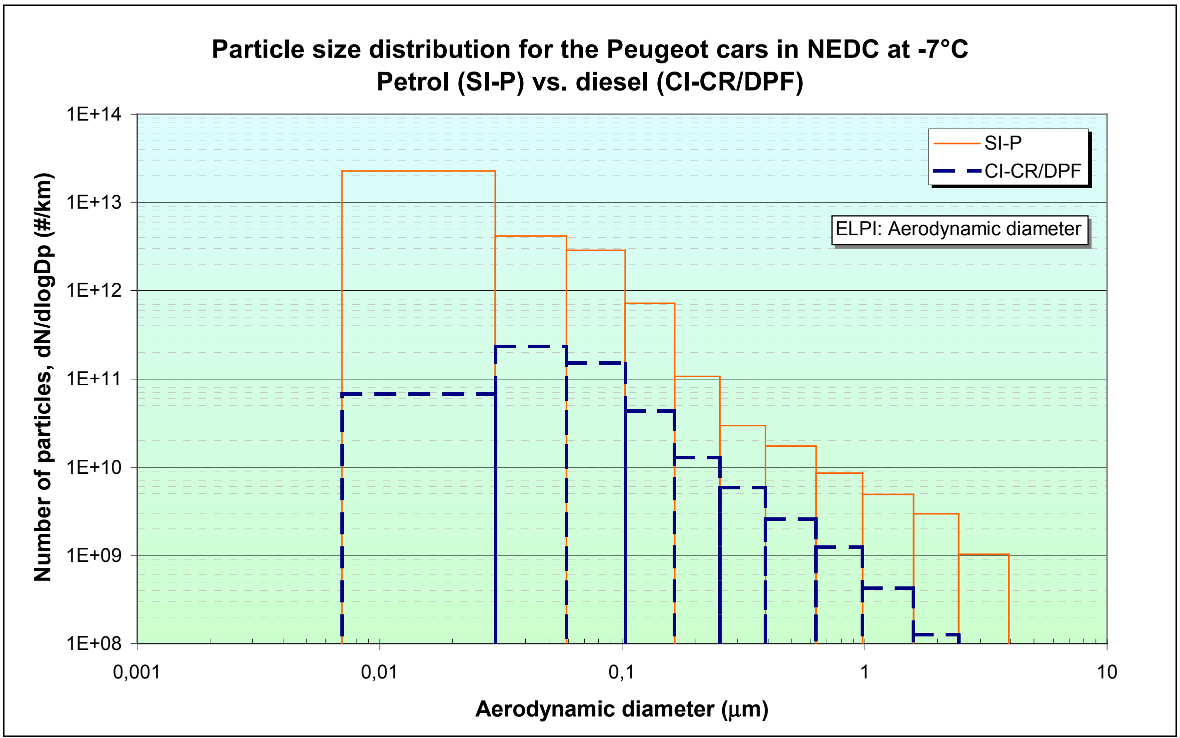


Figure 37. Particle size distribution in NEDC, Peugeot cars at -7°C

In **Figure 38**, the particle size distribution for the VW cars in NEDC at an ambient temperature of +22°C is shown. As indicated before, the diesel car had a significantly greater level. In this case, the difference in number of particles was relatively consistent for all sizes but the smallest, where the difference was smaller. However, the difference was nevertheless more than one order of magnitude.

The results in **Figure 39** at –7°C for the VW cars showed a considerable advantage for the petrol car compared to its diesel counterpart. The level at this temperature was relatively similar for the diesel car compared to the results at +22°C. The level for the petrol car at –7°C was increased in the size range between 25 nm to approximately 400 nm compared to the level at +22°C. However, the level for the smallest particles was lower at the lower temperature.

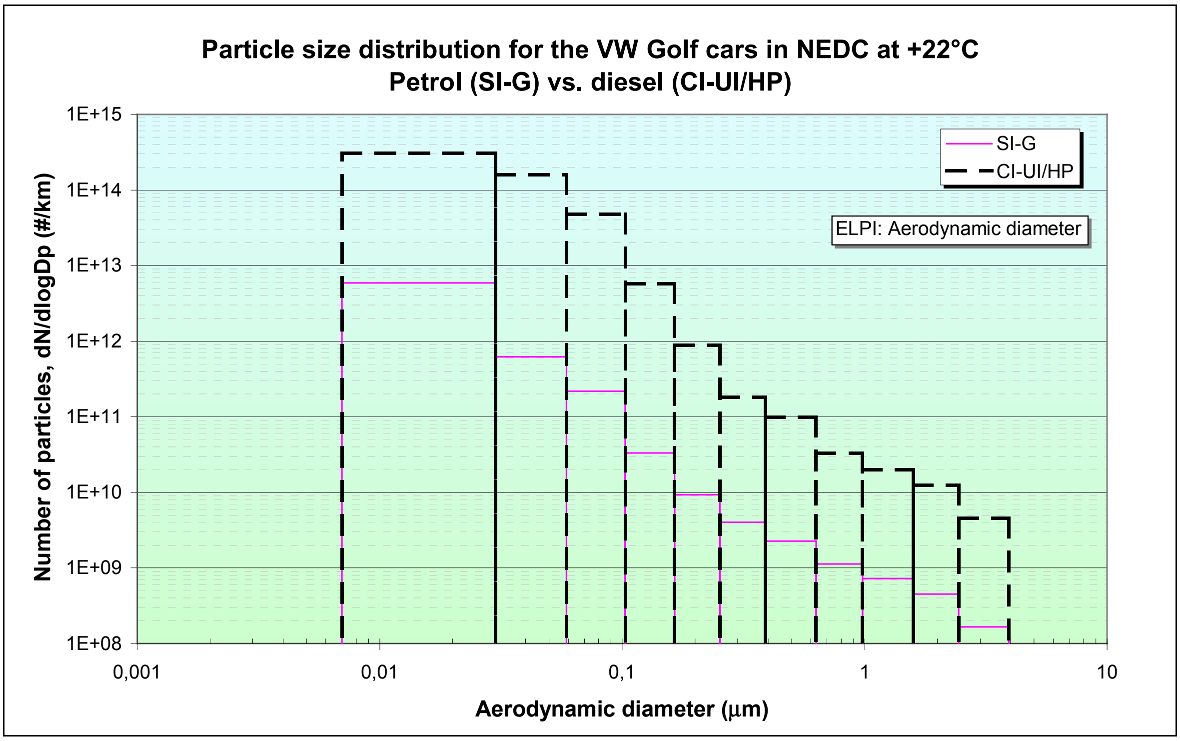


Figure 38. *Particle size distribution in NEDC, VW cars at +22°C*

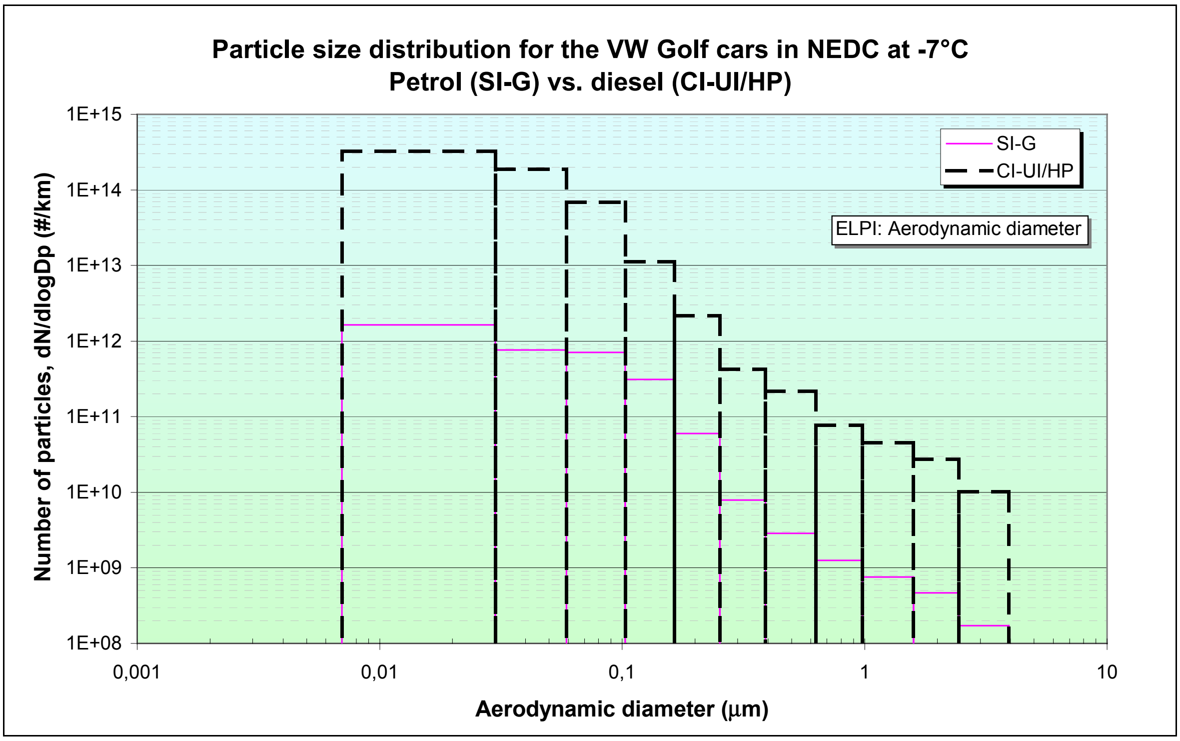


Figure 39. *Particle size distribution in NEDC, VW cars at -7°C*

In **Figure 40**, the particle size distribution in the US06 is shown for the Peugeot cars. As expected, the diesel car with particulate filter had lower particle number for all size classes in comparison to its petrol counterpart. However, the difference for the smallest size class was even greater than in NEDC (**Figure 36**).

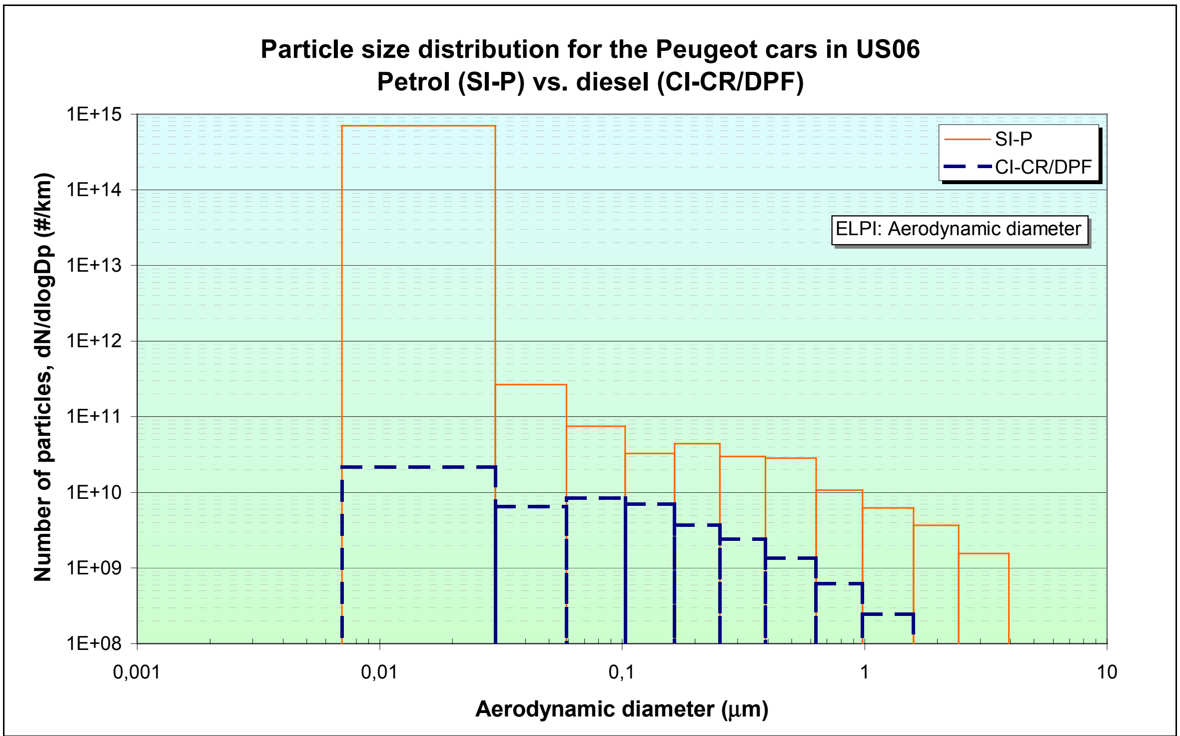


Figure 40. Particle size distribution in US06 for the Peugeot cars

In **Figure 41**, the particle size distribution in the US06 is shown for the VW Golf cars. As in the NEDC case, the petrol car had significantly lower number of particles for all classes larger than the smallest size class. However, the difference for the smallest class was relatively small. Hence, it can also be concluded that, for the petrol car, the higher level of the total number of particles in the US06 cycle (**Figure 34**) compared to NEDC was due to the significant increase of the smallest particles in the US06.

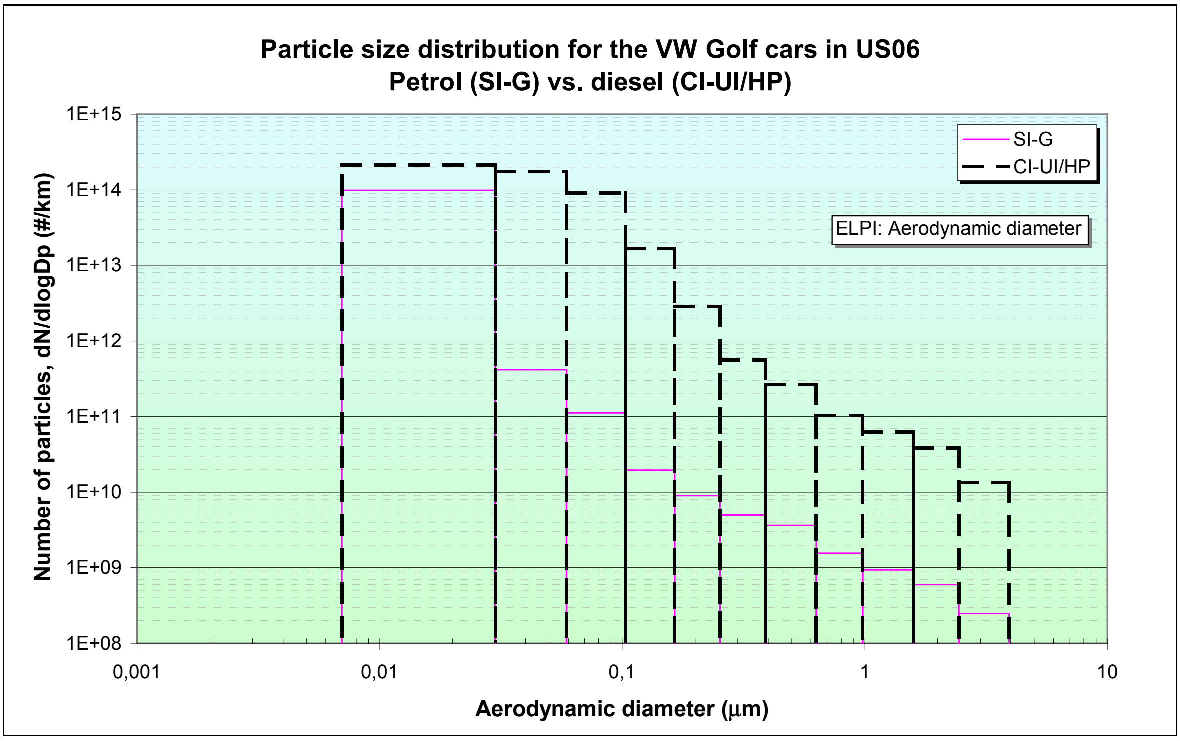


***Figure 41**. Particle size distribution in US06 for the VW Golf cars*

In **Figure 42**, the particle size distribution during overtaking is shown for the Peugeot cars. Contrary to the NEDC and US06 cycles, the difference for the larger size classes was smaller, although there was a noticeable difference. Again, there was a considerable difference for the smallest size. However, the relative difference was smaller than for the NEDC and US06 cycles.

In **Figure 43**, the particle size distribution during overtaking is shown for the VW Golf cars, where the diesel car was tested in 5^{h} gear. The results for the 6th gear are not shown as they were very similar to the results in 5th gear. In **Figure 43**, the petrol car had a clear advantage for all size classes. The difference was two orders of magnitude (smallest size) or greater (all other sizes).

Ecotraffic's comments

Particle size measurements

Comparing data on particle size distribution generated at MTC with data from other laboratories often show a shift towards very small particles in the MTC case. The apparent difference could be due to the instrument used (ELPI vs. SMPS) or the sampling system. The "best" measurement principle and methodology in this respect has not yet been found. However, results on particle size distribution must treated with care, due to the lack of general understanding of all the phenomena in this area.

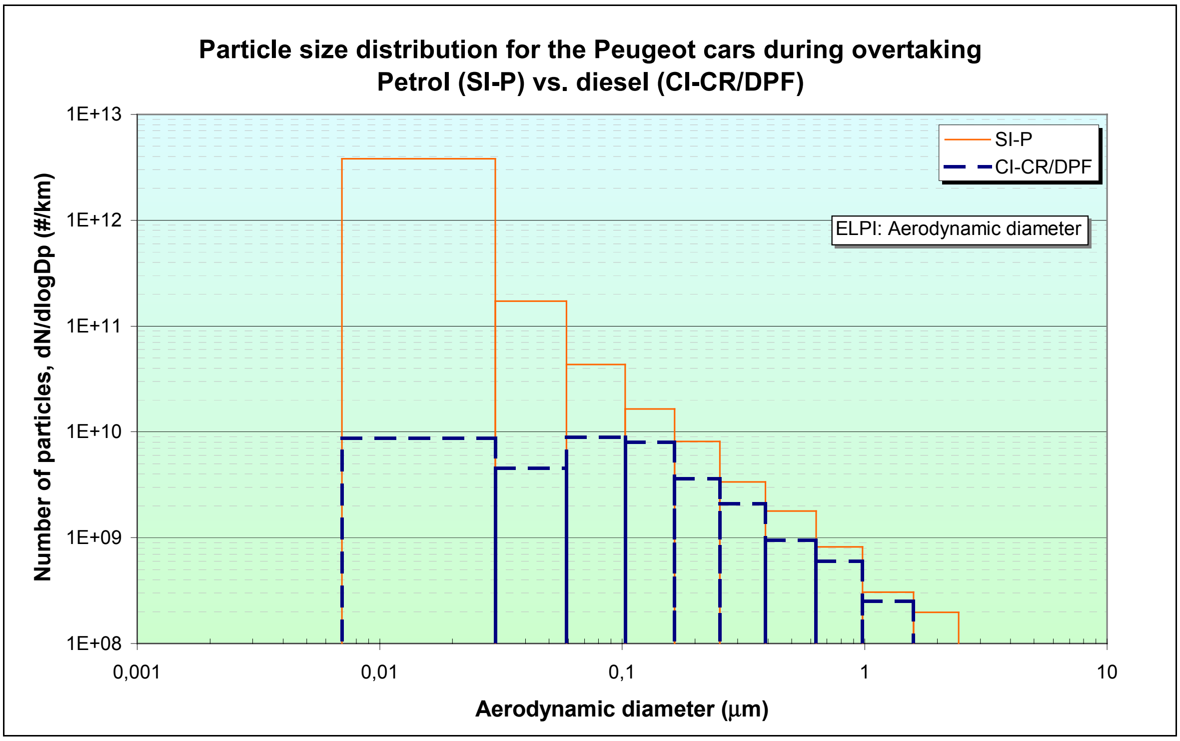


Figure 42. *Particle size distribution during overtaking for the Peugeot cars*

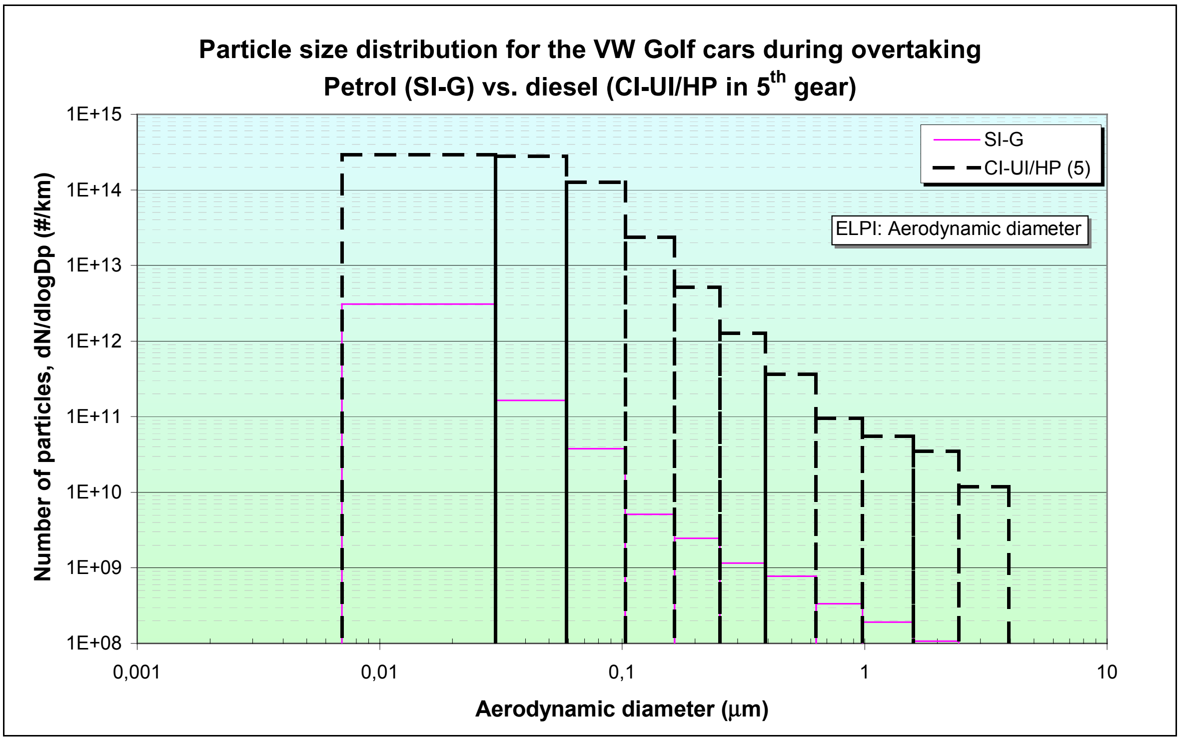


Figure 43. *Particle size distribution during overtaking for the VW Golf cars (VW Golf diesel tested in 6th gear)*

Impact of high-pressure direct injection on particle size and number

It has been more or less accepted by the public opinion that *new* diesel cars emit smaller particles and greater number of particles than *old* diesel cars. Thus, the health impact of new diesel cars could be even greater than from old cars provided that smaller particles pose a greater health hazard than larger. However, there is very little evidence in support of this hypothesis in the open literature. In a previous study by this author, 2 IDI and 3 DI cars were studied [4]. It was found that the car with *DI engines did not emit more particles than the cars with IDI engines*. Instead, there was a trend to an opposite result, although the difference was small. Neither did the DI engines emit larger number of small particles. However, the tested DI engines in that study had rotary pumps that could not provide the high injection pressure of modern injection systems. The particulate mass emissions were also on a roughly similar level. Therefore, the question about the impact of high-pressure injection is still valid.

In a study commissioned by the engine manufactures association ACEA, a number of petrol and diesel-fuelled cars were tested [48]. In this case, DI diesel cars with high-pressure injection could be compared to older cars. Again, the results did not support the hypothesis about higher particle number and smaller size for the modern cars. Other researchers have also reported similar results.

An example can illustrate the difference between a car with an older IDI engine and a car with a modern engine with high-pressure injection. Data from the car with the IDI engine were obtained from a study on particulate size measurements the author participated in [49]. These data were compared with the data generated in this study. To ensure that the comparison was made correct, the number of channels in the ELPI instrument included in the evaluation was reduced for the data in this study to correspond to the previous study (8 channels). Likewise, the absolute filter was not included. The results for the total number of particles are shown in **Figure 44**. *The new Golf with the DI engine had about 40% lower number of particles.* Although this difference was too small to draw any firm conclusions, there is not much support for the hypothesis of an increased number of particles for new diesel cars, either.

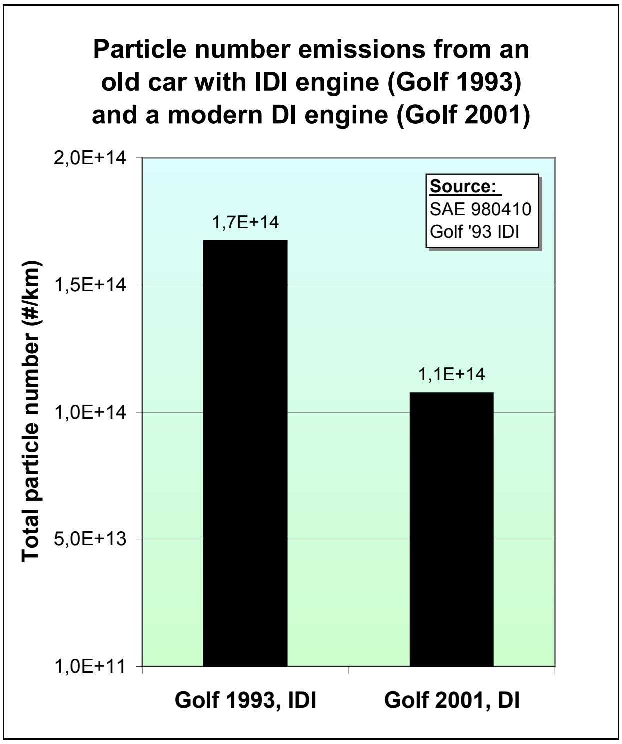


***Figure 44**. Total particle number emissions for IDI and DI engines (VW Golf)*

The total particle number traces for the two cars mentioned above are shown in **Figure 45** (shown in a different scale than previous figures to highlight differences).

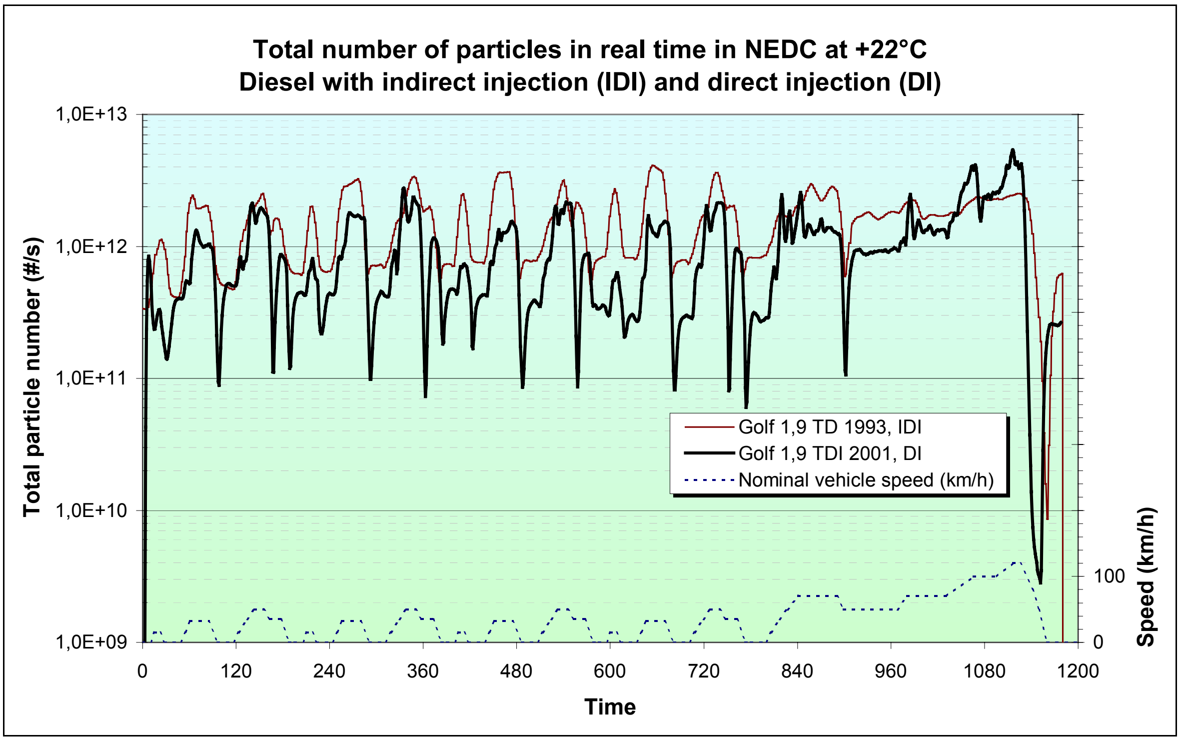


Figure 45. Total number of particles (#/s), VW Golf TD (IDI) vs. VW Golf TDI (DI)

Scrutinising the data in **Figure 45** reveals that the level was lower for the new Golf for most of the time, although there were cases where the spikes were higher (e.g. at highest speed in the EUDC phase). Another interesting observation is that the downward spikes for the new car were significantly deeper than for the old car. This could be due to differences in the sampling system that might smooth the trace but there are also other possible explanations. The cause could be differences in the fuel cut-off during decelerations. Some evidence to confirm this hypothesis could be the great drop in number of particles at the end of the EUDC phase. This is a section of the cycle where the brakes are applied for a long period, hence it is plausible that fuel cut-off is also used for a longer period.

Measurements with the SMPS instrument

The measurements with the SMPS instrument were most likely incorrect in some way. For certain periods of the cycle, zero levels were measured. This problem occurred for all cars to a certain extent but for the diesel car with a particulate trap, only a few measurement points showed any results at all. One could argue that the level could have been below the detection limit in this case, as the level for the lowest channel in the ELPI measurements also showed low levels. The objection against that hypothesis for the other cars is that the results on these cars also showed missing values close to the peaks. This is illustrated in **Figure 46** showing real time measurements in the NEDC cycle at +22°C. Note that the y-axis show the results divided by the width of the channel (a value of 0,044) in contrast to previous figures. An enlargement of the measurements in **Figure 47** for the first 5 minutes provides a more detailed view of the problem.

As can be seen for some of the curves in both figures mentioned above, specifically for the diesel without a particulate filter, missing values also occur at higher levels of particle number. Therefore, the results from the SMPS measurements may result in considerable errors in evaluations for the whole test cycle.

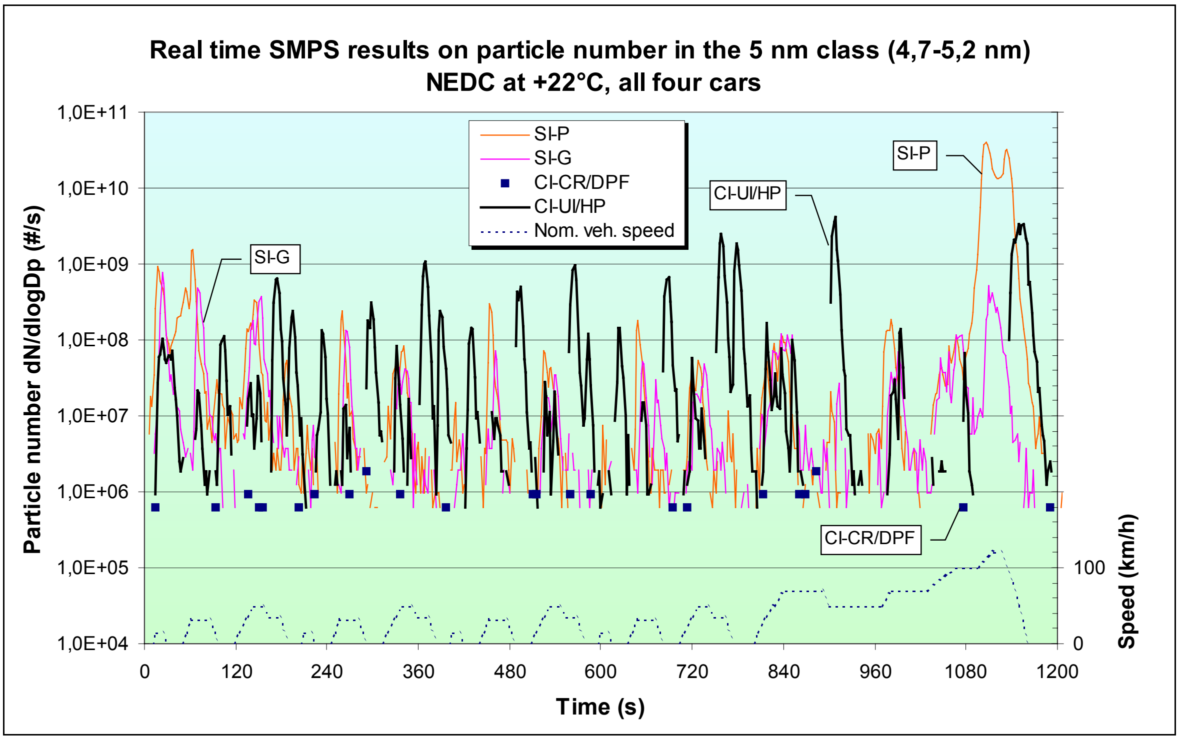


Figure 46. Real time SMPS results in NEDC on 5 nm particles (#/s)

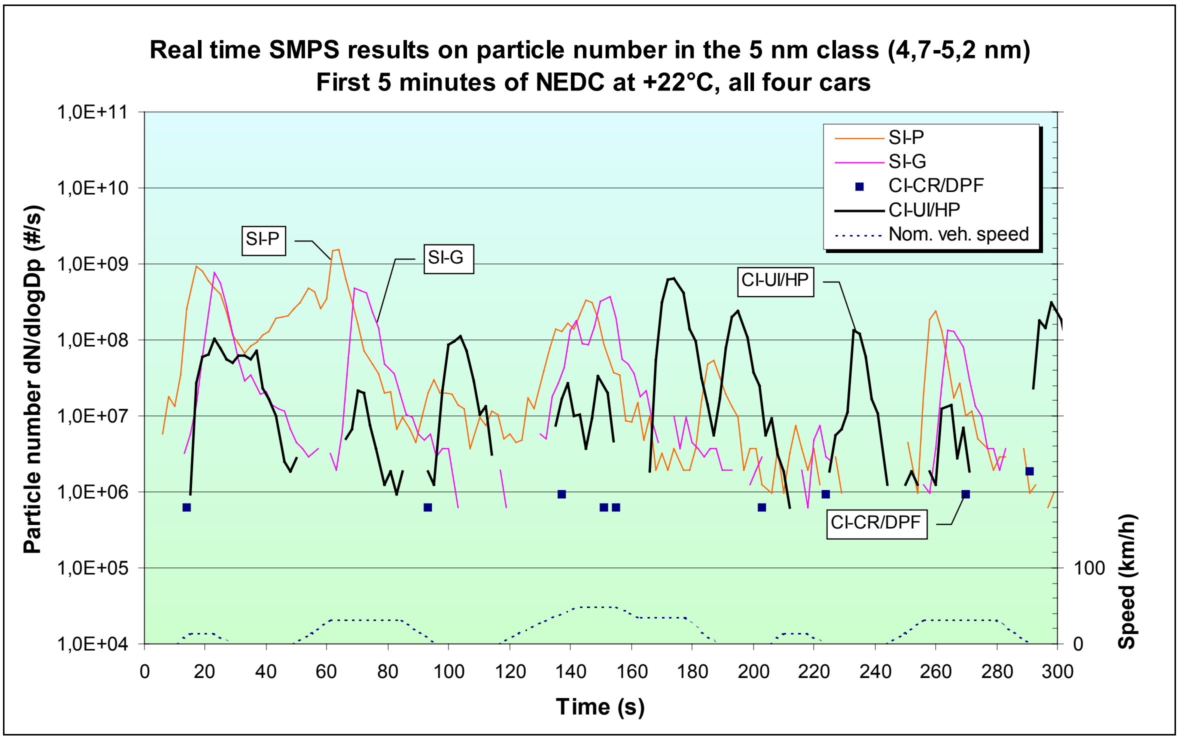


Figure 47. Real time SMPS results for the first 5 minutes of NEDC on 5 nm particles (#/s)

An attempt to evaluate the number of particles in the cycle was made by averaging the values that were not zero and multiplying this value with the length of the cycle. This gives the results in **Figure 48**. As can be seen the diesel car with a particulate filter had the lowest level but on the other hand, only a few measurement points were recorded on this car. The petrol cars show somewhat lower (SI-G) or significantly higher (SI-P) levels than the diesel car without a particulate filter. However, as mentioned above, the results from the SMPS measurements may not be reliable. Therefore, the results from the other tests with the SMPS instrument are not reported here.

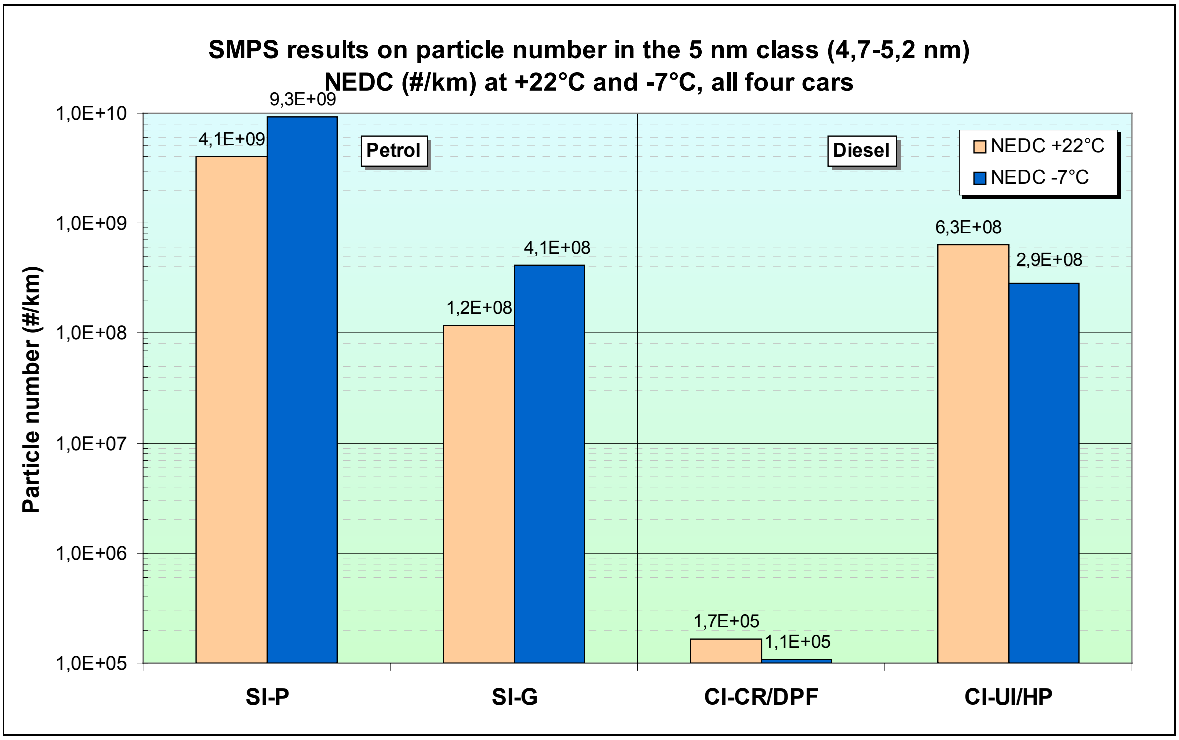


***Figure 48**. SMPS results on 5 nm particles in NEDC (#/km)*

4.3 Impact on environment and health

As mentioned before, the evaluation of the impact on environment and health include the results on older cars (model year 1993/1994) generated in a study mentioned before [1]. Although the Swedish emission regulation at that time corresponded to previous regulations in the USA and in California, one can say that the emission level of these cars roughly corresponded to Euro 1.

Showing the old data provide some perspective to the results generated in this study. However, there are some important comments that should be made. The previous study took driving pattern, ageing (emission deterioration) and climate into consideration. Driving pattern is not an issue, as the NEDC cycle is used extensively for the evaluation in this study as well. Climate is also taken into consideration, as the same average temperature (+7°C) is used in all cases. However, one should note that no correction for the ageing is made for the new cars evaluated in this study. The emission level for the old cars had been corrected to an average odometer reading of 80 000 km. Therefore, the improvement shown here is probably an overestimation. One should also note that only two cars running on each fuel has been tested in this study. Consequently, these cars cannot be considered representative for the whole population of new cars.

4.3.1 Local effects, acute respiratory diseases

Ozone (O_3) formation potential

As mentioned before, the ozone formation potential was calculated by using HC emission data interpolated to +14°C and applying reactivity adjustment factors for each fuel. To reflect the improvement of the new fuel qualities, the results for the old cars was recalculated as well. The results for the ozone forming potential are shown in **Figure 49**.

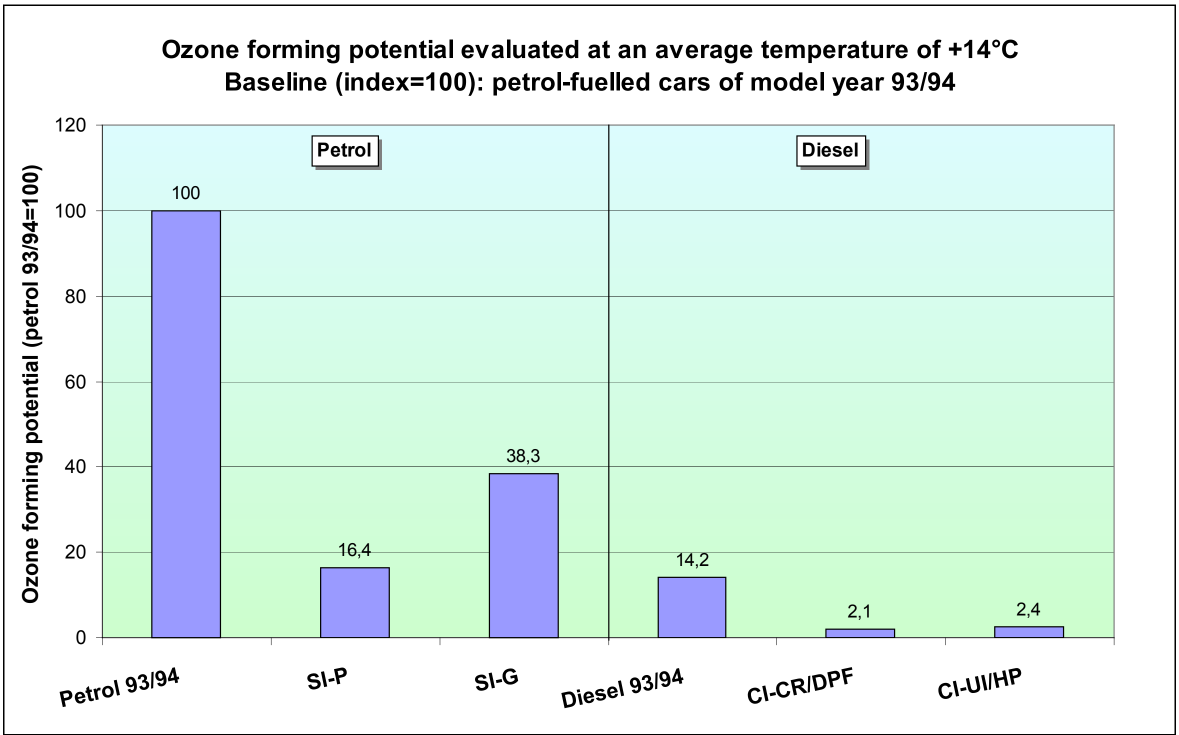


***Figure 49**. Ozone forming potential*

Due to the significantly lower HC emissions from the diesel cars, the ozone forming potential, as shown in **Figure 49**, was generally significantly lower for this category of vehicles compared to the petrol cars. This is valid regardless whether new or old cars are compared. However, one should also note that the improvement for the new petrol cars was vast for both fuel categories. Comparing the ozone forming potential averaged for the for the new petrol cars with the average for the new diesel cars, yields a difference of more than one order of magnitude.

Note that the evaporative emissions from the vehicles were not included in the evaluation of the ozone forming potential, neither was this done for the evaporation losses from fuel distribution and refuelling. As these emissions were higher for petrol cars, the ozone formation from these cars is underestimated.

There is some concern about the validity of the RAF values used in the evaluation and new data on this issue might slightly change the results. It is also important to note that the evaporative emissions from the vehicles, or from fuel distribution and refuelling has *not* been included in the analysis. Should this be taken into account, the *relative* “disadvantage” for the petrol cars would increase substantially[21].

Nitrogen dioxide (NO_2) forming potential

As mentioned before, the total NO_X emissions (calculated as NO_2) were compared as the *potential* for NO_2 formation. Therefore, the results and comments are similar to the results in **Figure 9**, except that the results have been evaluated for +7°C in this case. To simplify the presentation, an index has been shown. As the NO_X emissions have been commented before, only a few notes are added here.

It can be seen in **Figure 9** that the improvement of NO_X emissions for the petrol cars since 1993/1994 has been considerable. The improvement for the diesel cars was less, both in relative and absolute numbers. As mentioned before, the higher NO_X emissions at –7°C compared to +22°C for the new diesel cars is a contributing factor to that the reduction has not been as great as expected. In the future, a significant reduction of the NO_X emissions from diesel cars will be necessary. As the aftertreatment devices used on diesel cars today has very little impact on the NO_X emissions, a NO_X reducing catalyst could reduce the level significantly. With a conversion efficiency of 90%, a similar level to the results on the petrol cars could be achieved[22]. Such devices are currently being developed.

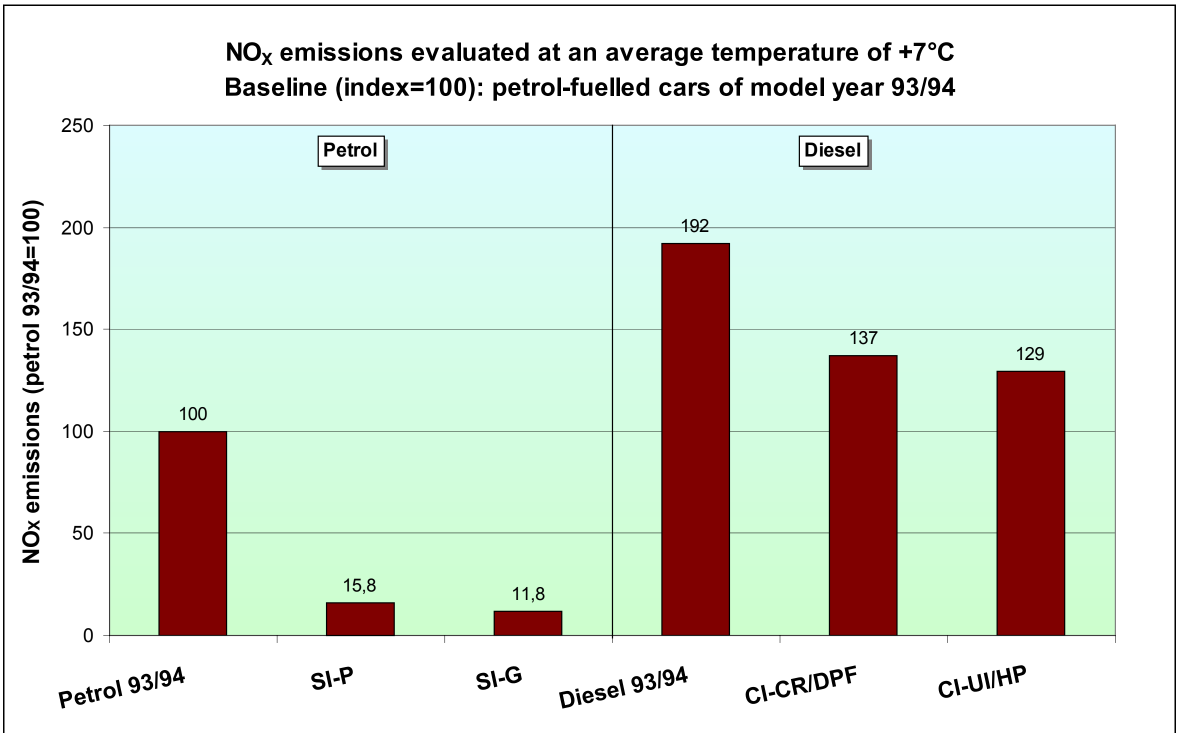


***Figure 50**. Local NO_X emissions*

[21] Note that the evaporative emissions from diesel cars and from the fuel distribution of diesel fuel are negligible.

[22] Reducing the engine-out NO_X emission level by 50% (to Euro IV) would require “only” 80% reduction efficiency of the catalyst to achieve similar results as in the example showed.

Organic gases

As the emissions of various organic gases were discussed extensively in the section on unregulated emissions (section 4.2), no further comments are added here. It can only be concluded that the level on the new cars tested in this study was far lower than for the older cars.

Particulate emissions

The improvement on particulate emissions for new cars was significant for both types of fuels. The results in **Figure 51** illustrate this development. Probably the most surprising result was the improvement by a factor of 5 to 10 for the new petrol cars compared to the old cars. It is likely that some 50% or so of this improvement would due to an improved fuel quality. The particulate level for the diesel car without a particulate filter has been improved by more than a factor of 3 during the same timeframe. However, the level was still about 2 times higher than for the old petrol car. Bearing in mind that the particulate emissions for diesel cars without particulate traps with an emission level below Euro IV[23] will be reduced by another factor of 2, this level would be comparable to MY'93/94 petrol cars. However, the particulate emissions from the new petrol cars were on a significantly lower level. Again, it should be noted that the particulate level on the diesel car with a particulate filter was very low. Compared to the 93/94 petrol cars, the level was about a factor of 50 lower (i.e. 98% less). The comparison with the petrol counterpart of this car and the other petrol car gives factors of 5 and 10.

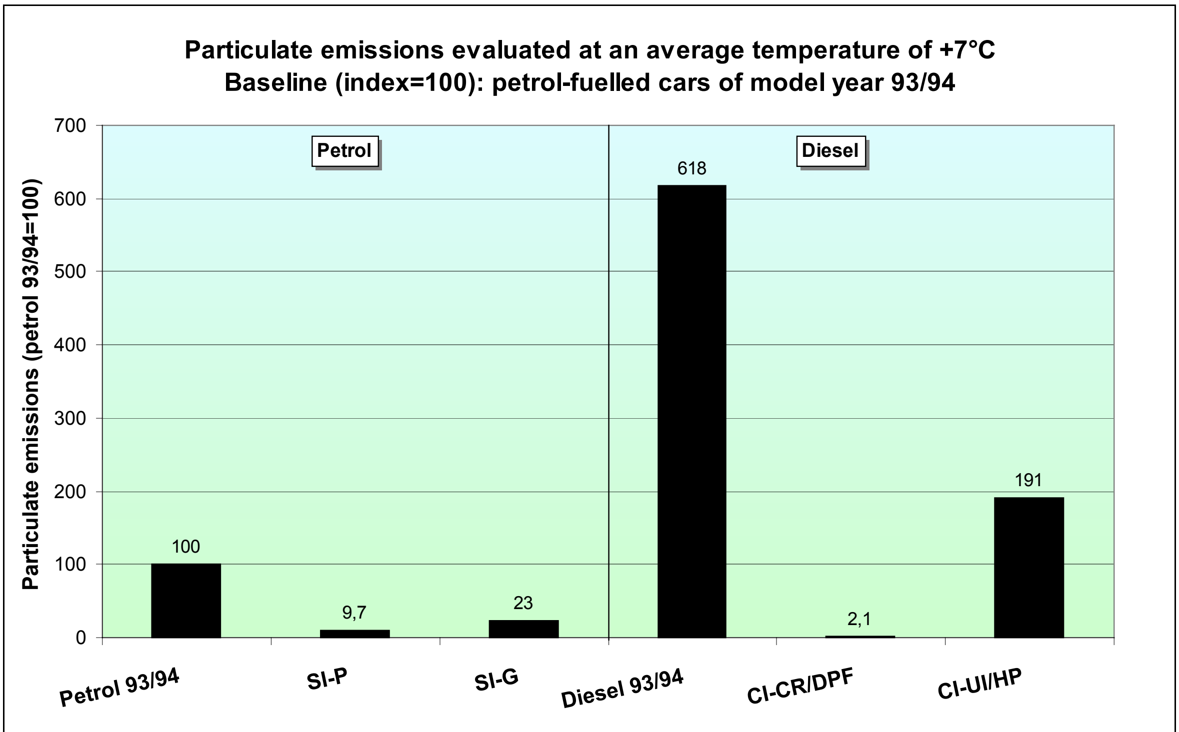


***Figure 51**. Local particulate emissions*

[23] As mentioned before, the VW group has already started the production of cars with this technology in high numbers. Other manufacturers will follow this example.

4.3.2 Local effects, cancer risk

The results on the cancer risk index are probably the most interesting results. However, the uncertainty about the results is also greatest for this effect. In particular, the values for the unit risk factors is an area of concern but also the measurement of some of the unregulated emission components is a difficult task. Therefore, results should differ by at least a factor of 2 or more to be considered as a real difference.

In **Figure 52**, the cancer risk index is shown. To simplify the presentation, the alkenes and aldehydes are grouped together.

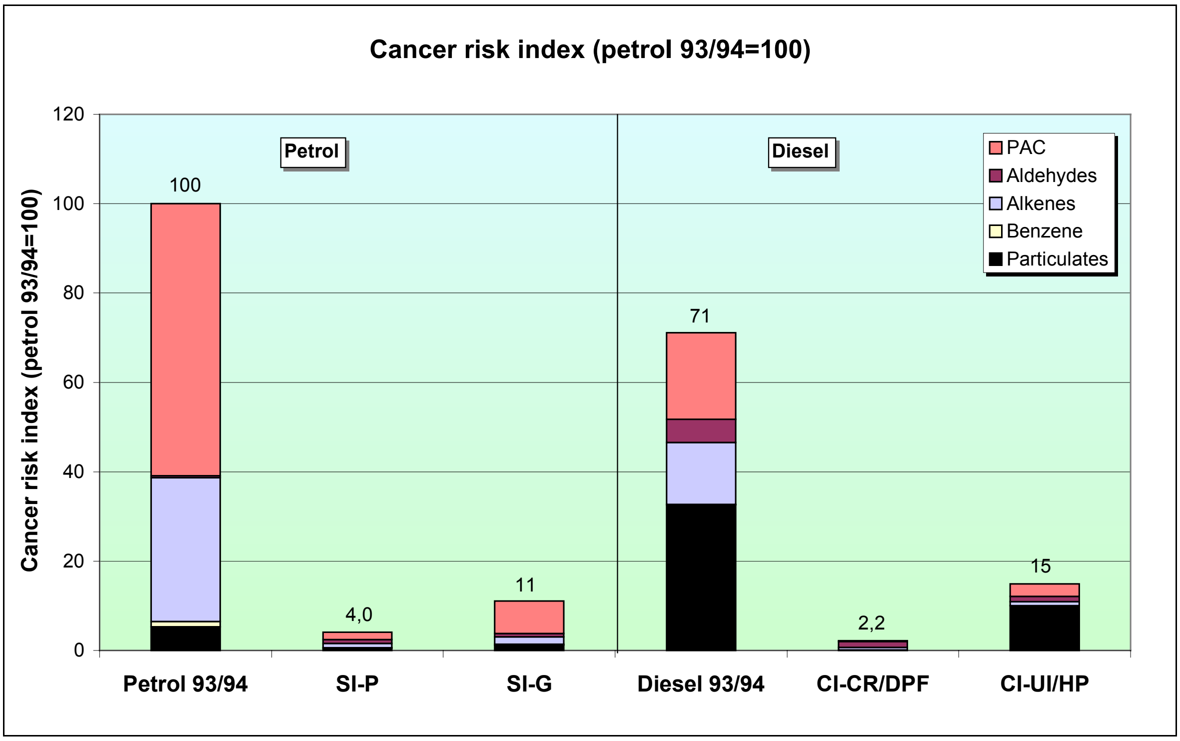


Figure 52. Cancer risk index

For the 93/94 cars, there was a difference between petrol and diesel cars, but as the difference was only about 30%, it should not be considered as significant (**Figure 52**). However, these results were considered somewhat sensational when the report previously cited was published[24] [1]. The projections in the report for 2000 (Euro III) and 2010 showed an approximately similar level for petrol and diesel cars, but of course, a substantial improvement with new technology in both cases. It should be noted that the recent improvement of fuel qualities for petrol and diesel fuel was not taken into consideration in the evaluation of the 1993/1994 cars. As the data for making corrections to consider the fuel improvements is somewhat limited, it was decided to keep the old data unchanged. This would also better illustrate the *total* improvement over time (by both fuel and engine technology).

[24] Emission data for making this kind of analysis had been more or less available already 5 – 10 years earlier. A set of unit risk factors had also been established by Swedish researchers. However, an analysis of this kind had not been carried out before using all the available data and making the necessary corrections of the emission factors.

As can be seen in **Figure 52**, the improvement for the new petrol cars was substantial. All emission components were reduced but the reduction of PAC and alkenes (primarily 1,3-butadiene is most striking. The improvement made on the diesel cars was substantial as well. The particulate emissions still make a great contribution for the diesel car without a particulate trap. On the contrary, the reduction of the volatile compounds is considerable. The almost complete removal of the particulate matter and PAC on the diesel car with a particulate filter is remarkable. The level for the cancer risk index for this car compared to petrol cars of MY'93/94, being almost 98% lower, is also impressive.

As the reduction of the cancer risk index for the new cars was so great, it is of interest to show these cars in a diagram having a different scale and to provide some further comments. These results are shown in **Figure 53**.

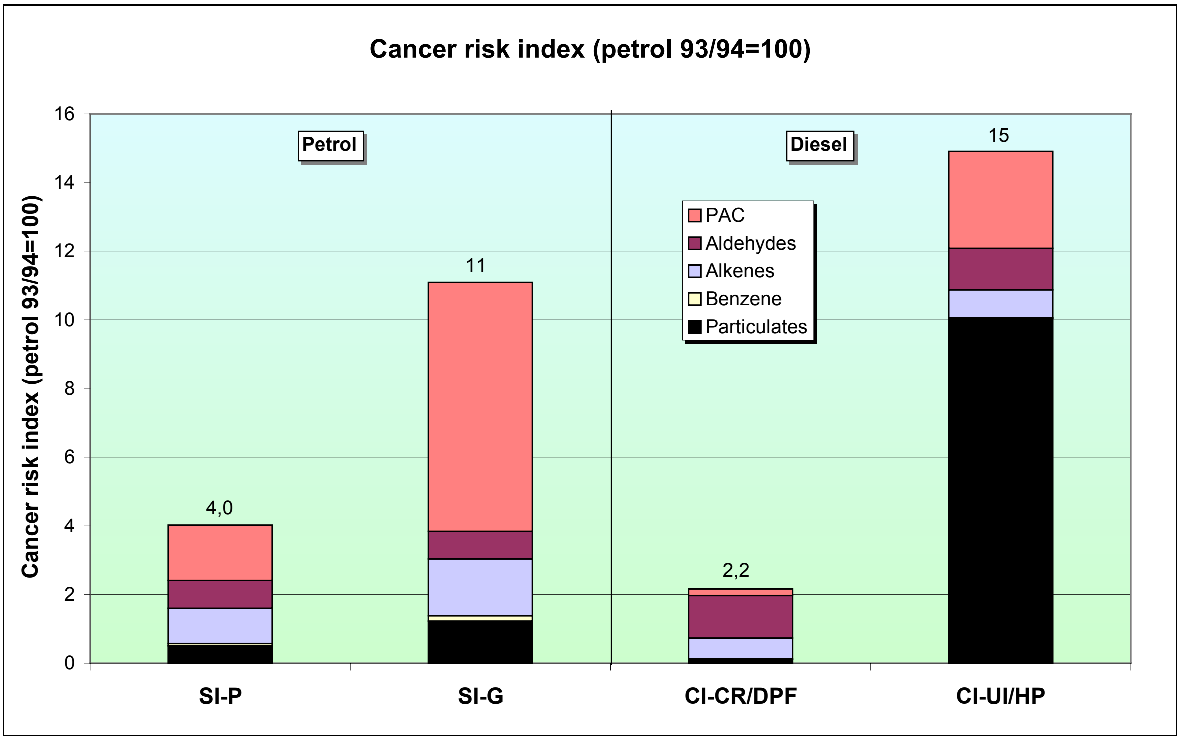


Figure 53. Cancer risk index

For one of the petrol cars in **Figure 53**, the contribution from PAC was still substantial. As shown before, PAC emissions for this car was dominated by the contribution from the emissions at the low ambient temperature. PAC was also responsible for a great contribution for the other petrol car and for the diesel car without a particulate trap. Since only 12 compounds of PAC were measured in this study, a correction was used to obtain comparable results with older data. As mentioned in a previous section, the correction for the petrol cars was derived from the petrol car with the lowest emissions tested in a report by Almén et al [11]. The corresponding correction for the diesel cars was derived from the diesel car tested in the same study. The factors obtained were 1,17 for the petrol cars and 1,33 for the diesel cars. It should be noted that these factors were applied only for the evaluation of the cancer risk index; the data on PAC shown before did not include any corrections.

The aldehyde level was on or below the detection limit at +22°C for all cars but one, where the level was right on the limit. A level corresponding to the detection limit was set for the cars that had a level below the detection limit. This could lead to an overestimation of the contribution from the aldehydes in these cases but it was motivated by the "precautionary principle". Both diesel cars had a level 2 times higher than the detection limit at –7°C and this level was used in the calculations. Note that the unit risk factor (URF) used for formaldehyde (the greatest contributor of the aldehydes) was relatively high, e.g. 10 times higher than in the previously cited EPA evaluation. Using a significantly lower URF would also reduce the importance of formaldehyde in this respect.

As the emissions of 1,3-butadiene were higher for petrol cars than for diesel cars, this is also shown in the greater total contribution from the alkenes. Anyway, the contribution from the alkenes was totally dominated by 1,3-butadiene for all vehicles.

Benzene has very little impact on the cancer risk in this evaluation. However, one should note that as the evaporative emissions are not included in the results, the contribution from benzene would be significantly greater if this had been taken into account as well. Note that the contribution from benzene for the MY'93/94 petrol cars in **Figure 52** was also small. Recent measurements of ambient air quality in Sweden show that the level of benzene is still relatively high, and in many cases, it is higher than the future limits for ambient air quality in the EU. There are many other sources to benzene in ambient air than catalyst cars (e.g. wood burning and cars w/o catalyst). However, in view of the apparent improvement by the introduction of catalysts, it is still puzzling to find that the reduction of the ambient level of benzene progress at such slow speed.

The contribution to the cancer risk index from particulate matter was discussed above but the picture is even more clear in **Figure 53**. It should be noted that only the total particle mass has been taken into account. Whether the particle size distribution has any impact on cancer risk is yet somewhat unclear. The other issue to take into account is the relation between volatile and solid particles.

4.3.3 Regional effects

Acidification

The evaluation of acidification in this study comprises NO_X, SO_X and NH_3. Data for fuel production have been obtained from "Life of fuels" a previous lifecycle analysis carried out by Ecotraffic [15]. This study contained no data on emissions of NH_3 from fuel production but the levels that could be expected are very low. A recalculation of the results for the old cars have been carried out to take into account that the sulphur level in both fuel types has been reduced. A level of 4 ppm (limit: <10ppm) for diesel fuel and a level of 30 ppm (limit: 50 ppm) for petrol was anticipated to be representative levels for commercial fuels. In both cases, the sulphur level was so low that the contribution to the acidification from fuel sulphur was negligible.

In **Figure 54**, the results on acidification potential have been shown. The results are divided into the stages *fuel production* (including distribution and refuelling) and the end use in the *vehicle*.

The results in **Figure 54**, show that the level for acidification from diesel cars in general was considerably higher than from petrol cars. The new diesel cars were about equal to the old petrol cars in this respect. The relatively high level for the diesel cars was mainly due to the high NO_X levels from the vehicles. The contribution from fuel production was greater for petrol in comparison to diesel fuel. Diesel cars have lower fuel consumption and the production of diesel fuel generates less NO_X and SO_X per unit of energy in the fuel than the production of petrol does. Hence, the contribution from fuel production was also lower in the diesel case.

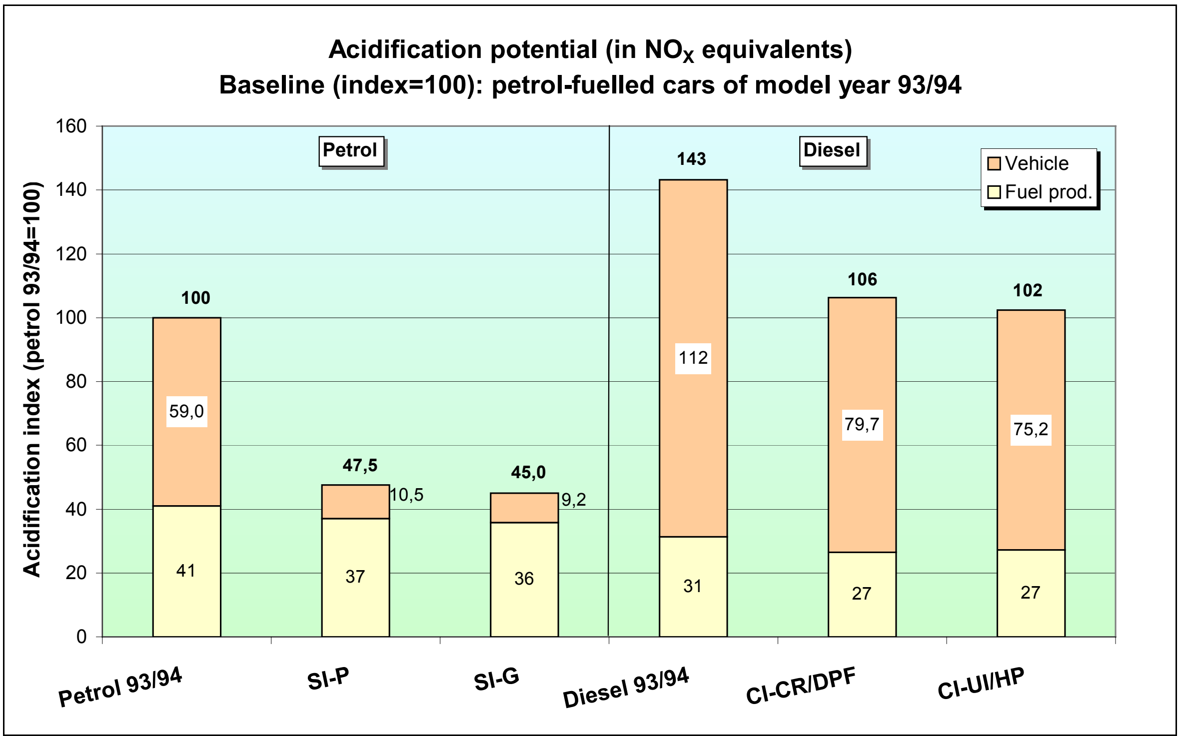


Figure 54. Acidification potential

The reduction in NO_X emissions, as seen in previous results, can be noted in **Figure 54** as well, since the contribution from SO_X and NH_3 from the vehicles was negligible. Due to the significant reduction of NO_X emissions from the petrol cars, the acidification was dominated by the emissions from fuel production. It could be noted that the level for fuel production in modern plants probably would be somewhat lower than in the Life of Fuels report, since this report is 10 years old. Anyway, the necessity of reducing the NO_X and SO_X emissions from fuel production as well as from the vehicles is evident.

Eutrophication

As noted before, the emissions of ammonia (NH_3) were very low for all cars in this study. A similar conclusion can be made for the N_2O emissions. Therefore, NO_X emissions are the main source of nitrogen containing compounds in the exhaust from these vehicles. As mentioned before, NH_3 emissions were not included in the calculation of effects on the old cars. Consequently, a slight underestimation might be the case for the old petrol cars, as the NH_3 emissions would probably not have been negligible in this case. It should also be noted that the nitrogen counting compounds do not behave in a similar manner in the atmosphere. NO_X and NH_3 are deposited relatively fast, in contrast to N_2O that has lasts in the atmosphere for well over hundred years. Therefore, only NO_X and NH_3 have been taken into account in calculating the eutrophication potential.

The results for the eutrophication potential are shown in **Figure 55**. The results on eutrophication are showing a somewhat similar trend to the results on acidification above

(**Figure 54**), except that the contribution from fuel production was smaller. Again, the improvement for the petrol cars was vast and the impact of fuel production was more prominent for the new cars tested in this study. The main drawback of high NO_X emissions from diesel engines is evident in this case as well. It should be noted that the contribution from new light-duty vehicles to eutrophication is relatively small in general, compared to other major sources (e.g. agriculture).

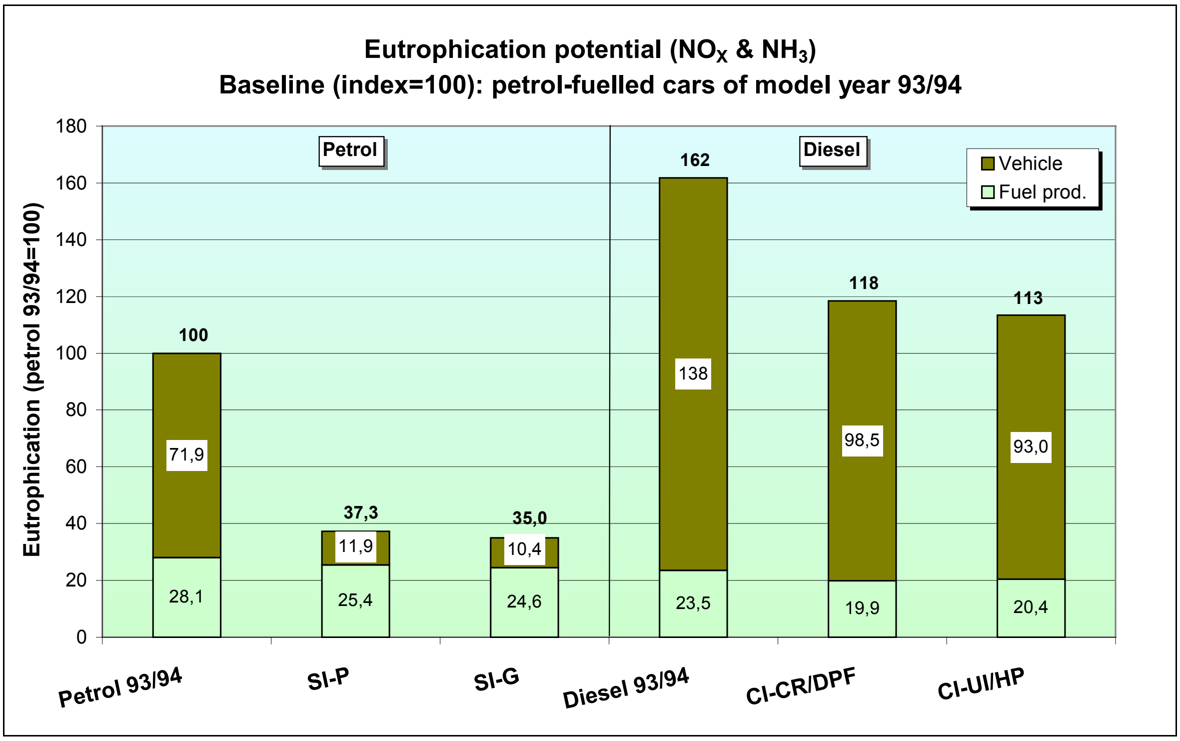


Figure 55. *Eutrophication potential*

4.3.4 Global effects

When the impact on climate change and energy use are discussed, one should note that only 4 cars were tested in this study. Of course, these cars cannot represent the whole population of new cars. Therefore, only general conclusions can be made regarding the impact on climate change and energy use. Statistics on CO_2 emissions from new cars is provided on a yearly basis by the EU and the vehicle manufacturers of Europe (ACEA), Japan (JAMA) and Korea (KAMA).

Climate change

The impact from transportation on climate change is probably one of the most difficult problems to solve. Initiatives to produce new fuels from renewable sources in larger scale are one route that will be investigated in more detail in the future. Increasing the energy efficiency and limiting transportation in general are also two possible measures. As the latter option could have a great impact on economy, renewable fuels and efficiency improvements remain the preferred solutions. Increasing the efficiency is equally important for renewable fuels, as well as for fossil fuels, since fossil fuels are to be substituted by renewable fuels (i.e. an increased efficiency increases the substitution rate). The diesel engine, being the most efficient of all combustion engines and, in the long-term future, fuel cells are the most interesting options for efficient energy converters in passenger cars.

In **Figure 56**, the emissions of greenhouse gases are shown. The contribution is shown separately for fuel production and end use in the vehicles. As expected, the level for the greenhouse gases was considerably lower for the diesel cars than for their petrol counterparts. This is partly due to the lower fuel consumption in the vehicle but the diesel fuel production is also more efficient than the production of petrol.

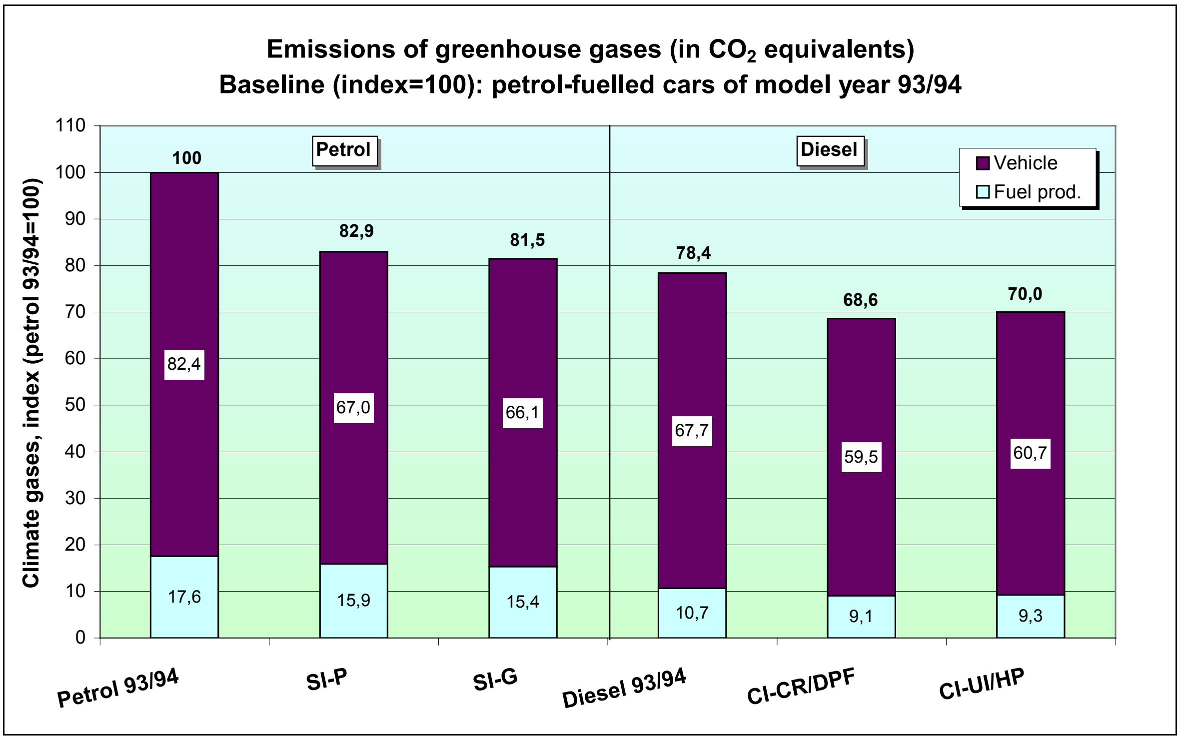


Figure 56*. Emissions of greenhouse gases*

It should be noted that Swedish EC1 diesel fuel has been used in the calculations. Presumably, contemporary European diesel fuel specification could yield somewhat better results for the fuel production. On the other hand, the European diesel fuel must be improved in the future and this would reduce the efficiency to a similar level as for the EC1 fuel. As the petrol fuel specification used did not correspond to future petrol fuel quality, one could expect that this would lead to a slight underestimation in the petrol case. On the other hand, improvements in the production processes imply that the efficiency might not differ too much in the future after all. It should be noted that the improvement for the cars tested here compared to the old cars is partly due to that former category of cars were somewhat smaller than the average old Swedish cars.

Resource use

The results on energy use in the whole fuel chain showed in **Figure 57** complete the presentation of the global effects. As expected, the results in this figure do not differ too much from the previous results on climate gases. In general, other climate gases than CO_2 from the newer vehicles are reduced compared to the older vehicles and therefore, the relative difference was greater for climate gases than for energy use.

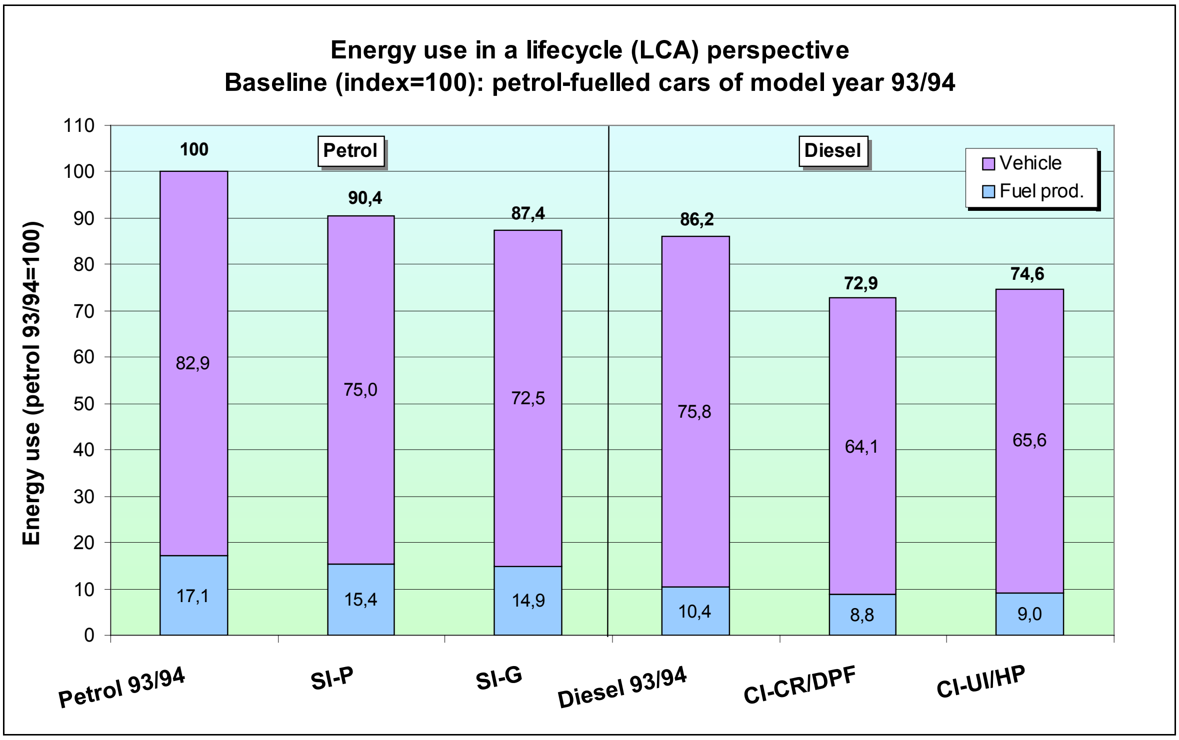


Figure 57. Energy use

5 DISCUSSION AND CONCLUSIONS

The introduction of new emission control technology has decreased the emissions from petrol-fuelled passenger cars during the past decade. Since the introduction of the three-way catalyst (TWC) emission control system, subsequent improvements of this technology has decreased the emissions even further. In view of this progress, the emissions from diesel cars have received more attention from government authorities and environmental groups. However, the increase in emissions at low ambient temperatures from petrol cars still have not completely been solved, although this is often forgotten as emission tests are usually carried out in the +20°C to +30°C temperature interval. In the cold Nordic climate, low ambient temperatures must be considered. Eventually, the two petrol cars tested in this study showed a considerable improvement at such temperatures compared to older cars.

Although the emissions from diesel-fuelled cars have decreased considerably during the last decade, the general perception has been that these cars emit significantly higher quantities of harmful emissions compared to their petrol counterparts. The results in this study showed that several unregulated emission components from diesel cars are on the same level as from petrol cars, and in some cases, lower. Two major problems remain – NO_X and particulate emissions. Today, there is no equivalent technology to the TWC for diesel cars for reducing NO_X emissions but such aftertreatment is currently in development. Emerging particulate filter technology has been commercially introduced by PSA and other car manufacturers will follow this path.

The calculation of the impact on health and environment from exhaust emissions provide a better insight than only showing the results on the emission components. However, it should be noted that in some cases, the input data for these calculations (e.g. cancer risk) is not fully developed yet.

The number of cars in this study was too few to allow generalisation of the results for all cars. The selection of cars was made on the condition that the impact of new technology could be compared with previously generated results on older cars. The following main conclusions can be drawn:

- The regulated emission results on all tested cars were very close to the certification data. Therefore, they could be considered representative samples of each car model. The two petrol cars in this study proved to be on pair with some of the best cars that have been tested previously at MTC.
- As expected, CO and HC emissions were generally lower from diesel cars than from petrol cars, while the results for NO_X emissions was the opposite. Particulate emissions were higher from the diesel car without particulate filter compared to its petrol counterpart. However, the diesel car with a particulate filter had lower particulate emissions than the corresponding petrol car.
- Emissions of some nitrogen containing compounds, as ammonia (NH_3) and nitrous oxide (N_2O), were low from all cars.
- The aldehyde emissions, a well-known problem for diesel engines, were at or below the detection limit for the diesel cars at high ambient temperature (+22°C). At the lower ambient temperature (–7°C), the level was approximately twice the detection

limit. This implies that considerable improvements have been made in this area compared to diesel cars of the past.

- The petrol cars had higher emissions of benzene, ethene, propene and 1,3-butadiene than their diesel counterparts, although the levels of these emission components were low for all cars.
- PAC/PAH emissions are usually low from petrol cars at high ambient temperatures. As the level of these emissions has previously been higher for diesel cars at these ambient conditions, this has been considered as one of the main emission problems for diesel cars. It has seldom been recognised that *the level increases considerably for petrol cars when the ambient temperature decreases*. The PAC level for the petrol cars tested in this study were considerably reduced compared to previous tests on older cars at the low ambient temperature. The PAC levels for the diesel cars were generally lower than for their petrol counterparts at the average yearly temperature of +7°C. The PAC level for the diesel car with a particulate filter was one order of magnitude lower than the petrol car from the same car manufacturer. A comparison with data on 1993/1994 model years of petrol cars gives a difference of more than 2 orders of magnitude. Although the diesel car without a particulate filter had lower PAC emissions than its petrol counterpart, the great variation between cars implies that new diesel cars (w/o particulate filters) are not necessarily better than new petrol cars in this respect.
- The diesel car without a particulate filter emitted about 2 orders of magnitude more particles than its petrol counterpart in the NEDC cycle at both temperatures. However, in the US06 test cycle the number of particles was on roughly the same level as for the petrol cars. The increase in particulate number for the petrol cars in this cycle compared to the NEDC cycle was mainly attributable to an increase of the smallest particles (7 – 30 nm). The diesel car with a particulate filter was outstanding in this respect having particulate number emissions at least one order of magnitude lower than the petrol cars. The particulate filter was particularly effective in reducing the number of nanoparticles. Comparison with older data showed a reduction of the particulate number for the diesel car without particulate filter.
- The ozone forming potential was considerably lower for the diesel cars, i.e. roughly one order of magnitude lower than for the petrol cars. This is mainly due to the low level of HC emissions for diesel cars compared to the petrol cars. Should the evaporative emissions have been taken into account, the relative difference would have been even greater.
- The cancer risk index was generally significantly lower for the cars tested in this study compared to older vehicles. The diesel car with a particulate filter had a lower cancer risk index than its petrol counterpart. For the diesel car without a particulate filter, the level was slightly higher than for the petrol car from the same manufacturer. In general, the lowest value was obtained for the diesel car with a particulate filter, i.e. almost 98% lower than petrol cars of model year 1993/1994. It should be noted that the uncertainty is high for the cancer risk index due to the varying level for the unit risk factors, depending on which source is used. Therefore, small differences should not be considered.
- The environmental effects mostly related to the emissions of NO_X, such as NO_2 forming potential, acidification and eutrophication, were greater for the diesel cars than their

petrol counterparts, due to the higher NO_X emissions. The contribution from fuel production was higher for the petrol cars.

- As expected, climate change and energy use was lower for the diesel cars than for the petrol cars. This is partly due to the lower fuel consumption, partly to the higher efficiency in fuel production.

Although the scope of this study was to compare the emissions from diesel cars with the emissions from petrol cars, it cannot be avoided to point out that the focus was shifted towards the results on the diesel cars. This is mainly because most data on unregulated emissions on new cars have been generated on petrol cars. Relatively little is known on the impact of new technology in this respect. As expected, the NO_X and particulate emissions are the main emission problem on diesel cars. The results on particulate emissions show that a particulate filter is very effective in reducing these emissions. For both emission components, solutions that can alleviate these problems have been introduced, or will be introduced on the market in the near future. Nevertheless, as diesel cars are improved in this respect, so will petrol cars. The test results on the unregulated emissions, and the effects on health and environment that were evaluated, showed lower levels in some cases for diesel cars and higher levels in other cases compared to petrol cars. Eventually, as the emissions from vehicles running on both types of fuels will be reduced to a negligible level, energy efficiency and the emissions of greenhouse gases will become more pronounced in the future.

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